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Satellite-based energy balance model to estimate seasonal evapotranspiration for irrigated sorghum: a case study from the Gezira scheme, Sudan

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Abstract. The availability of the actual water use from agricultural crops is considered as the key factor for irrigation water management, water resources planning, and water allocation. Traditionally, evapotranspiration (ET) has been calculated in the Gezira scheme as the point of reference with evapotranspiration (ET_o) and crop coefficients (k_c) being derived from actual measurements of soil-water balance. Recently developed, advanced energy balance models assisted in estimating the ET through the remotely sensed data. In this study Enhanced Thematic Mapper Plus (ETM+) and MODerate Resolution Imaging Spectroradiometer (MODIS) images were used to estimate the spatial distribution of the daily, monthly and seasonal ET for irrigated sorghum in the Gezira scheme, Sudan. The daily ET maps were also used to estimate k_c over time and space. Results of the energy balance, based on being remotely sensed, were compared to actual measurements conducted during 2004/05 season. The seasonal actual ET values, obtained from the seven MODIS images for irrigated sorghum, were estimated at 579 mm. The values for remotely sensed k_c, derived during the initial mid-season and late-season crop development stages, were 0.62, 0.85, 1.15, and 0.48, respectively. On the other hand, the values for the experimental k_c during the pervious mention stages were 0.55, 0.94, 1.21 and 0.65, respectively. The estimated seasonal ET of the sorghum, derived by remotely sensed k_c, was 674 mm. The Landsat data and the Free MODIS provided reliable, exhaustive, and consistent information on the water use, relevant for decision support in the Gezira scheme.

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1 Introduction

The yield of crops in the rain-fed sector in the Sudan has progressively declined with time, owing to changes in both quantity and distribution of the rainfall (El-Karori, 1986; Olsson and Rapp, 1991). This has put great pressure on the irrigated sector to increase the acreage to meet the population's food demand. Moreover, it is estimated that, by 2025 cereal production will have to increase by 38% to meet world food demands (Seckler et al., 1999), putting even more stress on the scarce water resources. However, the limited quantity of water available and the cost of its pumping, make it mandatory that irrigation water be used efficiently. Therefore, balancing the limited water resources is a big challenge facing the irrigation system managers and engineers for the coming years.

To accurately estimate evapotranspitation is considered to be the key factor in water resources management in the arid environment where irrigation is necessary and water is quite expensive. Recently, computer-simulation models are being used to estimate evapotranspiration from heterogeneous natural landscapes, which are in a dynamic state due to a spatial and a temporal variation of interactions between soil, vegetation and atmosphere (Allen, 2000a). Such models require a complex and high-quality input data to obtain accurate results. One of the most important developments in the field of remote-sensing hydrology is the determination of distributed aerial actual evapotranspiration from spectral satellite data, based on the energy balance approach (Menenti, 1984; Parodi, 1993; Bastiaanssen, 1995; Bastiaanssen et al., 1998a; Su, 2002).

The main advantage of the energy balance, based on remotely-sensed data, is that large areas are covered and

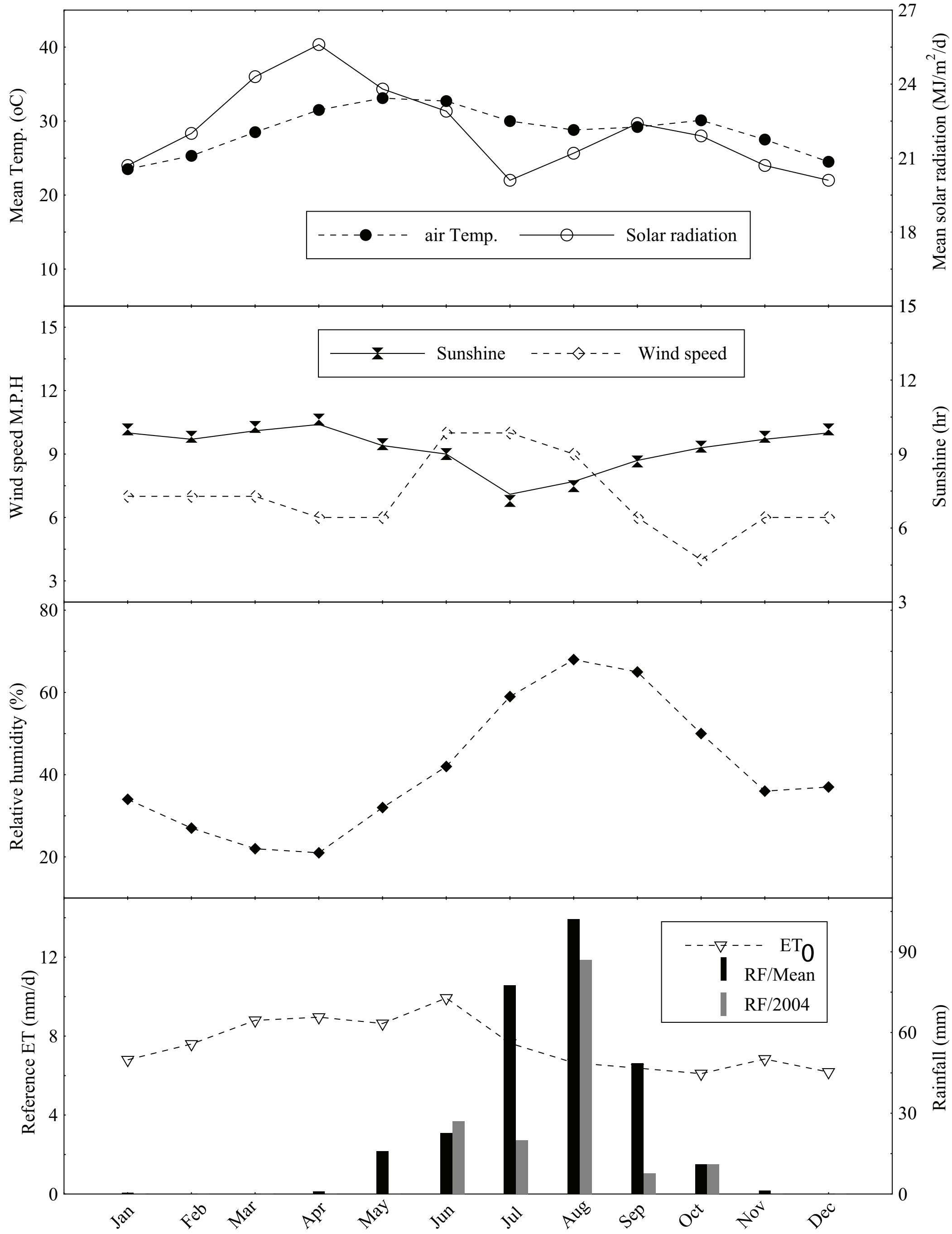

Fig. 1. Monthly mean of various weather variables of the study area (Sudan Meteorological Authority 1971–2000).

information is easily obtainable without extensive monitoring networks in the field. However, the potential limitation of the energy balance model is the decrease in satellite image availability due to clouds.

In this study, a satellite-based energy balance model for surface fluxes, known as Surface Energy Balance Algorithm for Land (SEBAL) developed by Bastiaanssen et al. (1998a) was used with Enhanced Thematic Mapper Plus (ETM+) and MODerate Resolution Imaging Spectroradiometer (MODIS) data to estimate actual evapotranspiration of irrigated sorghum on a daily, monthly and seasonal basis. The SEBAL enables the calculation of the actual evapotranspiration during the time of satellite over pass, which involves complex procedures and the purpose of a number of variables, such as surface temperature, Normalized Difference Vegetation Index (NDVI), emissivity and albedo. A

Table 1. Brief description of imagery used in this study.

Platform	Sensor	No. of images	Dates
Landsat 7	ETM+	4	28 Jul, 29 Aug, 16 Oct, 17 Nov (all 2004)
Terra	MODIS	7	29 Aug, 7 Sep, 21 Sep, 16 Oct, 23 Oct, 1 Nov, 15 Nov (all 2004)

temporal integration of the daily ET for the period August–November was used to provide the seasonal actual ET map.

The objectives of this study were (i) to estimate the spatial seasonal actual ET of irrigated sorghum in the Gezira scheme and compare the results with the actual measurements (ii) to apply SEBAL to derive at actual k_c for sorghum and compare the values with the experimental k_c of the Gezira scheme (iii) to compute crop water requirement of sorghum using remote-sensing derived k_c.

2 Materials and methods

2.1 Study area and conditions

The research was conducted in the Gezira scheme during 2004/05 season. The study area is located between latitudes 13°30′ N and 15°15′ N, and longitudes 32°15′ E and 33°45′ E. The climate is semi-arid with annual precipitation of about 280 mm (30-year average) most of it occurring between July and October, which indicates the requirement of irrigation to sustain agriculture production. The agriculture depends on supplementary irrigation from the Blue Nile. Furrow irrigation is the main irrigation system in the scheme. Temperatures are hot in summer, reaching an average of 41.5°C in May, while the average minimum temperature is 14.1°C in January. The annual mean air temperature is 28.7°C. Annually, the average relative humidity is 41%. The annual mean bright sunshine duration and solar radiation are 9.3 h and 22.1 MJ/m^2/d, respectively (Fig. 1). The major crops are cotton, sorghum, groundnut and wheat. However, sorghum is considered to be the main staple food in Sudan. The area that is annually cultivated with sorghum is estimated to be 0.25 million hectares.

2.2 Remote sensing input

Remotely sensed data used in the study were Landsat 7 and MODIS images of different dates. The MODIS images from seven different dates, representing the period August–November, were downloaded from the website of MODIS Data Support, the EOS Data Gateway (http://daac.gsfc.nasa.gov/). The descending mode images from Landsat ETM+ data at daytime, having spatial resolution of 28.5 m^2 at satellite nadir, were used. In this study, four Landsat satellite images (path 173/row 50), acquired by Landsat 7, were processed. Images with zero percent cloud cover were selected for the processing. The Landsat overpass time was approximately 09:58:07 a.m. local standard time (LT). All images (MODIS and Landsat) were radiometrically and geometrically corrected and geo-registered. Table 1 shows brief description of the data used.

Due to an instrument malfunction occurring onboard Landsat 7 on 31 May 2003, the total loss of the image data has been estimated to be approximately 22% over any given scene. The problem was caused by failure of the Scan Line Corrector (SLC) which compensates for the forward motion of the satellite. Without an operational SLC, the Enhanced Thematic Mapper Plus (ETM+) line of sight now traces a zig-zag pattern along the satellite ground track, resulting in missing data spanning across most of the image with scan gaps varying in size from two pixels near the center of the image to 14 pixels along the east and west edges. The impacts are more pronounced along the edge of the scene and gradually diminish towards the center of the scene. The middle of the scene (approximately 22 km) should be very similar in quality to pervious Landsat image data that was acquired prior to the failure of SLC. In this study, the analysis was applied to the middle part of the scene using four Landsat ETM+ images, acquired on different dates, to estimate the actual evapotranspiration for summer sorghum crop during 2004 season.

2.3 Energy balance approach

There are many remote-sensing algorithms for assessing the energy balance fluxes on the surface; each algorithm has its own advantages and disadvantages. The SEBAL procedure allows us to estimate the ET at a regional scale using a small amount of ground based inputs. The model also does not require a crop classification map. However, the disadvantages are that it requires cloud-free conditions and heterogeneity in moisture conditions.

The SEBAL is the most promising algorithm and it has been widely applied in several countries due to its accurate estimation of actual evapotranspiration (Bastiaanssen et al., 1998b, 2005; Bastiaanssen and Bos, 1999; Hemakumara et al., 2003). The SEBAL calculates both the instantaneous and 24-h integrated surface heat fluxes. The latent heat flux represents the energy required for ET, and is computed as the residual of the surface energy balance. The simplified form of the energy balance equation is given by

$$Rn = H + G_o + \lambda E \tag{1}$$

where *Rn* is net radiation (W/m^2), H is sensible heat flux to warm or cool the atmosphere (W/m^2), G_o is soil heat flux (W/m^2), and λE is latent heat flux (W/m^2), associated with the evaporation from soil, water and vegetation.

The net radiation is computed from spatially variable reflectance and emittance of radiation. This model requires spectral radiances in the visible, near infrared and thermal infrared regions of the spectrum to determine the intermediate parameters such as surface albedo, NDVI and surface temperature. The soil heat flux is the energy connected to soil warming, and it is computed as an empirical fraction of the net radiation using surface temperature, surface albedo and NDVI as the depending variables.

In the SEBAL method, the initial estimate of rough surface length for momentum transport (z_{om}) is based upon the soil adjusted vegetation index (SAVI) using an empirical relation (Moran and Jackson, 1991). The observed wind speed measurements are used to determine the friction velocity (u_*) at each pixel, based on the assumption that the wind speed at blending height (200 m) is aerially constant. Reference heights Z_1 and Z_2 (usually 0.01 and 2.0 m above the ground, respectively) are defined as the vertical limits for specifying sensible heat flux (H) and near surface temperature difference *dT*. Then, according to the sensible heat transfer equation, these limits become applicable for aerodynamic resistance (r_{ah}) (Farah and Bastiaanssen, 2001). The extremes of wet (zero sensible heat flux assumed, Rn=G_o+λE) and dry (zero latent heat flux assumed, Rn=G_o+H) pixels within the image, enable partitioning of the available energy on the surface. This implies that dT_{wet}=0 and $dT_{\text{dry}}= (Rn - G_o)\, r_{ah}/\rho_a Cp$ and allows the estimation of dT_{dry} using the initial estimate of r_{ah}. It is assumed that *dT* is linearly related to surface temperature at all pixels and, hence, the determination of the relationship is possible with the aid of the extreme pixels. The first estimate of sensible heat flux is used to correct the turbulent heat transport for buoyancy effects, according to Monin-Obuhkov's similarity hypothesis. The estimation of sensible heat flux requires iterative solution until H converges to the local non-neutral buoyancy for each pixel.

The evaporative fraction (EF) describes the partitioning of the surface energy balance as the latent heat flux/net available energy, with the net available energy being defined as the difference in net radiation and soil heat flux. In this study, we used the concept "ETo fraction" (EToF), which represents the ratio of ET of each pixel to the reference ET (ET_o) as computed by Penman-Monteith method (EToF is the same as the crop coefficient, k_c), ET_oF is calculated and applied instead of EF:

$$\text{ET}_o F = k_c = \text{ET}/\text{ET}_o \tag{2}$$

The instantaneous EF and EToF are shown in the literature to be similar to the 24-h evaporative fraction and 24-h EToF, respectively, (Shuttleworth et al., 1989; Brutsaert and Chen, 1996; Trezza et al., 2003) and this allows estimating the latent heat flux at a daily basis. The crop reference evapotranspiration was obtained by applying Penman-Monteith method as fallows:

$$\text{ET}_o = \frac{0.408(Rn - G_o) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{3}$$

where ET_o denotes the crop reference evapotranspiration (mm/d), *Rn* the net radiation at crop surface (MJ/m^2/d), G_o the soil heat flux density (MJ/m^2/d), T the mean daily air temperature at 2 m height (°C), u_2 the wind speed at 2 m height (m s^{-1}), e_s the saturation vapour pressure (kPa), e_a the actual vapour pressure (kPa), $e_s - e_a$ the saturation vapour pressure deficit (kPa), Δ the slope vapour pressure curve (kPa °C^{-1}), γ the psychometric constant (kPa °C^{-1}). The REF-ET software version 2.0 that was developed by Allen (2000b) was used to compute ET_o. The monthly and seasonal EToF and ET were estimated by linear interpolating the EToF values for the period inbetween two consecutive images using the following equation:

$$\sum_{i=a}^{b} \text{ET} = \sum_{i=a}^{b} \left(\text{EToF}_{(i)} \times \text{ET}_{o(i)} \right) \tag{4}$$

where a and b are the start and end dates of integration, $\text{EToF}_{(i)}$ is EToF for day i, predicted by linear interpolation of EToF between two consecutive satellite images, and $\text{ET}_{o(i)}$ is grass reference ET for date i, calculated from the point-based weather data. The concept was used by many researchers (Tasumi et al., 2005; Chemin et al., 2004). For more details, description and calculations of SEBAL, refer to Bastiaanssen et al. (1998a) and Tasumi et al. (2000).

2.4 Calculation of actual crop evapotranspiration

The water content in the effective root zone is estimated by using the water balance equation on a daily basis, according to the equation below:

$$\text{ET} = I + P - D - SR + \Delta S \tag{5}$$

where ET is the evapotranspiration (mm), I is the irrigation applied (mm), P is the precipitation (mm), D is the amount of drainage below the root zone, *SR* is the surface runoff and ΔS is the change in soil moisture storage (mm). Because of the negligible values of runoff, deep percolation and capillary rise, the above water balance equation for the Gezira clay soil was reduced to:

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

Irrigation and precipitation are the deposits in water balance and are measured or calculated values. In this study, applied irrigation water was measured using gravimetric samples (to

Table 2. Emissivity, albedo and surface roughness of wheat, cotton and rice used in the model compared to literature values.

	Crop	Value	Literature biophysical values
Emissivity	Wheat	0.987	0.981–0.986[a]; 0.976[b]
	Cotton	0.973	0.96[c]
	Rice	0.970	0.97–0.85[d]
Albedo	Wheat	0.168	0.14–0.22[e]; 0.16–0.22[c]; 0.16–0.23[f]
	Cotton	0.151	0.21[f]
	Rice	0.168	0.17–0.22[e]; 0.25[g]; 0.12[f]
Surface roughness	Wheat	0.013	
	Cotton	0.014	
	Rice	0.016	

[a] Chen and Zhang (1989); [b] Huband and Monteith (1986); [c] Campbell and Norman (1998); [d] Coll et al. (2004); [e] Allen et al. (2002); [f] Halstead et al. (1957); [g] Mohan and Arumugam (1994)

reduce the error of calculations, more than three gravimetric samples were randomly taken from the same point) before each irrigation and 2–3 days after irrigation. Rainfall was measured using the rain gauges. During the short post-irrigation periods, the roots suffer from temporary anaerobic conditions and consequently ET was very small and, hence, neglected (Fadl, 1978). The data of the soil volume-weight ratios, introduced by Abdine and Farbrother (1969), were used to generate regression equations that link soil bulk density to soil depth and moisture content. For a depth of 0–60 cm, second degree polynomial equations were used in the regression as it provided a better match than the simple linear regression (R^2=0.996), while linear regression showed a high coefficient of determination than polynomial for the 60–100 cm depth (R^2=0.967). The generated regression equations were used to transform the gravimetric moisture contents to volumetric values. The actual evapotranspiration during each irrigation cycle was calculated from soil water balance between each post and pre-irrigation moisture sampling cycles (Abdelhadi et al., 2006). The gravimetric moisture samples were taken with 20 cm increments up to one meter depth.

3 Results and discussions

3.1 Evaporative depletion of the study area

During the 2004/05 season, the actual evapotranspiration (ET_a) via SEBAL and water balance (WB) was quantified for irrigated sorghum in the Gezira scheme, Sudan. In particular, the soil of the study area is a deep, heavy soil with 58–66% clay, 0.5% organic matter, a water infiltration rate of 1 mm h^{-1} and a pH of 8.5.

To judge the quality of the model output, a comparison to ground based measurements, taken from secondary sources, are shown in Table 2. Biophysical values for wheat, cotton and rice of the input parameters albedo and emissivity,

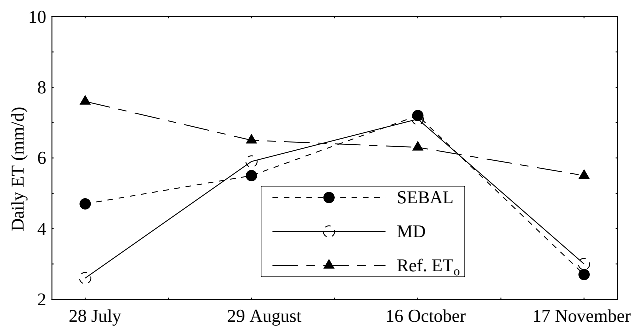

Fig. 2. Comparison of the daily actual ET (mm/d) estimated by SEBAL and the daily actual ET calculated by the water balance (WB) method (Landsat data).

points to the validity of the data. The model input values were in agreement with literature values (Campbell and Norman, 1998; Huband and Monteith, 1986; Allen et al., 2002). Figure 2 shows the daily actual ET estimated by SEBAL and calculated by the WB method (ET_a computed as a residual of soil water balance, Eq. 5). The results from Fig. 2 indicate that ET_a estimated by SEBAL were similar to those calculated by the WB method during the last three dates (29 August, 16 October and 17 November), while at the beginning of the season the SEBAL overestimated the WB, the underestimation of the WB method could be attributed to the difficulties of measuring actual ET by WB during the first irrigation due to the special nature of Gezira Vertisols (soil had huge cracks at the beginning of the irrigation season). During 28 July, 29 August, 16 October and 17 November the SEBAL ET_a values were 4.7, 5.5, 7.2, and 2.7 mm/d, respectively, while for the WB method, the calculated ET_a were 2.6, 5.9, 7.1, and 3.0 mm/d. The comparison provides an indication of the amount of confident that can be given to ET estimated via remotely sensed based-energy balance model such as SEBAL. Figure 3 also demonstrates the comparison

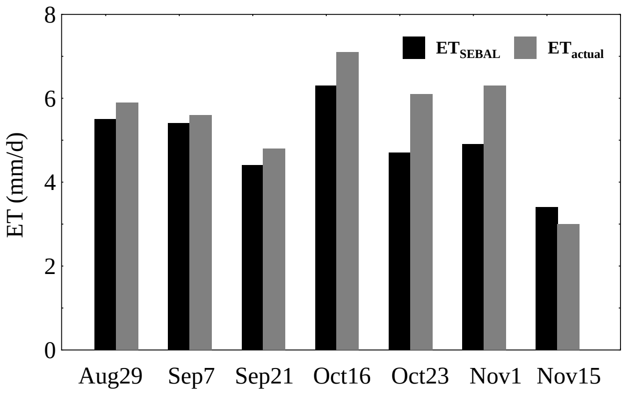

Fig. 3. Comparison of daily actual ET (mm/d) estimated by SEBAL and daily actual ET calculated by water balance (WB) method (MODIS data).

between ET estimated from MODIS images and was measured using the water balance method. The average absolute error between the ET estimated and measured values found to be around 0.9 mm/d compared to 0.7 mm/d for the Landsat images. The MODIS data can predict the ET losses from the agricultural field accurately as well as Landsat, if it is used routinely throughout the season.

The frequency distribution of the daily actual ET for the different Landsat image dates, including all land use types, are presented in Fig. 4. The histograms in Fig. 4 associate the higher ET to irrigated crop grown in the study area, while low ET was observed from bare soil and settlements. In 28 July, irrigated crops showed relatively high ET, although most of the crops were at the initial stage. This could be attributed to high soil moisture (a substantial rain occurred one day prior to the image acquisition) at the root zone at the time of the satellite overpass. Two clear peaks appear in the histograms, distinguishing between vegetation fields and fallow areas (sparse vegetation), on 28 July one peak around 3.5 mm/d (fallow soil) and the second one around 4.6 mm/d (irrigated crops), cotton crop obtained more than 4 mm/d during 29 August, during 16 October the first peak represents fallow soil (2.7 mm/d) and the other represents sorghum and cotton areas, while during 17 November the fallow soil shows very low ET_a. It should be noted that during 17 November, the high evaporation signature (greater than 6 mm/d) represents the cotton field as sorghum was harvested or due to the harvest, ET was reduced to less than 3 mm/d. The ET maps also include values for areas near the irrigation system that include natural vegetation, bare soil and riparian vegetation. All of these ET values are important for the hydrological balance of the area as well as for groundwater modeling.

In this study, the monthly and seasonal evapotranspiration ET_s maps on a pixel-by-pixel basis were produced for the summer irrigated season of 2004/05. Figure 5 demonstrates the comparison of monthly ET (mm) estimated using SEBAL

Table 3. Remote sensing-derived crop coefficient compared with experimental k_c from Farbrother (1973) for irrigated sorghum at different growth stages.

Method	Crop coefficient values: Initial stage	Crop-develop. stage	Mid-season stage	End-season stage
Farbrother k_c	0.55	0.94	1.21	0.65
RS k_c	0.62	0.85	1.15	0.48

and monthly ET calculated using the water balance approach (WB) for irrigated sorghum in the Gezira scheme. The absolute error% values between monthly estimated ET by SEBAL and monthly calculated ET by the WB for sorghum during September, October and November were 4%, 4%, and 19%, respectively.

Figure 6 illustrates the spatial distribution map of ET_s (mm/season) for the summer season (1 August to 27 November). The pattern of ET determined with SEBAL for all features in the image was compared to a simple false color composite (FCC) of MODIS band 4, 2, and 1 (RGB) the degree of associations is noteworthy. However, such simple band combination gives a first approximate visual impression of the relative ET distribution in the study area. The estimated seasonal ET for land cover in the study area lies between 52–800 mm. Using the water balance approach, the accumulated ET of irrigated sorghum for a period of 92 days (28 August–27 November) was 489 mm. SEBAL estimated ET from MODIS, for the same period, was 451 mm with 8% deviation from the actual measurements. Bastiaanssen et al. (2005) reported that, the accuracy of SEBAL measured on a field scale by lysimeter, scintillometer, Bowen ratio towers, or Eddy correlation fluxes varied between 1 and 33% for instantaneous ET and between 2 and 30% for 10-day ET. At the catchment scale, accuracies were estimated by the water balance, which led to results of less than 11%.

The seasonal ET consumption at the administrative level (group) in the Gezira scheme was monitored using the MODIS data (period from August to November). Figure 7 provides details of seasonal water depleted at each group in the scheme. The eastern group shows the lowest seasonal ET (424 mm). Seasonal ET estimated from Masalamia, Wadhabouba, Wadishaier, North and Matori groups is more than 550 mm. Variation of ET between the different groups has the potential to identify areas of water stress and that of water logging to improve water use efficiency in the scheme. This could be achieved from the analysis of the ET in the dry and wet areas of the different groups shown in Fig. 7.

The quantification of accurate daily and seasonal evapotranspiration for different land cover types in the irrigated scheme will provide valuable information for the farmers and irrigation engineers to determine the delivered amount

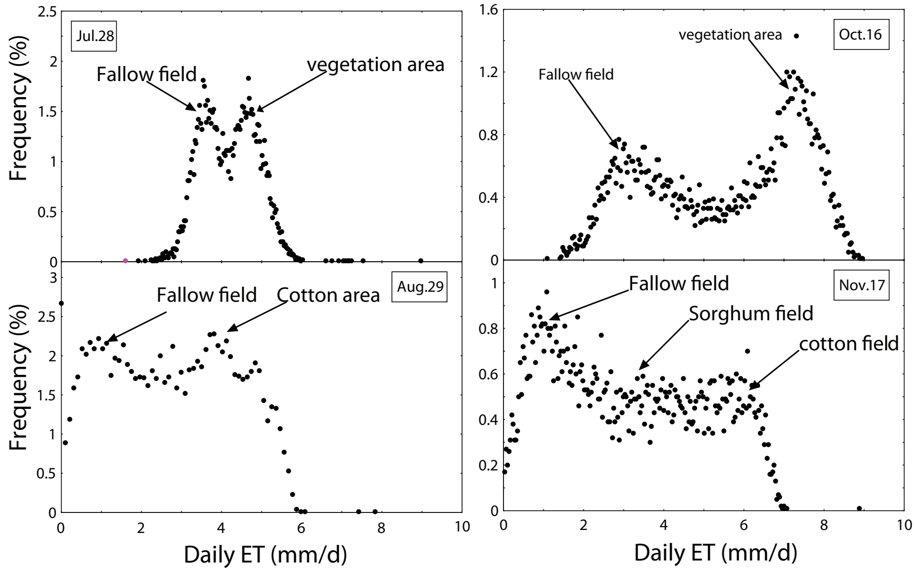

Fig. 4. Histogram showing the actual evapotranspiration (mm/d) of the study area during the acquisition time.

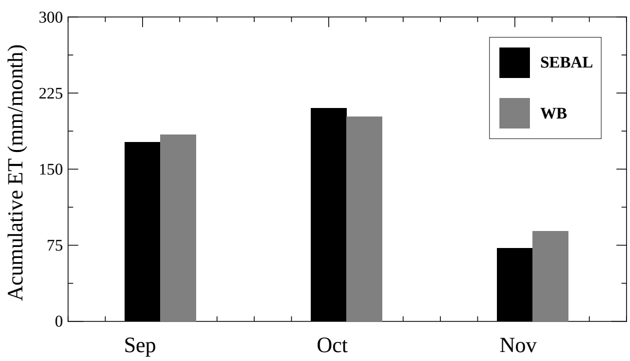

Fig. 5. Monthly accumulated actual ET (mm) as estimated by SEBAL and calculated by water balance (WB) method.

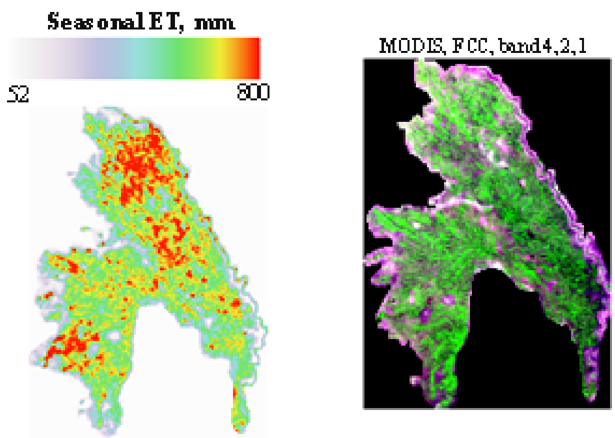

Fig. 6. Spatial distribution map of seasonal evapotranspiration (ET_s) of the study area during the period 1 August to 27 November using MODIS data.

of water and for this reason, enhanced the irrigation and application efficiencies for the whole system. Consequently, this will lead to sustainable management of the limited water resources in the country.

3.2 Remotely derived crop coefficient, k_c

Remote sensing-derived k_c (RS k_c) values were determined for each pixel by dividing the actual ET from SEBAL by reference crop evapotranspiration ET_o as estimated by using Penman-Monteith equation. Table 3 demonstrates the comparison of the derived k_c with the experimental crop coefficient by Farbrother (1973) for irrigated sorghum in the Gezira scheme at different crop stages. Farbrother and his co-workers, during the early 1970s, associated crop reference ET_o to evaporation from open water and called the ratio crop factor (k_f). These crop factors were converted later to crop coefficients (k_c=1.1×k_f) by Adam (2005) and it has been used to quantify crop water requirements for all the irrigated crops in the scheme. The remote sensing-derived k_c values for the different crop stages (initial, crop development, mid-season and end-season stages) were 0.62, 0.85, 1.15, and 0.48, respectively, while the experimental (Farbrother) k_c values for the corresponding crop periods were 0.55, 0.94, 1.21 and 0.65, respectively.

According to the results of this study, the estimated value of crop coefficient by SEBAL during mid-season looks similar to the k_c values suggested by Farbrother (during early 1970s) with only 5% deviation. During the initial stage, the derived k_c value was overestimating the experimental value

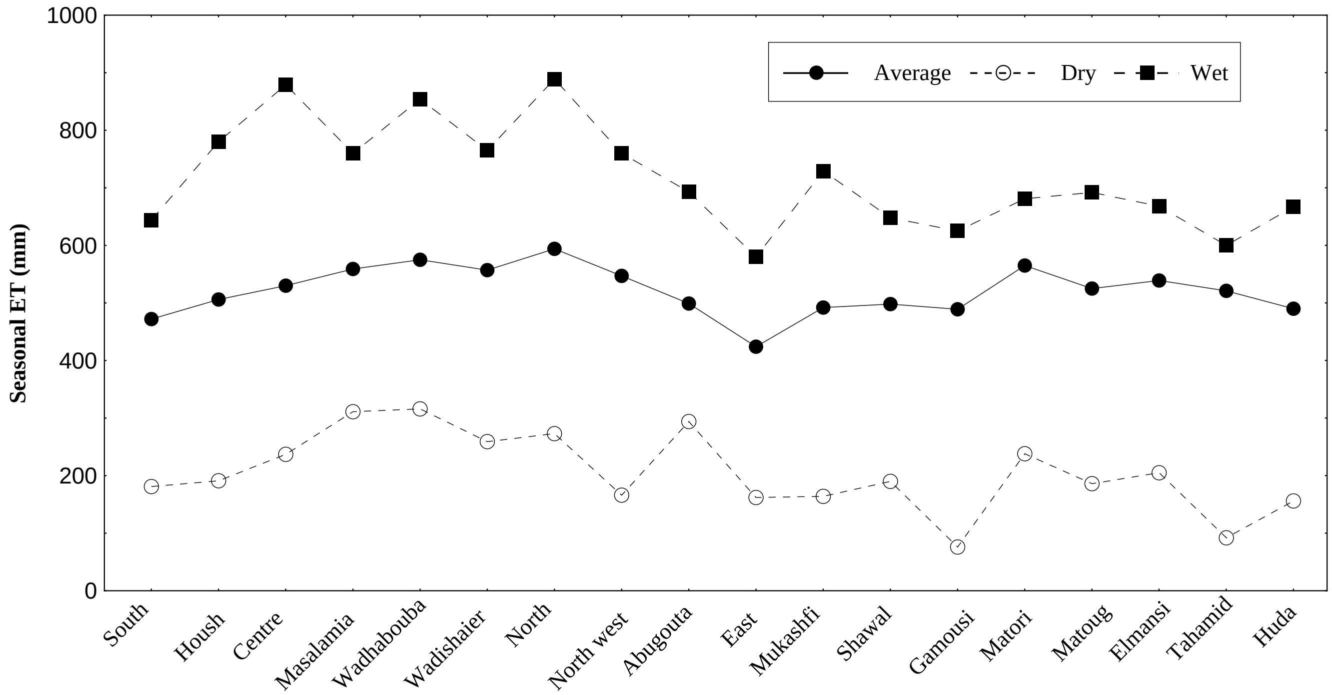

Fig. 7. Estimated seasonal actual evapotranspiration for various administrative units (groups) of the Gezira scheme.

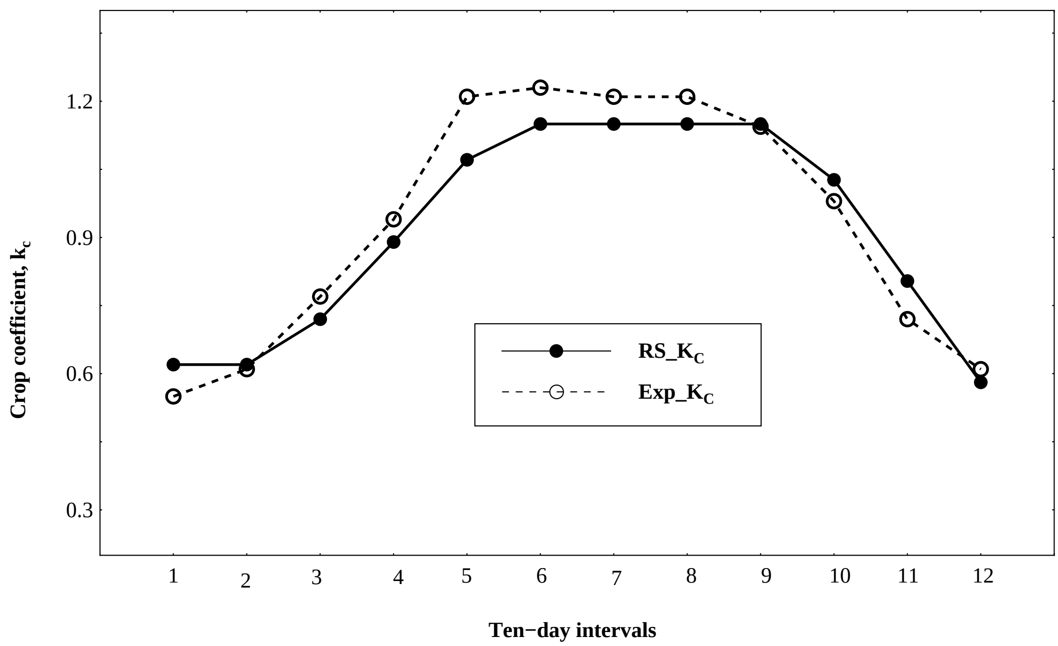

Fig. 8. Crop coefficient curve of sorghum.

by 13%, while during crop development stage, the remote sensing-derived k_c value underestimating the Farbrother by 10%. Significant differences were observed during the late season stage and the derived k_c, underestimating Farbrother by 26%. Above variations were expected and could be attributed to differences in crop varieties, differences in the date of sowing, changes in the climatic conditions and cultural practices. Such variations explain the difficulties of interpolating traditional k_c, determined for specific crop varieties and specific regions, to be used for large scale region.

Table 4. Evolution of crop water requirements of sorghum during the season estimated using remote sensing-derived k_c.

Month	10-days interval	Crop stage	ET_c/10-days (mm)	RF_{eff}/10-days	CWR/10-days (mm)
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

Thus due to the lack of actual crop coefficient, SEBAL can be used successfully to derive and update crop coefficient curves for large areas of crops in the Gezira arid conditions as the determination of field-measured k_c is expensive, labor intensive and time consuming.

3.3 Estimation of sorghum crop water requirements

Figure 8 shows the crop coefficient curve for sorghum derived from remote sensing data and Farbrother (Experimental k_c) based on ten-day intervals. Allen et al. (1998) stated that crop coefficient for any period of the season can be derived by considering 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 the k_c at the end of the pervious stage and k_c at the beginning of the next stage. The following equation was used in a spreadsheet program to compute k_c value at each single day of the entire season.

$$k_{c\,i} = k_{c\,\mathrm{prev}} + \left[\frac{i - \sum\left(L_{\mathrm{prev}}\right)}{L_{\mathrm{stage}}}\right]\left(k_{c\,\mathrm{next}} - k_{c\,\mathrm{prev}}\right) \tag{7}$$

where i is the day number within the growing season, k_{ci} is crop coefficient on day i, L_{stage} is the length of the stage under consideration (days), $\sum(L_{\mathrm{prev}})$ sum of the length of all previous stages (days). Both the derived and experimental crop coefficients were combined with the reference evapotranspiration to estimate crop water requirement (CWR) for sorghum based on ten-day intervals (Fig. 9). The seasonal CWRs estimated, based on the derived and the experimental crop coefficients, were found to be around 674 and 704 mm, respectively.

Table 4 shows the seasonal evolution of ET_c for the irrigated sorghum estimated using remote sensing-derived k_c. The ET_c increased from 35 mm per 10-day intervals to 67 mm per 10-day in the initial and development stages.

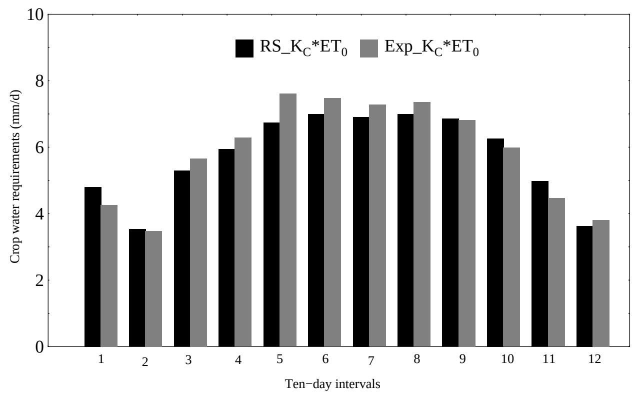

Fig. 9. Ten days interval crop water requirements for sorghum.

The mid-season stage was characterized by a maximum ET_c, reaching 70 mm then declining to 32 mm 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 canopy and climatic conditions. The average daily ET_c was 5.76 mm. The water from effective rainfall during the season was estimated at 103 mm, representing 15% of ET_c, an additional amount of 571 mm should be added by irrigation. It is clear that meteorological data and remote sensing measurements can be used to provide ET information on a seasonal basis, and then the farmer will be informed of the daily value of irrigation water requirements at field scale. The information obtained and the results achieved are very essential for managing scarce water in the region and to find options to "grow more crop per drop."

4 Conclusions

This study focused on the evaluation of multi-temporal ETM+ and MODIS data to calculate daily, monthly and seasonal ET based upon satellite energy balance model such as SEBAL. The seasonal ET estimated by SEBAL using MODIS data was 579 mm. A comparison of the seasonal ET estimated from MODIS with the actual measurements for a period of 92 days showed a deviation of 8%. Spatial daily maps were used to compute a crop coefficient curve for the irrigated sorghum, the derived crop coefficient values during initial stage, crop development, mid-season, and late season stages were 0.62, 0.85, 1.15 and 0.48, respectively. The derived crop coefficient from remote sensing was used to compute the crop water requirements of sorghum. The average daily ET was 5.76 mm. Considering the amount of effective rainfall, 571 mm should be added by irrigation throughout the season. The results above show that satellite-based energy balance model such as SEBAL is very useful in updating crop coefficient for specific crop.

Owing to low temporal resolution of high spatial resolution image and the cost involved with the acquisition, make their use unattractive. Therefore, the availability of free of charge daily basis satellites such as MODIS (Moderate Resolution Imaging Spectroradiometer) makes them a viable alternative for future estimation of ET. This kind of satellite data is sufficient for water management purposes on large irrigation systems such as Gezira scheme.

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