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Estimation of Evapotranspiration ET_c and Crop Coefficient K_c of Wheat, in south Nile Delta of Egypt Using integrated FAO-56 approach and remote sensing data

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Abstract Crop water requirements are represented by the actual crop evapotranspiration. Estimation of crop evapotranspiration (ET_c) and crop coefficient using remote-sensing data is essential for planning the irrigation water use in arid and semiarid regions. This study focuses on estimating the crop coefficient (K_c) and crop evapotranspiration (ET_c) using SPOT-4 satellite data integrated with the meteorological data and FAO-56 approach. Reference evapotranspiration (ET_o) were estimated using FAO Penman-Monteith and tabled single crop coefficient values were adjusted to real values. SPOT-4 images geometrically and radio metrically corrected were used to drive the vegetation indices (NDVI and SAVI). Multi linear regression analysis was applied to develop the crop coefficient (K_c) prediction equations for the different growth stages from vegetation indices. The results showed R^2 were 0.82, 0.90 and 0.97 as well as adjusted R^2 were 0.80, 0.86 and 0.96 for developing, mid-season and late-season growth stage respectively.

1. Introduction

The importance of water resources management is due to the increase of the population and water demand especially in the Middle East and North Africa, which are classified as arid and semi-arid regions. These are threatened by the water crisis in the future. Egypt is classified among the regions that are facing high-water shortages. This is mainly due to the combination of persistent drought and the increase of water demand effects, especially in the irrigation sector.

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The importance of wheat crop, that returns to its strategic value in the Egyptian diet commodities, is that it provides more than one-third of the daily caloric intake of Egyptian consumers and 45 percent of their total daily protein consumption (Rosen, 1993; Rowntree, 1993; Abdel Ghaffar, 1994).

Grain yield is affected by both the magnitude of water deficit, and the stage of growth subjected to the deficit (Salter and Good, 1994). Insufficient water supply caused by prolonging irrigation intervals, and or decreasing the available moisture in the soil clearly inhibits plant growth in terms of leaf area and plant height (Porro and Cassel, 1986).

The most common and practical approach widely used for estimating crop water requirement, and the operational monitoring of soil-plant water balance is the FAO-56 method. In the FAO-56 approach, crop evapotranspiration is estimated by the combination of a reference evapotranspiration (ET_o) and crop coefficients. There are two different FAO-56 approaches: single and dual crop coefficients. The single crop coefficient approach is used to express both plant transpiration and soil evaporation combined into a single crop coefficient (K_c). The dual crop coefficient approach uses two coefficients to separate the respective contribution of plant transpiration (K_{cb}) and soil evaporation (K_e), each by individual values (Allen et al., 1998).

Crop coefficients K_c primarily depended on the dynamics of canopies (cover fraction, LAI, greenness). Remote sensing data can be used to estimate some key-variables related to vegetation phonology (Bastiaanssen et al., 2000), which offer opportunities for monitoring the space and time variability of K_c. Use of remotely-sensed vegetation indices as the Normalized Difference Vegetation Index (NDVI) and the Soil Adjusted Vegetation Index (SAVI), has been tested to predict crop coefficients at field and regional scales (Rosue et al., 1974; Huete, 1988; Duchemin et al., 2002).

The remotely sensed spectral reflectance may provide an indirect estimate of crop coefficient or basal crop coefficients. Indeed, several authors have tested similarity between the seasonal patterns of different vegetation indices and transpiration over annual crops (Jackson et al., 1980; Bausch and Neale, 1987; Bausch, 1993, 1995; Hunsaker et al., 2003, 2005; Duchemin et al., 2006; Er-Raki et al., 2007). In addition K_c can be estimated from spectral vegetation indices since both are related to leaf area index and fractional ground cover (Heilman et al., 1982; Neale et al., 1989; Choudhury et al., 1994).

The main objectives of this study are: (1) Estimating the crop coefficient (K_c) and the crop evapotranspiration (ET_c) for the wheat crop in Egypt through the different growth stages from vegetation indices (NDVI, SAVI) derived from the SPOT-4 satellite images. (2) Mapping the crop coefficient and crop evapotranspiration within the entire field for different growth stages.

2. Materials and methods

2.1. Study area

The study area is located in south Nile Delta, Egypt. Where the soil is clay loam, has a relatively heavy texture permeable. The climate is arid Mediterranean type with an average annual precipitation of about 0.65 mm and temperature 25.7 co.31.5 acres are cultivated with wheat crop sub-species Bani-suief 1. The investigation was applied only on 10.5 acres (see Fig. 1).

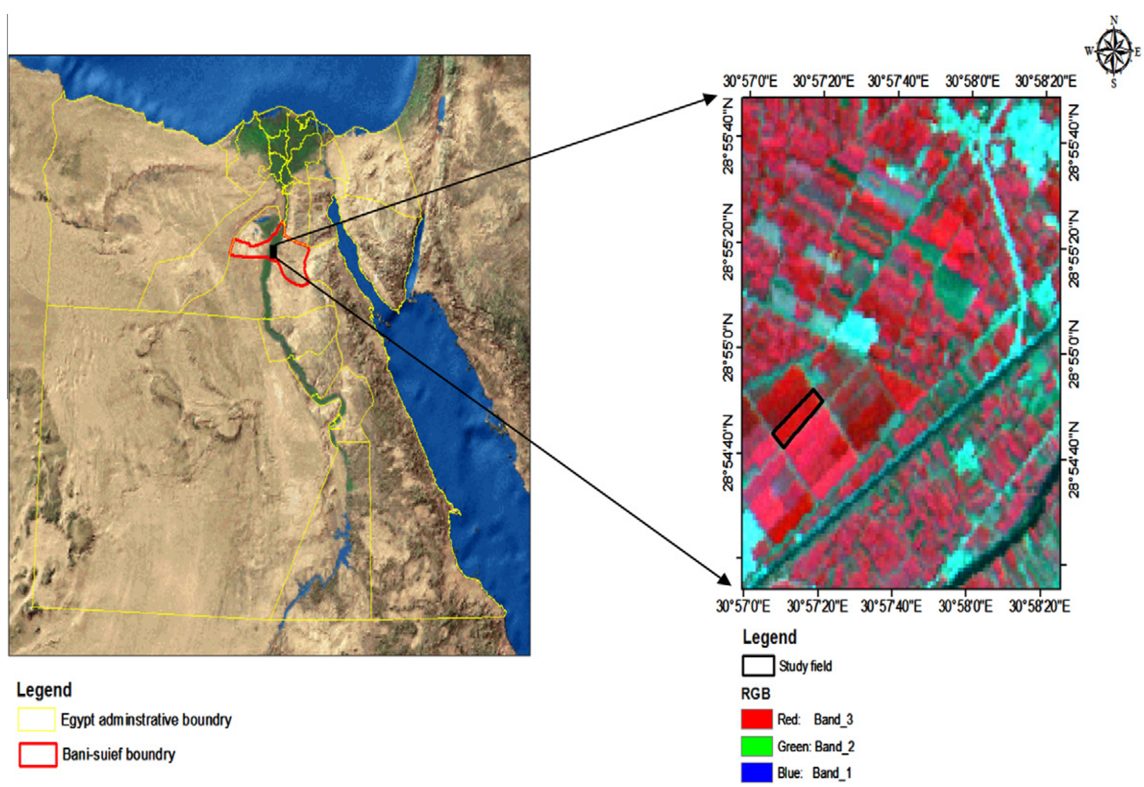

Figure 1 Location of study area SPOT-4 image in false color composition.

2.2. Data description

The field data were collected represented in the plant height to calculate the crop coefficient (K_c) using the equations and the tabled values of (K_c), in addition to meteorological data that gathered by the meteorological station used to calculate the reference evapotranspiration (ET_o). Set of three SPOT-4 satellite images were geometrically, radio metrically corrected and used to calculate the different vegetation indices such as Normalized Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI).

3. Methodology

The data acquired for 16 sample were systematic randomly distributed to cover the variation of crop overall the investigated area with an interval of 30 days starting from 60 days after plantation representing developing growth stage, 90 days after plantation representing the middle season growth stage and 120 days after plantation represents the late season growth stage.

The FAO Penman-Monteith method was used to estimate reference Evapotranspiration (ET_o) Eq. (1). The crop evapotranspiration (ET_c) can be calculated by multiplying the reference Evapotranspiration (ET_o) by Crop coefficient (K_c) Eq. (2).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_o is the reference evapotranspiration [mm day^{-1}]; R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}]; G is the soil heat flux density [MJ m^{-2} day^{-1}]; T is the mean daily air temperature at 2 m height [°C]; u_2 is 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]; Δ is the slope vapor pressure curve [kPa °C^{-1}] and γ is the psychrometric constant [kPa °C^{-1}].

$$ET_c = ET_o * K_c \tag{2}$$

where ET_c is the Actual evapotranspiration; ET_o is the Reference evapotranspiration and K_c is the Crop coefficient.

Crop coefficient is varying according to growth stage and also affected by the growth stage length. The tabulated values were modified to the real values of crop coefficient using Eq. (3).

$$K_{cStage(n)} = K_{cStage(n)(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{3}$$

where $K_{cStage(n)\,(Tab)}$ is the standard values according to FAO-56 approach (Allen et al., 1998) u_2 is the value for daily wind speed at 2 m height over grass during the growth stage [m s^{-1}]; $RH_{\min}$ is the value for daily minimum relative humidity during the growth stage [%] and h is the Plant height for each growth stage [m] (0.1 m < h < 10 m).

Normalized Difference Vegetation Index (NDVI) was calculated from three scenes of SPOT-4 for three different crop stages following Eq. (4). The principle behind NDVI is that the red band where chlorophyll is present causes considerable absorption of incoming sunlight, whereas the near infrared (NIR) band where a plant's spongy-mesophyll leaf structure is present creates considerable reflectance (Tucker et al., 1991). As a result, NDVI values vary according to the growth stage.

$$NDVI = \frac{(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + \rho_{red})} \tag{4}$$

where ρ_{NIR} is the Reflectance in the near infrared band and ρ_{red} is the Reflectance in the red band.

The Soil-Adjusted Vegetation Index (SAVI) was calculated from SPOT-4 satellite data for the three different crop stages following Eq. (5). According to (Huete, 1988), SAVI is the best index used to characterize the arid zone vegetation, knowing the sparse distribution of vegetation between bared soil patches.

$$SAVI = (1 + L) * \frac{(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + \rho_{red} + L)} \tag{5}$$

where ρ_{NIR} is the Reflectance in the near infrared band; ρ_{red} is the Reflectance in the red band and L is a parameter to minimize the soil influence (ranging from 0 to 1). Its value, as determined for arid zones by Huete (1988), is 0.5.

The stepwise linear regression model was used for statistically analyzing the data to drive linear equation for K_c prediction from NDVI and SAVI. Furthermore, the cross validation was applied to validate the model by using equal samples numbers for different positions within the same field (see Fig. 2).

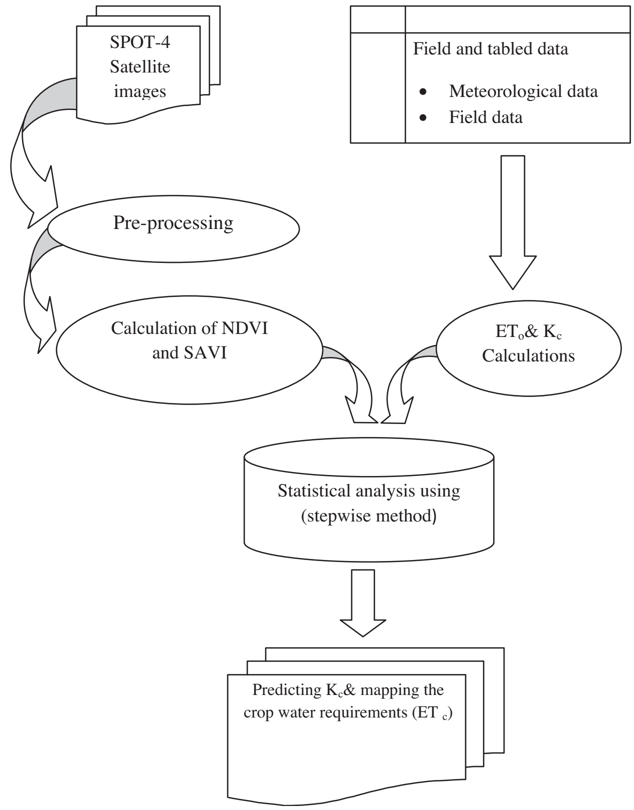

Figure 2 The methodology flowchart.

4. Results and discussions

The metrological data collected from the meteorological stations in the wheat research center were used to calculate the

Table 1 The meteorological data for the growth period.

Month	Min. temperature (°C)	Max. temperature (°C)	Relative humidity (%)	Wind speed (km day^{-1})	Avg. sun shine (h)	Avg. radiation (MJ m^{-2} day)	ET_o (mm day^{-1})
November	11.7	25.3	57	380	7.8	14.1	4.41
December	7.4	20.9	62	277	6.6	11.7	2.89
January	5.6	19.5	59	277	6.8	12.5	2.87
February	6.9	21.5	51	346	7.7	15.7	4.06
March	9.6	25	46	415	8.2	19.1	5.66
April	13.8	30.3	37	199	9.3	22.8	5.86

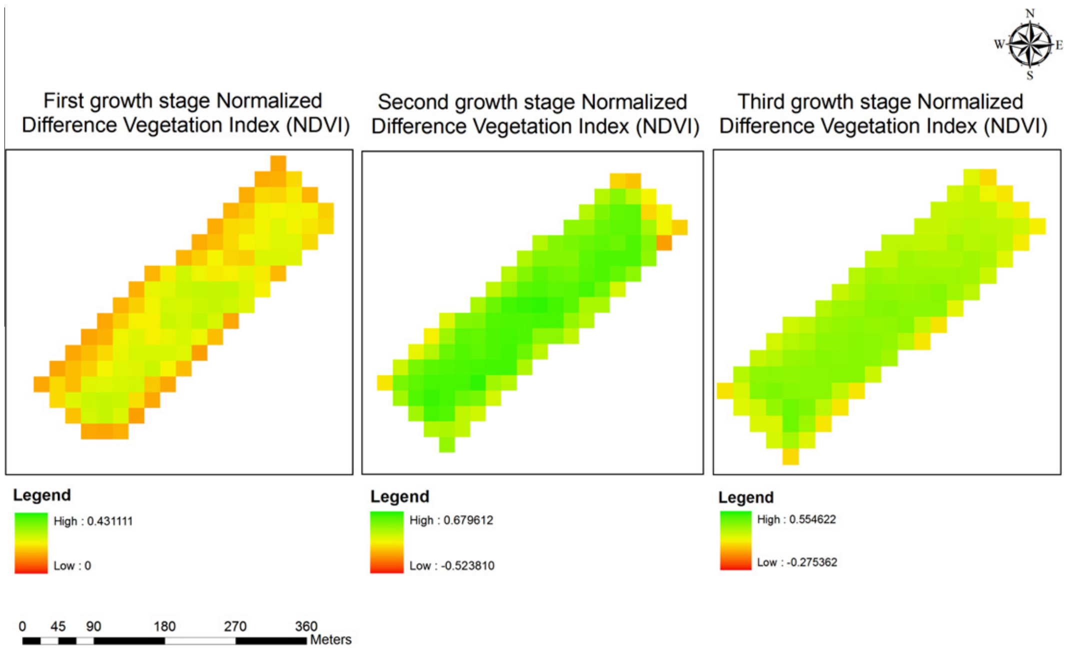

Figure 3 Normalized Difference Vegetation Index (NDVI) for growth stages.

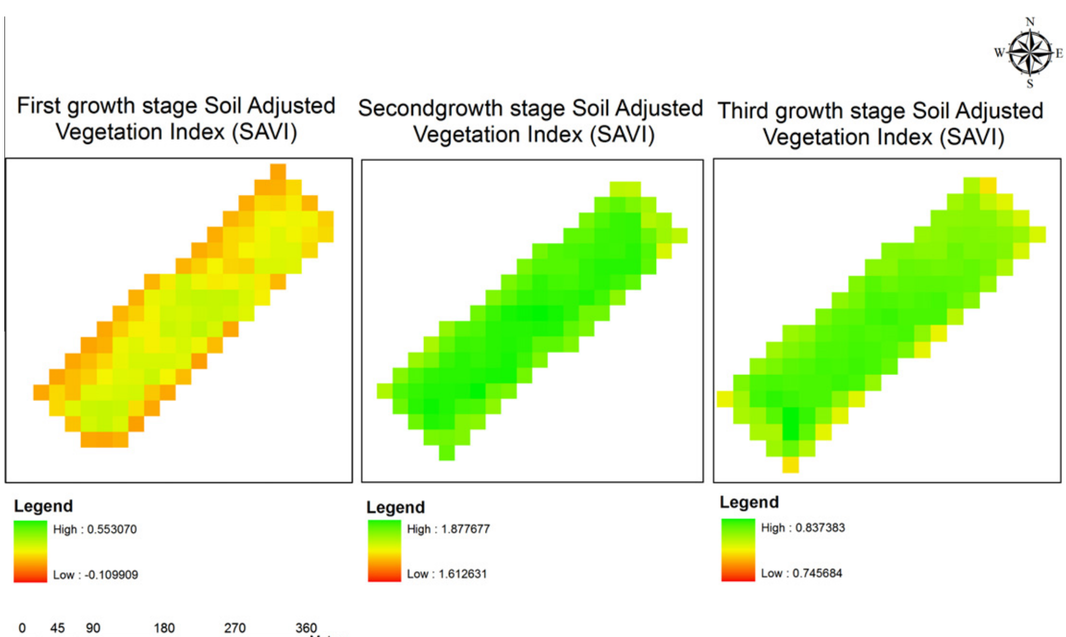

Figure 4 Soil-Adjusted Vegetation Index (SAVI) for growth stages.

Table 2 The prediction equations for different growth stages.

Growth stage	Prediction equation	R^2	Adj. R^2	RMSE
First growth stage	$K_c = 0.1099 + (-437.75*\text{SAVI}) + (654.943*\text{NDVI})$	0.827	0.808	0.0091
Second growth stage	$K_c = 1.877 + (-28.000683*\text{NDVI}) + (18.405*\text{SAVI})$	0.903	0.864	0.0014
Third growth stage	$K_c = 0.745 + (-17.901*\text{NDVI}) + (12.067*\text{SAVI})$	0.976	0.966	0.0007

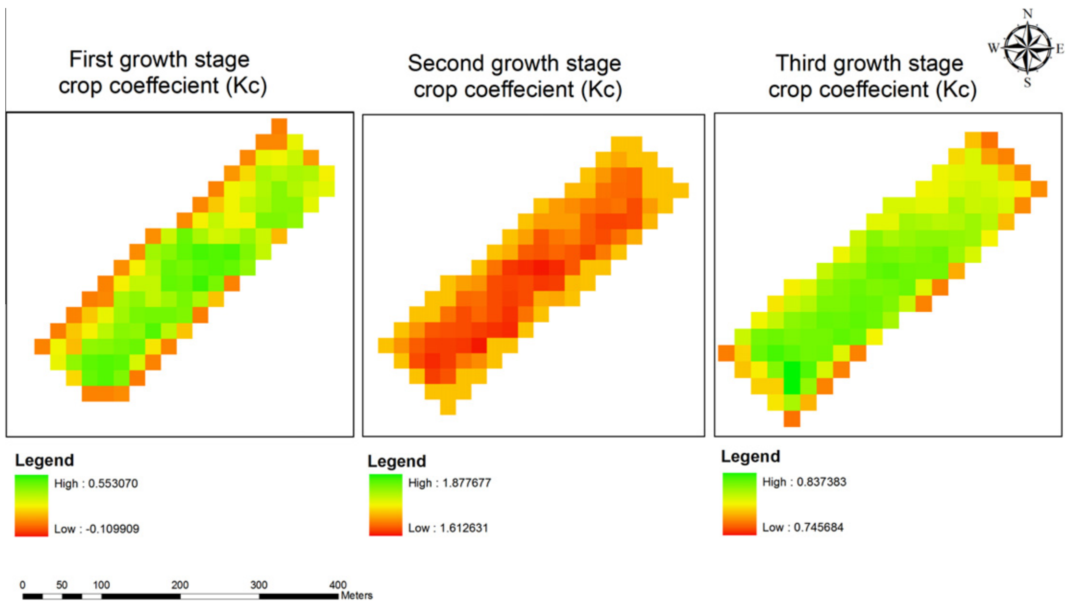

Figure 5 The predicted crop coefficient K_c for growth stages.

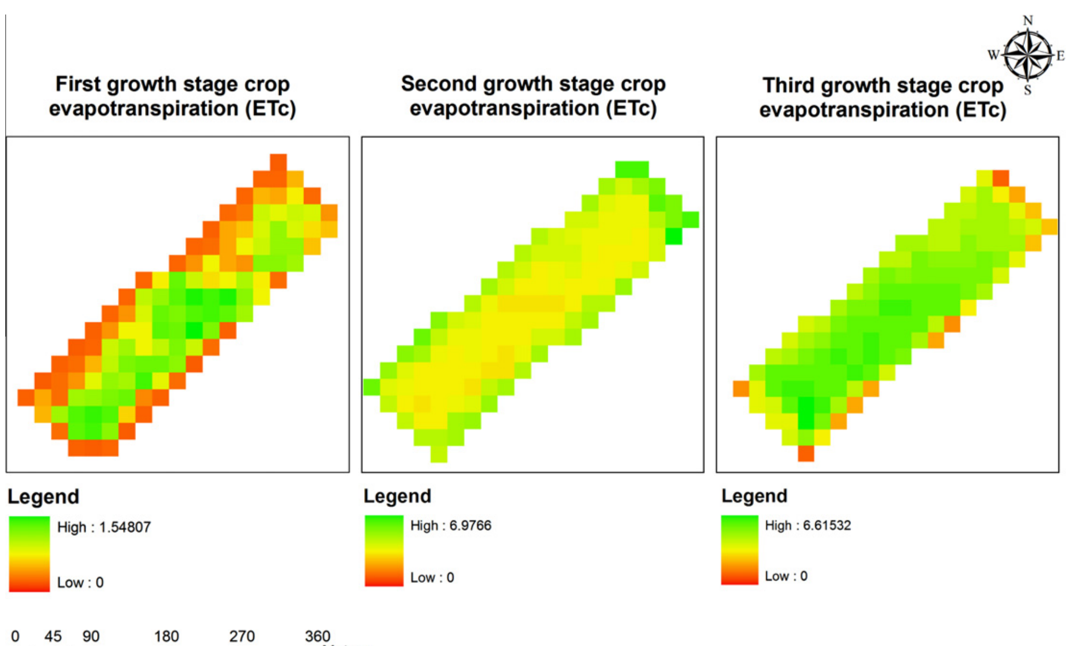

Figure 6 The predicted crop evapotranspiration ET_c for growth stages.

reference evapotranspiration (ET_o) Using (CROPWAT 8.0) (Allen et al., 1998). The wheat crop cultivation was started in November and was harvested in May in Upper Egypt. Those months show the lowest values of the (ET_o) from November until February, and starting from March the values of (ET_o) are rapidly increase until May (see Table 1).

Table 3 The correlation between calculated (K_c) and predicted (K_c) for different growth stages.

Growth stage	Correlation	Signif. prob.
Developing growth stage (first growth stage)	0.987624	<.0001*
Middle season growth stage (second season growth stage)	0.916483	0.0014*
Late-season growth stage (third season growth stage)	0.905253	<.0001*

* Significant values < 0.05.

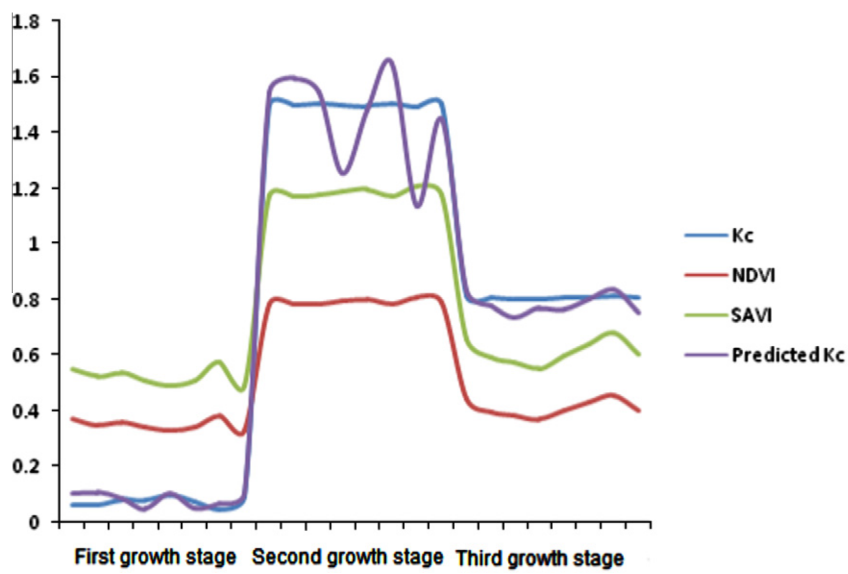

Figure 7 The trend of NDVI, SAVI, K_c and predicted K_c for the different growth stages.

The vegetation indices calculated from SPOT-4 satellite images showed that the values of NDVI and SAVI for the middle season growth stage were higher than both of developing and late-season growth stages. The layouts of the vegetation indices are shown in Figs. 3 and 4.

The results of the statistical analysis using the stepwise multiple linear regression for the different growth stages prediction equation of the K_c from SAVI and NDVI for each growth stage are demonstrated in Table 2.

The result prediction equations were used for predicting and mapping the wheat crop K_c for each growth stage. The analysis shows also that NDVI, SAVI, K_c and predicted K_c had the same trend through the different growth stages. The wheat crop actual crop evapotranspiration was calculated by multiplying the crop coefficient image by the value of the evapotranspiration. The layouts of the mapped wheat water requirements and crop coefficient for different growth stages are shown in Figs. 5 and 6. Cross validation was applied, and the result shows that correlation between the calculated (K_c) and predicted (K_c) for the three different growth stages as shown in Table 3.

The results show high R^2 and adjusted R^2 for the predicted values of crop coefficient for developing, mid-season and late-season growth stages 0.82, 0.90, 0.97 and 0.80, 0.86 and 0.96 respectively, which indicates that estimation of crop coefficient and water requirements using remote sensing data is essentially significant.

In conclusion: The analysis showed estimation of crop coefficient and crop water requirements using SPOT-4 data is significant as long as soil evaporation is negligible and plant is not under stress. Furthermore, vegetation indices drove from satellite images, and both crop coefficients calculated and predicted values follow the same trend through the different growth stages shown in Fig. 7.

5. Discussion

The study showed high R and adjusted R values to estimate the wheat crop coefficient using vegetation indices derived from remote-sensing data, which used integrated with metrological data to estimate wheat crop evapotranspiration. Crop evapotranspiration for middle season growth stage was higher than the other growth stage which agreed with (Er-Raki et al., 2010) remote sensing estimates of *ET*c that compare very satisfactorily with ground measurements, since the soil evaporation and plant water stress are negligible, and (Gaurav et al., 2010) wheat water requirement was higher in the vegetative and mid-season stage and shows decreasing trend toward the maturity stage. On the other hand, (Abou El-Magd, 2009) No doubt Penman-Monteith is proven as one of the best empirical models, but it requires precise climatic data measured in the field, which unfortunately, is difficult and costly for some of the developing countries. The tabulated FAO-5crop coefficient values seem to be not applicable in some parts of the world.

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