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ESTIMATION OF THE SPATIAL DISTRIBUTION OF CROP COEFFICIENT (K_C) FROM LANDSAT SATELLITE IMAGERY

I. H. Abou El-Magd
Environment Department, National Authority for Remote Sensing and Space Sciences (NARSS), Cairo, Egypt

ABSTRACT

Single crop coefficient factor (K_c) is an essential component for crop water allocation for efficient irrigation scheduling and irrigation water management. K_c is basically defined as the ratio of actual evapotranspiration and grass/alfalfa reference evapotranspiration and always measured by lysimeter in localized area in the field, which then generalized on the whole irrigated land. The lack of precise information about the crop coefficient particularly in our country together with both small sized fields and heterogeneity of agricultural crops calls for developing a new methodology for computing a real time crop coefficient from remotely sensed data. This paper discusses the methodology developed for obtaining a real time single crop coefficient from Landsat Satellite ETM+7 imageries. The methodology was applied and optimized on one irrigation field with two different dates and crop cover in the northern Delta of Egypt.

Keywords: single crop coefficient, evapotranspiration, remote sensing, irrigation, Egypt.

INTRODUCTION

Determination of crop evapotranspiration (Et_c) is a fundamental requirement for accurate irrigation scheduling (Hunsakar and Pinter, 2003). An extensive method for estimating the crop evapotranspiration is the crop coefficient (K_c) approach (Doorenbos and Pruitt 1977; Jensen and Allen, 2000), in which the reference evapotranspiration (traditionally grass or alfalfa) is multiplied by the crop coefficient to estimate the actual evapotranspiration. Therefore and basically, crop coefficient (K_c) is defined as the ratio between the potential crop evapotranspiration (Et_c) and the reference evapotranspiration (Et_o), and often taken from Penman/Monteith's methodology. K_c is a key parameter used by irrigation engineers and practitioners to scale the potential evapotranspiration to the actual level for irrigation scheduling (Penman, 1948; Monteith, 1965; Allen et al, 1998). Actual K_c values can be obtained from the field using lysimeters but unfortunately, the latter represent localized areas where they are installed. The limitations of these values are: 1) the poor installation of the lysimeters or/and poor maintenance could affect the value, 2) the K_c value obtained could not be truly generalized to the field/project level, and 3) ground water level at the location of the lysimeters could play a significant role in the K_c value .

Although crop coefficients vary from day to day, depending on many factors, they are mainly a function of crop growth and development (Doorenbos and Pruitt,1977) and state of soil moisture. It is a dimensionless number and is often calculated on a monthly basis. The rate of crop growth and development will change from year to year, but the crop coefficient corresponding to a particular growth and development stage is fixed from year to year. However, the season length is significant in the average of the crop factor.

Due to all or some of the above limitations, the Food and Agriculture Organization (FAO) Irrigation and Drainage Paper No. 56 (Allen et al, 1998) presented the dual crop coefficient approach, which suppose to be more accurate of estimating the daily Et_c particularly for the days after irrigation or rain.

Remote sensing techniques offer solution to the limitations shortcomings of conventional methods for estimating crop evapotranspiration by providing real time information on the daily crop water use as influenced by development pattern of the crop, the crop coverage, local atmospheric conditions and field spatial variability (Hunsakar and Pinter, 2003). Remotely sensed data can therefore give a real time mean of instantaneous estimation of energy balance and therefore the crop evapotranspiration, together with the percent of the crop stand. Sensible heat flux methodology (Bastiaanssen et al, 1998; Bastiaanssen., 2000; El-Magd and Tanton, 2005) using the optical satellite imagery found to be efficient to estimate the crop evapotranspiration as a residual of the latent heat flux. The objective of this paper is to investigate the field single crop coefficient (K_c) using Landsat satellite imagery at the pixel and field levels.

The methodology applied on the traditional irrigation schemes in the central region of Egyptian Nile Delta with the Mediterranean basin climate. The area is characterised by small field sizes and varied crop pattern. An optimization process is applied on the same area with different date and crop cover.

MATERIALS AND METHODS

Study Area

It is anticipated that this model would be a robust and generic model that could be applied on any agricultural land. However, in this particular research it is applied on a part of the Egyptian Nile Delta, which is a part of the Mediterranean basin climate. The fields are small in sizes and the irrigation is the typical tradition way of furrow irrigation. The area of study is chosen just to test the model and approve the methodology which could be applied anywhere.

Satellite Data

Two Landsat 7 (ETM$^+$) satellite images (Path 176 & Row 38) were acquired on 05/06/2006 at 10:13 am local time with zero cloud cover and on 04/03/2007 at 10: 14 am local time with less than 10% cloud cover.

Meteorological Data

24 hour climatic data was recorded on site giving the temperature at the time of the satellite overpath nearly similar to the mean daily temperature. Table (1) shows the instantaneous climatic data on both days on the time of the satellite data capturing. This is together with the mean daily values.

Table 1. The instantaneous and mean daily climatic data.

Date	Data Type	Time	Temperature	Wind speed	Wind direction	Humidity
04/03/2007	Instantaneous	10:15 am	23 °C	0.5 ms^{-1}	NNE	47 %
	Daily average	24 hours	18 °C	0.20 ms^{-1}	NNE	55 %
05/06/2006	Instantaneous	10:15 am	30 °C	5.1 ms^{-1}	NNE	52 %
	Daily average	24 hours	30 °C	0.35 ms^{-1}	NNE	50 %

Estimation of the Actual Evapotranspiration (Et_c) from Satellite Images

Initially, the satellite images were geometrically corrected to the Universal Transverse Mercator (UTM) grid system and radiometrically corrected. Then the brightness values were converted to irradiance at sensor. This was followed by applying the sensible heat flux methodology as shown in the logistic and schematic approach in Figure (1) and equation (1) to estimate the actual evapotranspiration (Et_c). The methodology is described in (Bastiaanssen et al., 1998; Bastiaanssen, 2000; El-Magd and Tanton, 2005).

The field meteorological data is used to estimate the reference evapotranspiration and to support the sensible heat flux methodology.

Statistical regression correlation was obtained between the Et_c and the Normalized Difference Vegetation Index (NDVI) to determine the NDVI-Et_c relationship.

$$\lambda Et = R_n - G_o - H \text{ ………………… (equation 1)}$$

Where:

λEt = *latent heat flux* (W/m^2)

R_n = *net radiation flux at the surface* (W/m^2)

G_o = *soil heat flux* (W/m^2)

H = *sensible heat flux to the air* (W/m^2)

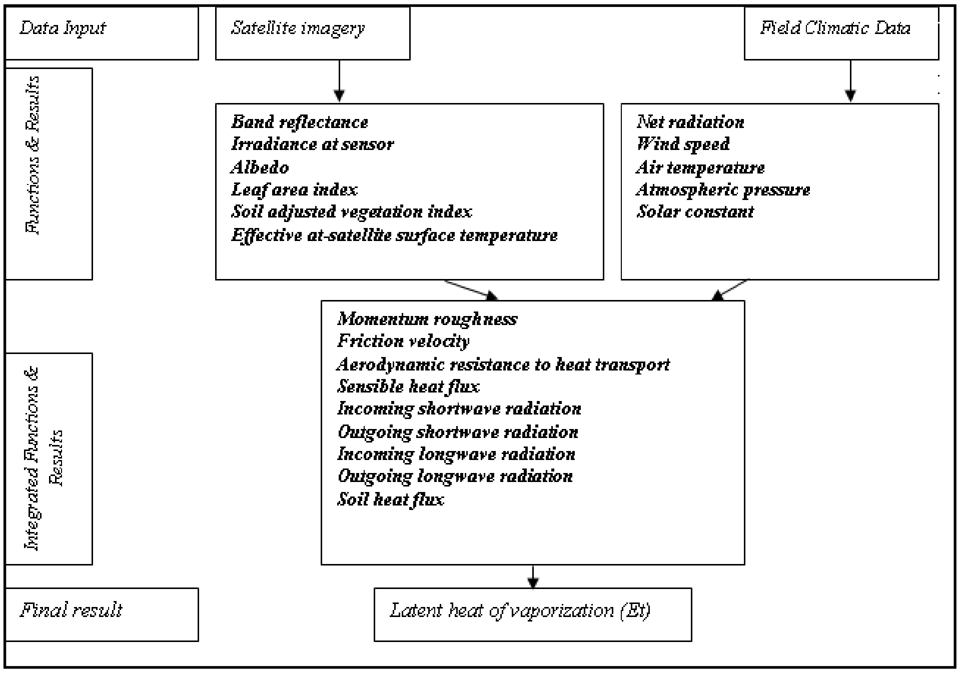

Figure 1: Conceptual model shows the logistic processes of the estimation of the latent heat of vaporization (actual crop evapotranspiration Et_c).

Estimating the Reference Evapotranspiration (Et_o)

The innovation of this research is to see the potential of estimating the reference evapotranspiration (Et_o) directly from the optical satellite imageries instead of localised points of climatic data measurements and mathematical models (El-Magd, 2004). This would be based on the standard parameters of a mature, healthy and good stand of alfalfa instead of grass. The assumption of these standard parameters would be the standard albedo, standard surface roughness, standard G/R_n as shown in Table (2). It is anticipated that this approach is cost effective which does not rely on the field lysimeters and avoid any uncertainties in the generalization of the lysimeters values or/and the local microclimatic changes.

Therefore, the estimation of the latent heat of vaporization was carried out again using the standard parameters of a mature and healthy well-stand of alfalfa (Table 2) to estimate the reference evapotranspiration Et_o.

Table 2. The standard parameters of alfalfa, for estimating Et_o.

Variable	Value
Albedo	0.21
Momentum roughness (Z_{om})	0.0738 (Z_{om}= 0.123 * height)
Height (h)	0.6 m
Soil heat flux/net radiation (G/R_n)	0.033

Estimating the Crop Coefficient (K_c)

The single crop coefficient factor (K_c) is simply the ratio between both the actual crop evapotranspiration (Et_c) and reference evapotranspiration (Et_o) (Equation 2). Et_o is normally estimated empirically using the Modified FAO-Penman-Monteith formula based on the daily meteorological data measured in the field. The actual crop evapotranspiration (Et_c) was computed from remotely sensed data using the sensible heat flux methodology, which is a function of the residual heat flux required for evapotranspiration (equation 2) (Bastiaanssen et al.,1998; Bastiaanssen, 2000; El-Magd and Tanton, 2005).

$$\mathbf{K_c = Et_c / Et_o} \quad \textbf{….. ……(equation 2)}$$

Where: K_c = the single crop coefficient;
Et_c = actual crop evapotranspiration;
Et_o = the reference evapotranspiration.

Reference evapotranspiration (Et_o) also computed empirically from meteorological data and mathematical formula to compare with the results from satellite imageries.

Then, in a simple division of both evapotranspiration outputs (i.e. Et_c and Et_o) the crop coefficient K_c on a pixel basis is estimated.

A statistical analysis is also carried out to obtain the mean crop coefficient in relation to the crop stand and coverage represented by the Normalized Difference Vegetation Index (NDVI).

RESULTS AND DISCUSSION

The Nile Delta is characterised by the mixture and heterogeneity of the crop types and landuse classes. The irrigation technique is the typical and traditional way of furrow irrigation. Indeed, this would result in a huge loss of water and inaccurate calculation of the supply/demand of water (Heaven et al, 2002).

Date 1 (5th June 2006)

The minimum air temperature on 5th June 2006 was 22 ^{0}C and maximum 38 ^{0}C with a daily average of 30 ^{0}C. The air temperature measured at 10:13 am when the satellite overpath the area of study was 30 ^{0}C, which is exactly similar to the mean daily temperature. This indicates that the instantaneous estimation of the crop evapotranspiration at 10:13 am could reflect the mean daily evapotranspiration; however, accumulation to the 24 hours is required. The average reference evapotranspiration Et_o on the 5th of June 2006 was calculated at 5.9 mm d^{-1} using Penman-Montieth formula and the climatic data measured on site.

The sensible heat flux model is used to estimate the crop evapotranspiration which is given an Et_c distribution with the maximum of 7.4 mmd^{-1} (Figure 2 – top left). The reference evapotranspiration Et_o is also estimated from the 5th June satellite image which is given a distribution of Et_o with maximum of 5.9 mmd^{-1} (Figure 2 – bottom left). The mean Et_o obtained from satellite image was 5.2 mmd^{-1} which is 11% behind that estimated from the empirical method of Penman-Monteith.

This 11% discrepancy is acceptable in such application, however, the comparison between the satellite image and the localised point of measurement is weak since the driving force of the higher value of 5.9 mmd^{-1} of the empirical method is the high wind speed at that point of 5.1 ms^{-1}. However, the satellite image considers the microclimate variation along the irrigated area.

A simple division between the two evapotranspiration images (i.e. Et_c and Et_o) produced the single crop coefficient K_c (Figure 2 – right). This is pixel by pixel Et_c and K_c values that reflect the condition of the pixel including the thermal, vegetation cover, soil wetness. The maximum K_c value obtained was at 1.33 which looks higher than the FAO-56 tabulated values. For realistic comparison with the FAO-56 tabulated data, an exercise was made with a field of crop cotton to see the discrepancies. This exercise shows that the K_c from satellite image is about 10% higher than the FAO-56, which could be attributed to a deficiency in the FAO-56 data due to it represents a flat rate of specific growth stage of the crop, however, the satellite image represents the existing crop coefficient as a function of the condition of the crop stand and climatic conditions as well as the soil conditions.

Date 2 (4th March 2007)

The minimum and maximum air temperatures on 4th March 2007 were 12 C^0 and 25 ^0C with a daily average of 18 ^0C. The air temperature measured at 10:30 am when the satellite over path the area of study was 23 ^0C, which is higher than the average daily temperature. The wind speed on this day was recorded at 0.5 ms^{-1}.

The average reference evapotranspiration Et_o on the 4th March 2007 was firstly calculated at 4.72 mm d^{-1} using the meteorological data measured in the field and the mathematical formula of Penman Monteith.

The actual evapotranspiration is estimated from the satellite image on 4th March 2007. The actual evapotranspiration distribution was plotted using the pixel values of Et against their frequency (Figure 3 – top left). This frequency curve shows an actual evapotranspiration between 1 and 6.2 mm d^{-1}. This evapotranspiration image reflects the variable evaporation from the soil or the transpiration from the vegetated pixels. The vegetation condition in March was representing the pre-plantation of few crops together with early stages of existing crops.

The reference evapotranspiration (Et_o) is estimated from the same satellite image using the typical parameters of alfalfa. The frequency distribution of the reference evapotranspiration (Et_o) is shown in Figure (3 – bottom left) with a peak between 3 and 5.1 mm d^{-1} with mean Et_o at 4.0 mm d^{-1}. It seems that the Et_o estimated from the satellite image is 15% behind the empirical Et_o of 4.72 mm d^{-1}. However, this variation could be attributed to the changes in the microclimatic conditions of the irrigated land and the lower value of temperature recorded at the climatic station.

In a simple division of both images, the crop coefficient factor K_c is computed. The distribution curve of the crop coefficient shows K_c distribution between 0.2 and 1.2 with a mean at 0.75 (Figure 3 – right). This K_c figure seems realistic for that time of the year where most of the crops are at early stages of crop growth.

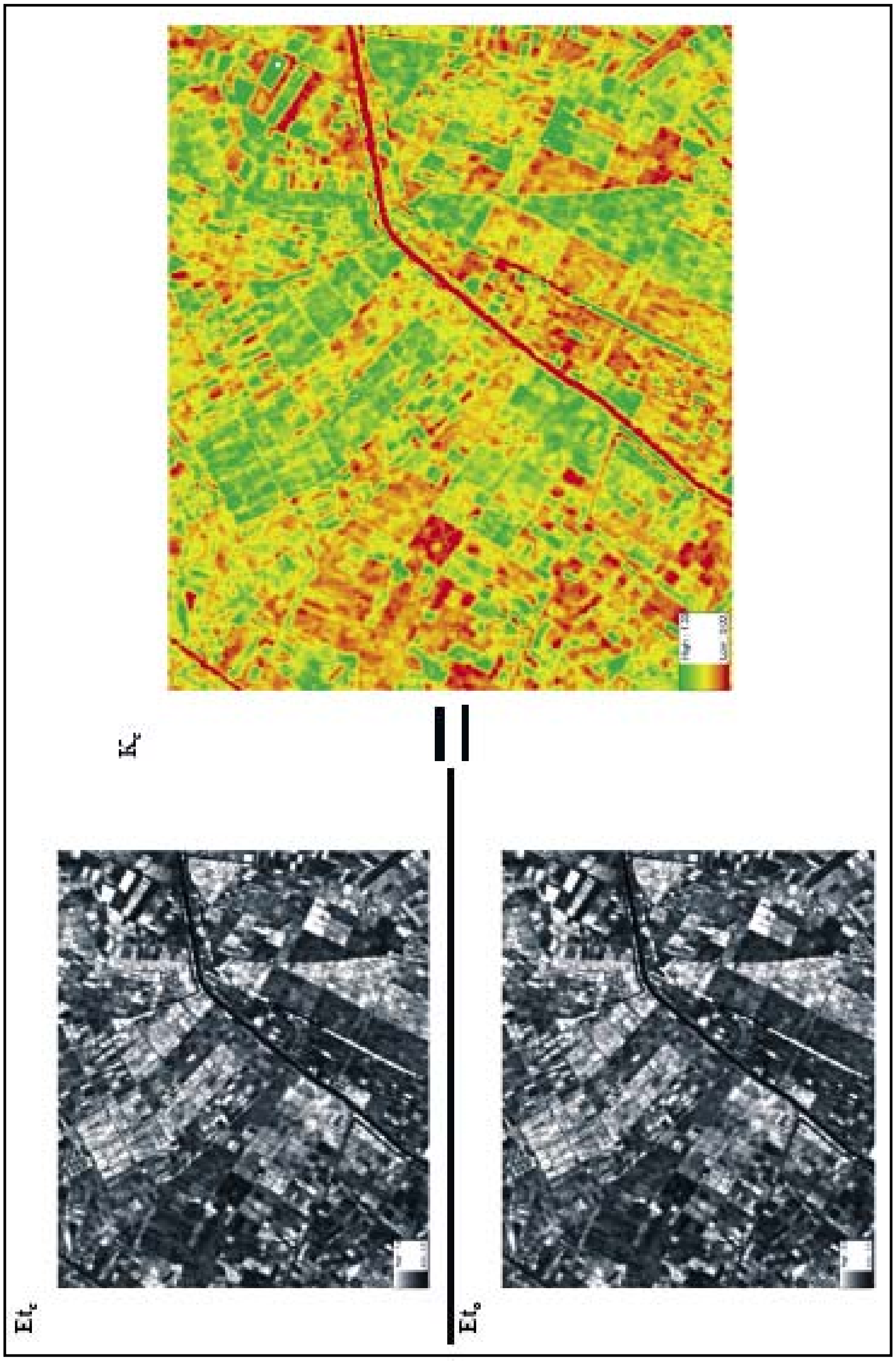

Figure 2: The estimated Et_c, Et_o and K_c from satellite image on 5th June 2006.

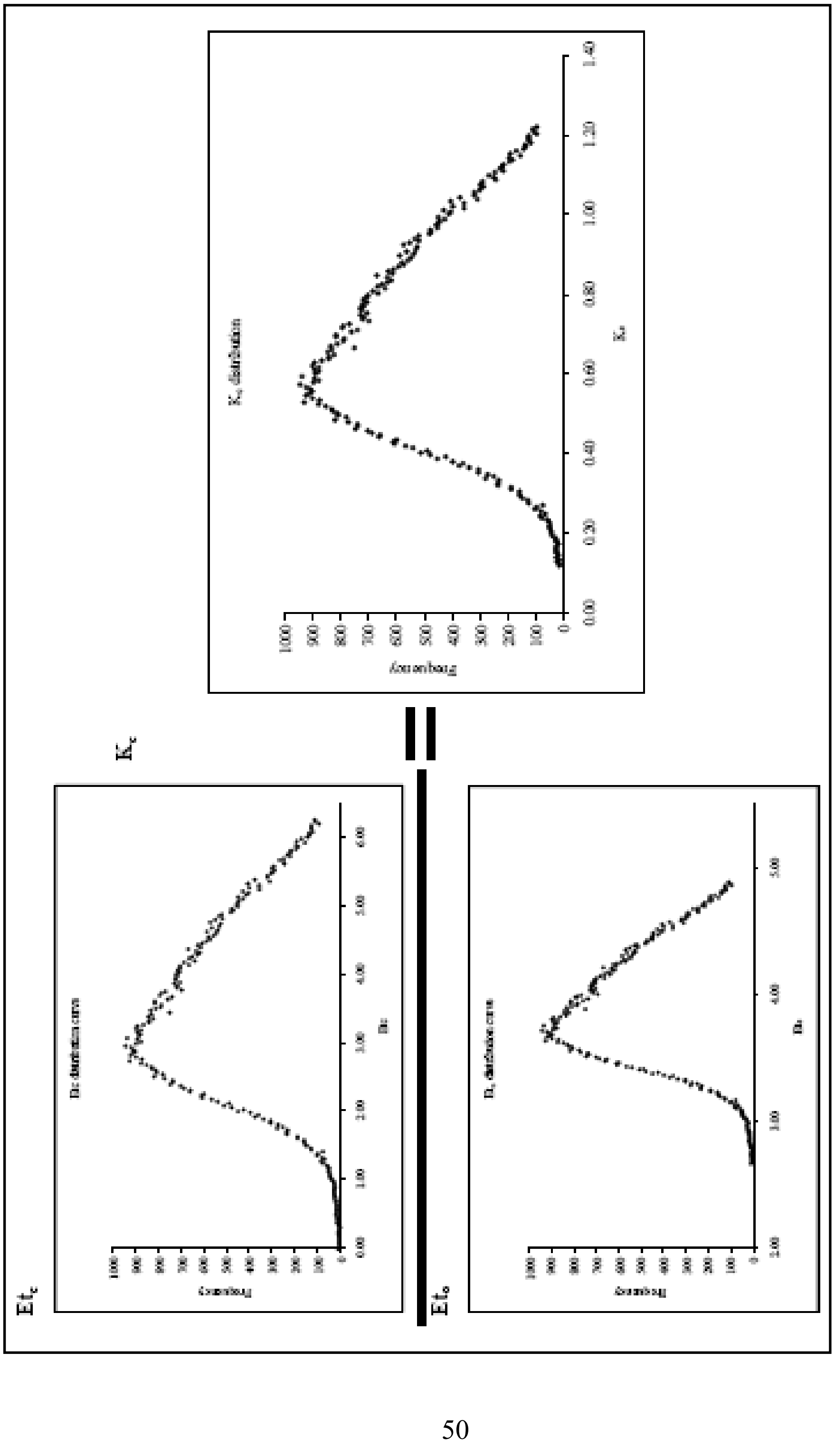

Figure 3: The distribution curves of estimating Et_c, Et_o and K_c from satellite image on 4th March 2007.

CONCLUSIONS

The crop coefficient (K_c) is an important variable in irrigation water scheduling and water management. It is the factor that scales the reference evapotranspiration (Et_o) to the potential evapotranspiration (Et_c). However, the accuracy and reliability of obtaining the crop water demand is a major constraint.

Most of the empirical models used in crop water allocation shows inconsistency of estimating crop water demand, whether due to over estimate of crop factor or field conditions that over/under estimate the crop water demand. Penman-Monteith formula out of others is found to be the appropriate method to estimate the daily crop coefficient for crop potato for example (Kashyap and Panda, 2001). There is no doubt that Penman-Monteith is proven as one of the best empirical models, but it requires precise climatic data measured in the filed, which unfortunately, is difficult and costly for some of the developing countries. The tabulated FAO-56 crop coefficient values seem to be not applicable in some parts of the world given higher estimation of crop water need.

Indeed, this insisted for approaching new methods for real time estimation with spatial coverage of K_c independently from satellite imageries, which being used recently to compute the crop evapotranspiration.

In terms of offering a technique to support effective water planning in arid and semi arid regions, the sensible heat flux method is potentially more useful as it does have the potential to estimate the actual water being effectively used by the crops. The cohesive conditions of the pixels is estimating the reference evapotranspiration (Et_o) using the typical parameters of alfalfa was given real time crop coefficient factor with ± 10 % margin of error with the FAO-56 values. The advantage of this method is the unified conditions that affect each pixel (field) in the whole irrigation scheme, including the net radiation of both advected and convected energy, temperature, etc. which could accurately identify the crop coefficient factor up to the field level rather than a localised point that be generalized over the whole irrigated land. It is also cost effective tool for real-time water planning particularly in large irrigation schemes where huge water is being wasted.

The spatial estimation of crop evapotranspiration from satellite imagery shows a realistic reflection of the crop water needs which is in response to the crop stand and its health conditions. This indeed, leads to an accurate crop water computation and efficiently managing the water resources in areas of huge losses such as the Nile Delta region. Therefore, the spatial and real-time estimation of crop coefficient is at the same magnitude of crop evapotranspiration.

The classification of the satellite images to identify the crop types and areas and then masking both the Et$_c$ and K$_c$ images to give an individual output of each crop is out of the scope of this research. However, the focus was on the possibilities of estimation the crop coefficient and evapotranspiration from the satellite images. Nevertheless, plotting the NDVI against the Et$_c$ reflects the relationship between the pixel coverage of vegetation and their evapotranspiration. Figure (4) shows a scatter plot diagram between the Normalized Difference Vegetation Index (NDVI) and the E$_t$c which shows a linear positive correlation with ^{r}2 at 0.97. This correlation shows the crop cover and stand would significantly affect on the actual Et on a pixel by pixel basis. The pixel conditions including the soil wetness, leaf area index, vegetation roughness and the surface temperature could be presented against the Et to see the correlation. It is anticipated that this method is given a realistic estimate of the crop evapotranspiration on a pixel by pixel basis and therefore on a field level.

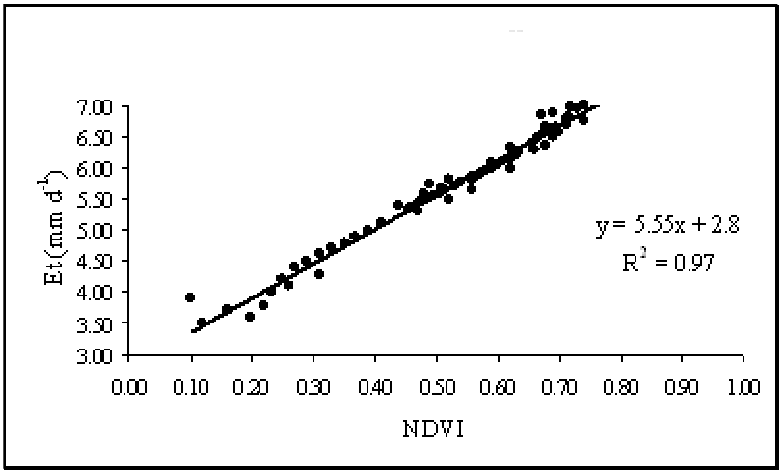

Figure 4: The distribution curve of actual evapotranspiration (Et$_c$) and NDVI.

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تقدير التوزيع الجغرافى للمعامل المحصولى من صور الأقمار الصناعية لاندسات

إسلام حمزة أبو المجد
الهيئة القومية للإستشعار من البعد وعلوم الفضاء، القاهرة - مصر

يعتبر المعامل المحصولى الفردى من المكونات الأساسية لحساب كمية المياه اللازمة لنموالمحصول ومن ثم تحسين كفاءة إدارةمياه الرى. وبشكل أساسى يعرف المعامل المحصولى على أنه النسبة بين معدل النتح/بخر الفعلى للمحصول ومعدل النتح/بخر المرجعى لنبات البرسيم والذى عادة ما يقاس فى الحقل بجهاز الليزيمتر ويكون هذا القياس فى مكان محدد (حيث يوضع جهاز الليزيمتر) ثم يعمم على الحقل قيد الدراسة. ويعتبرنقص المعلومات الدقيقة عن المعامل المحصولى وخصوصا فى بلادنا مع صغر مساحة الحقول الزراعية وعدم تجانس محاصيلها إحدى دواعى إقتراح منهجية جديدة لحساب معاملات المحاصيل لحظة بلحظة من صور الأقمار الصناعية. ويناقش هذا البحث تطوير منهجية جديدة للحصول على المعامل المحصولى فى أى وقت من عمر المحصول وذلك للتغلب على قصور المنهجيات السابقة. وتعتمد هذه المنهجية على صور الأقمار الصناعية والتى طبقت وحققت فى حقلين زراعيين بزمنين مختلفين فى شمال دلتا النيل بمصر.