INTEGRATED SURFACE ENERGY BALANCE APPROACH AND REMOTE SENSING TO ESTIMATE EVAPOTRANSPIRATION

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ABSTRACT

The purpose of this study is to apply and investigate simplified surface energy balance approach (SSEB), stating that the latent heat flux (actual evapotranspiration) varies linearly between the hot and cold pixels areas; thus aiming to produce an actual evapotranspiration estimates by using a combination of this approach, remotely-sensed MODIS thermal imagery, and global reference ETo over known irrigated fields in Delta region to estimate proportional fractions of ET on a per pixel basis (Etf), which is used in conjunction with reference evapotranspiration (ETo) to calculate ETa. A combination of 38 cloud-free, 1-km thermal data and 250-m Normalized Difference Vegetation Index (NDVI) data, both from the Resolution Imaging Spectroradiometer (MODIS) sensor were used for 2 years (2000-2002), over 3 areas namely, Kafr El Shikh, Munofia, and Bohera. This simplified method uses the concept of Energy Balance System (SEBS) that refers to the hot and cold extreme conditions as "dry" and "wet", respectively, thus actual evapotranspiration (ET) can be estimated from the land surface temperatures of the hot and cold pixels for study areas. With respect to evapotranspiration rate resulted from this study it varies from one month to another, and from year to year throughout the three study areas. The resulted values of Etf were in harmony with the crop coefficient (Kc) values obtained by Penman combination method, and there were significant differences among them, thus the correlation coefficient (r) were 0.93, 0.83, and 0.92 for Sunflower, Peanut, and Maize crops respectively in different areas. The results show that calculating the Etf by this technique could be a promising, reliable in determining actual evapotranspiration for irrigated areas rather than Kc for aiding in managing water resources; also obtaining the thermal-based ET fraction (Etf) using this approach is useful for applications in remote locations where field-based information is not readily available.

Keywords: Evapotranspiration, Surface energy balance, MODIS images, NDVI

1. INTRODUCTION

The need for studying Egypt's water balance is necessary to address current and future water use scenarios. One aspect of the water balance equation involves an assessment of the water demands by irrigated agricultural lands. A good estimation of evapotranspiration in Delta region is vital for proper water management, allowing for improved efficiency of water use, high water productivity, and efficient farming activities, Lee et al. [1]. Penman combination method (1948) and Blaney Criddle (1950) using the two steps crop coefficient methodology to estimate actual evapotranspiration (ETa) are the common methods already used in Egypt. The crop coefficient (kc) used in these methods is not appropriate but requires calibrations that involve ground measurements and local calibration. The ground-based calibrations are used to predict kc for areas located near where the measurements were taken. This fact makes many current methods site-specific and far for being routinely applied.

The surface energy balance method has been successfully applied by several researchers to estimate crop water use in irrigated areas, Allen et al. [2], Bastiaanssen et al. [3]. Their approach requires solving the energy balance equation at the surface where the actual evapotranspiration (ETa) is calculated as the residual of the difference between the net radiation to the surface and losses due to the sensible heat flux (energy used to heat the air) and ground heat flux (energy stored in the soil and vegetation), Equation 1, Senay et al. [4].

$$LE = Rn - G - H \tag{1}$$

However, applying this approach from remotely sensed imagery requires high quality data sets. Allen et al. [2] described the several steps required to estimate actual ET using the surface energy balance method that employs the hot and cold pixel approach of Bastiaanssen et al. [5]. Although solving this surface energy-balance approach has been shown to give good results in many parts of the world, the data and skill requirements to solve for the various terms in the equation are prohibitive for operational applications where year-to-year differences and long term anomalies are more useful than absolute values.

In this respect, a simplified version of the surface energy-balance approach has been utilized and investigated to estimate actual ET while maintaining and extending the major assumptions in the Surface Energy Balance Algorithm for Land (SEBAL, Bastiaanssen et al. [5]) and the Mapping Evapotranspiration at High Resolution using Internalized Calibration (METRIC, Allen et al. [2]), method. Both methods assume that the temperature difference between the land surface and the air (near-surface temperature difference) varies linearly with land surface temperature. They derived this relationship based on two anchor pixels known as the hot and cold pixels, representing dry and bare agricultural fields and wet and well-vegetated fields, respectively, Senay et al. [4]. Similarly, Su et al. [6] have developed a Surface Energy Balance System (SEBS) that refers to the hot and cold extreme conditions as “dry” and “wet”, respectively.

Recently, there has been a continued progress in determining actual ET by knowing the land surface temperatures of the hot and cold pixels in the study area. In other words, the hot pixel of a bare agricultural area experiences little ET and the cold pixel of a well-watered irrigated field experiences maximum ET, and the remaining pixels in the study area will experience ET in proportion to their land surface temperature in relation to the hot and cold pixels, Senay et al [4], and what is called Etf fraction can be computed from T_H, T_C pixels values rather than crop coefficient (Kc). The Etf is used in conjunction with ETo to calculate the per pixel actual ET (ETa) values for a given scene of the study area.

The purpose of the study is to apply and investigate this simple approach of Senay et al. [4], stating that the latent heat flux (actual evapotranspiration) varies linearly between the hot and cold pixels areas; thus aiming to produce an actual evapotranspiration estimates by using a combination of this simplified surface energy balance approach (SSEB) and remotely-sensed MODIS thermal imagery and global reference (ETo) over known irrigated fields in Delta region, to estimate Etf which is used in conjunction with ETo to calculate actual evapotranspiration (ETa).

2. METHODOLOGY

2.1. Study sites

The study focuses on three major expanses of irrigation in the delta region (Fig. 1): Bohera, Kafr-El Shikh, and Mnufia, in west, north, and middle of delta region respectively .Because this method relies heavily on temperature variability, each of these areas was chosen with minimum variation in elevation to minimize the effects of elevation differences on surface temperature measures. The irrigated areas consist of both well-vegetated and sparsely vegetated areas, with some urban areas at the periphery as in the case of Bohera area.

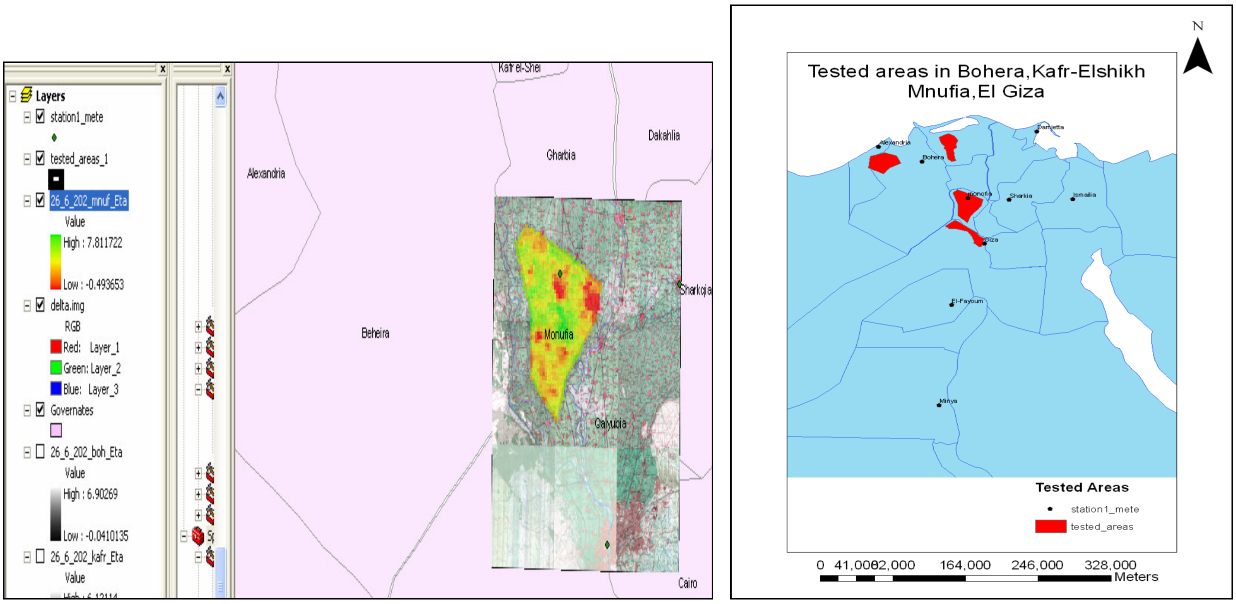


Figure 1: Study areas in delta region (Bohera, Mnufia, and Kafr El Shikh)

2.2 Data Acquisitions

The data used in this study were derived from the MODIS sensor flown on board the Terra satellite which described as follows:

- MODIS Land Surface Temperature:

Thermal surface measurements were collected from the MODIS 8-day Land Surface Temperature/Emissivity (LST/E) product (MOD11A2.5). The MODIS instrument provides 36 spectral bands, including 16 in the thermal portion of the spectrum; the generalized split-window LST algorithm was used to retrieve LST for MODIS pixels with known emissivity in bands 31 and 32. The LST/E images provide per-pixel temperature and emissivity values at 1-km spatial resolution for the 8-day composite product (Fig. 2). About twenty five 8-day images composite with time period beginning in early April through the middle of October were processed for years (2000-2002). Table 1 shows the used MODIS LST data.

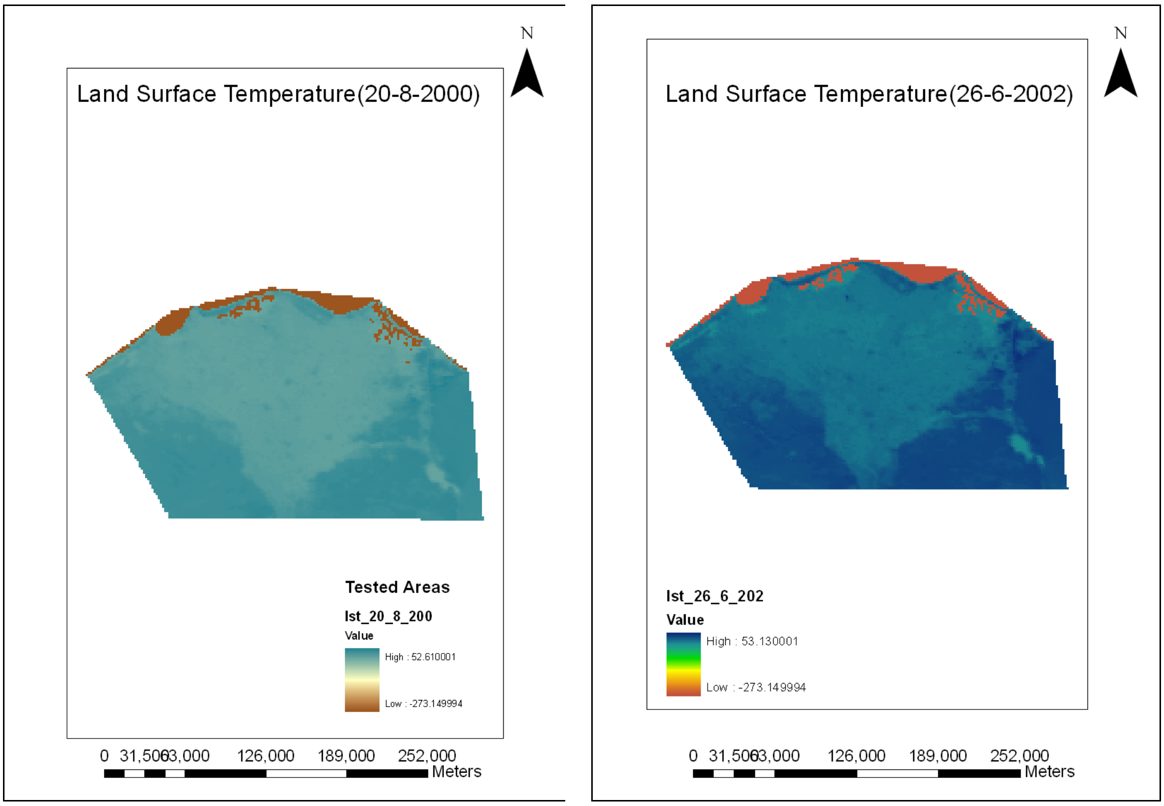


Figure 2: An 8-day composite of MODIS Land Surface Temperature (LST, °C) for Delta region in (2000-2002)

Table1: Description of MODIS data

Date of acquisition	**Spatial /Temporal Resolution**	**Image Type in HDF-EOS format**	**Cloud %**
lst_6_4_2000	1 kilometer (0.93-km)/8 days	MOD11A2.5	0
lst_14_4_2000	=	=	0
lst_30_4_2000	=	=	0
lst_8_5_2000			
lst_16_5_2000			
lst_24_5_2000			
lst_1_6_2000			
lst_9_6_2000			
lst_17_6_2000			
lst_1_7_2000			
lst_17_7_2000			
lst_20_8_2000			
lst_28_8_2000			
lst_5_9_2000			
lst_13_9_2000			
lst_21_9_2000			
lst_7_10_2000			
lst_23_10_2000			
lst_23_4_2002			0
lst_1_5_2002			
lst_9_5_2002			
lst_17_5_2002			
lst_25_5_2002			
lst_2_6_2002			
lst_10_6_2002			
lst_18_6_2002			
lst_26_6_2002	1 kilometer (0.93-km)/8 days	MOD11A2.5	
NDVI_8_5_2000	250m/16 days	MOD13Q1.5	0
NDVI_22_5_2000	250m/16 days	MOD13Q1.5	
NDVI_25_6_2000			
NDVI_27_7_2000			
NDVI_28_8_2000			
NDVI_29_9_2000			
NDV_9_5_2002			
NDV_25_5_2002			
NDV_12_7_2002			
NDV_13_8_2002			
NDV_16_10_2002			0

- MODIS Vegetation Index:

MODIS Vegetation Index (VI) products use reflectance measures in the red (620 – 670 nm), near infrared (841 – 876 nm), and blue (459 – 479 nm) bands to provide spectral measures of vegetation vigor. The MODIS VI products include the standard normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). Because this research focused on irrigated agriculture, we used the standard 16-day NDVI product at 250-m resolution for this analysis (Fig. 3). Table 1 shows the used MODIS VI data.

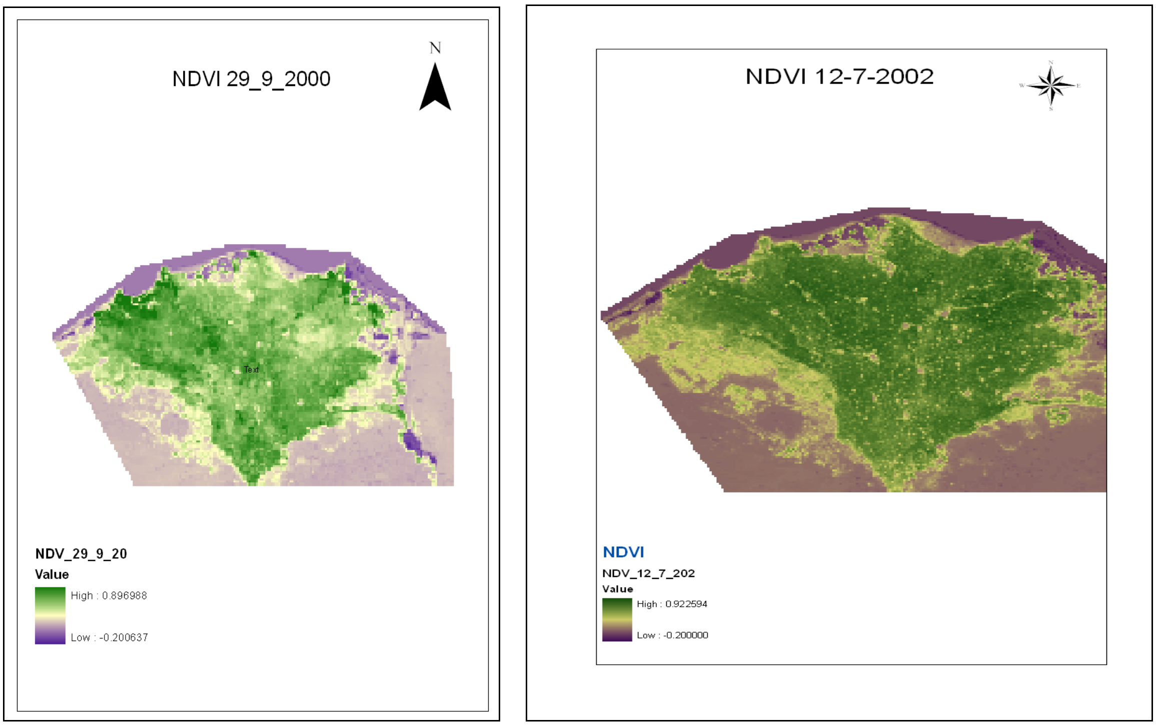


Figure 3: MODIS 250m 16-day NDVI composite in (2000-2002)

- Reference ET:

Reference evapotranspiration (ETo) data were obtained from different sources, the archives data of the FAO organization in binary format, and from Water Management Research Institute, WMRI, also from the computed data of meteorological stations in delta region. All previous data were calculated using the standard Penman-Monteith equation as outlined in the FAO publication for short-grass (ETo). Reference evapotranspiration data (ETo) were averaged for period of 15 days for each study area, from daily values to be corresponding to the LST composite 8 days periods.

MODIS Land Surface Temperature (LST) data were used to calculate the crucial evapotranspiration (ET) fractions Additionally, MODIS NDVI data were used for irrigated area delineation and identifying highly-vegetated versus sparsely vegetated areas within the agricultural zone. The global reference ET data were obtained from different sources. The MODIS vegetation index and land surface temperature data are distributed, at no cost, by the Land Processes Distributed Active Archive Center (LPDAAC), (http://LPDAAC.usgs.gov).

2.3 Processing work flow:

a- All MODIS satellite raster data are produced in HDF format which cannot be used in GIS / remote sensing environments so we need a conversion tool to change the HDF format to more useful and informative format (GeoTIFF), to process the raster data.
b- Digitize vector layers for the three study areas (Kafr-El shikh, Mnofia, El Bohera).
c- Design logical flow diagrams for the GIS spatial analyst models to process the approach's equations on all LST and NDVI raster images.

These models are described as follows:

*Model 1

Subset each land surface temperature (LST) raster image to the required study areas, and calibrate each output LST scene by applying Equation 2 using raster calculator tool (Fig. 4).

Data values (calibrated) = scale factor* (stored numbers-offset) (2)

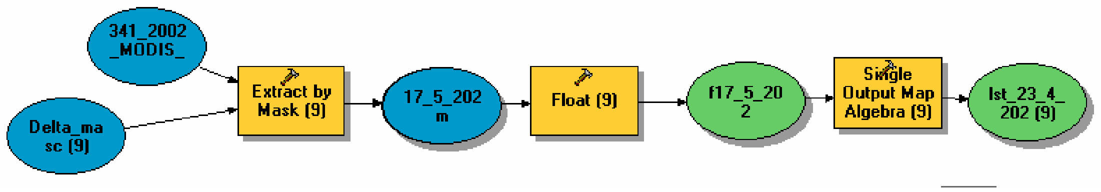


Figure 4: Calibration and subset procedures

*Model 2

This model is needed to calculate NDVI values using raster calculator tool by applying equation 5 on red and infrared bands values, and then subset the scene for the required study areas (Fig. 5).

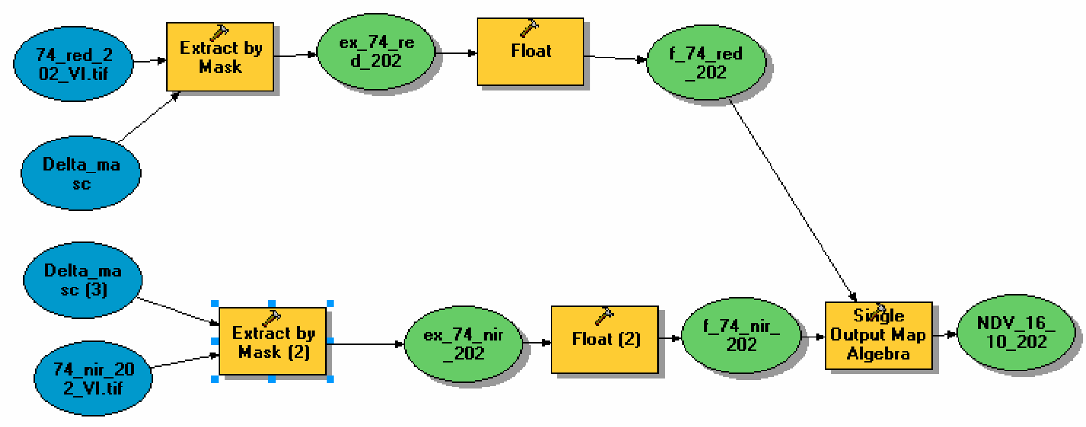


Figure 5: NDVI calculation procedures

*Model 3

This model calculates Etf values according to equation 3 after performing all required procedures to calculate average hot and cold selected pixels from LST raster data as descried later (Fig. 6).

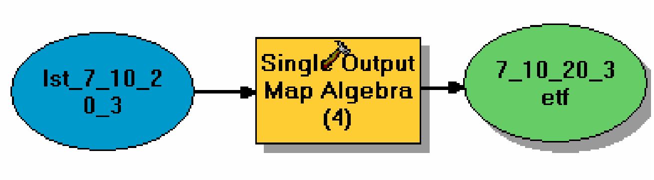


Figure 6: Determination of evapotranspiration fraction (Etf)

* Model 4

This model calculates the final ETa according to equation 4 by multiply the two raster scenes Etf and ETo for all MODIS scenes by applying map algebra tool (Fig. 7).

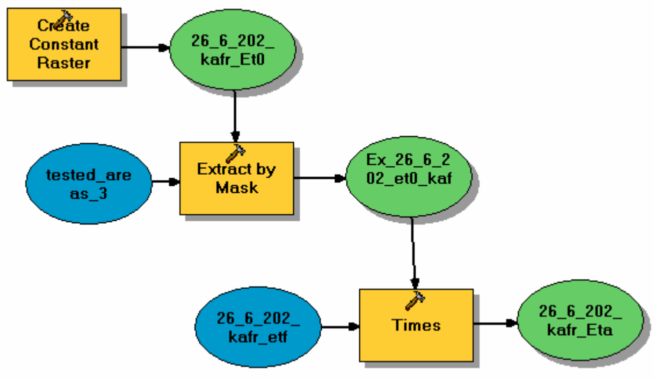
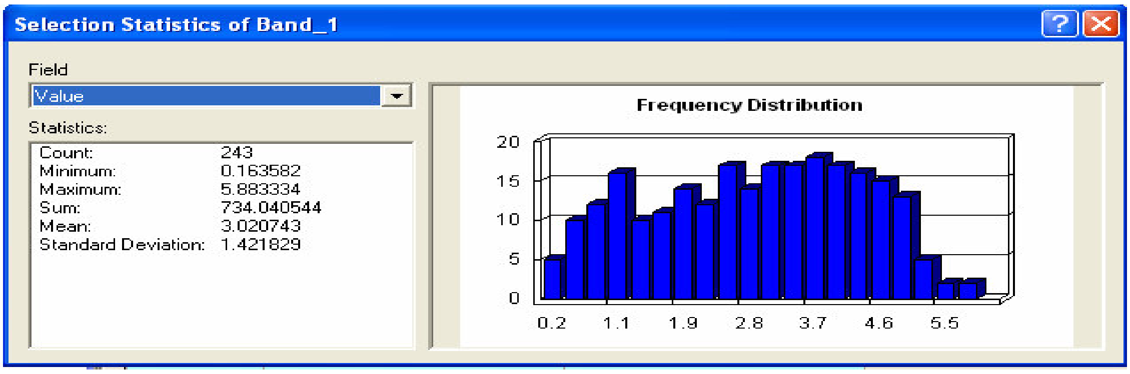


Figure 7: Actual evapotranspiration calculations

d- Determine the proportional fractions of ET (Etf) as follows:

An average of the 3 pixels was used to represent the hot and cold values in each of the 3 study areas, for each 8-day composite LST image, for years (2000-2002), and for a specific time period. Cold pixels, representing well vegetated and well watered crops, were selected based on a combination of low LST values and high values in the MODIS NDVI. Similarly, hot pixels, representing low density vegetation and relatively dry land, were identified by high LST values and very low NDVI values. Cold and Hot pixels were extracted and averaged using ArcGIS 9 (Fig. 8).



Count:	243
Minimum:	0.163582
Maximum:	5.883334
Sum:	734.040544
Mean:	3.020743
Standard Deviation:	1.421829

Figure 8: Averaged values for hot and cold pixels were extracted using ArcGIS, Kafr El shikh (1-6-2000)

With the assumption that hot pixels experience very little ET and cold pixels represent maximum ET throughout the study area, the average temperature of hot and cold pixels could be used to calculate proportional fractions of ET on a per pixel basis. The ET fraction (Etf) was calculated for each pixel by applying Equation 3 to each of the 8-day MODIS land surface temperature grids.

$$Etf = (T_H - T_S) / (T_H - T_C) \qquad (3)$$

where T_H is the average of the three hot pixels for a given scene; T_C is the average of the three cold pixels for that scene; and T_S is the land surface temperature value for any pixel in the composite scene. The Etf equation was applied to each 8-day LST average composite scene for each period. The Etf is used in conjunction with ETo to calculate the per pixel actual ET (ETa) values in a given scene (Equation 4).

$$ETa = Etf * ETo \qquad (4)$$

The calculation procedure is similar to the use of a crop coefficient (Kc) where a ETo is adjusted using Kc that is dependent on crop type and stage, Senay et al. [4].

e- Calculate 16-day NDVI composite for each scene as follows:

Vegetation index (NDVI) values can be calculated using Equation 5:

$$\text{NDVI} = (\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red}) \qquad (5)$$

where ρ is reflectance after atmospheric correction, the subscript ‘‘nir’’ represents the MODIS near-infrared band (band 2 at 0.841–0.876 mm), ‘‘red’’ represents the MODIS red band (band 1 at 0.620–0.670 mm), Huete et al. [7].

f- Run every processing tool inside the models individually to check its output data and its performance, taking into consideration that the model should be interactive, and can be re-run to evaluate the new results of all raster scenes.

3. RESULTS AND DISCUSSION

From this study work some of the resulted actual evapotranspiration rate values in (mm/day) are demonstrated in Table 2 for years 2000/2002.

Table 2: Resulted actual evapotranspiration data

Study area	**Duration**	**ETa (mm/day) (Max/Min/Mean)**	**Area (km^2)**
Bohera (West delta)	6-4... 14-4 -2000	(5.89/0.21/2.887226)	668.784533
Kafr_El Shikh (North delta)	6-4... 14-4 -2000	(4.9/0.1/1.9)	442.53526478
Mnufia (Middle delta)	6-4... 14-4 -2000	(5.22/0.183/3.52)	821.12247
Bohera	1-6…9-6- 2000	(7.02/0.12/3.36)	
Kafr_El Shikh	1-6…9-6- 2000	(5.9/0.164/3.021)	
Mnufia	1-6…9-6- 2000	(7.50/0.242/3.513)	
Bohera	20-8…28-8-2000	(6.34/0.265/3.475)	
Kafr_El Shikh	20-8…28-8-2000	(5.732/0.8/3.1904)	
Mnufia	20-8…28-8-2000	(6.151/0.502/3.91)	
Bohera	7-10…15-10-2000	(4.49/0.177/1.82)	
Kafr_El Shikh	7-10…15-10-2000	(3.882/0.136/1.73387)	
Mnufia	7-10…15-10-2000	(4.2039/0.1298/1.981)	
Bohera	23-4…30-4-2002	(5.234/0.4026/2.5562)	
Kafr_El Shikh	23-4…30-4-2002	(3.551/0.1025/1.78)	
Mnufia	23-4…30-4-2002	(5.66/0.212/3.129)	
Bohera	25-5…1-6-2002	(5.89/.2131/3.24)	
Kafr_El Shikh	25-5…1-6-2002	(6.2951/0.101/3)	
Mnufia	25-5…1-6-2002	(7.325/0.375/3.333)	
Bohera	26-6…3-7-2002	(6.903/0.11/3.57)	
Kafr_El Shikh	26-6…3-7-2002	(6.121/0.288/3.581)	
Mnufia	26-6…3-7-2002	(7.812/0.51/4.93)	

Some points need to be illustrated for this study:

- The seasonal water use can be calculated by converted ETa values into volumetric by calculating irrigated basin areas. The ETa results are time series that allow for the assessment of temporal trends in volumetric water use; an annual accounting of the irrigated water demand can be met by calculating the total seasonal ETa for each year and multiplying by area and converted to m^3/feddan unit.

- From the temporal patterns of the actual crop ETa for each 8-day period (year 2000), it is clear that, the max value of ETa was in June (Fig. 11), although the maximum average value was in August due to the presence of a lot of low ET pixel values in some semi urban areas and low density vegetation fields throughout the study areas (Fig. 9).

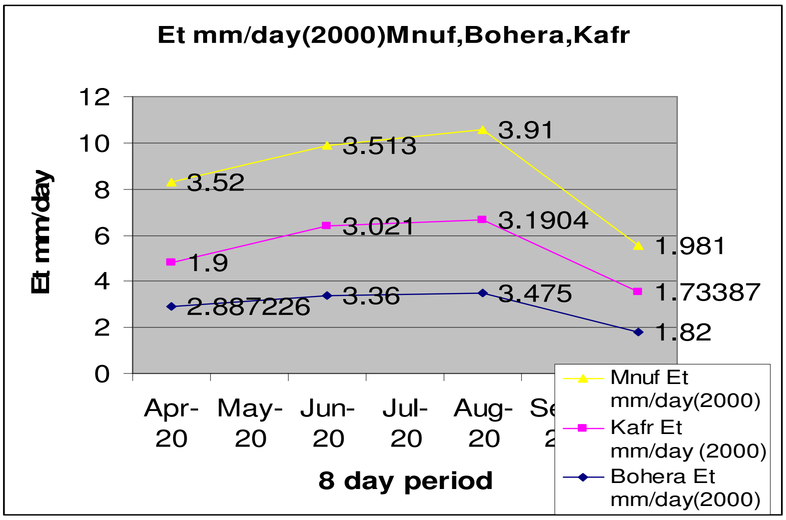


Figure 9: The temporal averaged values for ETa for all study areas

- A time series of hot and cold pixel values for each 8-day time period in 2000, 2002 had similar temporal patterns (Fig. 10). The hot and cold pixels were separated by an average of approximately 9 °C through the season between May and October. Furthermore, they appeared to increase or decrease in the same direction by about the same magnitude during the peak portions of the crop growing season for all study areas.

- These temporal patterns between hot and cold pixels can be useful in detecting time of start of season for crop monitoring activities.

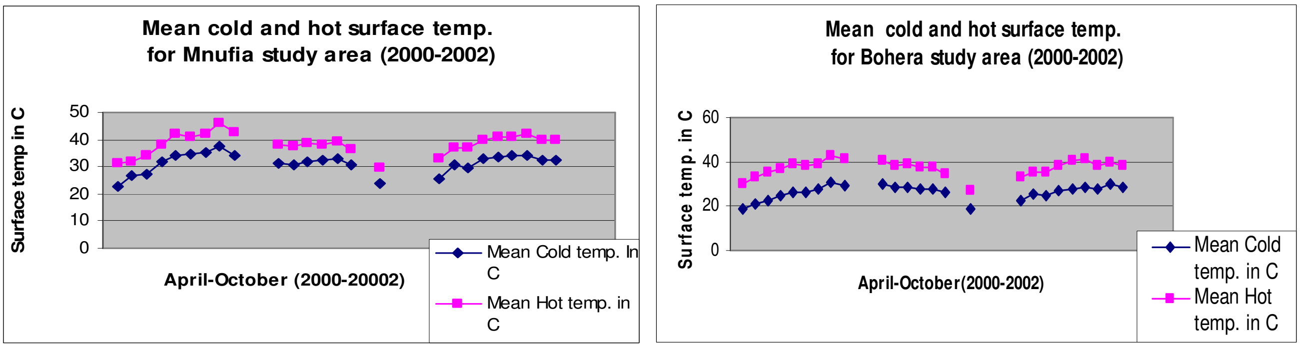


Figure 10: Temporal variation of the hot (T_H) and cold (T_C) pixel values during the 2000, 2002 seasons in °C

- Figure 11 shows that the actual ET values of the irrigated fields in the study area varied from month to month in a way that was consistent with the seasonal maximum NDVI, also Figure 12 shows the opposite relation between ranged values of normalized difference vegetation index (NDVI) and land surface temperature (LST), and this opposite relation due to the concept of the extreme temperature areas representing the hot (dry/bare) and the cold (wet/vegetated) land areas, the remaining pixels in the study area will fall in between these temperature values. The two extreme temperatures also correspond with extremes in ET values. The range of these values varies from zero ETa for the hot and dry areas to a high ETa, for the cold and wet areas, Allen et al. [2]. In this study, this assumption was extended to all pixels, by assigning land surface temperature values in between these extremes to all remaining pixels in the scene, and it will experience an ET value in direct proportion to the ET fraction (Etf) as shown in equation 3.

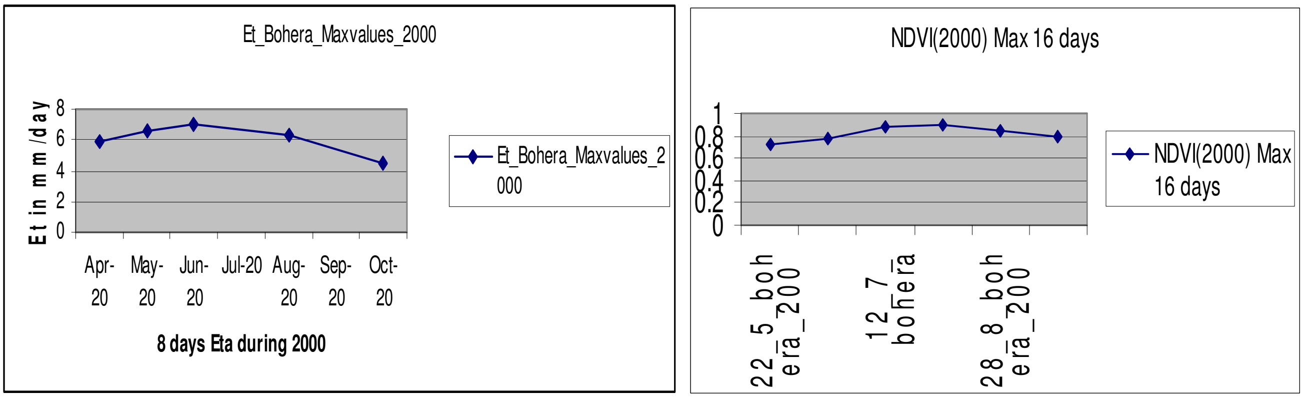


Figure 11: Temporal comparison of spatially max. 16-day average NDVI and max 8-day ETa during year 2000 season

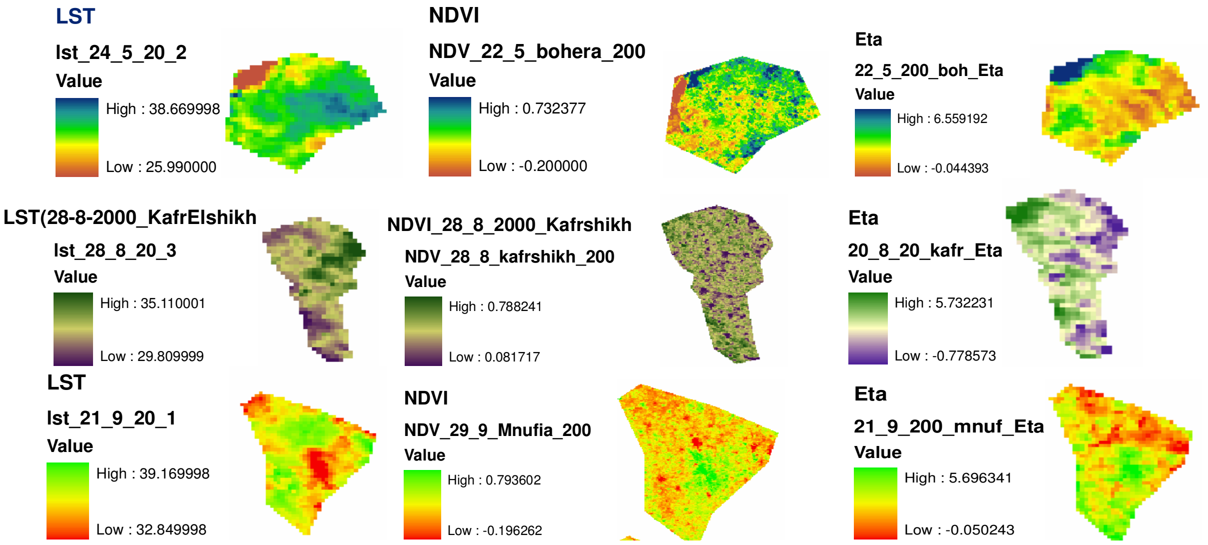


Figure 12: Comparison of spatially averaged values of NDVI 16-day, LST 8 day, and Eta 8-day during year 2000 season

Evaluation for the Etf values were made for 3 crops, Sunflower, Peanut, and Maize, by comparing modified used Kc's values for these crops in specific time period, which were determined using field data measurements and the Etf values which were resulted from applying simplified surface energy balance approach (SSEB), using spatial analyst model techniques. The relationship between Etf values and Kc values for the three mentioned crops was significant, such values of the correlation coefficient (r) were 0.93, 0.83, and 0.92 respectively in the tested areas (Fig. 13).

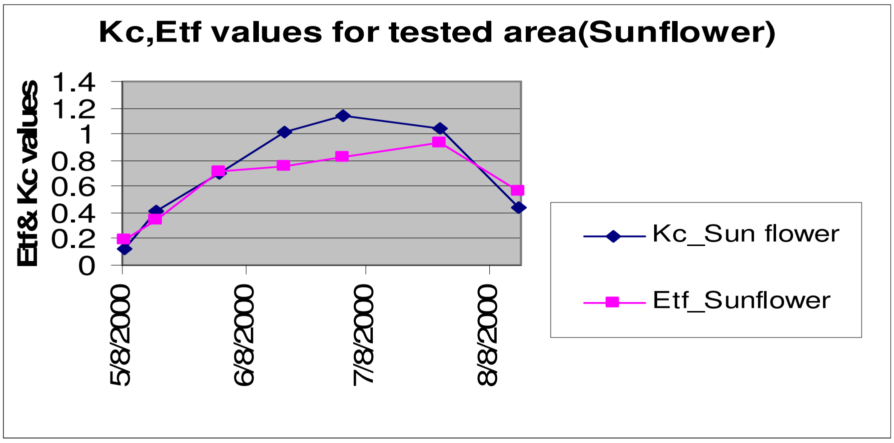


Figure 13: Kc and Etf for sunflower crop

- The applied Models run time varied based on their complexity. Every model can be run in 0.5–2 minutes depending on the complexity of the functions and the speed of the processor

CONCLUSION

This research is considered as a good application for coupling remotely sensed data and a simplified surface energy balance (SSEB) approach in producing estimates for actual ET in irrigated agricultural areas for Delta region. A major advantage of the energy-balance approach is that it can be used to quantify spatial extent of irrigated fields and their water-use dynamics without a reference to source of water as opposed to a water balance model which requires knowledge of both the magnitude and temporal distribution of rainfall and irrigation applied to fields. The actual ET values of the irrigated fields in the study area varied from month to month in a way that was consistent with the seasonal maximum NDVI. This method also captured probable water management scenarios where a unique year-to-year variability was identified. The existence of a variable temporal pattern between the *hot* and *cold* pixels during the crop season is useful in detecting time of start of season for crop monitoring activities. However, further examination of the relationship between time series of ETa and NDVI is needed. It is recommended that the used method needs to be further investigated and validated using more detailed surface energy balance methods and field data under different hydro-climatic conditions.

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