

Changes in irrigation water consumption in the Nile Delta of Egypt assessed by remote sensing

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Abstract This paper quantified irrigation water consumption according to vegetation cover changes in the Nile Delta using remote sensing data. Soil in the Nile Delta is clay, so the common irrigation system is tradition surface irrigation with less than 60 % irrigation efficiency. Agricultural field consumes more than 80 % of water resources under surface irrigation. In the previous decades, vegetation cover decreased in old lands because of urbanization. Vegetation cover changing studied at years 2002, 2007 and 2013 using Landsat 7, Landsat 8 and SPOT 4 satellite data. Monthly MODIS evapotranspiration (ETa) data were used to estimate the quantity of water consumed by vegetation cover in the Nile Delta. MODIS products land surface temperature (LST) and Normalized Difference Vegetation Index (NDVI) were used to estimate water deficit index (WDI). The FAO-Penman-Monteith (FPM) model was used to calculate reference evapotranspiration (ET_o). The crop coefficient (K_c) was estimated according to NDVI. WDI and potential crop evapotranspiration (ET_c) were used to calculate actual crop evapotranspiration (ET_a). A linear relation between ET_a based on MODIS product and ET_a based on estimated method was established with R^2 as high as 0.86. The Nile Delta agricultural water consumption changed as a result of vegetation cover changing. The vegetation cover changing were 691,870, 698,510 and 693,340 (ha), and it consumed 3.78×10^9 , 4.21×10^9 and 3.78×10^9 (m³/year) at years 2002, 2007 and 2013 respectively according to MODIS ET_a product. On the other hand,

vegetation water consumption according to estimated ET_a changed and the results were 4.7×10^9 , 5.3×10^9 and 4.8×10^9 (m³/year) at years 2002, 2007 and 2013 respectively.

Keywords Water deficit index (WDI) · Normalized Difference Vegetation Index (NDVI) · Vegetation cover · Actual evapotranspiration (ET_a) · Landsat · SPOT 4 and MODIS

Introduction

Agricultural production depends on a lot of parameters, and the most important one is water. In the past, irrigation water enabled farmers to increase crop yields by reducing their dependence on rainfall patterns, thus increasing the average crop production while decreasing the annual rainfall (Tubiello 2005). Nowadays, the irrigated area has expanded to over 270 Mha worldwide, about 18 % of total cultivated land (Fischer et al. 2007). Agriculture is the largest user of water among human activities. Surface irrigation is the most common method of irrigation and accounts for 95 % of irrigation in the world (FAO 1996), and it is well suited for use on both small and large schemes. Basin, border and furrow are all surface irrigation methods. Traditional surface irrigation system is common in old lands of Egypt because of lower cost and simplicity compared with other methods.

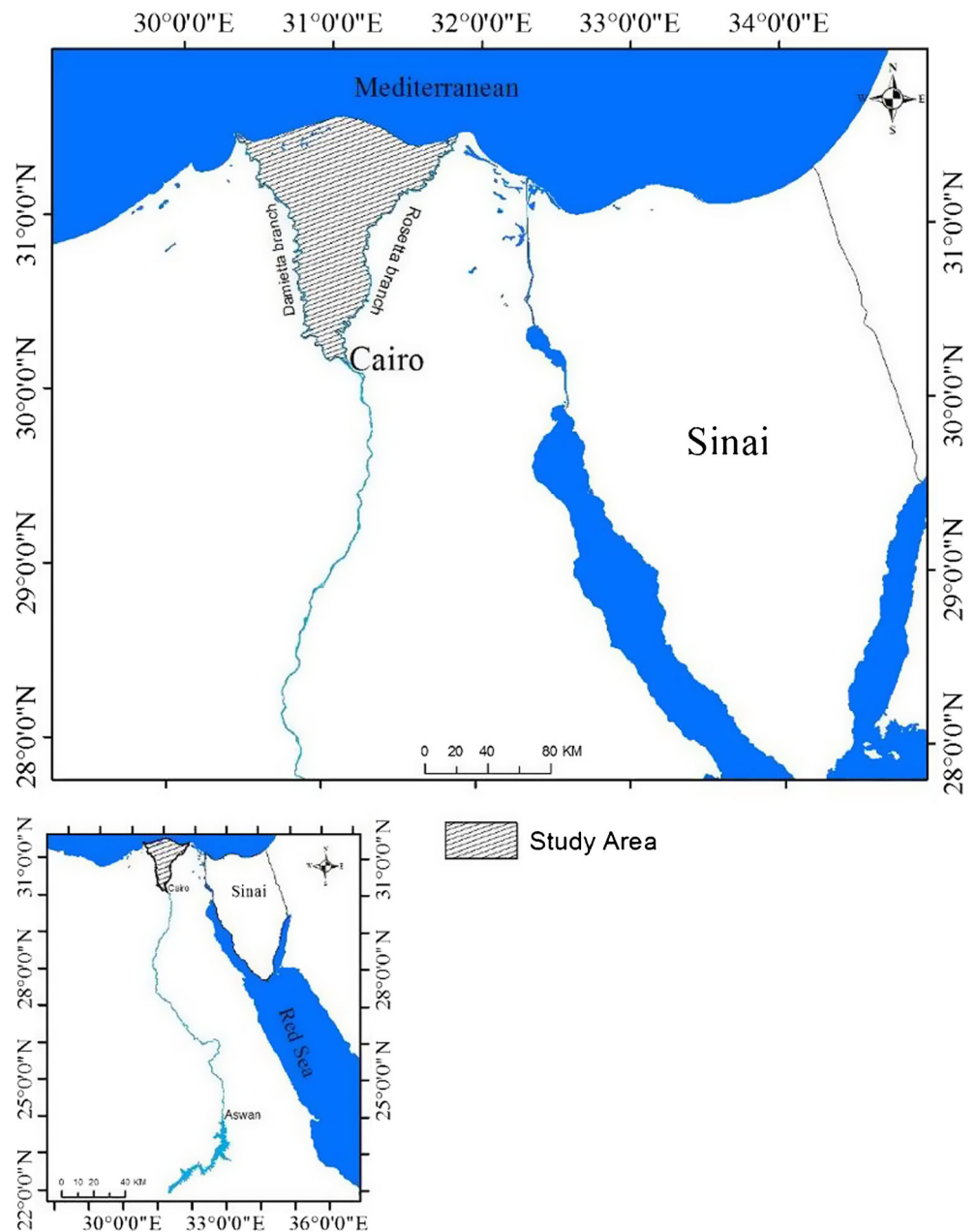
In arid and semi-arid regions, consumptive use is the best index for assessment of irrigation requirements. A large part of the irrigation water applied to farmland is consumed by evapotranspiration (ET). Maeda et al. (2011) reported that ET is an important component of the hydrological cycle, and its accurate quantification is crucial for the design, operation and management of irrigation systems. However, the lack of meteorological data

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Fig. 1 Study area location



from ground stations is a clear barrier to the proper management of water resources in poor countries, increasing the risks of water scarcity and water conflicts. Irrigation

water consumption under each of the physical and climatic conditions at a large scale will be easier with remote sensing techniques.

Table 1 Average annual weather parameters in the study area (Cairo, Baltim, Alexandria, Ismailia and Wadi El-Natroon meteorological stations)

2002						2007						2013					
TM	Tm	T	U ₂	RH	P	TM	Tm	T	U ₂	RH	P	TM	Tm	T	U ₂	RH	P
26.6	16.8	21.6	14.9	61	164	27.9	17.9	22.9	13.5	56.6	115	27	17	21.7	14.3	60.9	141
Changing based on 2002						+1.3	+1.1	+1.3	-1.9	-4.4	-49	+0.4	+0.2	+0.1	-0.6	-0.1	-25

TM maximum air temperature, Tm minimum air temperature, T mean air temperature, U₂ wind speed (km/h), RH relative humidity (%), P precipitation (mm)

Table 2 The path, raw and date of used satellite data

Image	Path and raw	Date
Landsat 7 ETM+	176/38	13-08-2002
	177/39	25-08-2002
SPOT 4	110/288	10-08-2007
	110/287	11-07-2007
	110/289	10-08-2007
	111/289	10-08-2007
	111/287	04-07-2007
	111/288	10-08-2007
	111/291	10-08-2007
	112/287	26-08-2007
Landsat 8	112/288	26-08-2007
	112/289	11-07-2007
	112/290	11-07-2007
	176/38	03-08-2013
	117/38	25-07-2013

A series of advanced satellite sensors have been launched to provide data at regional to global scales for various environmental monitoring applications. Since ground observation networks cover only a small portion of global land surface, it is important to use remote sensing data to overcome the spatial problems involved in conventional methods of ET estimation. Remote sensing provides spatial coverage by measurement of reflected and emitted electromagnetic radiations, across a wide range of wavebands, from the Earth’s surface and surrounding atmosphere. The general approach to account for all environmental factors is to use a combination of remote sensing data, ancillary surface data and atmospheric data for the estimation of ET (Bastiaanssen et al. 1996; Moran et al. 1994). Satellite-based remote sensing is an active, economic and

efficient tool for estimating actual ET from irrigated regions and for developing crop coefficient (Kc) curves (Tasumi and Allen 2007; El-Shirbeny et al. 2014a; El-Shirbeny et al. 2014b). This technique can cover hundreds of sampled fields at a time so that large populations of reference evapotranspiration (ET_o) and Kc can be used to develop representative mean values. Ryu et al. (2012) developed a temporal upscaling scheme using satellite-derived instantaneous estimates of ET to produce a daily sum ET averaged over an 8-day interval.

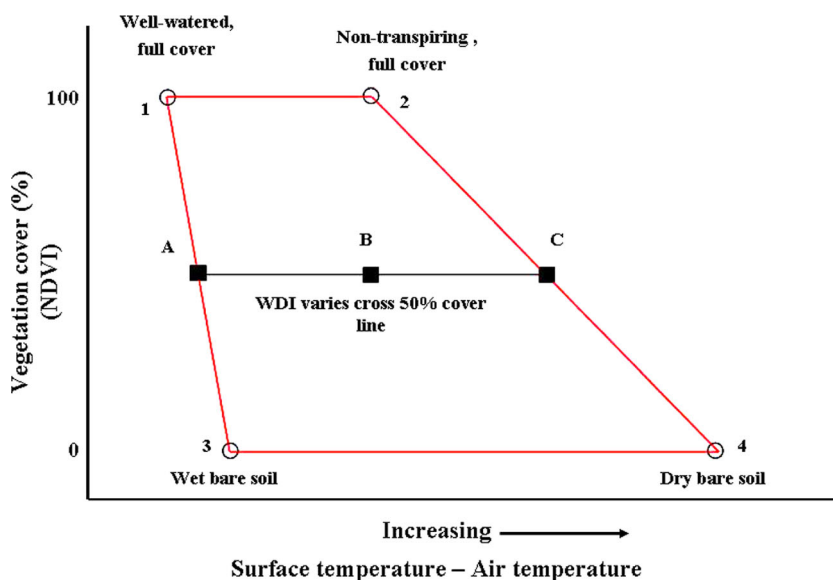
Changing in vegetation cover will lead to changing in irrigation water consumption. Various studies on agricultural applications using remote sensing and GIS techniques were done in Egypt by Aboelghar et al. (2010; 2011), and land use/cover change has been extensively studied at various scales ranging from local to global using remote sensing and GIS by Lambin and Ehrlich (1997), Foody (2001), Loveland et al. (2002), Rogan et al. (2003) and El-Shirbeny et al. (2014c). It was reported that land use/cover changes caused significant changes in regional climate (Zhao et al. 2001). Changing in vegetation cover will lead to changing in irrigation water consumption. The main objective of this study is to assess the irrigation water consumption changing in the Nile Delta using remote sensing.

Materials and methods

Study area

The study area is located between Damietta and Rosetta branches, in the northern part of Egypt (Fig. 1). The Damietta and Rosetta branches drain in the Mediterranean Sea. The study area is 8900 km² (890,000 ha). In the Nile Delta, the

Fig. 2 Water deficit index (WDI) trapezoid



agricultural cycle is often two agricultural seasons yearly: summer and winter. Common summer crops are maize, rice and cotton while common winter crops are clover and wheat. The traditional surface irrigation system is the common system. The climate in the study area is arid, and Table 1 shows the average annual weather parameters which affect crop water requirements.

Remote sensing data

Low-resolution MODIS satellite imagery was used to collect ET while high-resolution satellite imagery (Landsat and SPOT) were used to estimate vegetation cover changes in the Nile Delta.

Landsat and SPOT images

Landsat 7, SPOT 4 and Landsat 8 imageries were used to produce vegetation cover maps for the years of 2002, 2007 and 2013 respectively. Landsat 7 data (30 m ground resolution) were acquired on Aug. 2002, SPOT 4 (20 m ground resolution) acquired on Jul. and Aug. 2007 and Landsat 8 data

(30 m ground resolution) acquired on Jul. and Aug. 2013. The space and time of satellite data which were used in the study are shown in Table 2. The difference between Landsat data spatial resolution and SPOT 4 is not very high, and it gives almost the same results especially in data resolution merge cases.

MODIS data

ET, Normalized Difference Vegetation Index (NDVI) and land surface temperature (LST) products from MODIS data for 2002, 2007 and 2013 were used. The data has a 5-km spatial resolution and a 30-day temporary resolution. The MOD16 ET datasets were estimated using Mu et al. (2011) after improving the ET algorithm of Mu et al. (2007). The ET algorithm is based on the Penman-Monteith equation (Monteith 1965). The ET algorithm improved by (1) simplifying the calculation of vegetation cover fraction; (2) calculating ET as the sum of daytime and nighttime components; (3) adding soil heat flux calculation; (4) improving estimates of stomatal conductance, aerodynamic resistance and boundary layer resistance; (5) separating the dry canopy surface from the wet;

Fig. 3 Nile Delta vegetation cover map based on Landsat 7 data (2002)

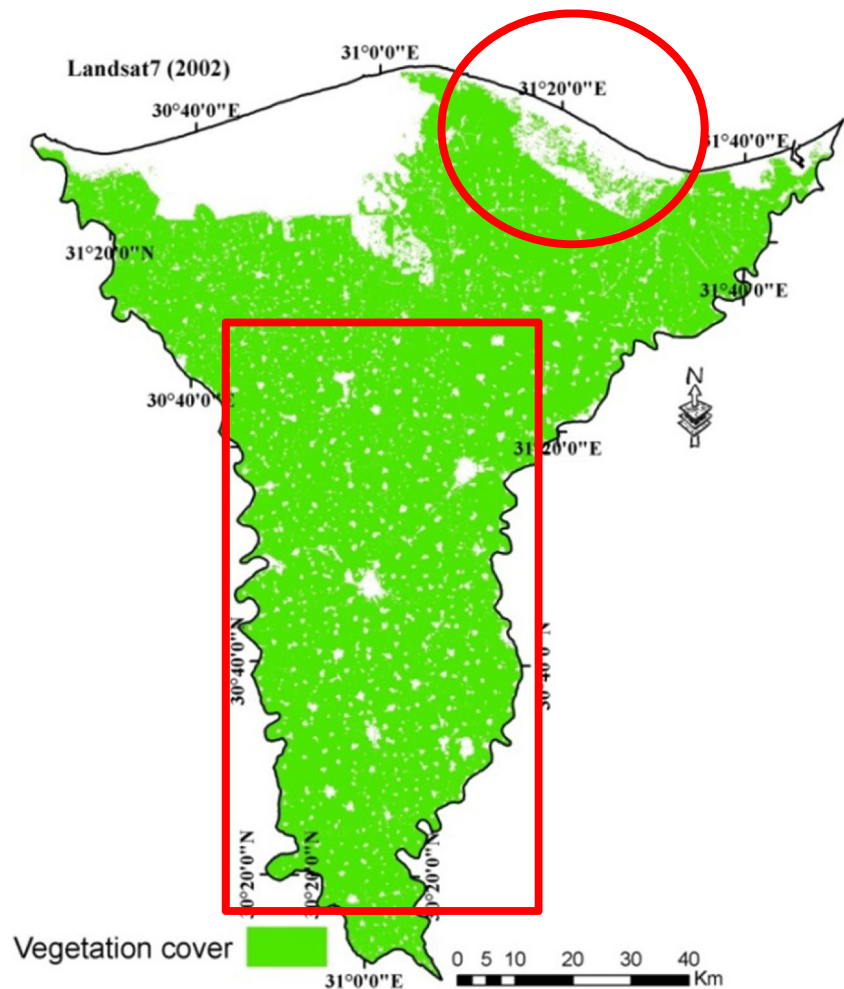
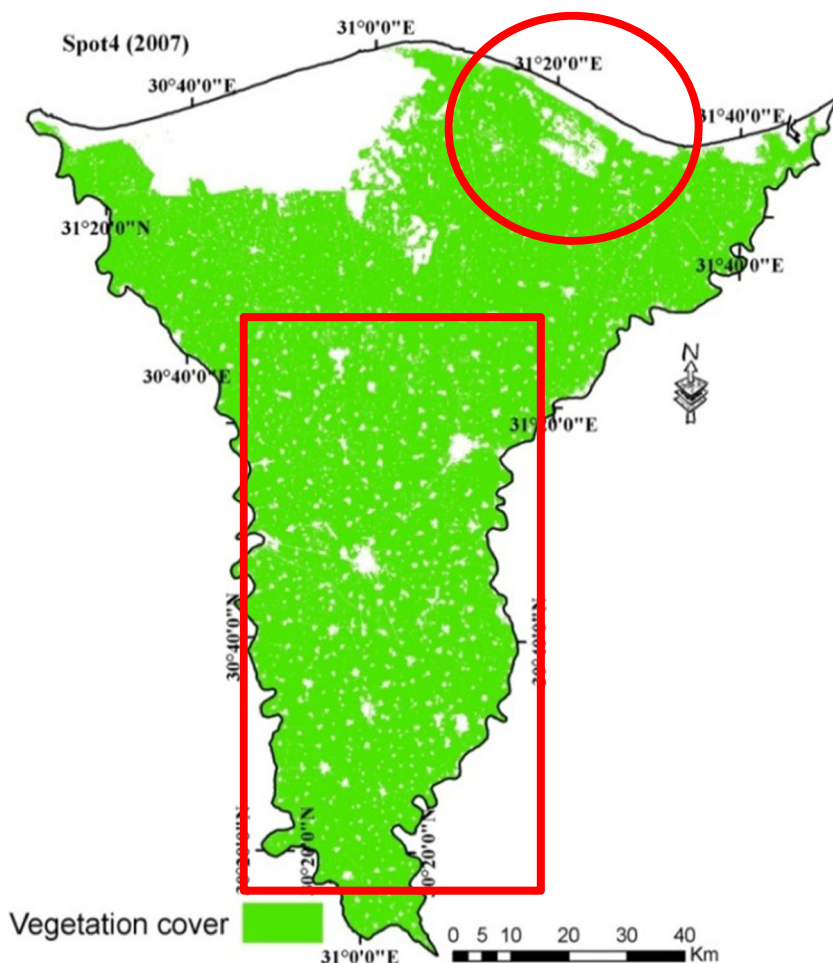


Fig. 4 Nile Delta vegetation cover map based on SPOT 4 data (2007)



and (6) dividing soil surface into saturated wet surface and moist surface. They also compared the algorithm locally at 46 eddy flux towers. Surface resistance is an effective resistance to evaporation from land surface and transpiration from the plant canopy. NDVI and LST were used to estimate the water deficit index (WDI) which was used with crop evapotranspiration (ETc) to estimate actual evapotranspiration (ETa).

Normalized Difference Vegetation Index

NDVI were extracted from Landsat and SPOT data. NDVI transformation is computed as the ratio of the measured intensities in the red (R) and near infrared (NIR) spectral bands using the following formula:

$$NDVI = (NIR - R) / (NIR + R) \tag{1}$$

The resulting index value is sensitive to the presence of vegetation on the Earth’s land surface and can be used to address issues of vegetation type, amount and condition. Many satellites have sensors that measure the red and near-infrared spectral bands.

Vegetation cover changes

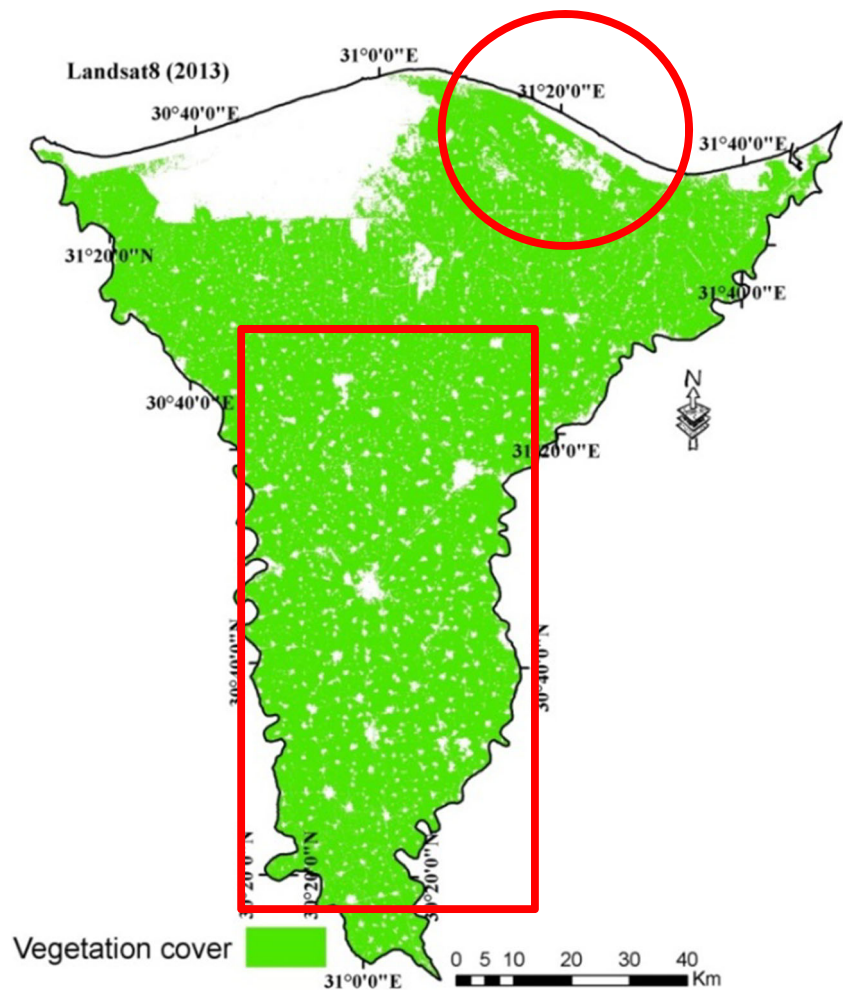
Stacked NDVI with spectral bands of Landsat and SPOT were used to classify vegetation cover using unsupervised classification. Initial unsupervised classification was applied which is an automated cluster analysis technique that uses a minimum spectral distance cluster algorithm to assign a pixel to a cluster of pixels with similar attribute (Campbell 1996).

ERDAS Imagine software was used to calculate error matrix and kappa statistics. The kappa was computed as:

$$k = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} \cdot x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} \cdot x_{+i})} \tag{2}$$

where *N* is the total number of sites in the matrix, *r* is the number of rows in the matrix, *X_{ii}* is the number in row *i* and column *i*, *x_{i+}* is the total for row *i* and *x_{+i}* is the total for column *i*.

Fig. 5 Nile Delta vegetation cover map based on Landsat 8 data (2013)



Actual evapotranspiration estimation

The WDI is a very interpreting method to measure the amount of ET actually occurring to the ET_c (Eq. (3)).

$$WDI = 1 - ET_a / ET_c \quad (3)$$

Moran et al. (1994) developed the WDI (Eq. (4)). The WDI uses both LST subtracting T_{air} and a vegetation index to estimate the relative water status of a field (Fig. 2).

$$WDI = (dT - dTL_{13}) / (dTL_{24} - dTL_{13}) \quad (4)$$

where dT is the measure of surface subtracting air temperature at a particular percent cover, dTL_{13} is the surface minus air temperature determined by the line from points 1 to 3 for the percent cover of interest and dTL_{24} is the temperature difference on the line formed between points 2 and 4.

The relation between K_c and NDVI is represented by Eq. (5), which was used by El-Shirbeny et al. (2014a) and calibrated for wheat by El-Shirbeny et al. (2014b).

$$K_c = \frac{1.2}{NDVI_{dv}} (NDVI - NDVI_{mv}) \quad (5)$$

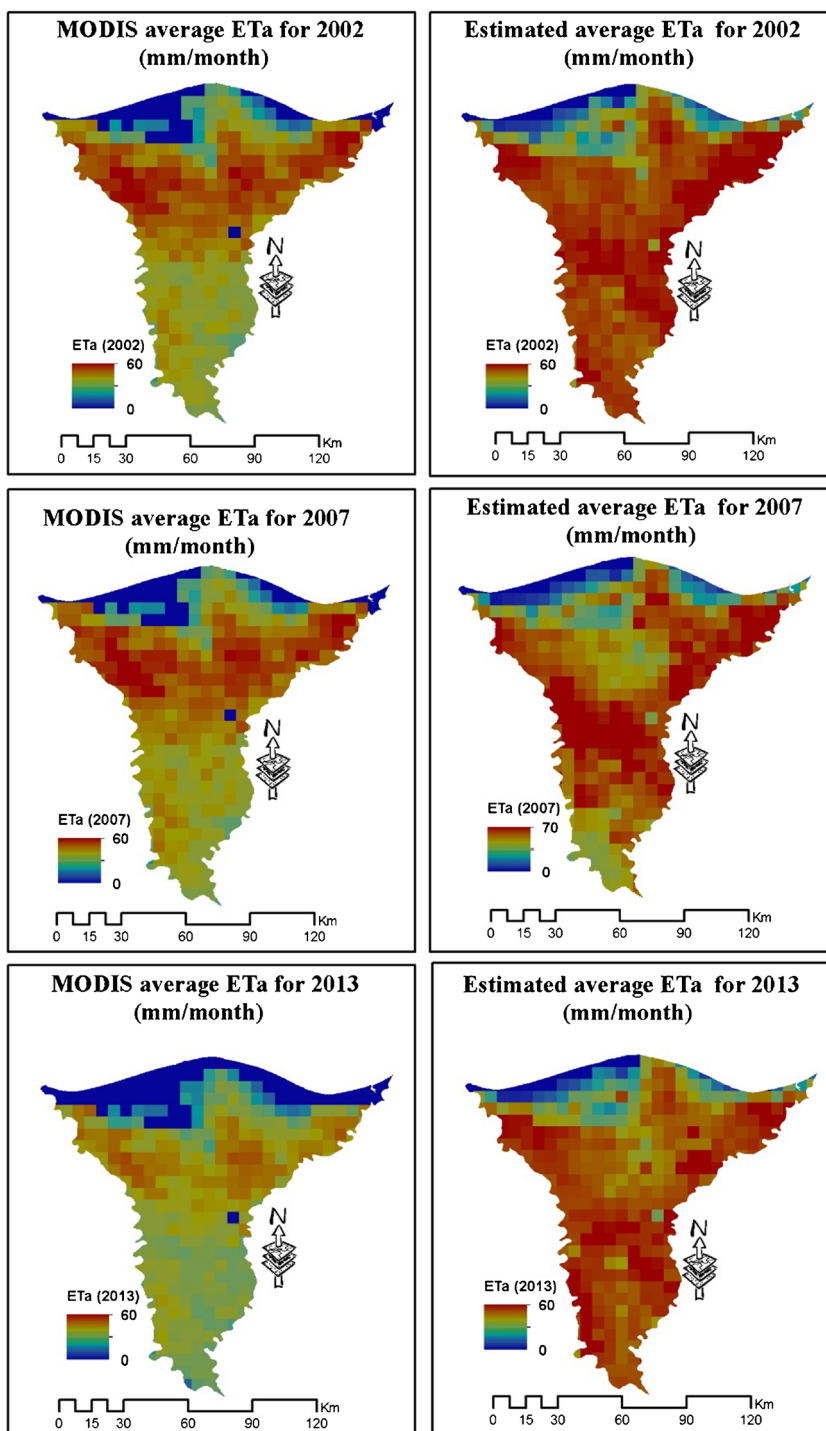
where 1.2 is the maximum K_c under Egyptian conditions, $NDVI_{dv}$ is the difference between minimum and maximum NDVI values for vegetation and $NDVI_{mv}$ is the minimum NDVI value for vegetation.

ET_o was calculated from meteorological data using the FPM method (Eq. (6)) which was prepared by Allen et al. (1998). This formula was applied to calculate ET_o .

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \quad (6)$$

where ET_o is the reference evapotranspiration (mm/day), R_n is the net radiation at the crop surface ($MJ/m^2/day$), G is the soil heat flux density ($MJ/m^2/day$), T is the mean daily air temperature at 2 m of height ($^{\circ}C$), u_2 is the wind speed at 2 m of height (m/s), e_s is the saturation vapour pressure (kPa), e_a is

Fig. 6 Annual average ETa maps according to MODIS product and estimated method at years 2002, 2007 and 2013



the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve (kPa/°C) and γ is the psychrometric constant (kPa/°C).

Equations (5) and (6) were used to estimate ETc as shown in Eq. (7).

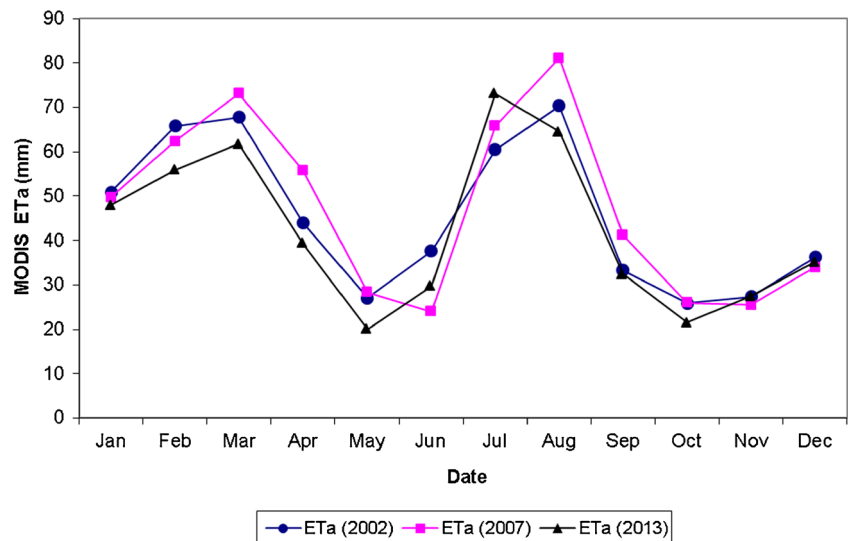
$$ETc = ET_o * Kc \tag{7}$$

Results and discussion

Vegetation cover changes

An error matrix and kappa statistics were used on a classified map based on 177 ground truth points to determine the percentage of vegetation cover accuracy. The accuracy of

Fig. 7 Monthly MODIS ETa product (mm/month) at years 2002, 2007 and 2013



vegetation class was 99.44, 98.87 and 97.74 % in 2002, 2007 and 2013 respectively.

Vegetation cover has an important impact on irrigation water consumption. Vegetation expanded in the northern part of the Nile Delta (red cycle is an example) because of converted bare soil to cultivated land and decreased in old lands specially around cities and villages (red rectangle is an example) because of urbanization. Generally, vegetation cover changed and areas were 691,870, 698,510 and 693,340 (ha) for 2002, 2007 and 2013 respectively. Vegetation cover increased about 1 % between 2002 and 2007 and 0.2 % between 2002 and 2013. On the other hand, the vegetation cover decreased 0.75 % between 2007 and 2013. Figures 3, 4 and 5 illustrate the geographical changing in vegetation cover.

Actual evapotranspiration

Limited water resources and scarcity of water in Egypt are the main challenges for agricultural horizontal expansion policies and strategies. To solve this problem, adopted policies of

horizontal and vertical expansion in agricultural lands and activities had been considered based on saving irrigation water to cultivate another area.

Changing in weather condition and/or changing in vegetation cover means changing in ETa. The mean of ETa according to MODIS product was changed, and the results were 45.6, 50.2 and 45.4 (mm/month) at years 2002, 2007 and 2013. On the other hand, the mean of ETa according to WDI changed and the results were 56.6, 62.7 and 57.4 (mm/month) at years 2002, 2007 and 2013 respectively (Fig. 6). The northern part of the study area consumes water more than the southern part because of rice cultivation in summer in this part which consumes a lot of water; on the other hand, rice cultivation is not allowed in the southern part. In the last decade, the government started developing field irrigation systems in the northern part of the Nile Delta shared with the German government.

From Figs. 7 and 8, there are two seasons: the first one starts from the beginning of June and finishes at the end of September, and the second from the beginning of November

Fig. 8 Monthly estimated ETa (mm/month) at years 2002, 2007 and 2013

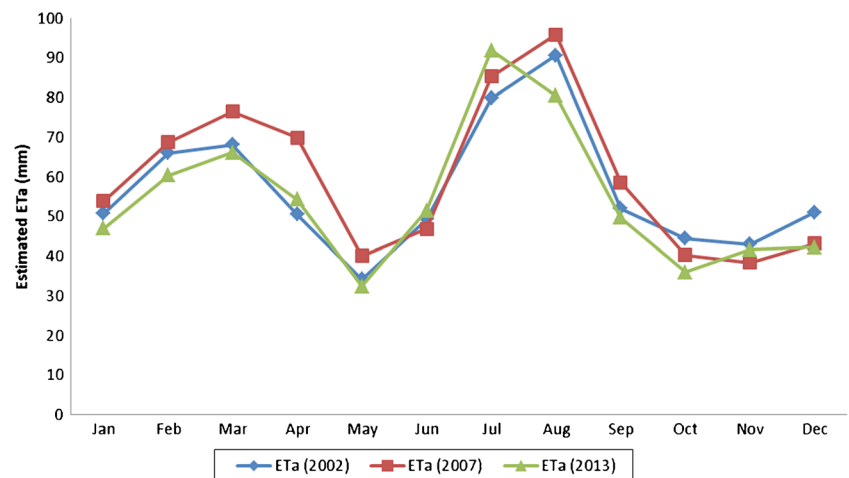
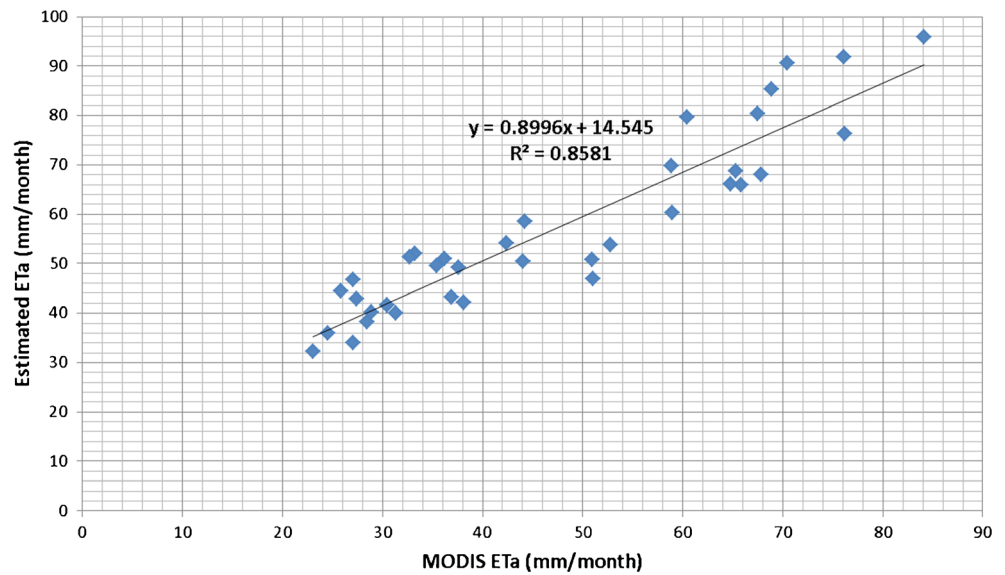


Fig. 9 The relation between MODIS ETa product and estimated ETa



to the end of April. On the other hand, May and October almost are in-between seasons. The maximum ETa according to MODIS product in 2002 and 2007 were 70.7 and 84.2 (mm/month) in August respectively, but the minimum were 25.8 and 27 (mm/month) in October and June respectively. In 2013, the minimum of ETa was 23 (mm/month) in May and the maximum was 76.1 (mm/month) in July.

On the other hand, the maximum ETa according to WDI in 2002 and 2007 were 90.5 and 98.8 (mm/month) in August respectively, but the minimum were 34.1 and 41.3 (mm/month) in May and November respectively. In 2013, the minimum of ETa was 35.4 (mm/month) in May and the maximum was 94.8 (mm/month) in July. A linear relation between ETa based on MODIS product and ETa based on estimated method was established with R^2 as high as 0.86 (Fig. 9).

The quantity of water used by vegetation cover according to MODIS product ETa changed, and water consumption were 3.78×10^9 , 4.21×10^9 and 3.78×10^9 ($m^3/year$) at years 2002, 2007 and 2013 respectively. The maximum vegetation

water consumption in 2002 and 2007 were 487.1 and 587.8 (million $m^3/month$) in August respectively, but the minimum were 178.7 and 188.8 (million $m^3/month$) in October and June respectively. In 2013, the minimum vegetation water consumption was 159.7 (million $m^3/month$) in May and the maximum was 527.6 (million $m^3/month$) in July.

On the other hand, vegetation water consumption according to estimated ETa changed and the results were 4.7×10^9 , 5.3×10^9 and 4.8×10^9 ($m^3/year$) at years 2002, 2007 and 2013 respectively. The maximum vegetation water consumption in 2002 and 2007 were 626.2 and 690.2 (million $m^3/month$) in August respectively, but the minimum were 235.9 and 288.8 (million $m^3/month$) in May and November respectively. In 2013, the minimum vegetation water consumption was 245.6 (million $m^3/month$) in May and the maximum was 657.4 (million $m^3/month$) in July.

Water consumption in 2007 was higher than that in 2002 because of vegetation cover increasing, and annual weather parameters in 2007 were higher than those in 2002. Figures 10

Fig. 10 The vegetation water consumption calculated according to MODIS ETa product (million $m^3/year$) at years 2002, 2007 and 2013

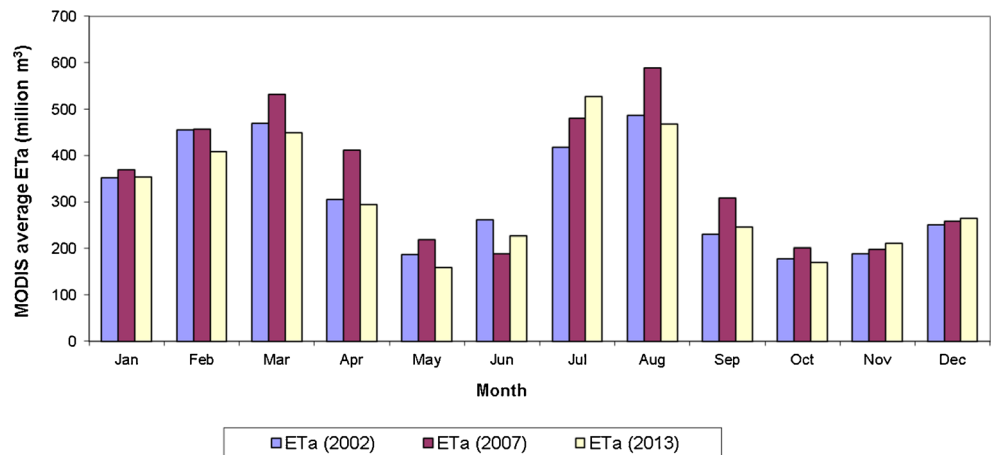


Fig. 11 The vegetation water consumption calculated according to estimated ETa (million m³/year) during the years 2002, 2007 and 2013

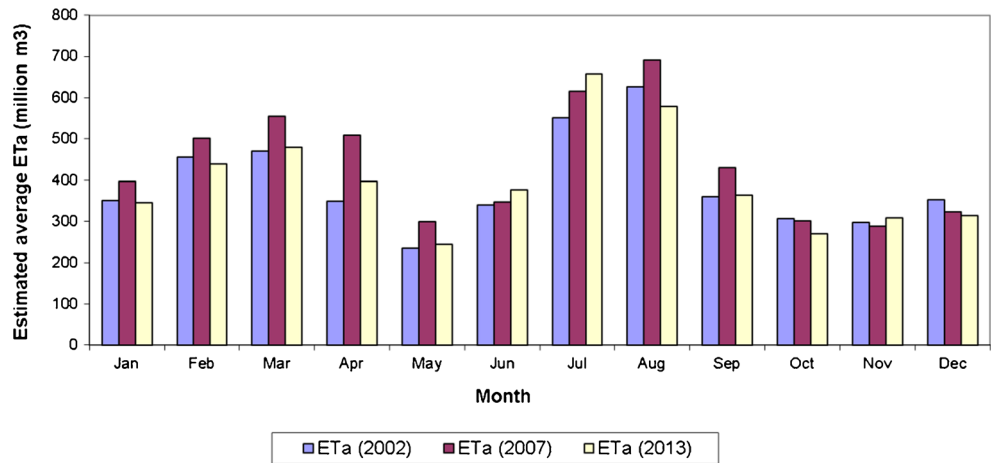
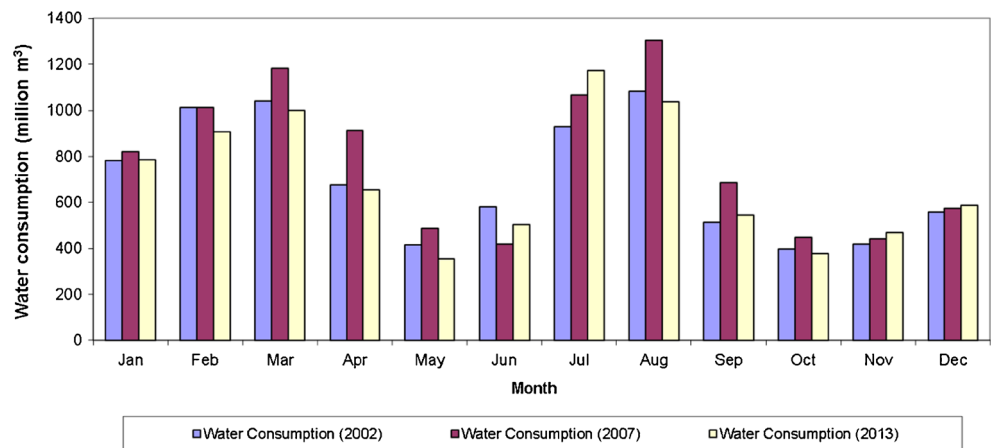


Fig. 12 Agricultural water consumption in the Nile Delta at years 2002, 2007 and 2013 based on MODIS product

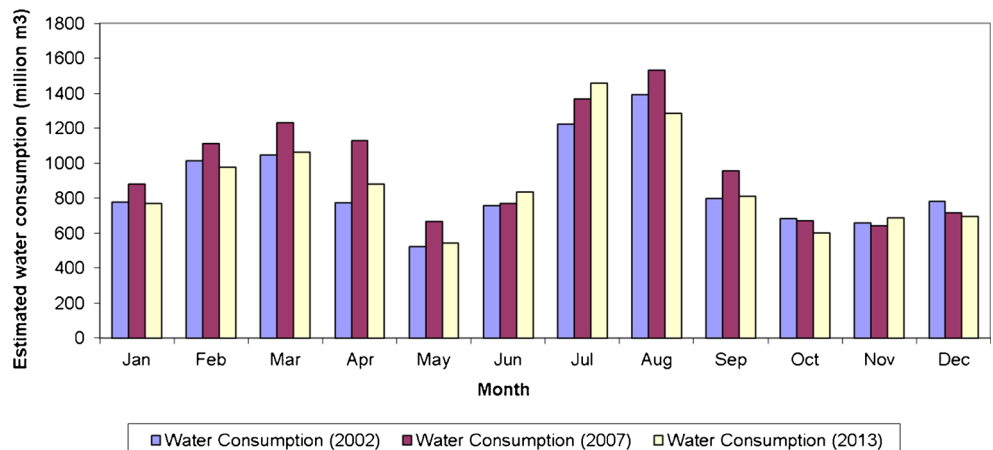


and 11 illustrate the changing in quantity of vegetation water consumption according to MODIS product and estimated ETa at years 2002, 2007 and 2013.

The water losses in the agricultural sector are very high, such as canal evaporation and percolation. The efficiency of water distribution in the field especially under traditional

surface irrigation methods is low. Agriculture consumes about 70 % of all water use globally, and water use efficiency in this sector is not higher than 45 % (Zhang and Yang, 2004). The calculation of irrigation water used in the Nile Delta was according to 45 % water use efficiency, and it is represented in Figs. 12 and 13. Agricultural water needs were changed

Fig. 13 Agricultural water consumption in the Nile Delta during 2002, 2007 and 2013 based on estimated method



according to MODIS product ETa, and irrigation water consumption were 8409.2, 9359.8 and 8396.7 (million m³/year) at years 2002, 2007 and 2013 respectively. On the other hand, irrigation water consumption was changed according to estimated ETa and the results were 10,440.1, 11,683.1 and 10,611.4 (million m³/year) at years 2002, 2007 and 2013 respectively.

Conclusion

Remote sensing techniques are very useful to monitoring and developing the agricultural sector. The monitoring of irrigation water consumption changing will be useful to manage water resources effectively especially in arid and semi-arid regions. In this study, four satellite data were used, which are Landsat 7, Landsat 8, SPOT 4 and MODIS. Two images for Landsat 7 in 2002, two images for Landsat 8 in 2013 and 11 images for SPOT 4 data in 2007 were used to study changing in vegetation cover through the period of 2002 to 2013. On the other hand, the monthly MODIS ETa product was used to study vegetation water consumption through the years 2002, 2007 and 2013. The agricultural water consumption changed because of changing of vegetation cover and weather parameters. The vegetation cover increased by 1 % between 2002 and 2007 and 0.2 % between 2002 and 2013. The variation in irrigation water consumption increased by 11.4 and 10.6 % in 2007, from the base consumption of 2002 based on MODIS ETa product and estimated ETa method respectively, while consumption in 2013 was almost the same and 1.6 % increasing in 2002 based on MODIS ETa product and the estimated ETa method respectively. It happened because of weather conditions in 2007 which drove ET up and increasing in vegetation cover. The vegetation cover must be studied every 5 years to monitor changing in agricultural areas which affects the agricultural sector especially in arid and semi-arid regions.

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