Actual evapotranspiration evaluation based on multi-sensed data

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ABSTRACT

On overcast days, the significance of active and passive remote sensing data integration becomes clear. On cloudy days, the absence of passive remote sensing data limits the benefit of large-scale satellite data in cloudy regions, while active remote sensing has the advantage of being able to pierce the cloud and gather data underneath the cloud. The primary goal of this study is to assess the advantages of integrating active and passive remote sensing data to identify real evapotranspiration (ETa). Sentinel-1 radar data is active data, while Landsat-8 data is passive data. During the 2016 summer season, multi-date Landsat-8 and Sentinel-1 data were utilized. Clay is the predominant soil texture in the research area. The meteorological data were used to calculate ET0 using the FAO-Penman-Monteith (FPM) method, and the Lysimeter data were used to test the calculated ETa. The Normalized Difference Vegetation Index (NDVI) and Crop Water Stress Index (CWSI) are calculated using Landsat-8 data (CWSI). Crop Coefficient (Kc) is computed using NDVI. ETa was calculated using the CWSI, Kc, and ET0. Data from the Sentinel-1 satellite’s backscattering (dB) C-band Synthetic Aperture Radar (SAR) was correlated with Kc and used to determine ETa. The Root Mean Square Error (RMSE) calculated relevant findings for active and passive satellite data individually, as well as the combining procedure. The RMSE for Sentinel-1, Landsat-8, and combination techniques was 0.89, 0.24, and 0.31 (mm/day), respectively.

KEY WORDS: Sentinel-1, Landsat-8, Backscattering (dB), Lysimeter, Water Stress, and Egypt

INTRODUCTION

Because ET computation is dependent on the application target, it is critical to differentiate between ET0, ETr, ETe, and ETa. The canopy resistance is measured as a function of wind speed that is specific to the height of the reference surface when calculating reference evapotranspiration for short canopies (ET0) and tall canopies (ETr), and aerodynamic resistance is measured as a function of wind speed that is specific to the height of the reference surface when calculating reference evapotranspiration for short canopies (ET0) and tall canopies (ETr) (ASCE-EWRI, 2005; Ghandour et al., 2006). ETe denotes crop evapotranspiration under normal circumstances, while ETa denotes crop evapotranspiration under abnormal conditions (Allen et al., 1998). The ETa is the physical amount of plant-water consumption throughout the course of its life, from phenological phases of culture to senescence. ETa is driven by climate conditions, crop traits, and water availability (Allen et al., 1998). The ETa is estimated using many factors, including the ET0, the Crop Coefficient (Kc), and the Crop Water Stress Index (CWSI).

Satellite and aerial data, as well as remotely sensed ground-based data utilized at the farm level, have been used to estimate ET at regional and global sizes during the past several decades. Remotely sensed data and methods have been utilized and assessed for determining ET (Rwasoka et al., 2011; El-Shirbeny et al., 2014a; Tadesse et al., 2015; El-Shirbeny et al., 2015, El-Shirbeny et al., 2015, El-Shirbeny et al., 2015, El-Shirbeny et al., 2015, El-Shirbeny et al., 2015, Oki & Kanae, 2006; Mohamed et al., 2020; El-Shirbeny et al., 2020). Water stress, stomata conductivity, heat flux, transpiration, and cooling all lead plants to close their stomata, resulting in less evaporation and a higher canopy temperature than non-stressed plants (Stokele, & Dugas, 1992; Tolba et al., 2020).

ET is a key component in many environmental phenomena, including meteorological, agricultural, and hydrological uses (Baionmy et al., 2016; El-Shirbeny & Abu-Talib, 2018, El-Shirbeny et al., 2019; El-Shirbeny et al., 2021). When using traditional techniques, reliable measurement of in situ ET is often expensive, time-consuming, and restricted in size. Furthermore, frequent observations are required to determine temporal variations caused by adverse weather influences. One of the most important topics in remote sensing operations is satellite-based ET estimate. Using passive remote sensing, several studies have been conducted to determine ET...
Based on remotely sensed data, curves (Kc) may be detected and established (Dibella et al., 2000; El-Shirbeny et al., 2015; El-Shirbeny et al., 2016). Several studies have been conducted to describe the Kc Curve fluctuation and its relationship with satellite-derived NDVI, as well as the direct relationship between NDVI and leaf area index (LAI) (i.e., Aboelghar et al., 2010, El-Shirbeny et al., 2014b, El-Shirbeny et al., 2015).

Crop water stress must be monitored and identified in order to discover actual water use throughout the growing season. Direct measurements of plant water content are time-consuming and expensive procedures. Therefore they are inapplicable to long-term and large-scale studies. The thermal infrared (TIR) spectrum was used to create the remote sensing system (Idso et al., 1981; Jackson et al., 1981). The rate of crop sweat is shown by the connection between surface temperature and crop water stress. The transpired water cools the crop canopy. When a crop is subjected to water stress, transpiration decreases, and the crop’s surface temperature rises (Jackson, 1982).

Crop water stress is linked to soil moisture. Because soil moisture has a complex structure, monitoring regional and temporal variations in soil moisture is critical for ecological equilibrium (Mohamed et al., 2020). Active microwave remote sensing technologies have lately been preferred in soil moisture investigations because of the impressive penetrating capabilities of the radar signal to the surface. The availability of soil water on a large scale is critical for irrigation water management and water resource planning.

Data from active and passive remote sensing are very useful for estimating soil water availability (Oki & Kanae, 2006; El-Shirbeny & Abu-Talib, 2017; Mohamed et al., 2020). The most popular active microwave remote sensing technology for Earth observation is Synthetic Aperture Radar (SAR).

In the 1970s and 1980s, the triangle and (CWSI) methods were utilized and developed. Thermal data was formerly collected using a portable infrared thermometer instrument, but with the launch of the second generation of Landsat satellite series (TM, Landsat 4), scientists began to rely on space-borne data. The SEBAL (Bastiaanssen et al., 1998) and SEBS (Su, 2002) models represent a new era in the development of evapotranspiration models in the 1990s and early 2000s. The primary inputting thermal data for these models come from Landsat, MODIS, and NOAA/AVHRR. METRIC (Allen et al., 2007), ETWatch (Wu et al., 2008), and ETlook (Bastiaanssen et al., 2012) have been created during the past decade to cope with fresh satellite data and address the gaps in the SEBAL and SEBS models. Researchers are continually working to improve and combine these models in order to improve performance and accuracy (El-Shirbeny et al., 2019). The primary goal is to examine the combined ET monitoring data from Sentinel-1 and Landsat-8.

MATERIALS AND METHODS

Study Area Description

The location of the study area is represented in Figure 1. The Zagazig station is used to estimate ETo, and the data of Lysimeter was used to evaluate the estimated ETa. Before planting, soil samples were taken. The mechanical and chemical soil analyses were performed at Ain Shams University’s ALARC laboratory. The soil characteristics showed clay texture, where clay and sand contents were high as 56% and 17%, respectively, while bulk density ranged from 1.3 to 1.6 g/cm³. According to (Saxton & Willey 2006), the average of soil water parameters in the research region is as follows: available water is 0.14 (cm³/cm³), the wilting point is 0.33 (cm³/cm³), field capacity is 0.47 (cm³/cm³), and saturation is 0.54 (cm³/cm³). The drainage rate was 0.2 (cm/hr).

Data Availability

Ground meteorological data, Lysimeter data, optical satellite data (Landsat-8), and C-band SAR satellite Sentinel-1 were all utilized.

Weather Data

Meteorological data, including maximum temperature, minimum temperature, maximum relative humidity, minimum relative humidity, wind speed, and solar radiation, were collected...
using the Zagazig ground meteorological station. The FPM model was used to estimate ETo from May to September 2016 at the Zagazig meteorological station.

Lysimeter Data

The Lysimeter was designed to measure ET from a row crop. The data were gathered from three lysimeters, each with a surface area of 1.0 m by 1.0 m. On 0.5, 1.0, and 1.5 meters, the percolate was collected in different stages. The Corn field was planted on May 25, 2016, and harvested on September 3, 2016. Because precipitation is uncommon during the summer, the typical rain gauge did not gather water in 2016. Irrigation was the sole source of water in the research region. The scheduled irrigation for Lysimeter; irrigation time and quantity is indicated in Table 1. The water balance in the Lysimeter may be expressed as follows:

\[ \Delta S = I - ET - P \]  

Where; \( \Delta S \) is the change in soil moisture, I is irrigation, \( ET \) is evapotranspiration, and \( P \) is deep percolation. The main disadvantage of the Lysimeter was that it could only collect fluids under saturated gravity flow. If the applied water exceeds the saturation threshold, the percolation data is only recorded during two or three days after irrigation. The Lysimeter water volume measurements (Figure 2) have been used to estimate \( ET \) using Lysimeter (mm/day).

Remote Sensing Data

Landsat-8 and Sentinel-1 data from several dates were utilized. Table 2 shows the distribution of satellite data time for Landsat-8 and Sentinel-1 throughout the 2016 summer season. Around 10:15 a.m., the Landsat-8 (paths 176 and 177/row 039) was launched. Sentinel-1 radar data with a 10-meter ground resolution and local time with a 30-meter ground resolution were utilized.

Landsat Data Processing

Landsat 8 data were obtained from the USGS website and processed for radiometric and atmospheric corrections. The Quick Atmospheric Correction (QUAC) method was used to convert digital number (DN) values into reflectance values and reduce the effects of atmospheric scattering.

Radar Data Processing

SNAP software is used to calibrate the sentinel-1 data. The goal of SAR calibration, based on SNAP assistance, is to provide pictures in which the pixel values may be directly linked to the radar backscatter of the scene. Four calibrations are provided by the level-1 goods. Look-Up Tables (LUTs) are used to get \( 0_\beta \), \( 0_\sigma \), and \( I_\text{or} \) to reach the Digital Number (DN). LUTs use a range-dependent gain that counts the absolute calibration constant. A constant offset is also utilized for GRD goods. The radiometric calibration is practical through the following equation:

\[ \text{value}(i) = \frac{\text{DN}(i)}{A(i)} \]  

where, based on the nominated LUT, value \( i \) = one of \( B_\beta \), \( \sigma_\sigma \), or original DN, \( A = \) one of bataNought \( (i) \), lsigmaNought \( (i) \), gamma \( (i) \) or dn \( (i) \), Bi-linear interpolation is used for any pixels that fall between points in the LUT. After calibration, the backscattered VV-polarization data are used to indicate the crop and soil water content.

Supervised Classification

Landsat-8 data are combined with ground data to identify land-use groups. A maximum likelihood classifier is a common approach for classifying satellite data using a pixel-based methodology in which each pixel has one value and is classified as a single land-use class (Li et al., 2014). The likelihood (Lk) is well-defined as the probability of a pixel fitting to a particular

Table 1: Scheduled irrigation for Lysimeter; irrigation time and quantity

| Date      | No of Irrigations | Applied water (m3/ha) |
|-----------|-------------------|-----------------------|
| 25-May-16 | Agriculture       | 1320                  |
| 10-Jun-16 | Irri. 1           | 950                   |
| 28-Jun-16 | Irri. 2           | 1230                  |
| 15-Jul-16 | Irri. 3           | 1250                  |
| 1-Aug-16  | Irri. 4           | 970                   |
| 16-Aug-16 | Irri. 5           | 900                   |
| Total     |                   | 6620                  |
Evapotranspiration (ET)

The crop evapotranspiration (ETc) is computed in two stages: first, the reference evapotranspiration (ETo) is determined, and then the crop coefficient (kc) is given (Allen et al., 1998). Equation (3) brings the two phases together.

\[ \text{ETc} = \text{ETo} \times \text{Kc} \] (3)

Meteorological data is required to calculate ETo. The FAO-Penman-Monteith (FPM) technique is appropriate for use in the research area (El-Shirbeny & Abdellatif, 2017). (Allen et al., 1998) developed Equation (4) to compute ETo (mm/day).

\[ \text{ETo} = \frac{0.408(R_n - G) + \frac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \] (4)

where: \( R_n \), net radiation [MJ/m²/day], \( G \), soil heat flux [MJ/m²/day], \( T \), daily air temperature [°C], \( u_2 \), wind speed [m/s], \( e_s \), saturation vapor pressure [kPa], \( e_a \), actual vapor pressure [kPa], \( \Delta \), slope vapor pressure curve [kPa/°C], \( \gamma \), psychrometric constant [kPa/°C].

The possibility of assessing \( Kc \) from satellite data is represented in the relation between \( Kc \) and NDVI (El-Shirbeny et al., 2019). Equation (5) shows the relation between \( Kc \) and NDVI.

\[ Kc = \frac{1.2}{\text{NDVI}_{dv}} (\text{NDVI} - \text{NDVI}_{min}) \] (5)

where; 1.2 is the maximum \( Kc \), \( \text{NDVI}_{dv} \) is the difference between the minimum and maximum NDVI value for vegetation, and \( \text{NDVI}_{min} \) is the minimum NDVI value for vegetation.

The NDVI categorizes the land surface classes according to red (R) and near-infrared (NIR). The R is represented as band 4 in Landsat-8, while NIR is represented as band 5 in Landsat-8. The R and NIR are used to calculate NDVI as follows:

\[ \text{NDVI} = \frac{\text{NIR} - R}{\text{NIR} + R} \] (6)

The calculated Kc from radar satellite data differs from the derived Kc from optical satellite data. The backscattered VV-polarization data (dB) show Kc; values greater than 0.18 are considered bare soil and urban, with no vegetation or moist soil. While the numbers ranging from 0.18 to 0.03 reflect various phases of crop development with varying amounts of water content. Surface water with a high potential for evaporation is defined as data ranging from 0.03 to zero. The utilized relation between backscattered VV-polarization data and Kc is shown in Figure (4).

\( \text{ETa} = (1 - \text{CWSI}) \times \text{ETc} \) (7)

Where: \( \Delta T \) is the difference between surface and air temperature. The \( \Delta T_m \), is the difference between minimum surface and air temperature and \( \Delta T_x \), is the difference between maximum surface and air temperature.

The subordinated border of \( \Delta T \) happens through non-water-stressed circumstances. On the contrary, the superior border of \( \Delta T \) happens through fully-water-stressed environments. The CWSI fluctuates from zero to one, where zero shows no stress while one shows maximum stress (Jackson et al., 1981).

**Root Mean Square Error (RMSE)**

The RMSE was applied to assess the reliability of Landsat-8, Sentinel-1, and combination methods for application.

\[ \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (X_i - X_{obs})^2}{n}} \] (9)

Where; \( n \) is a number of observations, \( X_{obs} \) is the observed value for sample \( i \), and \( X_i \) is the resulted value for sample \( i \).
human-environmental interactions, such as agricultural growth, resource consumption, distribution, and urbanization (Hegazy & Kaloop, 2015; Yang et al., 2017). The land use map is created to understand the variance in ET maps and, as a result, the quality of ET map descriptions based on satellite data.

Landsat-8 data has been categorized into three groups in order to create land use maps for the research region. The urban class (pink) is distributed across the research region and represents domestic dwelling areas (cities and villages), including major highways. The agricultural area class (green) indicates cultivated lands (field crops, vegetable crops, and horticultural crops). The water canals class (blue) is a longitudinal feature that traverses the research region from east to west, providing fresh water for irrigation purposes (Figure 5).

Evapotranspiration Seasonal Maps

ET is influenced by meteorological factors like radiation, air temperature, humidity, and wind speed. The ET rate is determined by crop type, transpiration resistance, crop height, crop roughness, reflectiveness, soil cover, and crop rooting properties. Aside from soil salinity, inadequate soil fertility, restricted fertilizer usage, complex or impenetrable soil horizons, disease and insect control failure, and poor soil management may all limit agricultural yield and decrease ET (Allen et al., 1998).

The ETo is computed using the FPM model, which was fed weather data from the Zagazig meteorological station. The ETo was used with two types of Kc: the first is based on Landsat-8 data, while the second is based on Sentinel-1 data. To compute ETa, the CWSI is used with ETo and the extracted Kc from Landsat-8. The ETa maps are created using Landsat-8 (Figure 6) and Sentinel-1 data (Figure 7).

The urban has a low ETa value (near zero) according to the Landsat-8 ETa map, indicating that it is well-classified compared to the land use map (Figure 5). A low value in urban has a low value in NDVI analysis, resulting in a low Kc calculation and a low water content (dry target), resulting in a low CWSI score. The cultivated areas are clearly defined when water consumption is high, although they vary from place to location depending on crop type, crop stage, vegetation density, and water availability. In this technique, water canals are not differentiated; canals recorded low water use and appeared roads. It occurred because shallow NDVI values (negative values near to zero) measured in the water were reflected in the Kc calculation. The ETa reached 836.7 mm/season.

According to the Sentinel-1 ETa map, the ETa reached 954.8 (mm/season). This technique clearly distinguishes water canals; canals recorded extremely high water usage and showed as a distinct class (dark red) compared to the land use map (Figure 5). The water recorded shallow dB values (near to zero), which was reflected in the dual Kc computation as vice versa. The farmed areas are well-defined, and water consumption is substantial but varies depending on crop type, crop stage, vegetation density, and water availability. The urban has a low

Figure 5: land used map includes three classes; urban, agricultural, and water canals

Figure 6: Evapotranspiration seasonal map produced based on Landsat-8 satellite data

Figure 7: Evapotranspiration seasonal map produced based on Sentinel-1 radar data.
ETα value (near to zero), even though it is poorly categorized compared to the land use map (Figure 5). A low number in urban has a high value in dB analysis, indicating a reverse relationship in dual Kc calculation and low water content (dry target). Interference exists between certain cultivated regions and some homogenous low elevation urban areas, which reflect near backscattering values.

**ETα Data Analysis**

The study of ETα (mm/day) shows an imminent relationship between Lysimeter and the combination of sentinel-1 and Landsat-8, with median values of 4.3 (mm/day) and 4.2 (mm/day) and mean values of 5 (mm/day) and 4.4 (mm/day) correspondingly. For the Lysimeter, Sentinel-1, Landsat-8, and combination techniques, the first quartile (Q1) recorded 3.9, 5.1, 2.9, and 3.8 (mm/day), respectively. For Lysimeter, Sentinel-1, Landsat-8, and the combination technique, the third quartile (Q3) recorded 5.9, 6.3, 4.3, and 5.1 (mm/day), respectively. On May 31, 2016, Lysimeter detected outliers; ETα showed 10.7 (mm/day). In summary, the ETα study revealed a 14 percent overestimation in the Sentinel-1 approach, whereas the Landsat-8 and combination methods revealed a 23 percent and 11 percent underestimate, respectively. Figure 8 depicts a boxplot analysis for ETα (mm/day) calculated from Lysimeter readings, Sentinel-1, Landsat-8, and a combination of Sentinel-1 and Landsat-8.

**Validation of ETα**

Sekertekin et al. (2018) used RMSE and coefficient of determination (R²) to assess Sentinel-1 SAR data, resulting in excellent findings; the results were close to in-situ measurements, with RMSE and R² as high as 2.46 percent and 0.84, respectively.

The RMSE showed that all techniques produced acceptable results. The RMSE for Sentinel-1, Landsat-8, and combination techniques was 0.89, 0.24, and 0.31 (mm/day), respectively. The best technique is Landsat-8, although Sentinel-1 may be utilized on overcast days. In the winter, the impacts of overcast days on Landsat-8 data availability are obvious. As a result, radar data is preferred above optical data during foggy seasons. For agricultural water accounting, a combination of optical and radar sensors will provide superior results.

The relationship between generated ETα measured by Lysimeter and produced ETα measured by Sentinel-1 data was linear, with an R² as high as 0.77 (Figure 9). This relationship shows that Sentinel-1 data offer adequate results for evaluating ETα. The sensitivity of Sentinel-1 data to soil moisture content aids in obtaining excellent ETα findings. These findings have been confirmed by (El-Shirbeny & Abu-Taleb, 2017; Sekertekin et al., 2018).

While the linear relationship between generated ETα based on Lysimeter readings and produced ETα based on Landsat-8 data was strong, with an R² as high as 0.63 (Figure 10), this relationship shows that the Landsat-8 data provide adequate results for estimating ETα. The sensitivity of thermal data to plant and soil water content contributes to excellent ETα results. These results are determined by (Jackson et al., 1981; El-Shirbeny et al., 2014a).

While the relationship between generated ETα based on Lysimeter readings and produced ETα based on Sentinel-1 and Landsat-8 data was exponential, with R² as high as 0.8 (Figure 11). This relationship demonstrates that the combination approach produces the best results for estimating ETα. The sensitivity of
radar and thermal data to soil and plant water content aids in delivering approved ETa products.

CONCLUSION

Weather conditions are significant driving elements in agriculture, but water availability is an essential driving factor in crop life cycle completion, with water scarcity directly impacting crop output in terms of yield quantity and quality. Water scarcity may occur throughout the whole agricultural season or at discrete times. Optical remote sensing is very helpful. However, it is rendered worthless during overcast days. The SAR C-band signals penetrate through the cloud and collect data through backscattering. Backscattering (dB) is a helpful method for determining the combined water content of crop and soil, mainly when there is cloud cover. The ETa may be calculated using both active and optical data. The findings were positive, with the RMSE for Sentinel-1, Landsat-8, and combination techniques being 0.89, 0.24, and 0.31 (mm/day), respectively. The Landsat-8 satellite is the best for calculating ETa, although Sentinel-1 may be used on overcast days. As a result, radar data is suggested for overcast conditions when optical data is unavailable. To achieve large-scale monitoring, a combination of optical and radar sensors is suggested for agricultural water accounting.

Data Availability

The authors affirm that the evidence confirming this study’s conclusions is included in the paper and its supplementary materials. For more available satellite data, the websites of NASA and ESA support free data downloading for weather and land monitoring satellites; Landsat-8 (https://earthexplorer.usgs.gov) and Sentinel-1 (https://scihub.copernicus.eu/dhus/#/home). The weather and satellite data are collected through Central Laboratory for Agricultural Climate (CLAC) and National Authority for Remote Sensing and Space Sciences (NARSS).

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