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APPLICATION OF HIGH-RESOLUTION SATELLITE IMAGERY FOR EVAPOTRANSPIRATION ESTIMATION - A SCIENTIFIC REVIEW

Vanya IVANOVA, Zhulieta ARNAUDOVA, Rossitza MERANZOVA

Agricultural University of Plovdiv, 12 Mendeleev Blvd, 4000, Plovdiv, Bulgaria

Corresponding author email: vanyast_ivanova@abv.bg

Abstract

The use of remote sensing technology can facilitate the acquisition of data pertaining to crop evapotranspiration, which can in turn inform precision irrigation practices. This is achieved through the analysis of satellite image data. The acquisition of accurate information regarding the utilisation of water is of significant importance within the domain of agricultural water management and crop production, particularly at the scale of human impact on the natural water cycle, in the context of global climate change and the increased prevalence of droughts. The objective of this study is to investigate and provide a summary of the potential for using satellite imagery and in situ measurements for meteorological factors, crop vegetation and soil water content, with a special focus on the assessment of evapotranspiration. The studies conducted are of significant value in predicting the potential water requirements of plants, the capabilities of irrigation systems and the efficient utilisation of irrigation water in agriculture through the implementation of adaptive irrigation regimes.

***Key words**: evapotranspiration, irrigation, satellite imagery, vegetation indices.*

INTRODUCTION

Evapotranspiration is a critical component of the water system, playing a pivotal role in the hydrologic cycle. Evapotranspiration, in conjunction with precipitation and runoff, exerts a profound influence on the availability and distribution of water on the land surface. This dynamic process plays a critical role in crop growth and water demand, making it a pivotal factor in hydrological processes and environmental dynamics.

The accessibility of accurate estimations of evapotranspiration is of critical importance for a multitude of applications within diverse scientific disciplines. These include, but are not limited to, climatology, meteorology and agricultural science (Guzinski et al., 2020; Douglas et al., 2009).

Evapotranspiration (ET) is crucial for determining irrigation requirements, optimizing water use, and improving crop yield in agriculture. Understanding ET helps farmers and irrigation planners balance water supply and demand, ensuring efficient water resource management (FAO, 1998). It is imperative to meticulously monitor soil conditions throughout the growing season to optimise production efficiency. As the crop matures, there is a concomitant change in transpiration and altered water requirements. For example, as a key indicator of crop growth, ET has been identified by scientists as a key indicator of crop growth. The calculation of the amount of water utilised by crops has been demonstrated to show the enormous potential in growing crops under irrigated conditions (Allen et al., 1998a; 1998b). The development of digital technology has led to an increase in techniques for calculating and modelling evapotranspiration based on advanced remote sensing techniques. These advancements have been developed to manage water resources more efficiently and facilitate a deeper understanding of the relationship between plant development and water demand, including climate feedback (Teuling et al., 2009; Vazifedoust et al., 2009; Hollmann et al., 2013; Wagle et al., 2017; Allam et al., 2021).

The most widely used and accessible methods for determining ET on a large scale are those carried out by means of Earth observation and satellite imagery, as well as spectral indices of vegetation. To optimize their effectiveness, images for evaluation of ET must have a spatial resolution that aligns with terrain characteristics and field size (Anderson et al., 2004; Guzinski et al., 2019)

To achieve this objective, it is imperative to undertake a comparative analysis of field measurements of ET with those obtained from remote sensing methodologies.

The comparison of field measurements of ET with those obtained from remote sensing has two principal purposes: to determine the accuracy of remote sensing of ET and to validate the remote sensing algorithms used for ETo estimation (Anderson et al., 2004; Mcabe et al., 2006; Kustas et al., 2018; Mokhtari et al., 2019).

To evaluate ET data obtained from satellite imagery or other remote sensing methods and determine whether their scatter in determination is appropriate for crop irrigation, it is critical that they be confirmed with field measurements of ET. (Anderson et al., 2004; Guzinski et al., 2019). The spatial resolution can range from 10 m per pixel to 300 m, depending on the temporal resolution of the acquisition (Allen et al., 2007).

Reliable estimates of actual ETo and crop water requirements are best achieved using satellite observations in the visible/near-infrared and thermal infrared electromagnetic spectrum (Anderson et al., 2012; Hoffmann et al., 2016).

The objective of this study is to investigate and provide a summary of the potential for using satellite imagery and *in situ* measurements for meteorological factors, crop vegetation and soil water content, with a special focus on the assessment of evapotranspiration.

MATERIALS AND METHODS

SYNTHESIS OF EXISTING LITERATURE

Description for evapotranspiration and Data Collection

The framework of the study is to integrate in situ and spatial measurements to determine ET during crop vegetation, such as traditional in field measurements with modern remote sensing data.

Evapotranspiration (ET) is the combined process by which water transfers from the land surface to the atmosphere both by evaporation from soil and plant surfaces and by transpiration through plant stomata. It represents the actual water loss under given field conditions (mm/day or mm).

Reference Evapotranspiration (ET_0)

The rate of evapotranspiration from an idealized reference surface - typically a well-watered, actively growing grass of uniform height - under prevailing climatic conditions. ET_0 provides a standard baseline (mm/day) that is independent of crop type or management; it is used to compare atmospheric demand for water across locations and times.

Crop Evapotranspiration (ETc)

The evapotranspiration rate of a specific crop under standard field conditions. It is calculated by adjusting reference evapotranspiration (ET_0) with a crop coefficient (Kc):

$$ETc = Kc \times ET_0$$

where:

- Kc accounts for crop characteristics (e.g. canopy cover, growth stage), climate and soil evaporation;
- ETc represents the crop's water use requirement (mm/day).

Traditional ETo Estimation Methods

ET can be quantified using two primary methodologies:

Direct Measurement Methods:

Climatic Parameters: continuous recordings of air temperature, relative humidity, solar radiation, wind speed, and precipitation levels are used to calculate baseline ETo estimates.

*Crop Characteristics***:** detailed information on crop type, variety, growth stage, and morphological features (such as plant height and density) is collected. These factors are critical since they influence the rate of transpiration and, consequently, the overall ET.

*Soil and Agrotechnical Conditions**:*** variations in soil properties, moisture content, and cultivation practices (including tillage and irrigation methods) are monitored. These conditions modify the microclimate around the crop canopy, impacting both soil evaporation and plant transpiration.

Lysimeters: instruments that directly measure changes in soil moisture, thereby estimating the amount of water lost through ET. Although highly accurate, lysimeters are typically expensive and labour-intensive.

Field Moisture Sensors: devices that monitor the water content in the soil, offering real-time data on moisture variations within the root zone.

The only factors affecting ETo are climatic parameters. Consequently, ETo is a climatic parameter and can be computed from weather data.

The methods for calculating evapotranspiration from meteorological data require various climatological and physical parameters. Some of the data are measured directly in weather stations. Other parameters are related to commonly measured data and can be derived with the help of a direct or empirical relationship. (FAO,1998).

To facilitate the management of water resources, it is imperative to make estimates of evapotranspiration ET. This is particularly crucial in the context of climate change, as ET estimates are necessary to predict potential changes at both global and regional scales (Allen et al., 2005; Teuling et al., 2009).

Evapotranspiration is not easy to measure. Determining evapotranspiration requires specialized equipment and accurate measurements of various physical parameters or soil water balance in lysimeters. The methods are often expensive and demanding in terms of accuracy. Although these methods are not suitable for routine measurements, they remain important for evaluating ET estimates obtained by more indirect methods.

Indirect Estimation Methods:

A variety of empirical and physically based models have been developed to estimate crop or reference-crop evapotranspiration (ET_c and ET_0) from readily available meteorological data, yet each is valid only under climatic and field conditions. The FAO-56 Penman-Monteith equation combines radiation, temperature, humidity and wind speed to yield a robust reference ET (ET_0) applicable across humid, arid and temperate zones when comprehensive data are available (Allen et al., 1998).

By contrast, Shaumyan's temperature-based model (ET = k (T + a)) relies solely on mean monthly air temperature (T) and regionally calibrated coefficients (k and a), making it useful where only thermal records exist but requiring local calibration (Shaumyan, 1960).

Turk's semi-empirical formula, $ET = 0.013 (T/(T+15)) (23.885R_s+50)$, incorporates solar radiation (R_s) and temperature (T), performing well in humid climates but underestimating ET under arid conditions (Turc, 1961).

Finally, the Blaney-Criddle method, ETc = p (0.46T+8), uses temperature and daylight fraction (p) to estimate crop ET in temperate to semi-arid regions, though it omits humidity, wind and detailed radiation terms and thus loses accuracy in tropical or highly variable climates (Blaney & Criddle 1950).

The following conclusions and implications can be deducted from the practical applications of evapotranspiration determination.

- The FAO Penman-Monteith method has been approved as the standard method for the determination and calculation of reference evapotranspiration (ETo).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where:

- ETo reference evapotranspiration (mm day^{-1});
- R_n net radiation at the crop surface (MJ m^{-2} day^{-1});
- G soil heat flux density (MJ m^{-2} day^{-1});
- T mean daily air temperature at 2 m height (°C);
- u_2 wind speed at 2 m height (m s^{-1});
- e_s saturation vapour pressure (kPa);
- e_a actual vapour pressure (kPa);
- e_s - e_a saturation vapour pressure deficit (kPa);
- Δ slope vapour pressure curve (kPa/ °C^{-1});
- γ psychrometric constant (kPa/°C^{-1}) (Allen R. G. et al., 1998).

The crop surface evapotranspiration and crop-specific coefficient (Kc) are determined, thus relating the crop evapotranspiration to reference (Glen et al., 2010). The estimation of ET and soil moisture content is fundamental to the management of water resources, the provision of drinking water and irrigation, and the intensification of the water deficit crisis (Anderson et al., 2007; Mokhtari et al., 2019). Soil moisture content is directly related to the ET process, as it is contained in the soil surface and plant needs (Norman et al., 1995; FAO, 1998).

Empirical models derive ET estimates from relationships between climatic variables and crop characteristics. Single-factor models and multi-factor approaches (including the Penman-Monteith equation, Shaumyan's, Turk's, and Blaney-Criddle methods) are commonly used.

Remote Sensing Models

These methods utilize satellite data to estimate ET. Two prominent approaches include:

Spectral Vegetation Indices (SVI): these indices are derived from reflectance values in the visible and near-infrared spectra. They provide insight into crop vigour and canopy density, which are directly related to water use.

Energy Balance Models: these incorporate both optical and thermal data to assess the energy exchange at the land surface. Models such as Surface Energy Balance Algorithm for Land (**SEBAL**), Mapping Evapotranspiration with Internalized Calibration (**METRIC**), and the Surface Energy Balance System (**SEBS**) use thermal imagery to derive sensible and latent heat fluxes, thereby estimating ET.

Applications and case studies

Sensor Resolution Impact:

McCabe investigated the use of multiple satellite sensors to estimate evapotranspiration (ET) across different spatial scales. The focus is on understanding how satellite sensor resolution affects the accuracy of ET measurements, particularly in agricultural regions. The importance of ET in hydrological and agricultural systems is emphasized as it controls water availability, and there's a strong interest in improving its estimation for water resource management (McCabe et al., 2006).

The utility of satellite imagery is limited by temporal resolution. For practical purposes (i.e. irrigation scheduling/water allocation), the bi-monthly temporal observations offered by high-resolution platforms are insufficient. For estimating the average daily evapotranspiration of a watershed, MODIS provides an extremely valuable data source for assessing the current condition of the land and vegetation - useful for weather forecasting, flood forecasting, and other areas of water resource management.

The authors present different energy balance models that differ in their ability to characterize surface flux at specific model scales, the results presented can serve to predict evaporation flux at different scales regardless of the model used.

Data Fusion Techniques:

Researchers have examined the potential of Sentinel-2 and Sentinel-3 satellites to estimate high-resolution evapotranspiration (ETo), a process vital for agricultural and water resource management. Sentinel satellites have various spatial and spectral resolutions. They lack high-resolution thermal sensors, crucial for precise ET monitoring. The research uses machine learning algorithms to enhance Sentinel-3's low-resolution thermal data with Sentinel-2's high-resolution optical data. The enhanced data is then integrated into a land-surface energy balance model, facilitating more precise ET estimations (Guzinski et al., 2019).

Cloud Cover Mitigation:

Chintala focuses on modeling high-resolution actual evapotranspiration (ETa) using data from the Sentinel satellites, specifically addressing challenges like cloud cover during the monsoon season. The study uses the Sen-ET plugin, combining Sentinel-1, Sentinel-2, and Sentinel-3 data, to improve ETa flux estimations (Chintala et al., 2022)

Crop-Specific Models:

Rozenstein (2018) conducted a study to validate evapotranspiration for cotton water consumption using Sentinel-2 imagery and ground measurements. The research examined the relationships between the crop coefficient and various vegetation indices. The obtained results aim to support the development of irrigation models for cotton crops.

Singh and others researches explored a novel approach to estimate daily evapotranspiration (ET) using a fusion of Landsat 8 and Sentinel-2 data. ET is a critical component for hydrology, agriculture, and climate models, but field measurements are costly and impractical over large areas. While Landsat provides medium-resolution thermal data (30 m, 16-day revisit), Sentinel-2 offers higher spatial resolution (10–20 m, 5-day revisit) but lacks thermal bands. This study bridges these gaps by combining data from both satellites to enhance spatio-temporal resolution for ET estimation. (Singh et al., 2020)

Irrigation Detection:

Chakhar et al. (2024) investigated time series from Sentinel-1 and Sentinel-2, along with biophysical coefficients, to improve irrigation in orchards. The authors utilized meteorological data, specifically rainfall data from SAR (Synthetic Aperture Radar). To obtain time series of derived indices from the Sentinel-1 and Sentinel-2 satellite missions, Python scripts were used during development to retrieve processed NDVI.

Both remote sensing datasets have a spatial resolution of 10 m and are configured to have a temporal resolution of 7 days. In terms of temporal resolutions, the goal was to acquire

weekly information from both remote sensing sources and to use this information in an integrated manner. It should be noted that the normal coverage (temporal resolution) of Sentinel-2 in the study area is typically 3-4 days, while for Sentinel-1 it is 6 days.
(https://servicio.mapa.gob.es/websiar/ accessed on March 27, 2023), provided by the Spanish Ministry of Agriculture, Fisheries, Food, and Environment.

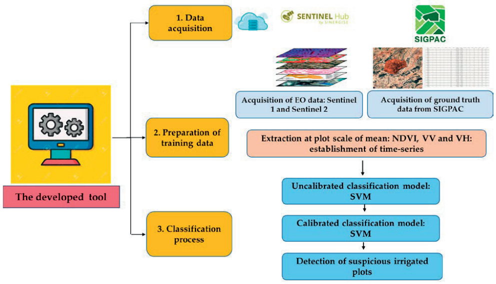

Figure 1 General workflow (Chakhar et al., 2024)

In conclusion, the authors found that integrating in situ measurements with multispectral sensors and radar imagery yields the highest accuracy and efficiency. The proposed method estimates crop water consumption through image classification and time series analysis. As a key outcome of the study, they optimized the Support Vector Machine (SVM) model for detecting irrigated plots, enhancing its performance and reliability. (Chakhar et al., 2024)

RESULTS AND DISCUSSIONS

Comparative insights between traditional and remote sensing approaches

Field measurements of evapotranspiration (ET) are accompanied by methods that are difficult to conduct with the requisite degree of accuracy in situ. Most methodologies rely on the estimation of ET from meteorological data. In contrast, Earth observation has been a powerful and advanced tool for estimating ET over large areas. Satellite imagery is utilized to analyze ET in spatial and time series that cannot be achieved by in situ measurements. The utilization of satellite imagery to estimate ET can be systematized into two primary approaches: spectral vegetation indices (SVI) and energy balance methods.

Evaluation of spatial and temporal resolution needs

Satellite imagery provides the ability to analyze ET in spatial and time series that cannot be achieved by in situ measurements. Research of the spectral vegetation indices time series, such as the normalized difference vegetation index (NDVI) and the soil adjusted vegetation index (SAVI), are evaluated to estimate crop coefficients for cotton and sugarbeet. (González-Dugo et al., 2008) This helps to estimate crop evapotranspiration in irrigated areas by multiplying reference evapotranspiration values by appropriate crop coefficients.

Cost-effectiveness and feasibility of field vs. satellite methods

Accurately measuring evapotranspiration (ET) in the field is often both challenging and expensive. In contrast, remote sensing has become a more practical and cost-effective alternative for estimating ET across large areas. This approach relies on satellite sensors that operate in the electromagnetic spectrum, particularly optical multispectral and thermal bands. One well-established model, the Surface Energy Balance Algorithm for Land (SEBAL), utilizes data from sources such as Landsat 7 and has been extensively calibrated and validated to assess spatial variations in crop yield, ET, and water productivity (Bastiaanssen et al., 1998).
The Surface Energy Balance System (SEBS), introduced by Su (2002), is a remote sensing-based model designed to estimate surface energy balance components. It offers a more detailed representation of the atmospheric boundary layer and surface roughness. SEBS is recognized for its reliability across various climatic conditions and has been successfully applied in a wide range of environments. An advancement of the SEBAL model, known as METRIC, was developed by Allen et al. (2007). This model enhances accuracy through additional calibration steps that incorporate ground-based reference evapotranspiration (ET) data.

Accuracy and limitations of current satellite-based ET Models

The two primary approaches for estimating ET using satellite imagery - spectral vegetation indices (SVI) and energy balance methods - have been extensively validated using lysimeters. Studies and analyses derived from the energy balance method exhibit a greater degree of similarity to the actual changes in crop condition. However, there are limitations to current satellite-based ET models, including the need for accurate calibration and validation to ensure the reliability of the estimates.

Knowledge gaps and future directions

Satellite base models for estimating crop evapotranspiration have their advantages and continue to develop and improve, despite some limitations.

Advantages:

- High spatial and temporal resolution: energy balance methods can provide detailed ET estimates over large areas and at frequent intervals, which is not feasible with traditional field methods.
- Validation and calibration: these methods have been extensively validated using ground-based measurements like lysimeters, ensuring their reliability.

Limitations:

- Data Requirements: accurate estimation requires high-quality input data, including surface temperature, radiation, and meteorological data.
- Complexity: the models can be complex to implement and require expertise in remote sensing and energy balance principles
- Need for standardization in remote sensing algorithms across climate zones
- Gaps in high-resolution thermal data for ET estimation
- Challenges in integrating multi-source satellite data

To improve the effectiveness of the models and their applicability in practice, it is necessary to make synchronous observations of the ground according to the specific soil, vegetation and climatic conditions. This is necessary due to the lack of sufficient data to validate the models themselves, which still work with wide range values and large scale area.

CONCLUSIONS

The variability in evapotranspiration is governed by a complex interplay of climatic conditions, crop development, and soil management practices. Satellite imagery emerges as a powerful tool for assessing these dynamics over vast areas with diverse landscape features. The integration of high-resolution optical, radar and thermal data, especially when enhanced through data fusion techniques, significantly improves the precision of ET estimates. These advancements support the development of adaptive irrigation regimes and contribute to the sustainable management of water resources in agriculture. The development of sustainable models for precise irrigation management is dependent upon the validation of current spatial observations of vegetation cover according to the specific soil and climatic conditions of a given crop. Future research should continue to refine these remote sensing methodologies to further reduce uncertainties and enhance their applicability across different environmental conditions.

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