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RESEARCH ARTICLE

Assessment of Sugarcane Evapotranspiration Across Growing Seasons Utilizing Remote Sensing and pySEBAL Model

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Abstract

The experiment explored AET seasonal dynamics of a sugarcane field at the Navsari Agricultural University (NAU) in Navsari using the high-resolution remote sensing to address the deficiency of ground-based micrometeorological instruments, e.g. lysimeters or eddy covariance towers. Surface Energy Balance Algorithm on Land (SEBAL) was run in a Python-GRASS GIS setting that combined Landsat 8 satellite data on land with local weather data. The outputs of SEBAL were checked by comparing the estimates with the cloud-based METRIC-EEFlux algorithm. Phenological measurements using NDVI time-series data monitored the sugarcane growth cycle with the greatest vegetative vigor in June and senescence during the months of November to December. Spatial analysis showed that seasonal AET calculated using SEBAL was between 1459 and 1496 mm. An effective rainfall of 676 mm was taken into consideration to estimate the total irrigation water requirements (IWR) of 783 to 820 mm. Conversely METRIC-EEFlux always gave higher values of AET, with the values falling between 1627 and 1698 mm. The pixel-by-pixel comparison of the two models each day showed a moderate correlation ($R^2 = 0.63$) with a Root Mean square error (RMSE) of 1.40mm/day. SEBAL had a mean error (MBE) of bias of -1.17 mm/day, which shows that it was generally underestimated compared to METRIC-EEFlux. The results notwithstanding these differences in the algorithms, SEBAL is a powerful, well-adjusted tool to measure crop water needs and support sound water management decisions in data deficient areas.

Keywords: SEBAL; Evapotranspiration; Landsat 8; Sugarcane; EEFlux METRIC

1. Introduction

The SEBAL is a remote sensing-based model designed to estimate land energy fluxes and ET between earth and atmosphere. The SEBAL model was developed by Bastiaanssen *et al.,* (1998), SEBAL combines satellite imagery (Landsat 8) with meteorological data to calculate Rn, G, H, and LE, thereby facilitating an in-depth understanding of ET variation at various spatial and temporal scales. Estimating land surface fluxes and ET across vast and diverse landscapes is challenging due to the high costs and limited spatial coverage of direct ground-based methods such as eddy covariance systems and lysimeter (McShane *et al.,* 2017). To overcome these constraints, remote sensing-based energy balance models have been developed over the past two decades, offering scalable and consistent ET estimation. Some widely used models include the SEBAL (Bastiaanssen *et al.,* 1998), the Two-Source Energy Balance (TSEB) model (Norman *et al.,* 1995), the Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) model (Allen *et al.,* 2007), the Simplified Surface Energy Balance Operational (SSEBop) model, and the Surface Energy Balance System (SEBS) (Su, 2002). These models rely on energy balance principles, where ET/LE is estimated as the remaining energy used for water vaporization after accounting for Rn, G, and H (Zhang *et al.,* 2011). Among these, SEBAL was selected for this study due to its minimal requirement for ground-based meteorological data, which is particularly important as the study area has limited meteorological observation facilities. Furthermore, SEBAL has been widely validated in various parts of India, further supporting its applicability and reliability for operational in similar agro-climatic conditions.

This study utilizes Landsat 8 satellite data to assess seasonal ET using the SEBAL model. The novelty of this research lies in its integration of SEBAL in a data-scarce region, where ground-based meteorological observations are minimal or unavailable. The model was employed to estimate seasonal dynamics of land surface energy balance components and actual ET for sugarcane, a regionally significant crop. Furthermore, the study contributes to current knowledge by calculating crop-specific IWR based on satellite-derived ET estimates. To enhance credibility and accuracy, SEBAL-derived ET was validated using METRIC-based EEFlux outputs. This multi-temporal and spatially distributed analysis provide valuable insights for irrigation planning and water resource management in data-limited agricultural zones.

2. Datasets

The present study integrated multiple data sources, including space-borne data from Landsat 8 satellites, ground-based meteorological observations, and reference evapotranspiration (RET) data. These datasets were utilized to estimate land surface fluxes viz., Rn, G, H, and LE using the SEBAL model for the study area. The digital elevation model (DEM) data was obtained from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/) by selecting the study area under "Data Set" > "Digital Elevation" > "SRTM." This DEM represents the bare ground topography, excluding surface objects such as vegetation and buildings. Cloud free Landsat 8 imagery with a 30 m spatial resolution, covering path 148 and row 46, was downloaded from https://earthexplorer.usgs.gov/. The study used Landsat 8 Collection 2 Level-2 surface reflectance and thermal data (Table 1), which are atmospherically, geometrically, and radiometrically corrected products provided by USGS. The optical bands were corrected using the Land Surface Reflectance Code (LaSRC), while the thermal bands underwent MODTRAN-based atmospheric correction, accounting for effects such as aerosols, water vapor, and ozone. These corrections ensure the accuracy and reliability of surface radiance and LST inputs required for SEBAL modeling.

Meteorological parameters, including temperature (°C), wind speed (m/s), and relative humidity (%) were collected from the Automatic Weather Station (AWS), Agrometeorological Observatory, NAU, Navsari, India. These parameters were used to determine the instantaneous reference evapotranspiration (RET rate in mm/hr) at the time of the satellite overpass and reference evapotranspiration (in mm/day) on the satellite acquisition date was also determine. The Landsat 8 satellite passed over the study area at approximately 05:30:54 UTC (11:00:54 IST), as indicated in the metadata file, which aligns well with the data acquisition time of the Automatic Weather Station (AWS). Since the AWS records meteorological parameters at 15-minute intervals, the satellite overpass time falls within the same observation window, ensuring excellent temporal compatibility between satellite data and ground-based measurements.

3. Methodology

3.1 SEBAL algorithm

The SEBAL algorithm to estimates land surface fluxes using Landsat 8 data by calculating latent heat (LE) as the residual component of the surface energy balance equation (Equation 1). The development of SEBAL is primarily based on methodologies outlined in the works of Bastiaanssen *et al.,* (1998), Bastiaanssen (2000), Waters (2002), Sun *et al.,* (2011), Silva *et al.,* (2016), Beg *et al.,* (2016), Caiserman *et al.,* (2021), and Virani *et al.,* (2024).

$$\mathbf{LE = R_n - H - G} \quad \mathbf{(1)}$$

Where, Rn is the net radiation, G is the soil heat flux and H is the sensible heat flux.

3.2 Automating SEBAL algorithm execution using python and GRASS GIS

The SEBAL model was implemented using a modified version of the open-source pySEBAL Python package (developed by IHE Delft), integrated within the GRASS GIS environment. The SEBAL model outputs are stored directly in the GRASS GIS environment. The core algorithmic structure follows the original SEBAL formulation by Bastiaanssen *et al.,* (1998).

4. Results and Discussion

4.1 Validation of SEBAL measurement ET with METRIC EEFlux derived ET

The validation of daily ET estimates from the SEBAL model is a critical aspect of assessing its accuracy. However, the study area lacks lysimeter or micrometeorological instruments like eddy covariance tower facilities, which are commonly used for ground-based ET measurements. To address this limitation, the SEBAL model output was validated using EEFlux METRIC (Allen *et al.,* 2007), a cloud-based ET estimation tool developed by the University of Idaho using the METRIC algorithm (https://eeflux-level1.appspot.com/). This approach underscores the adaptability of remote sensing-based models in regions with limited observational infrastructure.

Figure 1 illustrates the spatiotemporal comparison of ET estimates obtained from the SEBAL model and the EEFlux Metric model over a selected sugarcane field. The graphical representation highlights the alignment and discrepancies between the two models, providing insight into their performance in estimating ET for sugarcane cultivation. Figure 2 illustrates scatter plots comparing EEFlux METRIC and pySEBAL for key parameters, including ET, crop coefficient (Kc), albedo, and LST, using data retrieved from sugarcane field pixels. The comparison for ET reveals a moderate correlation (R^2 = 0.632) and a RMSE of 1.40 mm/day, indicating some level of uncertainty. Notably, SEBAL shows a tendency to underestimate ET, as reflected by an MBE of -1.17 mm/day. These discrepancies suggest differences in algorithm calibration or parameter sensitivity. Filgueiras *et al.,* (2019) reported that EEFlux consistently provides higher estimates of evapotranspiration compared to SEBAL.

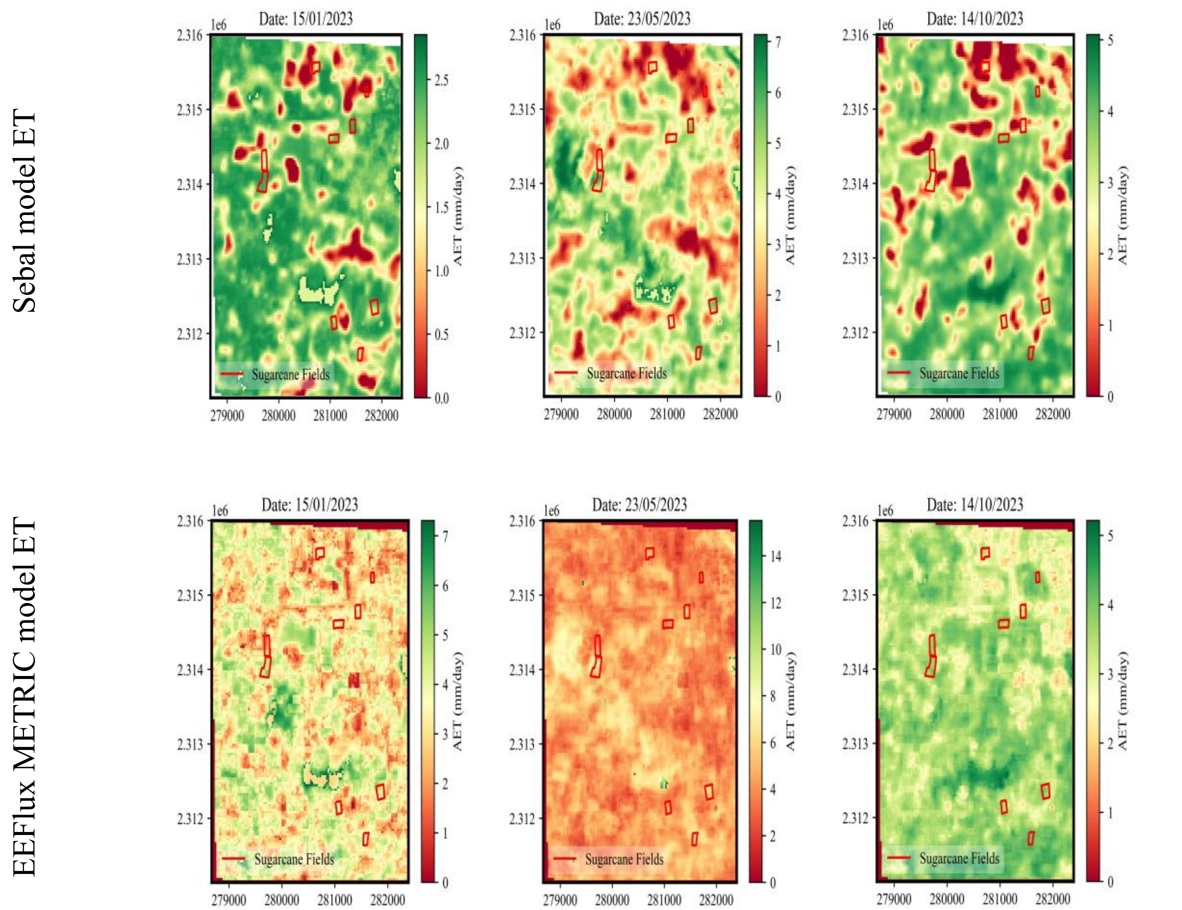

Fig. 1. Comparison of ET estimates derived from the SEBAL model and the EEFlux Metric model over a selected sugarcane field.

Furthermore, ET-EEFlux demonstrated agreement with the results obtained by the SEBAL algorithm. Albedo shows a moderate correlation (R^2 = 0.532) with a low RMSE of 0.06 and a slight overestimation (MBE = 0.05). Similarly, Kc demonstrates a moderate correlation (R^2 = 0.452) with a small RMSE of 0.18, indicating comparable estimates (MBE = 0.01). LST, on the other hand, exhibits a strong correlation (R^2 = 0.976), though pySEBAL underestimates it with an MBE of -5.22 and an RMSE of 5.63 K.

4.2 Estimation of seasonal actual evapotranspiration (AET) of sugarcane

Accurate estimation of AET is crucial for efficient water resource management, particularly in agricultural settings. This study investigated the seasonal AET patterns of a sugarcane field located at the Soil and Water

Management Research Unit Farm, NAU, Navsari (Figure 3) using the SEBAL and Metric EEFlux models. The results of this analysis will provide valuable insights into the water requirements of sugarcane cultivation in this region, enabling informed irrigation scheduling and optimizing water use efficiency. The NDVI time series graph (Figure 3b) reveals the seasonal vegetation dynamics of the sugarcane field. Starting from February, the NDVI values gradually increase, indicating a growth phase. The peak NDVI values are observed around June, suggesting the period of maximum vegetation vigor. Subsequently, the NDVI values decline around mid-November to December, likely due to senescence and harvesting.

The spatial distribution of seasonal AET within the study area was analyzed using the SEBAL and Metric-EEFlux models, as illustrated in Figure 3c. The total AET for the sugarcane field ranged from 1627 to 1698 mm according to the Metric-EEFlux model and from 1459 to 1496 mm as estimated by the SEBAL model. The Metric-EEFlux model indicated consistently higher AET values

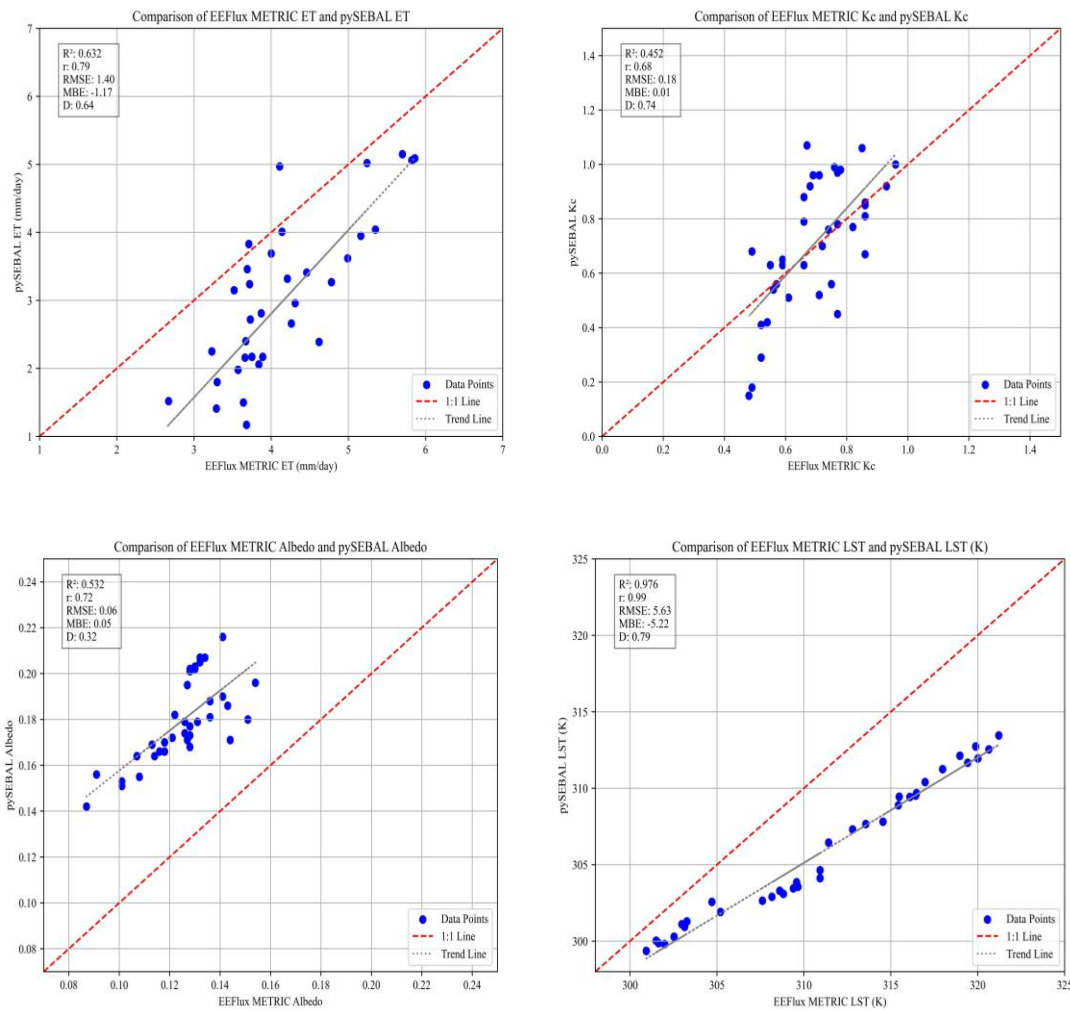

Fig. 2. Statistical comparison between SEBAL and EEFlux METRIC model parameters.

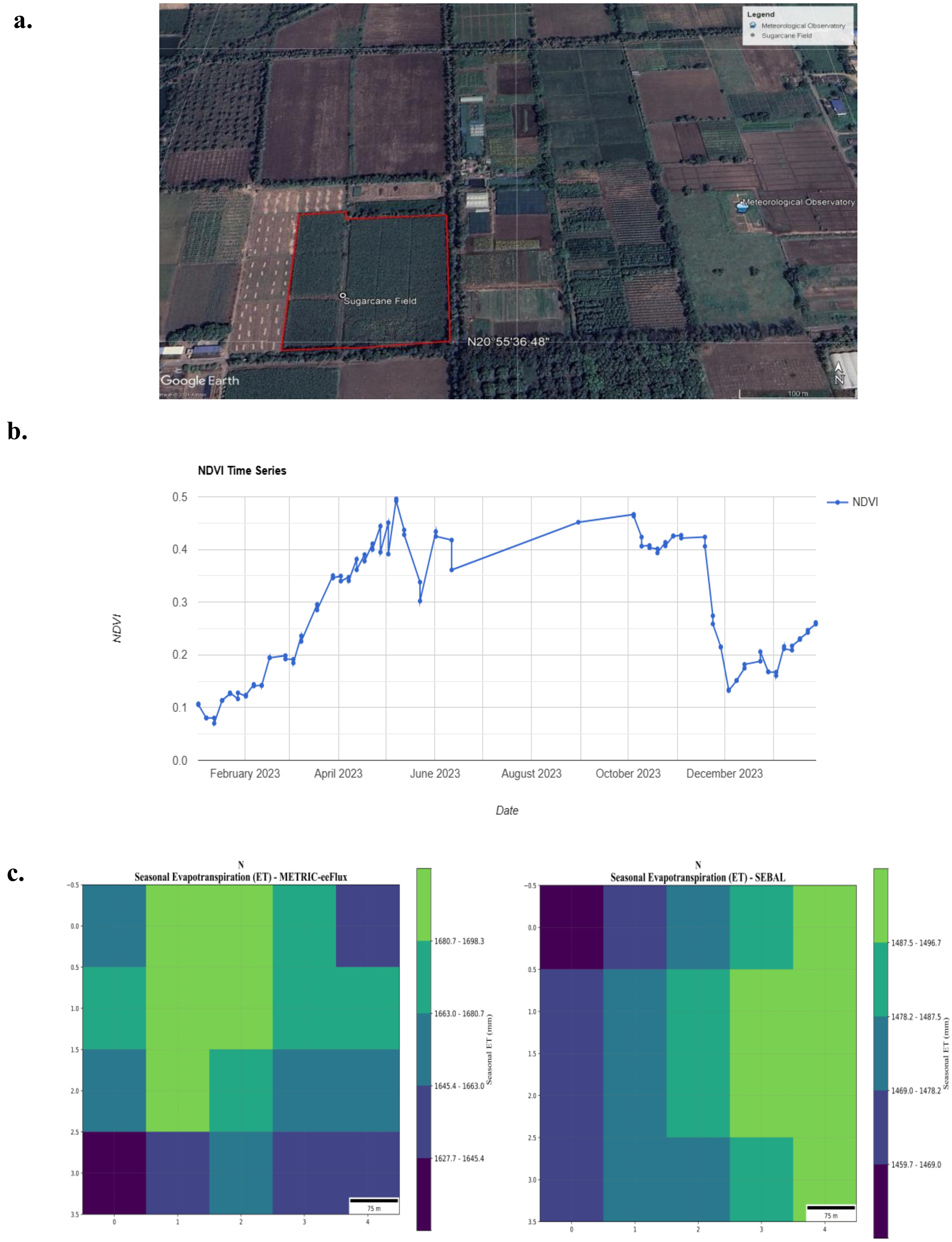

Fig. 3. Seasonal AET calculation of sugarcane: (a) Selected sugarcane field, (b) NDVI signature of sugarcane, and (c) Pixel-wise seasonal AET comparison using SEBAL (right) and METRIC EEFlux (left).

compared to SEBAL. The area received a total rainfall of 1771 mm throughout the season, of which the effective rainfall was calculated as 676 mm using the USDA SCS method. Considering the effective rainfall, the IWR was calculated as the difference between AET and effective rainfall. For the Metric-EEFlux model, the IWR ranged from 951 to 1022 mm, whereas for the SEBAL model, it ranged from 783 to 820 mm. The NAU, Navsari, has recommended to the farmer community that the IWR for sugarcane in the South Gujarat heavy rainfall zone (AES-III) is 1200 mm. The recommendation involves 15 irrigations scheduled at a 0.9 IW/CPE ratio, with each irrigation applied at 8 cm of water depth.

5. Conclusion

SEBAL is also a valid instrument to observe fluxes of surface energy balance especially in areas with no earth based observational networks, i.e. eddy covariance flux towers. Nevertheless, it can have low reliability in regard to seasonal conditions, land use/land cover complexity as well as require region-specific calibration, particularly in mixed-irrigation agricultural systems. Hence, physio graphically diverse landscapes should be approached cautiously in terms of the results and as much as feasible buttressed by local ground validation.

Also, its ability to approximate AET is especially important in those regions that do not have lysimeter stations, as it can aid better determination of crop water demands, as well as provide accurate timing of irrigation. This paper indicates how the SEBAL model is effective in the analysis of both the spatial and temporal variation of land surface fluxes throughout the study area, such as LULC-based analysis. Besides, the paper analyzes the real sugarcane water demands based on the SEBAL and METRIC EEFlux models. Further studies are required to come up with energy balance model algorithms that can be used with different satellite data to enable a better time resolution and to easily integrate various remote sensing data. These will improve the validity of the energy flux estimates on SEBAL, and will therefore prove to be a better instrument when it comes to large scale hydrological and agricultural research.

Although this paper manages to prove the usefulness of remote sensing in estimating sugarcane evapotranspiration there are a number of limitations that have to be admitted. The first limitation is that there is no a priori information and data of the field on the ground on the study area in terms of direct and ground-based micrometeorological instruments (such as weighing lysimeters or eddy covariance towers), implying that the outputs of SEBAL need to be cross-validated against yet another satellite-based algorithm (METRIC-EEFlux) and not against empirical field data. In addition, atmospheric and temporal constraints exist on the use of Landsat 8 images: Significant changes in daily ET may be lost to optical sensor constraints when clouds shield the Earth during monsoons and Landsat 8 has a 16-day revisit cycle, which has to be interpolated to operate on daily ET. Inherent uncertainties seen in the study include inherent algorithmic errors and subjectivity, both manifested in the fact that SEBAL tends to underestimate ET (MBE = -1.17 mm/day) when compared with METRIC-EEFlux and the fact that it would have been possible to create bias in the results by the user when manually deciding on the choice of hot and cold anchor pixels to compute sensible heat flux. Lastly, the Landsat 30-meter spatial resolution is suitably good, however, at the sugarcane field edges, there are mixed pixels that could contain the spectral signature of neighboring land covers, slightly biasing the estimated land surface temperature and vegetation indices.

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Declarations

Author contributions

Dr. M. H. Amlani: Conceptualization, Writing – original draft, Methodology, Visualization, Software. **B. M. Mote**: Data curation, Writing – original draft.

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This research was conducted without external financial support, reflecting the independent efforts and commitment of the authors.

Data Availability

The datasets generated and/or analysed during the current study are available in a publicly accessible repository.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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