Journal of Agrometeorology

ISSN : 0972-1665 (print), 2583-2980 (online)
Vol. No. 26 (3) : 271-278 (September - 2024)
https://doi.org/10.54386/jam.v26i3.2618
https://journal.agrimetassociation.org/index.php/jam

Research Paper

Quantifying energy fluxes in Tarai region of India during post-monsoon season: Insights from METRIC model, ET station and remote sensing

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ABSTRACT

Accurate evapotranspiration (ET) assessment is crucial for agricultural water management, encompassing crop water requirements, irrigation scheduling, water budgeting and drought monitoring. This study integrates remote sensing-based surface energy balance model with *in-situ* ET measurements to evaluate surface energy fluxes and ET in Pantnagar, Tarai region. The Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) model, using high-resolution remote sensing data, was validated against observations from an ET station equipped with large aperture scintillometer and micrometeorological tower, situated in sugarcane farm at Govind Ballabh Pant University of Agriculture & Technology (GBPUA&T), Pantnagar. On November 13, 2021, METRIC and Landsat-9 satellite data estimated an instantaneous ET of 7.39 mm day^{-1}, closely aligned with the observed value of 6.72 mm day^{-1} recorded by the ET station. The findings confirm the METRIC model's high accuracy for spatial ET estimation and its associated micrometeorological variables. This study underscores the utility of the METRIC model, ET station and remote sensing in determining ET and energy flux which may be further utilised in the estimation of crop water requirement, energy fluxes and irrigation water management for sugarcane cultivation in the Tarai region.

***Keywords*:** Evapotranspiration, METRIC model, Large aperture scintillometer, remote sensing, sugarcane.

Remote sensing has been established to be an invaluable tool in estimating ET, determining crop water requirements and enhancing water management practices across diverse agricultural regions. Numerous methods have been proposed for ET estimation, which are primarily categorized into two approaches: (a) physically based algorithms and (b) indirect methods. Physically based algorithms, such as the FAO Penman-Monteith method, estimate ET by integrating weather variables and surface features i.e. aerodynamic resistance and bulk resistance. In contrast, indirect methods utilize surface energy balance parameters along with vegetation indices and surface temperatures to estimate ET. Among these, the remote sensing-based energy balance technique has gained popularity due to its ability to derive components like surface reflectance, vegetation indices, and land surface temperatures from satellite imagery, enabling precise ET estimation (Danodia *et al.,* 2017).

Quantifying energy flux in agricultural landscapes is critical for effective water resource management and agricultural planning. This study employs advanced tools such as the METRIC (Mapping Evapotranspiration at high Resolution with Internalized Calibration) model, a Large Aperture Scintillometer (LAS) and a micrometeorological tower (MMT) to investigate energy flux dynamics in Pantnagar, India, during the post-monsoon period. The METRIC model is known for its superior accuracy compared to other remote sensing-based methods which, integrates remote sensing data with ground-based meteorological observations to provide spatially distributed ET and energy flux estimates, making

***Article info - DOI*:** *https://doi.org/10.54386/jam.v26i3.2618*
Received: 1 June 2024; Accepted: 15 July 2024 ; Published online : 01 September 2024

it particularly effective in heterogeneous agricultural landscapes where traditional approaches may be inadequate (Madugundu *et al.,* 2017).

The ET station in this study is equipped with LAS and MMT, which together offer high-resolution, ground-based measurements of atmospheric parameters. The scintillometer measures the path-averaged sensible heat flux by detecting fluctuations in the air's refractive index, influenced by temperature variations (Zheng *et al.,* 2023). Simultaneously, the micrometeorological tower captures detailed data on temperature, humidity, wind speed, and radiation, allowing for comprehensive profiling of the atmospheric boundary layer (Sudarsan *et al.,* 2016). These instruments provide a robust framework for validating and refining remote sensing-based models like METRIC, ensuring accurate and reliable quantification of energy fluxes across the study region.

Sugarcane is one of the most important cash crops in the Tarai regions of India, playing a pivotal role in the local economy (Shukla *et al.,* 2017). Given its status as one of the most water-consuming crops, accurate ET estimation is crucial for efficient water resource management and irrigation planning. Understanding energy fluxes in the Tarai region, especially for sugarcane cultivation, is vital for optimizing irrigation scheduling and improving water use efficiency. Accurate quantification of ET and energy fluxes helps to reduce water wastage and ensures sustainable agricultural practices, which are essential for meeting the growing water demand in this agriculturally intensive area (Mallareddy *et al.,* 2023).

With this context, the current study aims to assess the ET from LAS based ET station, Bowen ratio energy balance and compute the ET using the remote sensing energy balance model 'METRIC' for sugarcane crops in the Tarai region. This research utilizes Landsat-9 satellite data and micrometeorological variables to estimate ET and surface energy fluxes. The remote sensing-derived results are validated using observed data from the ET station located in Pantnagar, ensuring the accuracy and reliability of the findings.

MATERIAL AND METHODS

Site description

Pantnagar is a part of Udham Singh Nagar, which is located in Tarai region of Shivalik range of Kumaon division of Uttarakhand at 28.99 to 29.04°N, 79.43 to 79.52°E with an average altitude of 244m (Fig. 1). The geographical area of the district is 12,661 acres (51.24 km^2). The climate of Pantnagar varies from sub-tropical humid and sub-humid with three distinct seasons *viz.* summer, monsoon and winter. The maximum temperature ranges between 35°C-45°C while the minimum temperature ranges between 2°C-5°C. The annual rainfall of the region is about 1444 mm, of which 90% is expected during the monsoon season and remaining in non-monsoon period (CSIR-CIMAP, MAUSAM IMD). The soil of the Pantnagar is relatively fertile, which make it suitable for cultivation of all type of crops (CSIR-CIMAP).

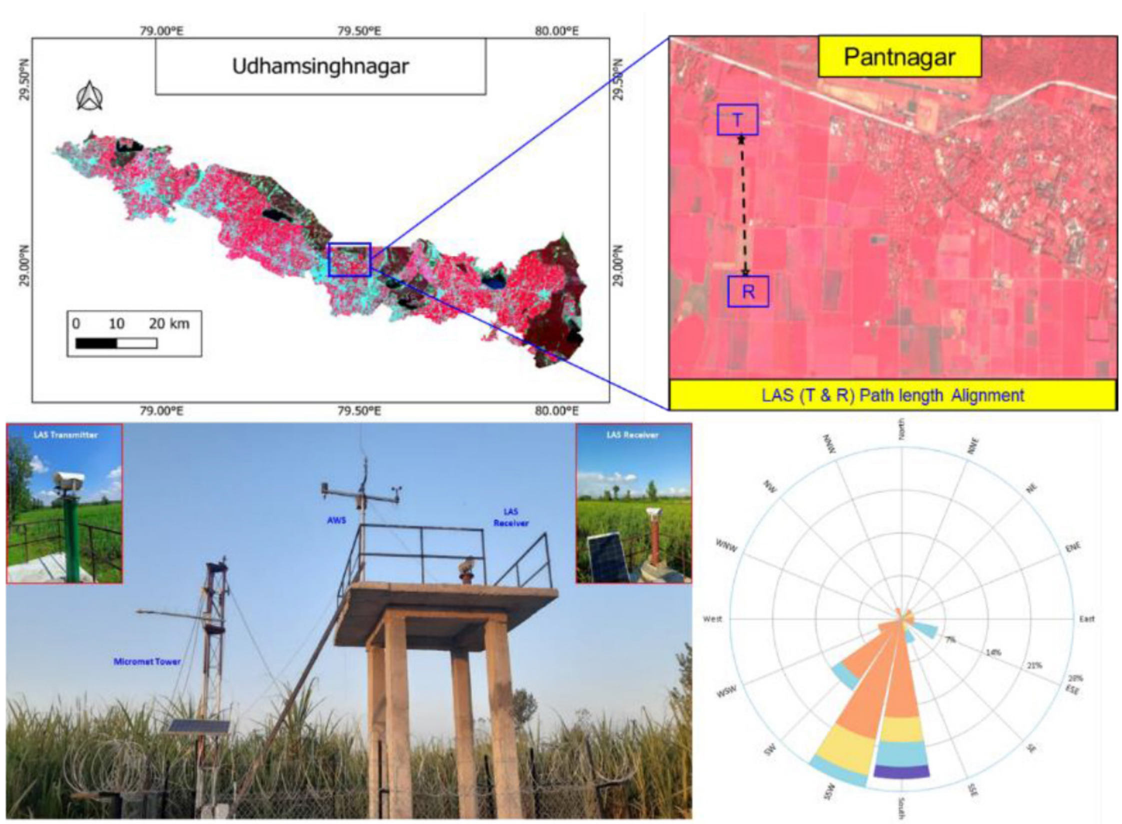

Fig. 1: Location of Larger Aperture Scintillometer based ET Station, situated at GB Pant University of Agriculture and Technology- Agricultural farm

ET station and instrumentations

The LAS-ET station comprises Larger Aperture Scintillometer (LAS) and a micrometeorological tower (MMT). The augmentation of LAS and MMT was done at Breeder Seed Production Center (BSPC) agricultural research farm of Govind Ballabh Pant University of Agriculture & Technology (GBPUA&T), Pantnagar, Udham Singh Nagar, Uttarakhand during second week of October 2021. The LAS transmitter and receiver end was installed at the 5-meter height platforms, which are at the path length of 1020 meter with integration of Automatic Weather Station (AWS) on receiver end side within sugarcane cropland (Fig. 1).

The LAS observes structure parameter of refractive index (which is mainly caused by temperature and humidity fluctuation (De Bruin and Wang, 2017; Danodia *et al.,* 2017). The principles of LAS, function and instrumentation are detailed in Danodia *et al.,* (2017, 2024). These all sensors are fast response sensors working at 10 Hz frequency, which format the datasets in 5 min integrated files. This site was developed for continuous measurement of ET, meteorological variables and surface energy fluxes. These observations are incorporated in the validation of remote sensing-based energy balance model. In this paper, post-monsoon period (second week of October to November months) data were utilized.

In this study, a variety of sensors were employed along LAS to measure meteorological parameters and energy fluxes at the study site located at GBPUA&T, Pantnagar. The Automatic Weather Station (AWS) comprised Kipp & Zonen Make ARTH for air temperature measurement at a height of 7.0 meters, along with an anemometer for wind speed measurement. Additionally, the MMT was equipped with a CNR4 Net Radiometer to measure radiation (four components) at a height of 5.0 meters, a HukseFlux SC sensor (0.10 m depth) for soil heat flux and Rotronics Hygroclip-2 sensors (2 & 4 m height) for air temperature and relative humidity. Wind speed and wind direction were measured using RM Young Wind monitors at a height of 5.0 meters. All data from these sensors were collected at 10 Hz frequency. Further analysis to derive ET was conducted using EVATION software.

Bowen ratio- based energy flux

The Bowen ratio can be estimated using two height-specific observations of air temperature and vapour pressure, simultaneously (Bowen, 1926; Holland *et al.,* 2013; Satpathi *et al.,* 2024). It calculated using the MMT observations. The Bowen ratio (β) depicts may be calculated using formula as:

$$\beta = \frac{H}{LE} = \frac{[P_a C_p(\Delta T)]}{[\lambda\varepsilon(\Delta e)]}$$

Where, H represents the sensible heat flux (W m^{-2}), LE denote the latent heat flux (W m^{-2}), P_a is the atmospheric pressure (kPa), C_p is the specific heat capacity of air (1004.67 J kg^{-1} K^{-1}), ΔT is the air temperature difference between two heights (K), λ is the latent heat of vaporization for water (2.45 MJ kg^{-1}), ε is the ratio of molecular weights of air and water (0.622), and Δe is vapour pressure difference between two heights (kPa). The LE is determined using the Bowen ratio value, net radiation (R_n) and ground heat flux (G):

$$LE = \frac{R_n - G}{1+\beta}$$

Where, R_n is net radiation (W m^{-2}) and G is the ground heat flux (W m^{-2}).

Remote sensing-based energy model: METRIC Model

The Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) model is a physical model for computation of ET utilizing optical and thermal remote sensing data, as described by Allen *et al.,* (2007). It operates on the principle of the surface energy balance (SEB), a crucial component in understanding energy exchange within various ecosystems such as agriculture, forests, and water bodies (Allen *et al.,* 1998; Danodia *et al.,* 2024). The SEB equation demoted by Allen *et al.,* (1998), which is depicted as:

$$R_n = H + G + LE + \Delta E + M$$

Where, ΔE is the heat stored or released in the plant and M is the used energy in metabolic activities, which are negligible. Thus, the residual energy balance equation can be framed as:

$$LE = R_n - G - H$$

The computation of different energy flux components such as albedo, incoming shortwave and longwave radiation, outgoing longwave radiation, net radiation and ground heat flux follows methodologies outlined by Allen *et al.,* (2007). Sensible heat flux (H) encompasses transferring heat energy to the atmosphere through conduction and convection. This process is quantified using the formula:

$$H = \rho_a \cdot Cp \frac{dT}{r_{ah}}$$

Where, ρ is air density (kg m^{-3}), dT (K) is the temperature difference between two heights and r_{ah} denotes the aerodynamic resistance to heat transport (s m^{-1}). The aerodynamic resistance (r_{ah}) under neutral stability conditions can be computed as:

$$r_{ah} = \frac{\left(ln\frac{z_2}{z_1}\right)}{u^* \times k}$$

where z_1 and z_2 are the zero plane displacement heights (m), u∗ represents the frictional velocity (m s^{-1}) and k is von Karman's constant (0.41). The frictional velocity defines the fluctuation in turbulent velocity in the air, which may be further calculated using wind speed at defined height and momentum roughness length. The second unknown variable; dT depicts the temperature difference at near-surface for each pixel. The dT may be computed as:

$$dT = Tz_1 - Tz_2$$

where, Tz_1 and Tz_2 are the air temperature at heights z_1 and z_2, respectively. In METRIC, temperature difference for individual pixel is determined by assumption of linear relationship between temperature difference and land surface temperature (LST), calibrated using coefficients (a and b) as:

$$dT = a * LST + b$$

Table 1: Specifications of Landsat-9 satellite data

Satellite parameter	Specifications
Total number of bands	11
Optical bands	Blue, Green, Red, NIR, SWIR
Thermal bands	Band 10[#], 11
Spatial resolution	30 meter
Temporal resolution	16 days

*NIR- Near infrared, SWIR- Short-wave infrared; # - Used in LST retrieval

Calibration coefficients (a) and (b) are computed using 'anchor' pixels representing extreme ET conditions. These anchor pixels, termed 'hot' and 'cold' pixels, which are chosen based on maximum and minimum LST and NDVI values in Landsat-9 imagery. The selection of anchor pixels was executed based on the Javadian *et al.,* (2019). The calibration process involves iterative analysis to establish a linear relationship between dT and LST. Once calibrated, dT values for all pixels are computed, and (H) is iteratively estimated until stability is achieved, correcting for atmospheric instability using the Monin–Obukhov theory as described by Allen *et al.,* (2007). Finally, the METRIC model results are validated against ET station observations.

METRIC model was executed on a cloud-free satellite image of Landsat-9 which was acquired on 13 November, 2021. The Landsat satellite comprises Operational Land Imager (OLI) and Thermal Infrared sensor (TIRS). The characteristics of Landsat-9 image are given in Table 1.

Reference evapotranspiration methods

In this study, a comparative assessment of different ETo methods was also done. The FAO-56 Penman–Monteith method (Allen *et al.,* 1998), American Society of Civil Engineers Penman–Monteith method (ASCE- PM) (Allen *et al.,* 2005), Penman ETo method (Penman, 1948) and Priestley-Taylor ETo method (Priestley and Taylor, 1972) were evaluated and compared with FAO-56 Penman–Monteith method.

Statistical analysis

The normalized Root Mean Square Error (nRMSE), Mean Absolute Error (MAE), Nash Sutcliffe Model Efficiency coefficient (NSME) and Willmott's d-index were utilized in evaluation and comparison of the ET$_o$ methods. The details of the formula are illustrated in Satpathi *et al.,* (2024).

RESULTS AND DISCUSSIONS

Micrometeorological variables at daily scale

The micrometeorological variables i.e. maximum and minimum air temperature (2 & 4 m), relative humidity I and II (2 & 4 m), wind speed and net radiation are plotted in Fig. 2. These observations were measured in sugarcane plot during post-monsoon season. Over the study period, a catastrophic event happened during 18-20 October 2021, when heavy rainfall occurred with 420 mm of total along 352 mm rainfall in one day (19 October 2021). This event had significant impact on observations of net radiation, air temperature, relative humidity and wind speed, which is clearly illustrated in Fig. 5. During this post-monsoon, the maximum temperature was observed on 16 October 2021 (36.63°C at 2 meter, 36.26°C at 4 meter), the maximum wind speed on 19 October 2021 (2.2 m s^{-1}) and the maximum net radiation on 15 October 2021 (132.7 W m^{-2}), however the minimum net radiation observed on 19 October 2021 (11.1 W m^{-2}).

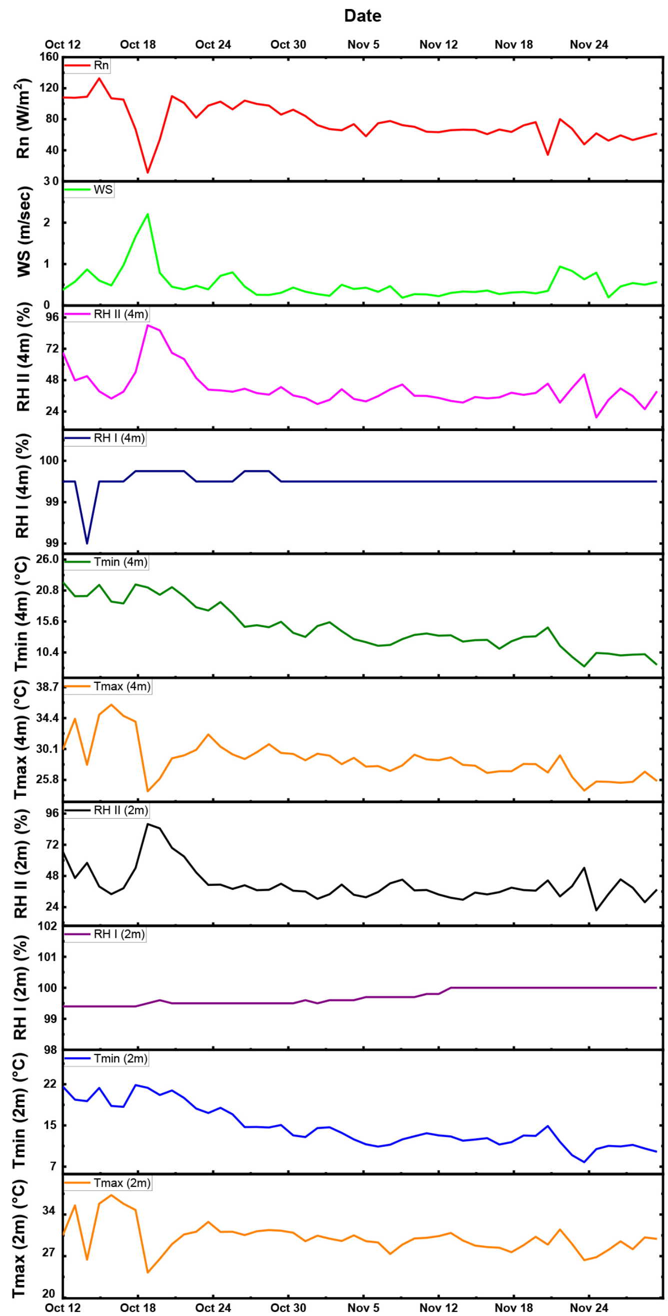

Fig. 2: Seasonal variation in micrometeorological parameters on daily scale

The possible reason behind heavy downpour was due to

Table 2: Statistical relationship of FAO-PM ET_o with other methods ET_o

Methods	ASCE P-M ET_o	Penman ET_o	Priestley-Taylor ET_o
nRMSE (%)	2.7	12.7	21
MAE (mm day^{-1})	0.07	0.35	0.56
NSME	0.98	0.75	0.31
Willmott's d-index	0.99	0.94	0.87

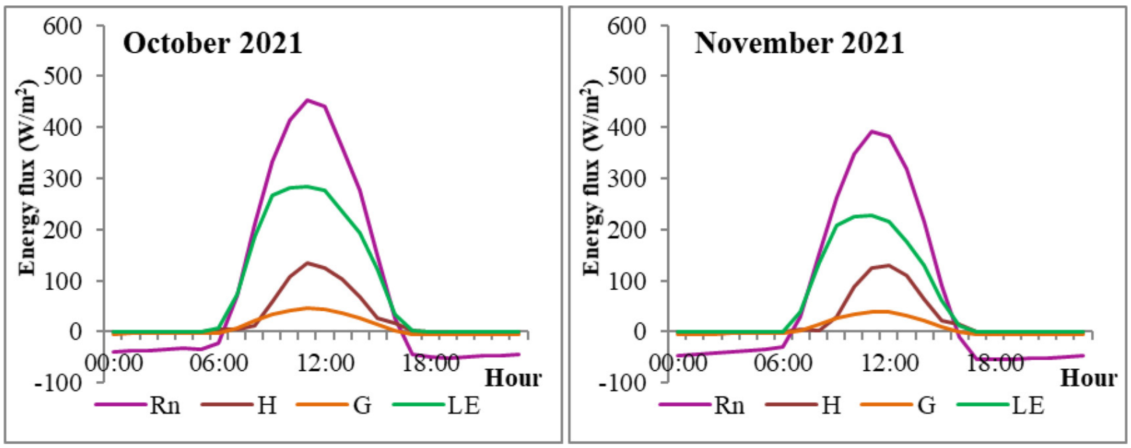

Fig. 3: Daily variation in surface energy fluxes at monthly scale

extreme heating and high net radiation just before the event happened as indicated by the observations. However, with progression of the season, the net radiation and air temperature decreased with cooling down of the landscape. The variation in micrometeorological parameters were analysed to understand the behaviour of individual parameter on daily basis. In similar of this, Liu *et al.,* (2013) plotted and analysed the different meteorological and biophysical parameters i.e. precipitation, air temperature, vapour pressure deficit, leaf area index, soil moisture and available energy from 2008 to 2010 to characterize the environmental conditions which directly associate in the study of ET and its variation.

Surface energy fluxes at monthly scale

Monthly mean surface energy fluxes at diurnal scale are represented in Fig. 3, which derived using LAS and MMT tower data integrated at hourly duration. Finally, the composite of surface energy flux was prepared at monthly scale to illustrate the overall diurnal pattern from 0 to 24 hours. In post-monsoon season, the maximum net radiation was observed at 11:00 hours in October (452.4 W m^{-2}) and November (392.8 W m^{-2}). In comparison with LE, the ratio of LE/R_n was determined 63% and 58% for October and November, respectively. It defines that the LE fraction is decreasing with season progression and it is because of the crop growth progress towards the maturity in sugarcane. The results were comparable with findings of Danodia *et al.,* (2017, 2024) where similarly R_n and LE had the decreasing trend in October and November month. However, the H had the increasing trend in Danodia *et al.,* (2017, 2024) because of the crop maturity period of maize crop in maize-wheat cropping pattern, while currently H value was almost stationary in sugarcane-based cropping pattern.

Estimation of reference evapotranspiration

During study period, the total reference evapotranspiration (ET_o) was 137.4 mm, 140.9 mm, 154.5 mm and 164.9 mm for the FAO Penman-Monteith, ASCE Penman-Monteith, Penman and Priestley-Taylor, respectively. The comparative assessment of FAO-PM and other ET_o methods was done and results are depicted in Table 2. Among all methods, the ASCE Penman-Monteith method demonstrated the closest alignment with the FAO-PM method as evidenced by the better statistics (nRMSE = 2.7%, MAE = 0.07 mm day^{-1}, NSME = 0.98 and Willmott's d-index = 0.99). These results indicated a near-perfect correspondence, underscoring the ASCE Penman-Monteith method's precision and reliability for ET estimation. These findings highlight the critical importance of selecting appropriate ET estimation methods in agricultural water management. The superior performance of the ASCE Penman-Monteith method suggested that it is the most suitable alternative to the FAO-PM method, especially in regions where accurate water use assessment is essential, such as the Tarai region for sugarcane cultivation. The estimated reference ET_o from aforementioned methods at daily scale is illustrated in Fig. 4.

Bowen ratio- based energy flux

The Bowen ratio- based energy fluxes are illustrated in Fig. 5 for the post-monsoon season. This period is one of the important phase for active crop growth of sugarcane, because of that the latent heat flux was always higher than sensible heat flux. Due to heavy rain during 18-20 October 2021, a sharp dip was observed in all the energy. Holland *et al.,* (2013) described the surface energy balance and ET derived from micro-Bowen ratio system for vineyard inter-row and found significant correlation with micro-lysimeter observations at fescue and bare soil, respectively (R^2 = 0.99 and 0.89).

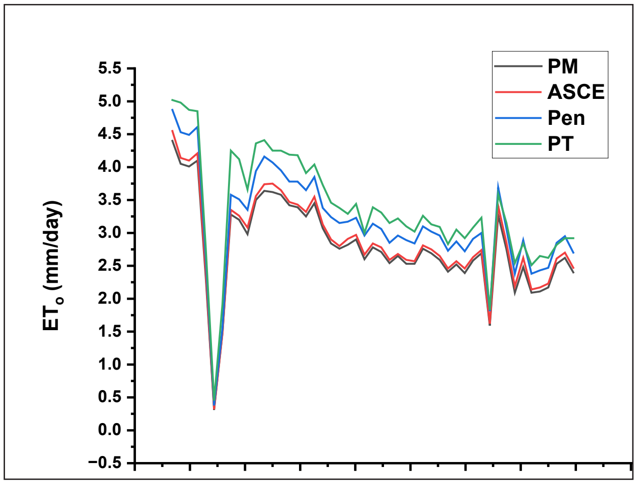

Fig. 4: Reference evapotranspiration rate (mm day^{-1}) derived from four methods

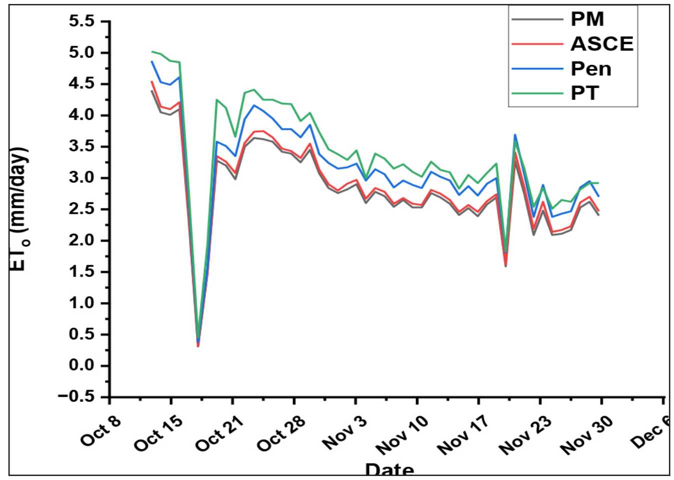

Fig. 5: Bowen ratio- based surface energy fluxes and rainfall pattern

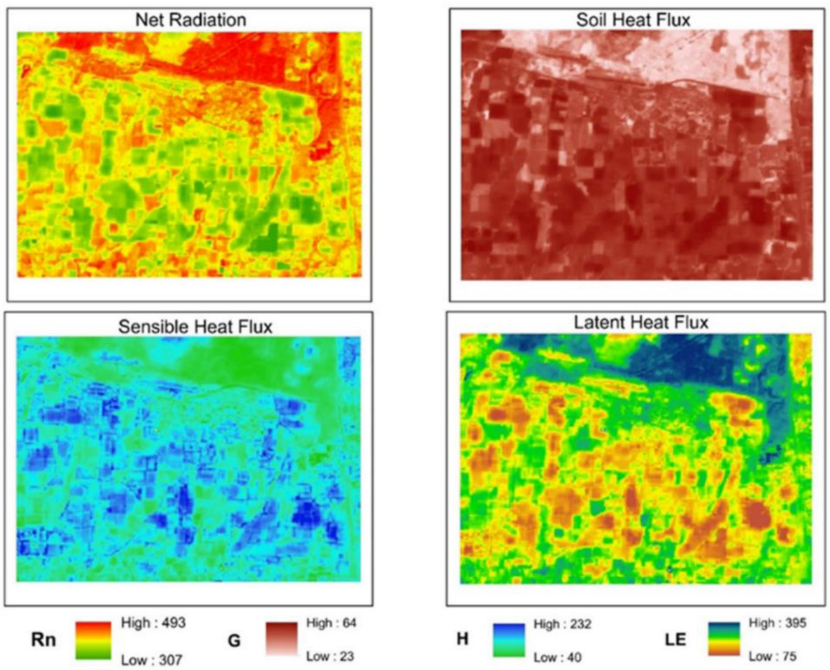

Fig. 6: Surface energy fluxes derived by METRIC model (Date of Acquisition: 13 November 2021)

METRIC derived surface energy fluxes

The surface energy fluxes derived by remote sensing-based energy balance technique i.e. METRIC model are shown in Fig.6. A comparative evaluation of METRIC model derived surface energy fluxes with large aperture scintillometer observations was conducted, where net radiation, soil heat flux, sensible heat flux and latent heat flux were 406, 52, 143 and 211 W m^{-2} (METRIC model) and 386, 46, 148 and 192 W m^{-2} (measured with scintillometer). The results reveal that Landsat-9 satellite and METRIC model derived instantaneous ET was 7.39 mm day^{-1} for 13th November 2021 while LAS observed instantaneous ET was 6.72 mm day^{-1}. There was 9.97% variation in ET of LAS and METRIC model. Similarly, da Silva *et al.,* (2024) assessed and compared the ET using METRIC and SAFER (Simple Algorithm For Evapotranspiration Retrieving) model with observed ET data from eddy covariance and surface renewal analysis.

CONCLUSION

This study assessed evapotranspiration and surface energy fluxes in the Pantnagar region during the post-monsoon season using remote sensing, a large aperture scintillometer-based ET station, and the METRIC model. The METRIC model demonstrated high accuracy in estimating ET, closely aligning with ground-based measurements. Comparative analysis of different ET estimation methods highlighted the superior performance of the ASCE Penman-Monteith method, which showed the closest agreement with the FAO Penman-Monteith method. The study underscores the efficacy of integrating remote sensing and ground-based observations for precise ET estimation, essential for efficient water management in sugarcane cultivation. The findings advocate for the adoption of advanced remote sensing technique to enhance agricultural water use efficiency and support sustainable practices in the Tarai region.

ACKNOWLEDGEMENT

This research work was carried-out as a part of TDP project funded by ISRO. The ET Station was augmented in the university farm on the basis of the MoU between IIRS-ISRO and GBPUA&T, Pantnagar under the TDP project fund. The authors are also very much thankful to the anonymous reviewers.

Declaration of Interests: The authors declare that there is no conflict of interest in authorship and research work.

Data Availability: Data are available on request basis only.

Conflict of Interests: The authors declare that there is no conflict of interest related to this manuscript.

Authors contribution: **A. Danodia:** Conceptualization, Methodology, Data collection, Data Analysis, Visualization, Writing-original draft; **N.R. Patel:** Resources, Supervision, Methodology, Writing-review and editing; **A.S. Nain:** Resources, Supervision, Writing-review and editing; **Suresh Kumar:** Resources, Supervision; **R.P. Singh:** Resources, Conceptualization, Supervision; **A. Satpathi:** Data collection, Visualization; Writing-review and editing; **P. Chauhan:** Resources, Supervision

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