

Satellite-Based Estimation of Evapotranspiration over India Using Remote Sensing Models: A Brief Review

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Abstract—Evapotranspiration (ET) is a major component of the hydrological cycle and plays an important role in agricultural water management, drought assessment, ecosystem functioning and regional water-resource planning. Its accurate estimation remains challenging in India because of substantial climatic variability, monsoon seasonality, heterogeneous land cover, intensive irrigation and the limited spatial distribution of ground-based measurement systems. Satellite remote sensing provides an effective means of estimating the spatial distribution of evapotranspiration by integrating observations of land-surface temperature, vegetation characteristics, surface reflectance and meteorological conditions. This review examines the principal approaches used for satellite-based ET estimation and discusses their applicability to Indian agro-climatic conditions. Particular attention is given to surface energy balance models, including the Surface Energy Balance Algorithm for Land (SEBAL), Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) and the Operational Simplified Surface Energy Balance model (SSEBop). Satellite-driven products and complementary approaches, including MODIS-based evapotranspiration, the Global Land Evaporation Amsterdam Model (GLEAM) and vegetation-based methods, are also considered. Indian applications demonstrate the potential of remote sensing for crop-water assessment, regional water accounting, drought monitoring and the analysis of long-term evapotranspiration variability. However, differences in input data, spatial and temporal resolution, calibration procedures and validation strategies complicate comparisons between models. Cloud contamination, thermal-infrared data gaps, meteorological uncertainty and scale mismatches between satellite pixels and ground observations remain important limitations. The review identifies priorities for improving ET estimation in India through systematic regional validation, transparent uncertainty analysis, multi-source data integration and the development of operational workflows that account for the country's diverse climatic and agricultural conditions.

Index Terms—Actual evapotranspiration; satellite remote sensing; India; SEBAL; METRIC; SSEB; MODIS; surface energy balance; irrigation management; water stress.

I. INTRODUCTION

Evapotranspiration (ET), the combined process of water evaporation from soil and other surfaces and transpiration through plants, links the hydrological, energy and carbon cycles. It influences soil-water availability, agricultural productivity, ecosystem functioning and the exchange of energy between the land surface and atmosphere. Reliable estimates of ET are therefore essential for irrigation scheduling, drought assessment, crop-water accounting, watershed management and climate-change studies (Monteith, 1965; Fisher et al., 2017).

India presents a particularly important setting for ET research because of its contrasting climatic regimes, ranging from humid tropical and monsoon-dominated regions to semi-arid agricultural zones and arid landscapes. The timing and intensity of monsoon rainfall, groundwater-supported irrigation, crop rotations, vegetation phenology and soil-water availability produce substantial spatial and seasonal variations in actual evapotranspiration. Consequently, estimates derived from a single meteorological station or a limited number of field observations may not adequately represent the spatial heterogeneity of water consumption across agricultural landscapes.

Conventional ET estimation relies on methods such as lysimetry, eddy covariance, energy-balance measurements and meteorological calculations. Although these approaches are valuable for direct or indirect measurement and model validation, their installation and maintenance can be expensive and their spatial representativeness is often limited.

Satellite remote sensing addresses part of this limitation by providing spatially distributed information on land-surface temperature, vegetation condition, surface reflectance and land cover.

Satellite sensors do not directly measure ET. Instead, remotely sensed observations are integrated with physical, empirical or statistical models to estimate water and energy fluxes. Surface energy balance approaches estimate latent heat flux as the residual of the surface energy balance, whereas vegetation-based and satellite-driven approaches use different combinations of radiation, meteorological variables, vegetation characteristics and environmental constraints. The resulting estimates differ in their assumptions, input requirements, spatial resolution and temporal coverage (Bastiaanssen et al., 1998; Allen et al., 2007; Tran et al., 2023).

In India, satellite-derived ET has been investigated for agricultural water management, regional water consumption, crop evapotranspiration and long-term changes in water use. Studies have applied Landsat-based surface energy balance approaches to agricultural regions, while satellite-driven products have been used to investigate ET variability over larger spatial domains. For example, a regional assessment of Indian subtropical environments examined long-term ET patterns and changes in water consumption across major land-cover classes. Landsat-based S-SEBI applications in northern India have also demonstrated the potential of thermal and vegetation observations for crop-water estimation.

Despite these developments, important questions remain concerning the relative suitability of different ET estimation approaches under Indian climatic conditions. Model performance may vary with vegetation density, surface moisture, atmospheric conditions, land-cover heterogeneity and the availability of reliable meteorological inputs. Furthermore, comparisons based only on agreement between two ET products may not establish their absolute accuracy because both estimates may share similar uncertainties.

The present review therefore aims to: (i) summarize the major satellite datasets used for ET estimation; (ii) explain the principles and requirements of widely used ET models; (iii) examine their applications in Indian agricultural and hydrological settings; (iv) discuss validation procedures and sources of uncertainty; and

(v) identify research priorities for improving satellite-based ET estimation and its operational use in India.

II. REVIEW SCOPE AND LITERATURE APPROACH

This manuscript presents a focused narrative review of satellite-based ET estimation, emphasizing methods and applications relevant to India. The literature was organized around four themes: model development and physical principles, satellite and meteorological inputs, applications in Indian environments and validation and uncertainty assessment.

Foundational studies describing SEBAL, METRIC, SSEBop, MODIS-based ET and related approaches were considered alongside Indian applications and recent reviews of remote-sensing-based ET uncertainty. The discussion emphasizes the interpretation and comparability of methods rather than assuming that all published estimates are directly comparable.

This is a narrative review, not a completed systematic review. A publication-ready version should include a reproducible database search, search dates, inclusion and exclusion criteria, duplicate removal and a documented study-selection process. Such a procedure would also help quantify the distribution of Indian ET studies by region, satellite platform, model and validation approach.

III. SATELLITE DATA AND ANCILLARY INPUTS FOR ET ESTIMATION

3.1 Optical and thermal-infrared satellite observations

Satellite-based ET estimation requires observations describing the land surface and, depending on the model, meteorological information describing the atmospheric environment.

Optical observations provide information about surface reflectance, vegetation condition and land-cover characteristics. The Normalized Difference Vegetation Index (NDVI) is commonly used to characterize vegetation greenness:

$$NDVI = (NIR - Red) / (NIR + Red)$$

where NIR and Red denote near-infrared and red reflectance, respectively. NDVI is useful for identifying vegetation development and distinguishing vegetated from sparsely covered surfaces. However, it is not a direct measurement of ET and may become

less sensitive to changes in vegetation density under high-biomass conditions.

Thermal-infrared observations are particularly important for surface energy balance methods because land-surface temperature responds to the balance between available energy, sensible heat transfer and latent heat consumption. A relatively warm surface

may indicate limited evaporative cooling, while a cooler surface may indicate greater evaporation or transpiration. This relationship is not unique: radiation, aerodynamic conditions, vegetation structure and thermal properties can also influence surface temperature.

Table 1. Principal satellite datasets and their potential contributions to ET estimation

Dataset or platform	Main contribution	Important limitation
Landsat 8/9	Field-scale reflectance and thermal observations; land-cover and surface-energy analysis	Cloud contamination and relatively infrequent clear-sky observations
MODIS	Frequent observations and established ET products	Coarser spatial resolution than Landsat
Sentinel-2	High-resolution optical reflectance and vegetation monitoring	No thermal-infrared land-surface-temperature band
Sentinel-3	Thermal observations and regional surface monitoring	Spatial resolution may be insufficient for individual fields
ERA5-Land	Meteorological and land-surface variables for model forcing and comparison	Reanalysis estimates are model-derived and may not represent local field conditions
Ground meteorological observations	Local radiation, temperature, humidity, wind and rainfall measurements	Limited spatial coverage
Eddy-covariance and flux-tower observations	Independent estimates of turbulent latent and sensible heat fluxes	Point-to-footprint representativeness and energy-balance closure issues

Landsat is especially useful where field-scale spatial detail is required. MODIS-based products are more suitable for frequent regional observations and long-term analysis. Combining these data sources can improve the balance between spatial detail and temporal coverage, provided differences in observation times, spatial support and retrieval methods are addressed.

3.2 Meteorological and ancillary information

Meteorological inputs may include air temperature, humidity, wind speed, incoming shortwave and longwave radiation, atmospheric pressure and reference evapotranspiration. Digital elevation models may be required for terrain correction, while land-cover information and vegetation parameters can support model parameterization.

The FAO-56 Penman–Monteith equation is widely used to calculate reference evapotranspiration:

$$ET_0 = [0.408 \Delta (R_n - G) + \gamma \times (900 / (T + 273)) \times u_2 \times (e_s - e_a)] / [\Delta + \gamma (1 + 0.34u_2)]$$

where ET_0 is reference evapotranspiration in mm day^{-1} , R_n is net radiation, G is soil heat flux, T is mean daily air temperature, u_2 is wind speed at 2 m, $e_s - e_a$ is vapour-pressure deficit, Δ is the slope of the saturation vapour-pressure curve and γ is the psychrometric constant.

Reference ET represents atmospheric evaporative demand over a standardized reference surface. It should not be interpreted as the actual water loss from

a specific crop or landscape without an appropriate relationship between reference and actual ET.

IV. MAJOR APPROACHES FOR SATELLITE-BASED ET ESTIMATION

Satellite-based ET estimation methods can broadly be classified into surface energy balance approaches, vegetation-based approaches and satellite-driven or hybrid models. Their suitability depends on the intended spatial and temporal scale, data availability and validation requirements.

4.1 Surface energy balance approaches

The surface energy balance is commonly expressed as:

$$R_n = G + H + LE$$

where R_n is net radiation, G is soil heat flux, H is sensible heat flux and LE is latent heat flux. The latent heat flux is calculated as the residual: $LE = R_n - G - H$.

Actual ET can then be derived from latent heat flux. For a daily mean latent heat flux expressed in W m^{-2} , a simplified conversion is $ET = 86400 \times LE / (\lambda_w \rho_w)$,

where λ_v is the latent heat of vaporization in J kg^{-1} and ρ_w is water density in kg m^{-3} . This expression yields daily ET in metres of water and must be multiplied by 1,000 to express ET in millimetres per day. The conversion assumes that the flux represents the daily mean; an instantaneous satellite overpass flux must first be appropriately integrated or extrapolated.

4.2 Surface Energy Balance Algorithm for Land (SEBAL)

SEBAL estimates ET by calculating the components of the surface energy balance. Surface reflectance, vegetation indices, land-surface temperature, albedo and meteorological information are used to estimate net radiation, soil heat flux and sensible heat flux. Latent heat flux is obtained as the residual.

A characteristic feature of SEBAL is the use of representative hot and cold pixels to help calibrate sensible heat flux. Hot pixels represent relatively dry surfaces with limited evaporative cooling, whereas cold pixels represent relatively wet surfaces with greater evaporative cooling. The suitability of these pixels is critical because inappropriate selection can introduce systematic errors in the estimated energy balance.

SEBAL has been applied to agricultural water management and regional ET estimation in India. Its reliability depends on calibration, input-data quality and independent validation.

- Strengths: Spatially explicit estimates, a physically interpretable energy balance and applicability to heterogeneous agricultural landscapes.
- Limitations: Sensitivity to anchor-pixel selection, aerodynamic parameterization, thermal observations and meteorological forcing.

4.3 Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC)

METRIC is an energy balance approach developed from the SEBAL framework. It estimates ET using remotely sensed surface properties, meteorological information and internal calibration procedures. A major feature is the use of reference ET and calibration of the energy balance using representative surface conditions.

METRIC is particularly relevant to irrigated agriculture, where field-scale differences in water supply and crop condition are important. However, a

simplified implementation should not be described as the complete METRIC algorithm unless its calibration, reference ET calculations, energy balance and temporal extrapolation procedures are implemented appropriately.

- Strengths: Field-scale mapping and an explicit relationship with reference ET, supporting irrigation assessment.
- Limitations: Dependence on calibration, meteorological data, thermal observations and assumptions about temporal stability.

4.4 Operational Simplified Surface Energy Balance (SSEBop)

SSEBop is a simplified thermal-based approach designed for operational ET estimation. It uses land-surface temperature relative to thermal reference conditions to estimate an ET fraction, which is combined with reference ET to obtain actual ET.

A simplified representation is $ET_a = ET_f \times ET_o$, where ET_a is actual ET, ET_f is an estimated ET fraction and ET_o is reference ET. Operational implementations require appropriate definitions of hot and cold reference conditions, thermal calibration and scaling procedures.

The simplified structure can be useful for regional monitoring, especially where detailed meteorological observations are scarce. Nevertheless, fixed thermal differences or locally assumed temperature thresholds should not automatically be treated as equivalent to the operational SSEBop parameterization.

- Strengths: Computational efficiency, operational suitability and potential application to large areas.
- Limitations: Sensitivity to thermal reference conditions, meteorological forcing and assumptions used to derive ET fractions.

4.5 MODIS-based ET products

The MOD16 algorithm estimates ET using a Penman–Monteith-based framework and satellite-derived vegetation properties together with meteorological inputs. Its principal advantage is the availability of spatially consistent observations over long periods, making it useful for regional and national assessments. MODIS products are suitable for examining seasonal variability and broad spatial patterns. However, their relatively coarse spatial resolution may obscure field-scale variability, particularly in fragmented

agricultural landscapes where irrigated fields, bare soil, settlements and water bodies occur within the same pixel.

4.6 GLEAM and related satellite-driven approaches
The Global Land Evaporation Amsterdam Model (GLEAM) estimates terrestrial evaporation using satellite observations and meteorological information, with separate consideration of evaporation components and environmental constraints such as vegetation and soil-water availability.

GLEAM and other satellite-driven products can provide broad spatial coverage and are valuable for regional water-balance studies. Their estimates, however, depend on input datasets, parameterization and assumptions about the processes governing evaporation and transpiration. They should therefore be evaluated locally before being used for field-scale irrigation decisions.

Table 2. Comparison of major ET estimation approaches

Approach	Main principle	Typical application	Principal limitation
SEBAL	Surface energy balance with hot and cold pixel calibration	Field-to-regional ET mapping	Anchor-pixel sensitivity
METRIC	Energy balance with internal calibration and reference ET	Irrigation management and crop water use	Calibration and meteorological requirements
SSEBop	Thermal ET fraction combined with reference ET	Operational regional monitoring	Sensitivity to thermal reference conditions
MOD16	Penman–Monteith-based satellite product	Regional and long-term ET analysis	Coarse spatial resolution and input uncertainty
GLEAM	Satellite-driven evaporation and transpiration modelling	Regional hydrology and ecosystem studies	Dependence on model structure and forcing data
Vegetation-based approaches	Vegetation indices and environmental relationships	Vegetation monitoring and ET approximation	Limited ability to represent all water and energy controls

These approaches should not be ranked universally. A model that performs well in irrigated cropland may not be optimal in sparsely vegetated arid terrain or cloudy monsoon environments.

V. APPLICATIONS OF SATELLITE-BASED ET ESTIMATION IN INDIA

5.1 Agricultural water management

Agriculture is a major application of satellite-based ET because crop water consumption varies with crop type, growth stage, irrigation, weather and soil moisture. Field-scale ET maps can help identify differences in water use within irrigation commands and provide information for irrigation scheduling.

Landsat-based surface energy balance approaches have been investigated in northern Indian agricultural regions. An S-SEBI study using Landsat-8 data reported mean crop ET estimates of approximately 2.72 mm day^{-1} during the Kharif season and 2.47 mm day^{-1} during the Rabi season. The study also reported a correlation coefficient of 0.85 between model-derived and scintillometer-observed evaporative fraction. These results demonstrate the potential of thermal and optical satellite observations for crop-water assessment, although they should not be generalized to all Indian crops or climates.

For operational irrigation management, satellite-derived ET should ideally be interpreted together with crop calendars, irrigation records, soil moisture and meteorological information. ET maps alone do not directly establish whether irrigation is excessive or insufficient because crop demand and water availability vary spatially.

5.2 Regional water accounting and long-term variability

At regional scales, ET can help quantify terrestrial water consumption and examine changes in land–atmosphere interactions. Satellite-derived ET products can be used to investigate seasonal patterns, long-term trends and differences among land-cover classes.

A study published in *Agricultural Water Management* developed baseline regional ET estimates for Indian subtropical environments and investigated long-term ET patterns over 1981–2010. It also examined changes in water consumption across major land-cover types, including irrigated cropland.

Such analyses can support water-resource planning but trend interpretation requires caution. Changes in ET may reflect climatic variability, irrigation expansion, land-cover change, vegetation dynamics or changes in the input datasets and retrieval algorithms. A statistical trend alone cannot establish which mechanism caused the change.

5.3 Drought and agricultural water-stress assessment

ET is useful for assessing water stress because actual water loss generally decreases when soil-water limitations constrain evaporation and transpiration. However, low ET is not necessarily evidence of drought: it may also reflect bare soil, sparse vegetation, crop dormancy or a naturally low-water-use ecosystem.

A useful indicator is the ratio $KET = ET_a / ET_o$, where ET_a is actual ET and ET_o is reference ET. A declining ratio may indicate that actual water use is increasingly constrained relative to atmospheric demand but it is not a universal stress threshold. Interpretation should account for crop type, growth stage, vegetation cover, reference surface definition and local climatic conditions.

For crop-specific water-stress assessment, the ratio should ideally be compared with crop coefficients, soil moisture, vegetation condition and field observations. ET-based indicators can also complement rainfall anomalies and other drought indices.

5.4 Evaporative fraction and cloudy conditions

Evaporative fraction (EF) expresses the fraction of available surface energy used for latent heat flux: $EF = LE / (R_n - G)$. Under suitable daytime conditions, EF may remain approximately stable over part of the day, allowing an instantaneous satellite-derived estimate to be used in daily ET calculations. This assumption is not universally valid, particularly where clouds, advection, irrigation events or rapidly changing atmospheric conditions alter the surface energy balance.

Cloud cover is a major challenge for thermal-infrared ET models because clouds obstruct surface observations. A missing thermal observation should not be interpreted as zero ET. Instead, temporal interpolation, data fusion, meteorological modelling or an independently generated ET product may be required to fill the gap.

Clear-sky and cloudy-day estimates should therefore be distinguished. Where cloud-free observations are unavailable, the method used to estimate ET must be reported explicitly, together with the uncertainty associated with temporal gap filling.

VI. VALIDATION AND UNCERTAINTY ASSESSMENT

Validation is essential because satellite-based ET is a model-derived quantity rather than a direct satellite measurement. A model may produce spatially realistic patterns but still exhibit systematic bias in its absolute ET estimates.

6.1 Ground-based validation

Potential validation datasets include:

- Eddy-covariance flux towers measuring turbulent latent and sensible heat fluxes.
- Bowen-ratio energy balance systems.
- Weighing or drainage lysimeters.
- Catchment or field water-balance estimates.
- Scintillometer-derived sensible heat flux and related energy balance observations.

Each source has limitations. Eddy-covariance observations represent a footprint that varies with wind direction and atmospheric stability, whereas a satellite pixel represents an area defined by the sensor's spatial resolution. Water-balance estimates may accumulate uncertainties from rainfall, irrigation, drainage and storage changes. Independent validation should therefore consider both measurement uncertainty and differences in spatial and temporal support.

6.2 Statistical evaluation

The following metrics are commonly used to compare satellite-derived ET with reference observations:

$$RMSE = \sqrt{[(1/n) \sum (P_i - O_i)^2]}$$

$$MAE = (1/n) \sum |P_i - O_i|$$

$$Bias = (1/n) \sum (P_i - O_i)$$

where P_i is the predicted ET, O_i is the observed or reference ET and n is the number of matched observations.

RMSE emphasizes large errors, MAE represents average absolute error and bias indicates systematic overestimation or underestimation. Correlation and coefficient of determination can provide additional information about agreement in temporal or spatial

variability but high correlation does not necessarily imply low bias or accurate absolute ET.

Comparisons should use consistent units, aggregation periods, spatial support and definitions of actual ET. Instantaneous latent heat flux, daily ET, monthly ET and reference ET should not be compared as if they were interchangeable variables.

6.3 Major sources of uncertainty

- Satellite retrieval uncertainty: Errors in land-surface temperature, reflectance, emissivity and albedo propagate into model estimates.
- Meteorological uncertainty: Errors in radiation, wind speed, humidity and air temperature affect energy balance and reference ET calculations.
- Parameterization uncertainty: Hot and cold pixel selection, aerodynamic resistance, surface roughness and thermal reference conditions influence model output.
- Cloud contamination: Missing or unreliable thermal observations limit temporal coverage, especially during the monsoon.
- Scale mismatch: Ground measurements and satellite pixels may represent different spatial areas.
- Temporal extrapolation: Converting an instantaneous estimate to daily or monthly ET introduces assumptions about flux variation throughout the day.
- Land-cover heterogeneity: Mixed pixels can combine vegetation, bare soil, water and built-up surfaces with different evaporation characteristics.

A systematic review by Tran et al. (2023) highlights substantial variation in how uncertainty is assessed and reported across satellite-based ET studies. Consistent validation protocols and explicit uncertainty estimates are therefore important for comparing models and evaluating their practical utility.

VII. RESEARCH GAPS AND FUTURE DIRECTIONS IN INDIA

Regional validation needs to be strengthened across India's diverse agro-climatic zones. Studies in irrigated croplands, semi-arid regions, humid environments and arid landscapes should use suitable

ground observations and clearly report their representativeness.

Comparisons between ET models require more consistent experimental designs. Where possible, different models should be evaluated using the same study period, common satellite observations, consistent spatial aggregation and independent validation data. Such comparisons would help distinguish differences arising from model structure from differences caused by input data.

Cloudy-period ET estimation requires further attention. Thermal-infrared observations provide valuable surface-temperature information but are frequently unavailable during cloudy conditions. Integrating optical observations, reanalysis, microwave observations and temporal modelling may improve coverage, although these approaches require independent assessment rather than an assumption of greater accuracy.

The integration of satellite data with soil moisture and crop information could improve the interpretation of water stress. Actual ET relative to reference ET may be a useful indicator but its interpretation should be crop- and climate-specific.

The role of cloud computing and open-source geospatial platforms should be expanded. Google Earth Engine facilitates satellite-data access, preprocessing, time-series analysis and regional mapping. Reproducible workflows can improve transparency and allow researchers to compare model implementations. However, platform-based processing does not automatically guarantee scientific validity; model equations, units, calibration assumptions and validation procedures must remain explicit.

Machine learning and hybrid approaches offer opportunities to combine satellite observations with meteorological and ground-based data. Their use should be supported by independent testing, physically meaningful constraints and uncertainty assessment. Data-driven models should not be assumed to outperform physical models across all climates or spatial scales.

VIII. CONCLUSIONS

Satellite remote sensing provides an important framework for estimating evapotranspiration across India's heterogeneous agricultural and natural

landscapes. SEBAL and METRIC offer physically interpretable surface energy balance approaches for spatially detailed ET estimation, while SSEBop provides a simplified framework suited to operational monitoring. MODIS-based ET products and GLEAM offer complementary capabilities for regional and long-term assessments.

The suitability of a particular method depends on the spatial and temporal requirements of the application, the quality of satellite and meteorological inputs, local climatic conditions, calibration procedures and the availability of independent validation data. Model comparisons should therefore emphasize context-specific performance rather than establish a universal ranking.

For India, the most important priorities are expanded ground-based validation, improved treatment of cloud-related gaps, transparent reporting of model assumptions and more consistent inter-model comparisons. Integrating satellite-derived ET with soil moisture, crop information and meteorological observations could further improve irrigation planning and drought assessment. Ultimately, satellite ET products will be most useful when their uncertainty and limitations are explicitly communicated alongside their spatial estimates.

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