

RESEARCH ARTICLE

Applicability of Hargreaves-Samani and Valiantzas' Models for Solar Radiation Estimation in Coimbatore using Temperature and Humidity Inputs

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ABSTRACT

Precise estimation of reference evapotranspiration (ET_0) is crucial for effective irrigation planning and water resource management, particularly in semi-arid regions such as Coimbatore, Tamil Nadu. The FAO56 Penman–Monteith (FAO56-PM) method is widely regarded as the standard approach for ET_0 estimation. Still, its application is limited by the requirement of multiple meteorological inputs, including solar radiation (R_s) and wind speed, which are often unavailable or unreliable in many regions. This study evaluates two simplified models for estimating R_s , the Hargreaves–Samani (HS) model and the modified version by Valiantzas (2017), which incorporates relative humidity (RH) along with temperature, and examines their impact on FAO56-PM ET_0 estimation using 21 years (2004–2024) of NASA POWER meteorological data for Coimbatore. Results showed a strong correlation between measured R_s and estimated R_s values, with the HS model achieving an R^2 of 0.7866 and the Valiantzas' model an R^2 of 0.7034. When used to compute ET_0 , both models showed excellent agreement with FAO56-PM ET_0 derived from measured R_s , with R^2 values of 0.9477 (HS) and 0.9281 (Valiantzas), and low standard error estimates ($SEE < 0.22 \text{ mm day}^{-1}$). Seasonal analysis revealed that the models accurately preserved the expected ET_0 patterns, with peak values in summer and minima in winter, aligning with trends in solar radiation. The findings confirm that both HS and Valiantzas' models provide reliable alternatives for R_s estimation and ET_0 computation in data-scarce environments. The HS model, due to its simplicity and robustness under clear-sky conditions, is particularly well-suited for semi-arid climates. In contrast, the Valiantzas' model offers added flexibility in regions with variable humidity. These results highlight the potential of simplified radiation models to enhance irrigation planning when comprehensive weather data are unavailable.

Keywords: Reference evapotranspiration, FAO56-PM, Hargreaves–Samani, Valiantzas' model, Solar radiation estimation, Semi-arid, Coimbatore, NASA POWER.

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INTRODUCTION

Accurate estimation of reference evapotranspiration (ET_0) plays an important role in designing efficient irrigation schedules and managing water resources sustainably, especially in semi-arid regions like Coimbatore, Tamil Nadu. Among the numerous models available, the FAO56 Penman–Monteith (FAO56-PM) method (Allen *et al.*, 1998) is internationally recognized as the standard method for estimating ET_0 due to its physical basis and reliability. However, its application requires a comprehensive set of meteorological inputs, including maximum and minimum air temperatures (T_{max} and T_{min}), solar radiation (R_s), maximum and minimum relative humidity (RH_{max} and RH_{min}), wind speed (u), and geographic parameters such as latitude and altitude.

In many developing countries, including parts of India, collecting all these inputs at consistent quality and resolution remains a significant challenge. Weather stations often suffer from incomplete data due to equipment malfunctions, limited instrumentation, or high maintenance costs. Furthermore, the sophisticated sensors required for solar radiation and wind speed measurement are expensive, making their widespread installation unfeasible (Valiantzas, 2012, 2013d; Exner-Kittridge, 2012; Exner-Kittridge & Rains, 2010). This results in gaps in long-term meteorological datasets, limiting the applicability of the FAO56-PM model in many regions, including Coimbatore.

To overcome these limitations, several researchers have developed simplified models that attempt to estimate ET_0 using fewer, more commonly available weather parameters without significantly compromising accuracy. Valiantzas (2006, 2013a, 2013b, 2013c, 2013d, 2014a, 2014b, 2015, 2018a, 2018b) introduced a series of progressively refined equations that simplify the estimation of reference evapotranspiration (ET_0) by reducing the number of input parameters required compared to the standard FAO56 Penman–Monteith (PM) method. His work builds on the physical foundation of the PM equation, systematically modifying and re-deriving components such as the aerodynamic and radiation terms to eliminate the need for hard-to-obtain variables, like wind speed and solar radiation. The first significant contribution (Valiantzas, 2006) proposed alternative formulations of the radiation term using air temperature and sunshine duration, making it suitable for areas where radiation data are missing.

In later studies, such as Valiantzas (2013a, 2013b), he developed empirical factors to approximate the aerodynamic component using only temperature and elevation, effectively removing the need for wind speed data. He further extended this idea in Valiantzas (2013c, 2013d) by presenting multiple forms of ET_0 equations that can be used under different data availability scenarios, for example, with or without relative humidity or wind speed. These forms offer flexibility and adaptability in application, depending on the available climatic data.

In his 2014a and 2014b studies, Valiantzas provided clarifications, performance evaluations, and methodological discussions to support the robustness of his simplified models. In Valiantzas (2015), the focus was on adapting his limited-data models specifically for humid locations, improving their accuracy in such climates. Finally, in his 2018 works, he compared the temperature- and humidity-based simplified models to other empirical methods, including the Hargreaves–Samani method, and further validated their suitability under diverse climatic conditions.

Overall, Valiantzas' models significantly contribute to expanding the usability of ET_0 estimation in data-scarce regions by providing reliable alternatives that require only a minimal set of routine weather observations (e.g., temperature, relative humidity, and elevation). This makes them especially valuable in regions like Coimbatore, where continuous and high-quality meteorological records, especially solar radiation and wind speed, are often unavailable.

These models provide a practical alternative for regions with limited data availability and have been demonstrated to yield results comparable to those of the FAO56-PM method under specific conditions (Djaman *et al.*, 2016).

A key variable in ET_0 estimation is solar radiation (R_s), but it is rarely measured directly at most weather stations due to the high cost and maintenance of pyranometers. To address this, Hargreaves and Samani (1982) developed an empirical model to estimate R_s using only T_{max} and T_{min} , two variables that are routinely recorded at nearly all-weather stations. This model, along with its later refinements (Samani, 2000; Samani *et al.*, 2011; Hargreaves & Allen, 2003), remains one of the most widely used approaches for estimating R_s when direct measurements are unavailable.

More recently, Valiantzas (2017) proposed an enhanced version of the Hargreaves–Samani model that incorporates relative humidity (RH) along with air temperature. This modification leverages the fact that RH sensors are significantly more affordable than radiation or wind sensors (Exner-Kittridge & Rains, 2010). The inclusion of RH helps improve the accuracy of solar radiation estimation, especially in humid and semi-arid climates. Studies conducted in diverse regions such as Iran (Valipour, 2014), the Mediterranean basin (Kisi, 2014), Western Australia (Ahooghalandari *et al.*, 2016), Senegal (Djaman *et al.*, 2015), and Burkina Faso (Djaman *et al.*, 2016) have validated the reliability and adaptability of Valiantzas' simplified models under various climatic conditions.

In this context, the present study was undertaken to assess the performance of the modified Hargreaves–Samani model proposed by Valiantzas (2017) for estimating solar radiation using daily temperature and relative humidity data. The goal is to evaluate whether these simplified models can provide reliable inputs for the FAO56-PM method, thereby accurately estimating reference evapotranspiration under data-limited conditions. Specifically, the study compares the ET_0 values obtained using the FAO56-PM method by substituting R_s estimated from both the original Hargreaves–Samani model and the Valiantzas' model.

The evaluation was carried out on a daily time scale using 21 years of meteorological data (from 2004 to 2024) retrieved from the NASA POWER database for the semi-arid region of Coimbatore, Tamil Nadu. This study not only investigates the suitability of these models under local climatic conditions but also provides insights into improving irrigation planning in areas where complete meteorological datasets are unavailable.

MATERIALS AND METHODS

Study area

Meteorological data required for estimating reference evapotranspiration using the FAO56-PM method were obtained from the NASA POWER database for a 21-year period (2004–2024), corresponding to the geographical location of Coimbatore, Tamil Nadu. The coordinates of the study area are approximately 11°00' N latitude, 76°97' E longitude, with an elevation of 411 meters above mean sea level (MSL).

Estimation of Solar Radiation

Hargreaves-Samani R_s formula based on T (HS R_s [T])

Hargreaves and Samani (1982) recommended a simplified equation to estimate solar radiation:

$$R_s = 0.16 * R_A (T_{\max} - T_{\min})^{0.5} \quad (1)$$

Where,

R_A is extra-terrestrial radiation [$\text{MJ m}^{-2} \text{day}^{-1}$];

$T_{\max}$ is the maximum temperature [$^{\circ}\text{C}$]; and

$T_{\min}$ is the minimum temperature [$^{\circ}\text{C}$].

The radiation (R_a) for each day of the year and at different latitudes can be estimated from the solar constant, the solar declination, and the time of the year using the following equation.

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega_s)] \quad (2)$$

Where,

R_a is extraterrestrial radiation [$\text{MJ m}^{-2} \text{day}^{-1}$],

G_{sc} is solar constant = $0.0820 \text{ MJ m}^{-2} \text{min}^{-1}$,

d_r is the inverse relative distance Earth-Sun,

ω_s is sunset hour angle [rad],

ϕ is latitude [rad] and

δ is solar declination [rad].

Valiantzas' R_s formula based on T and RH (Val R_s [T & RH])

Hargreaves' model for estimating the solar radiation as a function of RH (Hargreaves and Allen, 2003) is given as follows:

$$R_s \propto (1 - RH / 100)^x \quad (3)$$

Where x is an empirical exponent.

By combining Eq. (1) & Eq. (3), R_s is considered as a function of temperature and RH. Valiantzas (2017) identified the regression coefficients by following a calibration procedure. They used a global climatic data set, including monthly data from the FAO-CLIMWAT (Smith, 1993), which covers the typical range of thirteen countries, and proposed the following simple empirical and mathematical form of the equation, in which R_s is estimated from the T and RH data. The new version of the Hargreaves–Samani Model requires temperature and RH data:

$$R_s = 0.338 * R_A * (T_{\max} - T_{\min})^{0.3} * \left(1 - \frac{RH}{100}\right)^{0.2} \quad (4)$$

In Eq. (4), the value of 1.001 was used instead of 1 because of the singularity appearing when $RH/100 = 1$. Hence, the final form of Valiantzas' R's equation is given as:

$$R_s = 0.338 * R_A * (T_{\max} - T_{\min})^{0.3} * \left(1.001 - \frac{RH}{100}\right)^0 \quad (5)$$

Estimation of Reference Evapotranspiration

The FAO56-PM equation for estimating the daily grass-reference evapotranspiration is given by

$$ET_0 = \frac{0.408 * \Delta(R_n - G) + \gamma \frac{900}{[T + 273]} * u * (e_a - e_d)}{\Delta + \gamma(1 + 0.34 * u)} \quad (6)$$

Where,

ET_0 is reference evapotranspiration [mm day^{-1}],

R_n is net radiation at the crop surface [$\text{MJ m}^{-2} \text{day}^{-1}$],

G is soil heat flux density [$\text{MJ m}^{-2} \text{day}^{-1}$],

T is the mean daily air temperature [$^{\circ}\text{C}$],

U is wind speed at 2 m height [m s^{-1}],

e_s is saturation vapour pressure [kPa],

e_a is actual vapour pressure [kPa],

$e_s - e_a$ is saturation vapour pressure deficit [kPa],

Δ is the slope of the vapour pressure curve [$\text{kPa } ^{\circ}\text{C}^{-1}$],

Γ is the psychrometric constant [$\text{kPa } ^{\circ}\text{C}^{-1}$].

Comparison of methods

A comparison was made between the measured solar radiation and solar radiation derived under the HS R_s [T] model and the Val R_s [T & RH] models separately. In addition, a comparison was made between the reference evapotranspiration estimated from the FAO56-PM equation, using measured R_s values and solar radiation derived from the HS R_s [T] model and the Val R_s [T & RH] models, applied separately.

In this study, a comparison is made using simple error analysis and linear regression.

$$Y = S.X \quad (7)$$

Where,

S is the regression coefficient (slope of the line),

Y is the reference measured values of R_s , and

X = corresponding estimates of R_s by the comparison formula.

The indices used in the error analysis are the standard error estimate (SEE) and the long-term average ratio (rt).

$$SEE = \sqrt{\frac{\sum_1^n (Y_i - X_i)^2}{n-1}} \quad (8)$$

$$rt = \frac{X_{av}}{Y_{av}} \quad (9)$$

Where,

Y_i is the reference measured value at i^{th} data point;

X_i is the corresponding estimate by the comparison formula;

n is the total number of observations;

X_{av} and Y_{av} are the long-term average values of the tested models and the reference values, respectively.

RESULTS AND DISCUSSION

Evaluation of Solar Radiation Estimation Models

The primary objective of this study was to evaluate the performance of two empirical models, the Hargreaves-Samani (HS) model and the Valiantzas' (VAL) model, for estimating solar radiation (R_s) under semi-arid conditions in Coimbatore, using readily available meteorological parameters. The performance of these models was assessed by comparing estimated reference evapotranspiration (R_s) with measured reference evapotranspiration (R_s), and subsequently examining their impact on FAO56-PM reference evapotranspiration (ET_0) estimations.

Solar Radiation Estimation:

The mean solar radiation values show that both the Hargreaves-Samani (HS) model ($17.48 \text{ MJ m}^{-2} \text{day}^{-1}$) and the Valiantzas' (Val) model ($17.51 \text{ MJ m}^{-2} \text{day}^{-1}$) slightly underestimate the observed (measured) R_s ($18.36 \text{ MJ m}^{-2} \text{day}^{-1}$) by about 4.8–4.7%, consistent with earlier error metrics (rt values). The standard deviation (SD) of the Val R_s (3.35) is higher than that of HS R_s (2.73), suggesting that Valiantzas' model produces more variable R_s estimates, possibly due to the inclusion of relative humidity, which adds seasonal variability.

The minimum and maximum values indicate that Val R_s has a broader range (13.17 to $24.74 \text{ MJ m}^{-2} \text{day}^{-1}$) than HS R_s (13.89 to $23.36 \text{ MJ m}^{-2} \text{day}^{-1}$), again pointing to the greater sensitivity of the Val model.



The coefficient of variation (CV%) also supports this, with Val R_s showing the highest variability (19.13%) compared to measured R_s (15.34%) and HS R_s (15.62%), which may be a trade-off for capturing more dynamic climatic variations.

Reference Evapotranspiration Estimation:

The mean ET_0 values derived using the estimated R_s from HS (3.76 mm day⁻¹) and Val (3.77 mm day⁻¹) models are very close to that obtained using measured R_s (3.89 mm day⁻¹). This shows that both models are effective in reproducing average ET_0 values.

The standard deviation of ET_0 using Val R_s (0.92) is slightly higher than that of HS R_s and measured

R_s (both ~0.82), indicating that the Val-based ET_0 estimates also exhibit more variability, consistent with the more variable radiation inputs. The maximum ET_0 using Val R_s is 5.77 mm day⁻¹, slightly higher than that from measured R_s (5.55 mm day⁻¹), which may reflect the model's responsiveness during high evaporative demand periods.

The coefficient of variation (CV%) for Val R_s -based ET_0 (24.28%) is higher than both HS (21.8%) and measured R_s (20.95%), reinforcing its more variable output. Median (50%) and quartile (25% and 75%) values follow a consistent pattern across the board, with Val R_s and HS R_s estimates closely tracking the measured values, indicating that central tendencies are preserved well by both models.

Table 1. Summary Statistics of Solar Radiation and Reference Evapotranspiration

Index	Measured R_s	HS R_s	Val R_s	FAO PM ET (Measured R_s)	FAO PM ET (HS R_s)	FAO PM ET (VAL R_s)
Mean	18.36	17.48	17.51	3.89	3.76	3.77
SD	2.82	2.73	3.35	0.82	0.82	0.92
Min	13.26	13.89	13.17	2.76	2.67	2.58
Max	24.05	23.36	24.74	5.55	5.55	5.77
CV (%)	15.34	15.62	19.13	20.95	21.8	24.28
25%	16.1	15.44	15.1	3.22	3.19	3.15
50%	17.71	16.31	15.91	3.55	3.4	3.35
75%	20.92	19.65	20.05	4.52	4.36	4.42

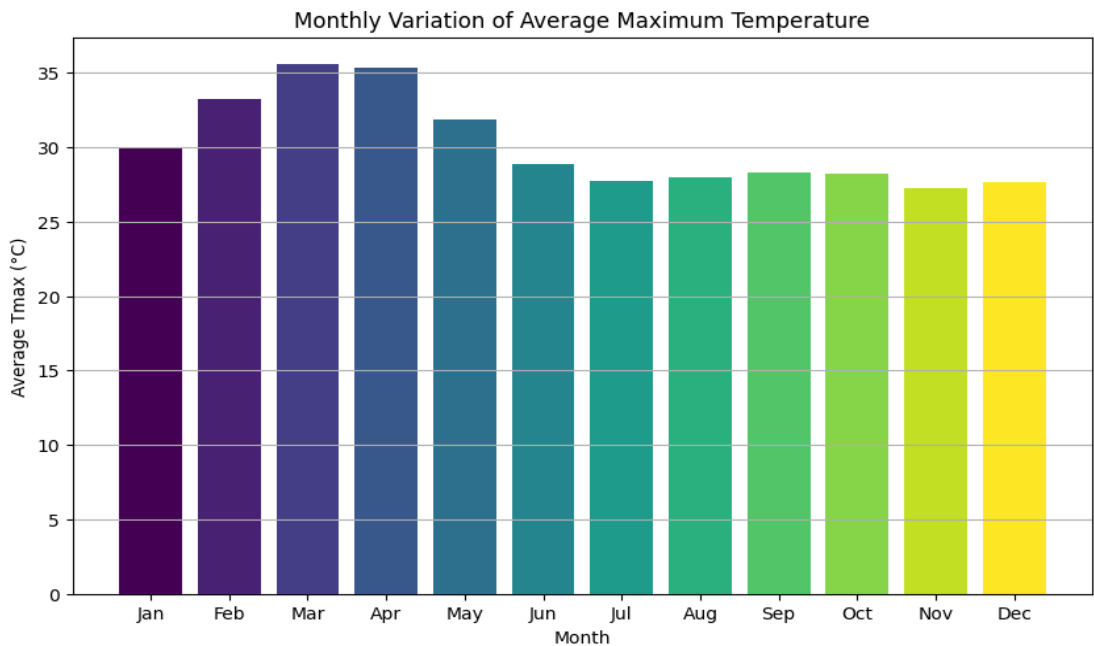


Figure 1: Mean Monthly Maximum Temperature for the study area

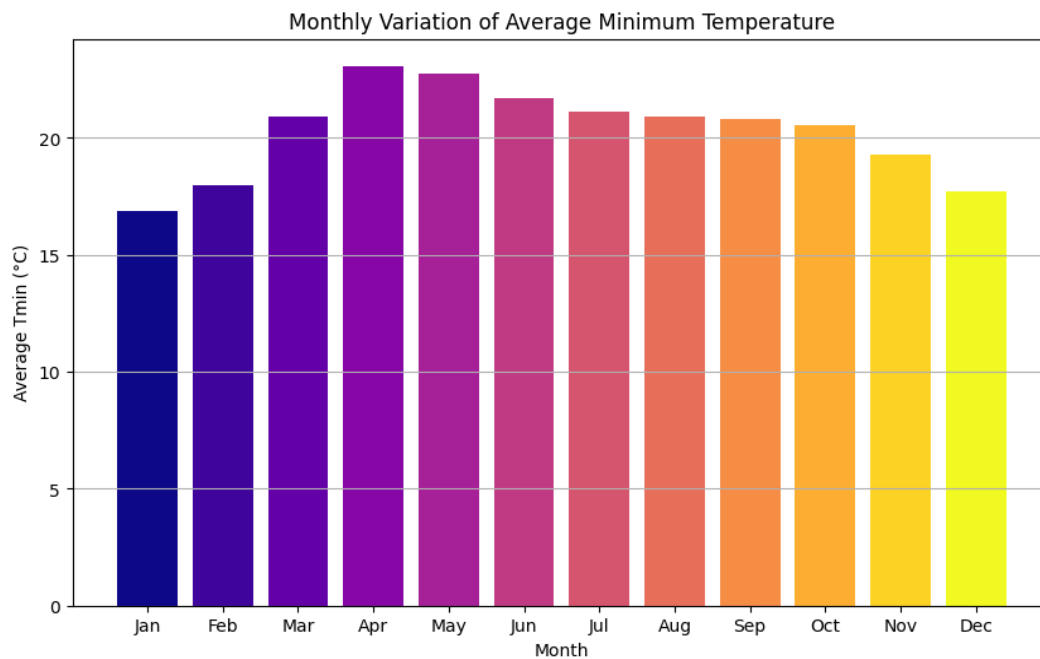


Figure 2: Mean Monthly Minimum Temperature for the study area

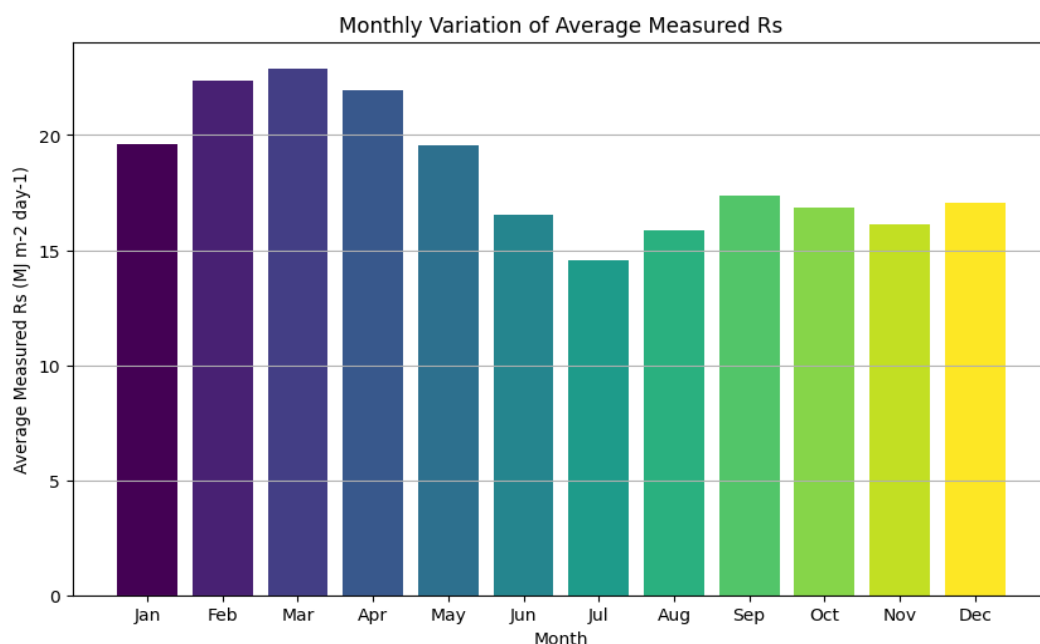


Figure 3: Mean Monthly Solar Radiation for the study area

Seasonal Trends in R_s and ET_0

Seasonal Pattern of Measured R_s

The seasonal trend of R_s was well-defined, with maximum average values observed during the summer months (May–July), peaking at around $20.3 \text{ MJ m}^{-2} \text{ day}^{-1}$ in July, and minimum values in winter months (December–January), with a low of approximately $4.2 \text{ MJ m}^{-2} \text{ day}^{-1}$ in December. This trend is closely tied to the sun's angle, day length, and atmospheric

clarity. The steady increase in R_s from January to peak summer months, followed by a gradual decline, reflects typical semi-arid tropical radiation dynamics, where clear skies dominate most of the year except during the monsoon transition.

Daily and Monthly Variation of ET_0

The daily variation plot of FAO PM ET_0 (Measured R_s) showed a pronounced seasonal pattern, with lower ET_0

values during the cooler months (December–January) and higher values during summer (March–May). This is primarily driven by increased R_s and air temperature, which directly influence ET demand. The monthly average bar plot confirmed this observation. The highest monthly average ET_o occurred in April and May, consistent with the period of peak solar radiation and high vapour pressure deficit. Conversely, December and January had the lowest ET_o , which coincided with lower temperatures, reduced solar radiation, and shorter daylight hours.

These trends underscore the critical seasonal variability in crop water demand, which must be taken into account when designing irrigation schedules in Coimbatore. Moreover, they validate that the simplified models (especially HS) are capable of preserving seasonal ET_o dynamics, reinforcing their practical relevance.

The results of this study have significant practical implications. In regions like Coimbatore, where high-resolution and uninterrupted meteorological datasets are rarely available, the reliability of simplified radiation models becomes crucial. Both the HS and VAL models demonstrated high statistical fidelity in reproducing R_s and ET_o values with minimal error. The Hargreaves–Samani model, despite its simplicity, performed remarkably well, especially under clear-sky conditions prevalent in semi-arid climates. Its use of only T_{max}

and T_{min} makes it ideal for routine field applications and long-term historical assessments. The Valiantzas' model, with added sensitivity to relative humidity, holds potential for slightly more humid regions or during post-monsoon periods, offering flexibility in a broader range of climatic settings. These findings support the adoption of simplified models in agro-climatic zones where access to complete meteorological data is limited. They also emphasize the importance of local calibration of these models to enhance their predictive accuracy and mitigate long-term biases.

Measured R_s vs HS and VAL R_s

The scatter plots between measured R_s and model-estimated R_s revealed a strong positive linear correlation in both cases, though the HS model showed marginally better alignment. The coefficient of determination (R^2) for the HS model was 0.7866, indicating that about 79% of the variability in measured R_s could be explained by the HS model using only T_{max} and T_{min} . This suggests a strong dependence of R_s on air temperature differences, especially in relatively dry and sunny climates, such as Coimbatore, where diurnal temperature ranges are high.

On the other hand, the Valiantzas' model, which incorporates relative humidity in addition to temperature, showed an R^2 of 0.7034. Although slightly lower, this still indicates a moderate to strong linear correlation. The inclusion of RH makes

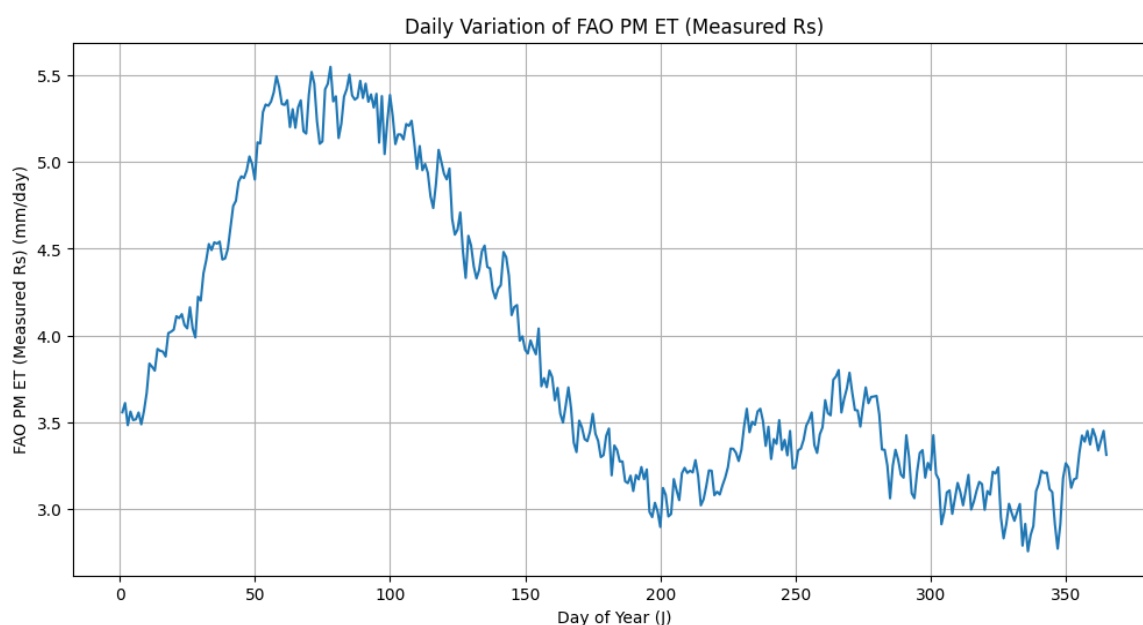


Figure 5: FAO Reference Evapotranspiration for the study area

this model theoretically more adaptable to varying humidity conditions. However, in semi-arid zones where RH variability is limited or more stable, the additional parameter may introduce scatter, explaining the slightly lower correlation.

The Standard Error of Estimate (SEE) values further supported this trend, with HS R_s showing a SEE of $1.3014 \text{ MJ m}^{-2} \text{ day}^{-1}$ and Val R_s having a SEE of $1.5341 \text{ MJ m}^{-2} \text{ day}^{-1}$, indicating a slightly higher average deviation from the observed values in the Valiantzas' model.

Despite these differences, the long-term average ratios (rt) for both models were almost identical, at 0.9521 for HS and 0.9538 for VAL, indicating that both models slightly underestimate measured R_s by approximately 4–5% over time. This systematic underestimation is consistent with earlier findings in similar climatic zones, suggesting that empirical models may need localized calibration to capture radiation dynamics under varying sky conditions fully.

Effect on FAO56-PM ET Estimation

The study also aimed to evaluate how substituting the measured R_s with estimated R_s values (from HS and VAL) impacts the accuracy of reference evapotranspiration (ET_0) estimates derived using the FAO56 Penman–Monteith method.

FAO PM ET (Measured R_s) vs HS and VAL ET

The scatter plots between FAO PM ET using measured R_s and model-derived R_s (HS and VAL) exhibited powerful linear relationships. With an R^2 of

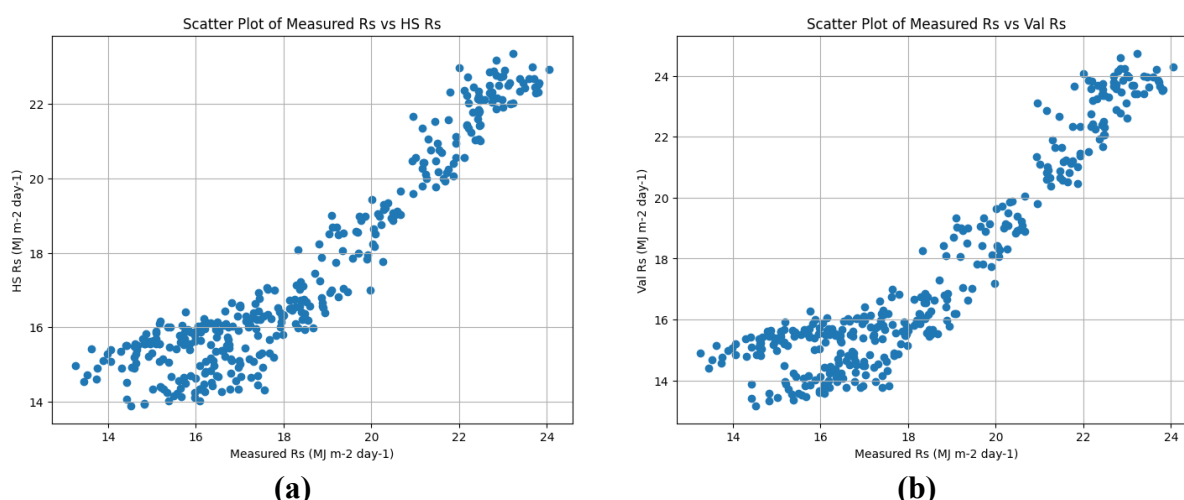
0.9477, the HS-based ET_0 estimates matched closely with those calculated using measured radiation. Similarly, the VAL-based estimates had an R^2 of 0.9281, still indicating an excellent correlation.

The SEE values were also low, 0.1862 for HS ET and 0.2183 for VAL ET, highlighting minimal deviation from the actual ET_0 values and suggesting that both models can serve as reliable substitutes in data-scarce scenarios. The rt values (0.9676 for HS and 0.9694 for VAL) again reflected a minor long-term underestimation (~3%) compared to ET_0 calculated from actual R_s values.

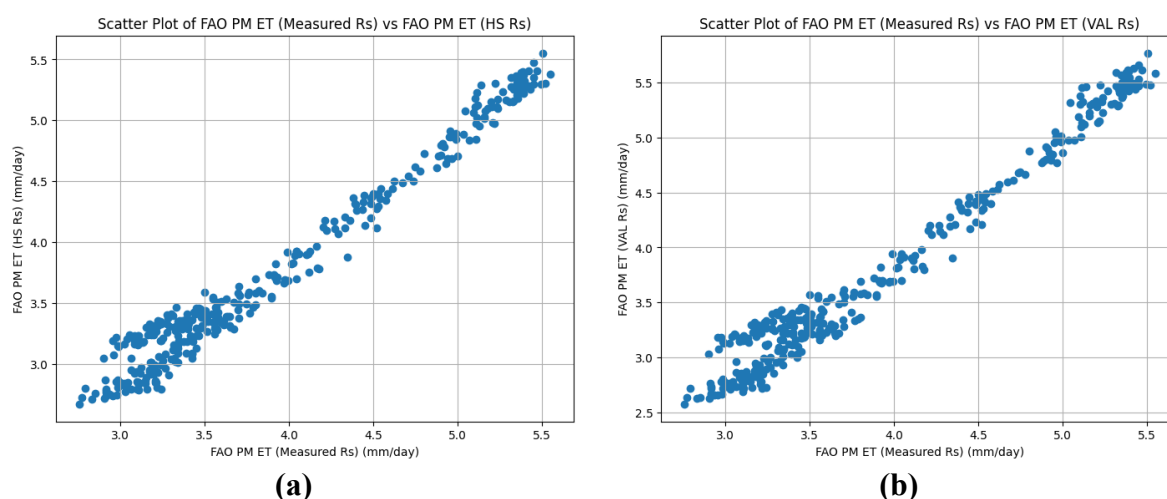
These findings suggest that although there are marginal differences in the R_s estimation accuracy between the two models, both produce highly reliable ET_0 outputs. The strong correlation indicates that errors in R_s estimation do not propagate significantly when calculating ET_0 , owing to the smoothing effect of multiple parameters in the FAO56-PM formulation.

CONCLUSION

This study evaluated the performance of two simplified empirical models, the Hargreaves–Samani (HS) model and the modified Valiantzas' model, for estimating solar radiation (R_s) and their subsequent impact on reference evapotranspiration (ET_0) estimation using the FAO56 Penman–Monteith (PM) method in the semi-arid region of Coimbatore, Tamil Nadu. Utilizing a 21-year daily dataset (2004–2024) from the NASA POWER database, the study provided a detailed statistical and seasonal analysis to assess



Figures 4a-4b: Comparison of daily Solar Radiation estimated by Hargreaves–Samani Model and Valiantzas' Model versus Measured Solar Radiation



Figures 6a-6b: Comparison of daily FAO ET_0 estimated by substituting measured and Solar Radiation obtained from the Hargreaves–Samanis Model and Valiantzas' Model

the accuracy and applicability of these models under limited data conditions. The results demonstrated that both HS and Valiantzas' models show strong agreement with measured R_s and ET_0 values, with the HS model slightly outperforming the Valiantzas' model in terms of correlation ($R^2 = 0.7866$ for HS vs 0.7034 for VAL) and lower error metrics. When used within the FAO56-PM framework, both models produced ET_0 estimates that closely matched those derived from measured solar radiation, with high R^2 values (above 0.92), low standard error of estimate ($SEE < 0.22$ mm day⁻¹), and minor long-term biases ($rt \approx 0.96$ – 0.97).

Seasonal trends in R_s and ET_0 were accurately captured, further validating the models' effectiveness in replicating agro-climatic dynamics relevant to irrigation scheduling. The HS model, which requires only maximum and minimum temperatures, proves particularly advantageous in resource-constrained settings due to its simplicity, ease of implementation, and robust performance in clear-sky, semi-arid conditions. The Valiantzas' model, incorporating relative humidity along with temperature, offers additional sensitivity in varying climatic regimes and may be more suitable for post-monsoon or humid seasons. In conclusion, both models provide reliable and practical alternatives to measured R_s in ET_0 estimation, particularly when complete meteorological datasets are unavailable. The successful application in this study supports the adoption of simplified radiation models for large-scale agro-climatic planning, long-term irrigation management, and water resource optimization in semi-arid regions, such as Coimbatore.

Future work should focus on localized calibration and validation across different agro-ecological zones to further enhance model accuracy and applicability.

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Ethics Statement

There were no human participants/or animals included in this research.

Consent for publication

All the authors agreed to publish the content.

Competing interest

There is no conflict of interest in publishing this content.

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