H$_2$Open Journal

H$_2$Open Journal Vol 6 No 2, 208 doi: 10.2166/h2oj.2023.069

Modification of the radiation-based Abtew reference evapotranspiration model under humid climate, Northeast India

Pankaj Kumar Pandey and Vanita Pandey*

Department of Agricultural Engineering, North Eastern Regional Institute of Science and Technology (NERIST), Nirjuli, Itanagar, Arunachal Pradesh, India

*Corresponding author. E-mail: vanita2@gmail.com

ABSTRACT

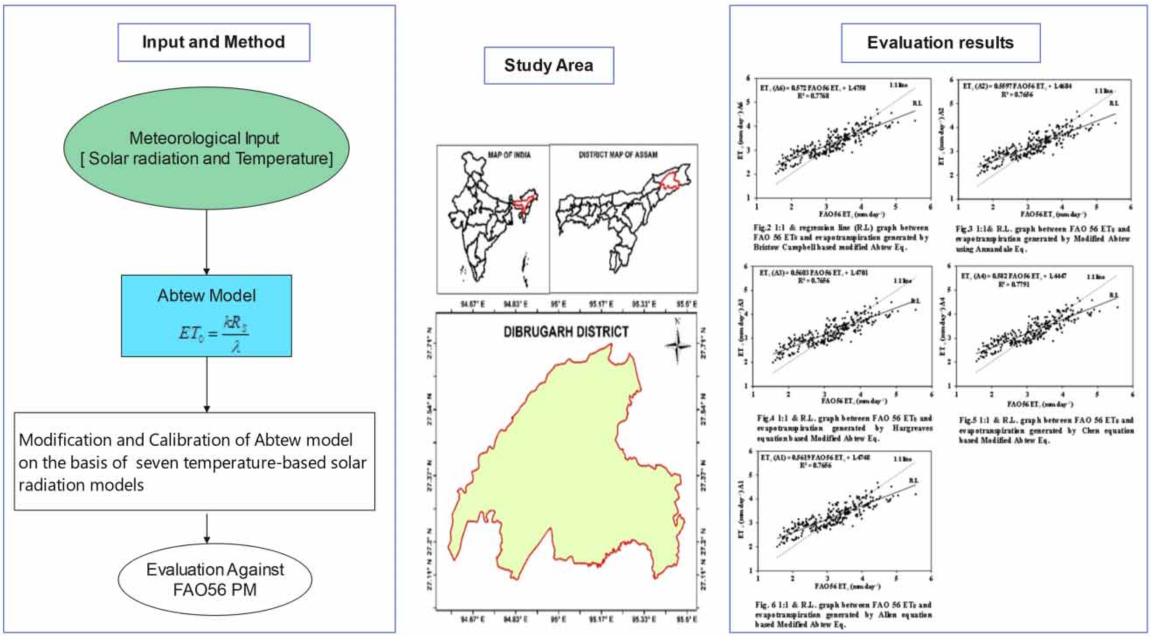
This study aimed to improve the Abtew model for reference evapotranspiration (ET_0) calculation in Northeast India using seven temperature-based solar radiation models. The temperature-based models require only air temperature as input data, which can be easily measured in most locations worldwide. The performance of the improved Abtew models (A1-A7), along with the Stephen Stewart model (SS), the Irmak model (Ir), and the modified Turc model (MT), was evaluated under the climatic conditions of Dibrugarh, Northeast India, using statistical indices such as mean absolute error (MAE), root mean square error (RMSE), standard error (SE), coefficient of correlation (r), coefficient of determination (R^2), and index of agreement (D). The results showed that the seven improved Abtew models (RMSE = 0.40–0.53 mm/day; D = 0.81–0.93) outperformed the four physical models (RMSE = 0.43–2.77 mm/day; D = 0.49–0.91) for the ET_0 estimate at Dibrugarh. The statistical analysis identified that the A6 model ranked highest for Dibrugarh. This study highlights the significant improvement in ET_0 estimation accuracy by utilizing temperature-based solar radiation models in the Abtew model. Therefore, we strongly recommend using the A6 model to estimate ET_0, which requires only temperature data as input, for estimating ET_0 under the climatic conditions of Dibrugarh, Northeast India.

Key words: Abtew model, ET_0, Northeast India, solar radiation, temperature

HIGHLIGHTS

- In this study, seven temperature-based solar radiation models were adopted to improve the Abtew model for ET_0 estimation in humid climate.
- Modified Abtew using Bristow–Campbell equation ranked best for the study region.
- In general, the seven improved Abtew models were more accurate than the others selected ET_0 models.

GRAPHICAL ABSTRACT



1. INTRODUCTION

In hydrology and irrigation, evapotranspiration and evaporation and transpiration are synonymous. Among the fundamental components of the hydrological cycle, evaporation is responsible for water loss from rivers, lakes, and reservoirs. Under changing climatic conditions, irrigation scheduling based on accurate evapotranspiration estimation is needed across regional climatic conditions (Wang & Liang 2008). ET_0 significantly impacts hydrology, climatology, vegetation, energy segmentation at the land mass across the season and interannual variability (Goroshi *et al.* 2017). Under changing climate scenarios, the ET_0 estimation accuracy is crucial not only for analyzing the impact of global climate change, environmental issues, and water resource appraisal but also for irrigation scheduling, flood drought assessment, and improving water resource utilization for agriculture (Zhang *et al.* 2015; Fan *et al.* 2016). Field-based measurement of ET_0 using lysimeters is considered an accurate and efficient approach; however, their practical application is challenging compared to the meteorological data-based estimation at weather stations (Pandey *et al.* 2014; Tabari *et al.* 2016). In practice, climate data from a weather station are frequently utilized to estimate ET_0 (Xing *et al.* 2008).

The FAO-56 Penman–Monteith (PM) model was determined to be the most appropriate alternative model for estimating evapotranspiration (ET_0) due to its proper and precise prediction of ET_0 when compared to the findings of other ET_0 estimation models (Pandey *et al.* 2017). ET_0 methods can be categorized based on their assumptions and input data as temperature data-based, radiation data-based, pan-evaporation data-based, mass transfer-based, and combination-based (Feng *et al.* 2016; Liu *et al.* 2017). Consequently, it is vital to determine the simplest model or model modification that satisfies the primary criteria for ET_0 estimation under any climatic situation without requiring the collection of a significantly larger dataset. In this study, the FAO-56 PM reference model is compared with various ET_0 estimation models, including the Abtew model (1996), Hargreaves and Samani model (1982), Modified Turc equation (1996), Makkink model (1957), Stephens-Stewart model (1963), Allen model (1997), Annandale model (2002), Chen model (2004), El-Sebail model (2009), Bristow–Campbell (1984) model, and Goodin model (1999) at Dibrugarh, Northeast India.

Literature implies that temperature and solar radiation factors are the most critical parameters for determining ET_0 (Samani 2000), and they are frequently utilized in radiation-based simple equations. Numerous studies have demonstrated the advantages of radiation-based techniques over temperature-based ones (Lu *et al.* 2005; Gebhart *et al.* 2013). The Abtew model is one of the most straightforward radiation-based models, resulting in reasonable estimations of ET_0 in numerous global investigations (Djaman *et al.* 2017; Bourletsikas *et al.* 2018).

Solar radiation (R_S) is one of the essential parameters for calculating the ET_0 using the FAO-56 PM method (Trajkovic & Kolakovic 2009). The values of R_S can be determined using empirical equations. Solar radiation can be accurately estimated using common meteorological factors like cloud cover, sunshine duration, air temperature, and relative humidity (Zhang *et al.* 2018). The studied region has only one solar measurement site, including measured data on sunshine duration. Generally, the most frequently used models worldwide are sunshine-based because of their accuracy and best results compared with other models like Bristow–Campbell (B-C) and Hargreaves–Samani. Usually, sunshine data are not available in many places, which restricts ET_0 estimation.

There are various research studies in which the R_S have been analyzed and applied in ET_0 estimation (Teke & Başak Yildirim 2014; Yao *et al.* 2014). Tabari *et al.* (2016) analyzed 11 R_S models and their impact on daily ET_0. The Allen model (1997) generally gave the best R_S values in semi-arid and arid climates. The Samani (2000) and El-Sebail *et al.* (2009) models had the most remarkable improvements after calibration in an arid climate. Gocic & Trajkovic (2014) analyzed the trends of ET_0 on monthly, seasonal, and annual time scales in Serbia. The FAO-56 PM and adjusted Hargreaves were used for the estimation of ET_0. Significantly increasing trends characterized approximately 70% of observed stations.

Previous research in India (Pandey *et al.* 2016; Poddar *et al.* 2021) indicated that radiation-based models were more accurate than temperature-based ones. The computation of ET_0 involves air temperature and solar radiation data; hence, the preceding model's calculation techniques are relatively simple (Zhang *et al.* 2018). In Northeast India, Pandey *et al.* (2016) tested the applicability of six temperature-based and ten radiation-based models against the FAO-56 PM model and identified that the Irmak model performed well. The improved performance of radiation-based models generally confirms that severe temperature and radiation are the major drivers behind the ET_0 process in the region. At the same time, wind speed has just a little influence. Poddar *et al.* (2021) tested 12 ET_0 models in sub-humid sub-tropical regions of India's western Himalayan agroclimatic zone. The researchers concluded that solar radiation, followed by maximum temperature and relative humidity, is the most sensitive metric for estimating ET_0 in the study area environment. Nandagiri & Kovoor (2006) evaluated seven models throughout India's climatic conditions, concluding that radiation-based models performed better in humid areas. Tomar (2015) investigated multiple ET_0 estimates in sub-humid regions of India and discovered that FAO24-Radiation outperformed other models. Considering the above, a study was conducted with the following objectives: To improve the Abtew model for ET_0 estimation by using seven temperature-based solar radiation models and evaluate the estimation accuracy of seven improved radiation-based Abtew models and selected ET_0 models at Dibrugarh, Northeast India.

The present study used different temperature-based solar radiation models to modify the Abtew model for ET_0 estimation under humid climates. Improvement in the Abtew model using temperature-based solar radiation models is an attractive and viable option for this study site and impacts local evaluation with the FAO-56 PM reference model.

2. MATERIALS AND METHODS

2.1. Study area and data collection

The Dibrugarh district is in the eastern section of Assam at 27.4728°N latitude and 94.9120°E longitude (Figure 1). Despite the district's considerable rainfall (about 2,076 mm per year), the uneven rainfall distribution over the year is a major limiting factor in crop productivity in the absence of an efficient and appropriate water resource management system. Almost 90% of the district's farmed land is rain-fed. Because most crops are grown as rain-fed crops, water resource management is vital in determining output. Water management, rainwater collection, and recharge can increase water availability in rain-fed settings. On the other hand, the district has a flood-prone area of around 45,061 ha, where unpredicted flooding damages standing crops and causes water stagnation, silt deposition, and erosion, posing severe hazards to crop cultivation.

The Brahmaputra River runs through the district's northwestern boundary. The single tributary in the district that flows into the Brahmaputra is the burdening tributary, which divides the region from east to west. It runs through Naharkatia in the east, Khowang in the middle, and forms the border between Dibrugarh and Sivasagar districts in the west. The Dibrugarh district is an almost plain area in Assam.

The entire area is level, with a modest incline from the East Arunachal hills to the west. The district's soil is mainly fertile alluvial soil, with varying quantities of sand and clay. The meteorological data for the research area was obtained from the India Meteorological Department (IMD).

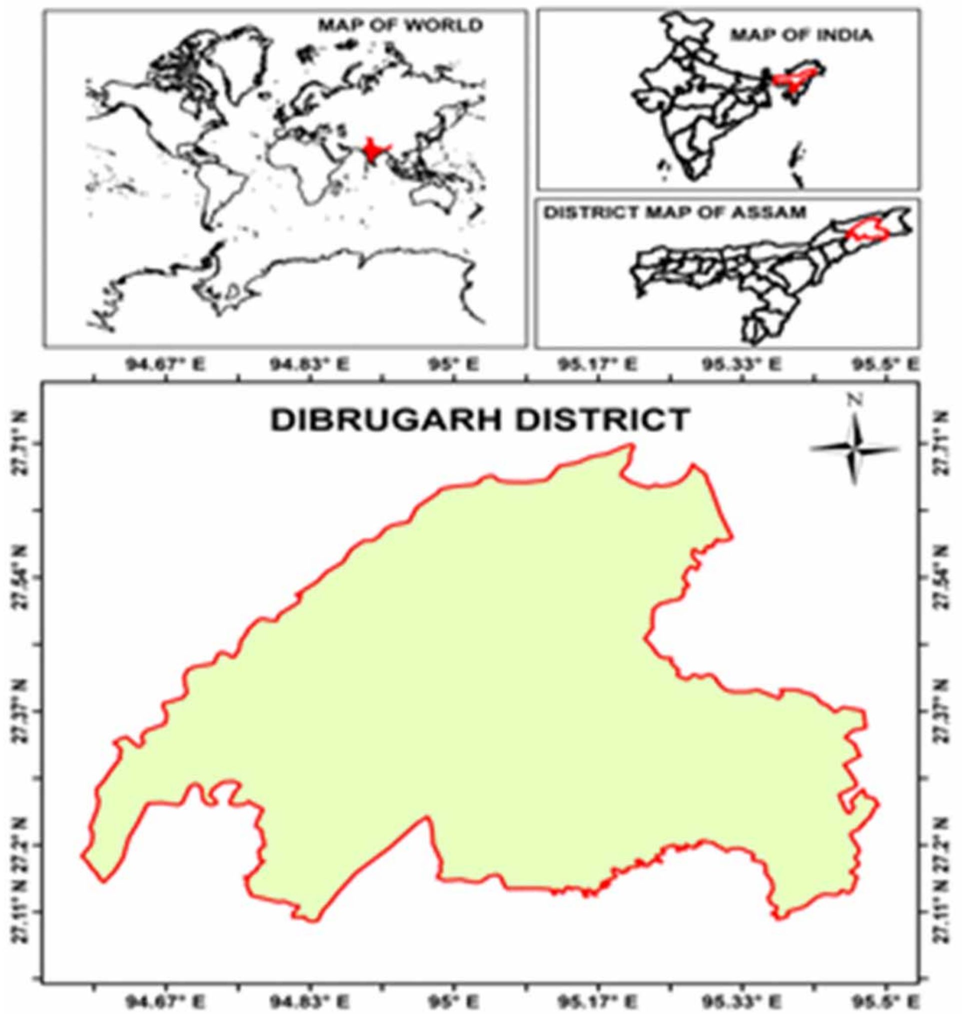


Figure 1 | Geographical map of the study area.

2.2. Calculation of reference evapotranspiration (ET_0)

2.2.1. FAO-56 PM model

The FAO-56 PM model was considered the standard to validate the other models, which was an acceptable and common practice. The equation of the FAO-56 PM model is expressed as:

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

Allen *et al.* (1998) recommended methods and procedures followed while calculating all the necessary variables for estimating ET_0. The u_2 and R_S were computed using data on u_{10} and sunshine duration as follows (Feng *et al.* 2017):

$$u_2 = u_{10} \frac{0.4087}{\ln(67.8z - 5,042)} \tag{2}$$

$$R_S = \left(a + b\frac{n}{N}\right) \tag{3}$$

2.2.2. Abtew model

The Abtew equation (1996) is a radiation and temperature-based model developed by comparing lysimetric studies in Florida.

$$ET_0 = \frac{kR_S}{\lambda} \tag{4}$$

2.2.3. Makkink model (Mkk)

The Makkink (1957) approach is radiation-based. The original Makkink equation is shown below:

$$ET_0 = 0.61\frac{\Delta}{\Delta + \gamma}\frac{R_S}{\lambda} \tag{5}$$

2.2.4. Stephens-Stewart model (SS)

The Stephens & Stewart (1963) model is an empirical linear equation that requires simply radiation and temperature data.

$$ET_0 = (aT + b)\frac{R_S}{\lambda} \tag{6}$$

2.2.5. Irmak model (Ir)

Based on solar radiation data and mean temperature data, Irmak *et al.* (2003) proposed the Irmak model (Zhang *et al.* 2018):

$$ET_0 = a + bR_S + cT \tag{7}$$

2.2.6. Modified Turc model (MT)

The Modified Turc (Abtew 1996) equation calculates ET_0 depending on solar radiation and maximum air temperature. The original Turc equation used average air temperature. However, the maximum air temperature was employed here since it showed a stronger association with evapotranspiration in humid climates than the average air temperature.

$$ET_0 = \frac{(aR_S + b)}{T_{max} + c} \tag{8}$$

In Equations (1)–(8), ET_0 is the reference evapotranspiration (mm/day), R_n is the net radiation (MJ/m² day), G is the soil heat flux density (MJ/m² day), T is the mean air temperature (°C), T_{max} is the maximum air temperature (°C), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure function (kPa/°C), γ is the psychometric constant (kPa/°C), u_2 is the wind speed at 2 m height (m/s), u_{10} is the measured wind speed at 10 m height (m/s), z is the height of measurement, R_S is the solar radiation (MJ/m² day), n is the sunshine duration (h), N is the maximum possible duration of sunshine or day–light hours (h), R_a is the extraterrestrial radiation (MJ/m day), and a and b are constant with a value of 0.25 and 0.50 recommended by Allen *et al.* (1998).

2.3. Solar radiation estimation based on temperature input

2.3.1. Allen model

Allen (1997) proposed using a self-calibrating model to predict solar radiation, and the equation is shown as follows (Zhang *et al.* 2018):

$$R_S = [K_r(T_{max} - T_{min})^{0.5}]R_a \tag{9}$$

$$K = K_{ra}\left(\frac{P_z}{P_0}\right)^{0.5} \quad (10)$$

2.3.2. Annandale model

Annandale *et al.* (2002) developed a model based on the Hargreaves–Samani model, considering the effects of lower height and atmospheric thickness on R_S (Zhang *et al.* 2018):

$$R_S = [a(1 + bZ)(T_{max} - T_{min})^{0.5}]R_a \quad (11)$$

2.3.3. Hargreaves model

Hargreaves & Samani (1982) recommended a model to estimate solar radiation based on temperature difference and extraterrestrial radiation (R_a) as input (Zhang *et al.* 2018):

$$R_S = [a(\Delta T)^b R_a] \quad (12)$$

2.3.4. Chen model

Chen *et al.* (2004) recommended a model to estimate solar radiation based on temperature difference and extraterrestrial radiation as input (Zhang *et al.* 2018):

$$R_S = [(a\ln(\Delta T) + b)R_a] \quad (13)$$

2.3.5. El-Sebail model

El-Sebail *et al.* (2009) recommended a model to estimate solar radiation based on mean temperature and relative humidity as input (Zhang *et al.* 2018):

$$R_S = \{(a + (bT) + (cRH))\}R_a \quad (14)$$

2.3.6. B-C model

Bristow & Campbell (1984) suggested a method for estimating solar radiation based on air temperature measurements:

$$R_S = a[(1 - \exp)(-b)(\Delta T)^c]R_a \quad (15)$$

2.3.7. Goodin model

Goodin *et al.* (1999) improved the B-C model by including an R_a term that serves as a scaling factor, allowing the temperature term difference to tolerate a broader range of R_S values (Zhang *et al.* 2018):

$$R_S = a\left[(1 - \exp(-b\frac{(\Delta T)^c}{R_a}\right]R_a \quad (16)$$

In Equations (9)–(16), P_z is the atmospheric pressure at the site (kPa), P_0 is the atmospheric pressure at sea level (kPa), K_r and K_{ra} are empirical coefficients, and Z is the altitude of the site (km). An empirical coefficient RH is the relative humidity (%), and a, b, and c are empirical coefficients. $\Delta T = T_{max} - T_{min}$ (°C).

2.4. Performance evaluation of models

Using meteorological variables from 1994 to 2016, the accuracy and performance of the models to estimate ET_0 were assessed using the following statistical indices.

2.4.1. Different accuracy statistical indices applied

2.4.1.1. Coefficient of determination (R^2)

$$R^2 = \frac{\left[\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})\right]^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n} X_i(Y_i - \bar{Y})^2} \tag{17}$$

2.4.1.2. Coefficient of correlation (r)

$$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}} \tag{18}$$

2.4.1.3. D *(Index of agreement)*

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)}{\sum_{i=1}^{n}(|P_i - \overline{O}| + |O_i - \overline{O}|)} \tag{19}$$

When the accuracy indices mentioned above are close to 1, it indicates a strong correlation between the observed and predicted values. Conversely, when the indices are close to 0, it suggests poor performance.

2.4.2. Different error statistical indices applied

2.4.2.1. RMSE (root-mean-square error)

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2} \tag{20}$$

2.4.2.2. MAE (mean absolute error)

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|Y_i - X_i| \tag{21}$$

2.4.2.3. Standard error (σ)

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n - 1}} \tag{22}$$

When the error indices mentioned above are close to 0, it indicates a strong correlation between the observed and predicted values. Conversely, when the indices are close to 1, it suggests poor performance.

In Equations (17)–(22), X_i and Y_i signify the ET_0 values estimated by the FAO PM model and the examined models, respectively, and represent the corresponding mean ET_0 values; the subscript i refers to the ith value of the ET_0. Accuracy indices, including R^2, r, and d, indicate how closely a model matches observed values, with higher values indicating better model performance. RMSE, MAE, and σ are in mm/day, with values ranging from 0 (perfect fit) to 1 (worst fit); P_i is the predicted value, O_i is the observed value, n is the number of observations, $\overline{O}$ is the observed mean, and $\overline{P}$ is the predicted mean.

3. RESULTS

3.1. Calibration of selected radiation equations

The parameters of the seven improved radiation models are presented in Table 1. For A1, A2, and A3, the calibration is done using regression analysis, whereas the remaining equation calibration coefficients are estimated

Table 1 | Calibrated parameters of the seven selected solar radiation equations

Model Abb.	Radiation-based equations	Equations	Calibrated coefficient of different equations *a*	*b*	*c*
A1	Allen equation	$R_S = [K_r(\Delta T)^{0.5}]R_a$ $K = K_{ra}\left(\frac{P_z}{P_0}\right)^{0.5}$			
	Modified Abtew using Allen equation	$ET_0 = \frac{K_{ra}}{K}\left(\frac{P_i}{P_0}\right)^{0.5}(\Delta T)^{0.5}R_a$			
A2	Annandale equation	$R_S = [a(1+bZ)(\Delta T)^{0.5}]R_a$	0.1481	2.7×10^{-5}	
	Modified Abtew using Annandale equation	$ET_0 = \frac{K}{\lambda}[(a(1+bZ)(\Delta T)^{0.5}R_a]$			
A3	Hargreaves equation	$R_S = [a(\Delta T)^b R_a]$	0.179		
	Modified Abtew using Hargreaves equation	$ET_0 = \frac{K}{\lambda}(a(\Delta T)^{0.5}R_a$			
A4	Chen equation	$R_S = [(a \ln(\Delta T) + b)R_a]$	0.2148	0.0162	
	Modified Abtew using Chen equation	$ET_0 = \frac{K}{\lambda}(a \ln(\Delta T) + b)R_a$			
A5	El-Sebail equation	$R_S = \{(a + (bT) + (cRH))\}R_a$	1.0057	− 0.0059	− 0.0055
	Modified Abtew using El-Sebail equation	$ET_0 = \frac{K}{\lambda}\{(a + bT) + (cRH)\}R_a$			
A6	Bristow–Campbell equation	$R_S = a[(1 - \exp)(-b)(\Delta T)^c]R_a$	44.798	0.0034	0.488
	Modified Abtew using Bristow–Campbell equation	$ET_0 = \frac{K}{\lambda}a[(1 - \exp)(-b)(\Delta T)^c]R_a$			
A7	Goodin equation	$R_S = a\left[(1 - \exp(-b\frac{(\Delta T)^c}{R_a}\right]R_a$	0.54	9.44	0.85
	Modified Abtew using Goodin equation	$ET_0 = a\left[(1 - \exp(-b\frac{(\Delta T)^c}{R_a}\right]R_a$			

using nonlinear regression analysis. The coefficients and the modified Abtew equations for respective solar radiation models are presented in Table 1 and are further used to estimate the evapotranspiration values using the Abtew model.

3.2. Performance of modified Abtew models and selected evapotranspiration models

Table 2 provides a detailed statistical analysis of the selected equations, including Makkink (Mkk), Stephens-Stewart equation (SS), Irmak (Ir), and Modified Turc (MT). To assess the performance of different models, the evapotranspiration series generated by each equation is compared to the original evapotranspiration values generated by the FAO-56 PM model.

A comprehensive analysis of the statistical performance of the predicted evapotranspiration series generated by Mkk, SS, Ir, and MT equations are provided in Table 2. The table presents two statistical indices categories: error and accuracy. The error indices measure the difference between the observed ET_0 values and the predicted values generated by the respective equations. These indices include mean absolute error (MAE), root-mean-square error (RMSE), and standard error (SE).

The accuracy indices, however, measure the reliability and precision of the predicted values generated by each equation. These indices include correlation coefficient (*r*), coefficient of determination (R^2), and Willmott's index of agreement (*D*) by analyzing both the error and accuracy indices. Table 2 provides a holistic assessment of the predictive power of each equation, helping researchers and practitioners choose the most reliable and accurate equation for their specific needs.

The study findings revealed that the improved Abtew models (A1–A7) were more accurate in estimating monthly ET_0 than the four selected physical models. Among the Abtew models, the A6 equation, which is a

Table 2 | Statistical parameters of the selected models against FAO-56 PM for Dibrugarh, Assam

	Error estimation (mm/day)				Accuracy estimation			
Equation	**Mean**	**MAE**	**RMSE**	**SE**	***r***	***R^2***	***D***	**Rank**
A1	3.2490	0.3546	0.4431	0.2500	0.8750	0.7650	0.9028	5
A2	3.2357	0.3540	0.4414	0.2500	0.8750	0.7650	0.9123	2
A3	3.2394	0.3542	0.4418	0.2510	0.8750	0.7650	0.9122	3
A4	3.2824	0.3547	0.4381	0.2610	0.8827	0.7790	0.8879	4
A5	3.3067	0.3908	0.4420	0.2950	0.8325	0.7930	0.8695	7
A6	3.2820	0.3526	0.4028	0.2480	0.8814	0.7760	0.9340	1
A7	3.2672	0.4222	0.5315	0.1760	0.8937	0.7580	0.8188	8
Mkk	2.72	0.3209	0.4336	0.3700	0.8435	0.7115	0.8915	9
SS	3.1787	0.659	0.774	0.358	0.865	0.748	0.790	10
Ir	3.314	0.2897	0.4174	0.3400	0.8704	0.7500	0.9170	6
MT	0.49	2.66	2.77	1.8	0.869	0.75	0.497	11

modified version of the Bristow–Campbell-based Abtew equation, exhibited the highest accuracy for Dibrugarh with a mean of 3.267 (mm/day) compared to the mean FAO 56 PM of 3.157 (mm/day), MAE of 0.3526 (mm/day), RMSE of 0.4428 (mm/day), *r* of 0.88, and SE of 0.2480 (mm/day). Additionally, the index of agreement *D* was found to be 0.88, while R^2 was 0.77. The relationship between the original and predicted series is visually presented in Figure 2.

The second-best equation was A2, which is a modified Abtew equation using the Annandale method, with a mean of 3.2357 (mm/day), MAE of 0.3540 (mm/day), RMSE of 0.4414 (mm/day), *r* of 0.875, SE of 0.2500 (mm/day), and index of agreement *D* of 0.8823. The ranking statistics are very close to the best rank model

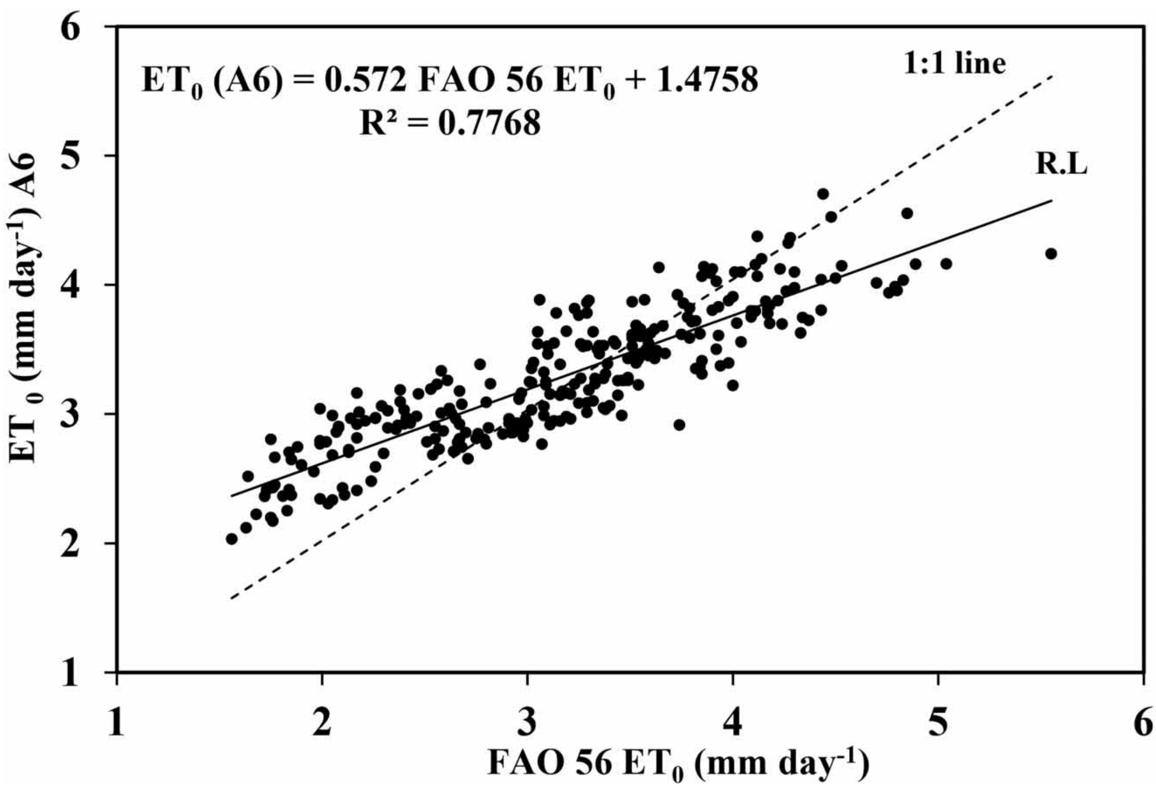


Figure 2 | 1:1 and regression line (R.L) graph between FAO-56 ET_0 and evapotranspiration generated by the Bristow–Campbell-based modified Abtew equation.

(A6). The R^2 of 0.7650 of A2 is similar to A6. The relationship between the original and predicted series is visually presented in Figure 3.

The study evaluated several modified Abtew equations for estimating monthly ET_0 in the Dibrugarh region. The third-best equation was found to be A3, which is a modified Abtew equation using the Hargreaves method, with a mean of 3.2394 (mm/day), MAE of 0.3542 (mm/day), RMSE of 0.4418 (mm/day), r of 0.87, SE of 0.2510 (mm/day), index of agreement D of 0.87 (same as the previous equation), and R^2 of 0.7650. The relationship between the original and predicted series is visually presented in Figure 4.

The fourth-best equation was A4, which is a modified Abtew equation using the Chen method, with a mean of 3.2824 (mm/day), MAE of 0.3547 (mm/day), RMSE of 0.4381 (mm/day), r of 0.88, SE of 0.2510 (mm/day), index of agreement D of 0.88 (same as the previous equation), and R^2 of 0.7790. The relationship between the original and predicted series is visually presented in Figure 5.

The fifth-best equation was A1, which is a modified Abtew equation using the Allen method, with a mean of 3.2490 (mm/day), MAE of 0.3548 (mm/day), RMSE of 0.4431 (mm/day), r of 0.88, SE of 0.2500 (mm/day), index of agreement D of 0.88 (same as the previous equations), and R^2 of 0.76. The relationship between the original and predicted series is visually presented in Figure 6.

The study's findings suggest that modified Abtew equations can be an effective and reliable method for estimating monthly ET_0 in the Dibrugarh region. The first-ranked A6 equation is a reliable and accurate method for estimating monthly ET_0 for the study region. The results of this study provide valuable insights for researchers and practitioners working on water resources management and agricultural planning in the region.

Table 2 provides the study's findings to estimate the error and accuracy of various equations. Table 2 presents several performance metrics for each equation, including mean, MAE, RMSE, SE, r, R^2, and the Durbin-Watson statistic (D).

The equations were evaluated based on their average error and accuracy estimation. The A5 and A7 models had similar error statistics, but there was a notable difference in their D index. As a result, the A5 model was assigned the 7th rank (Table 2). Based on Table 2, Equation A6 has the highest accuracy estimation (ranked 1) with the lowest MAE, RMSE, and SE values compared to other equations. The A2, A3, and A4 equations have

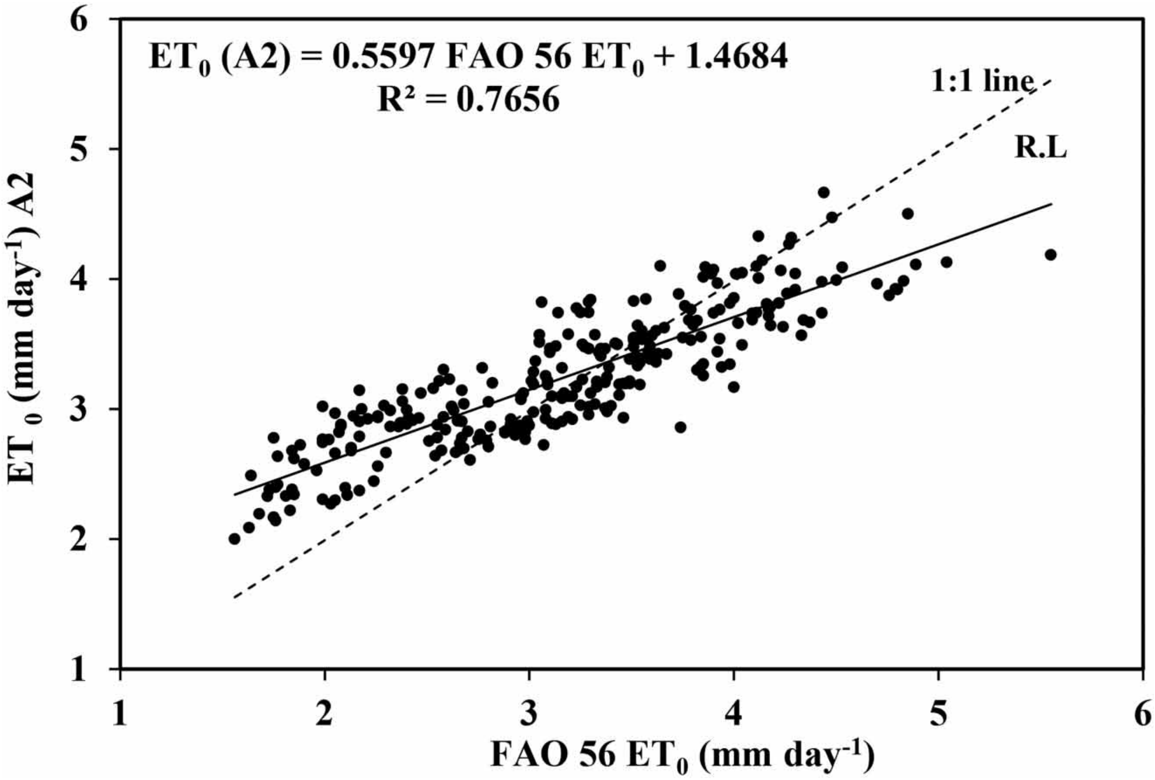


Figure 3 | 1:1 and R.L graph between FAO-56 ET_0 and evapotranspiration generated by the modified Abtew using the Annandale equation.

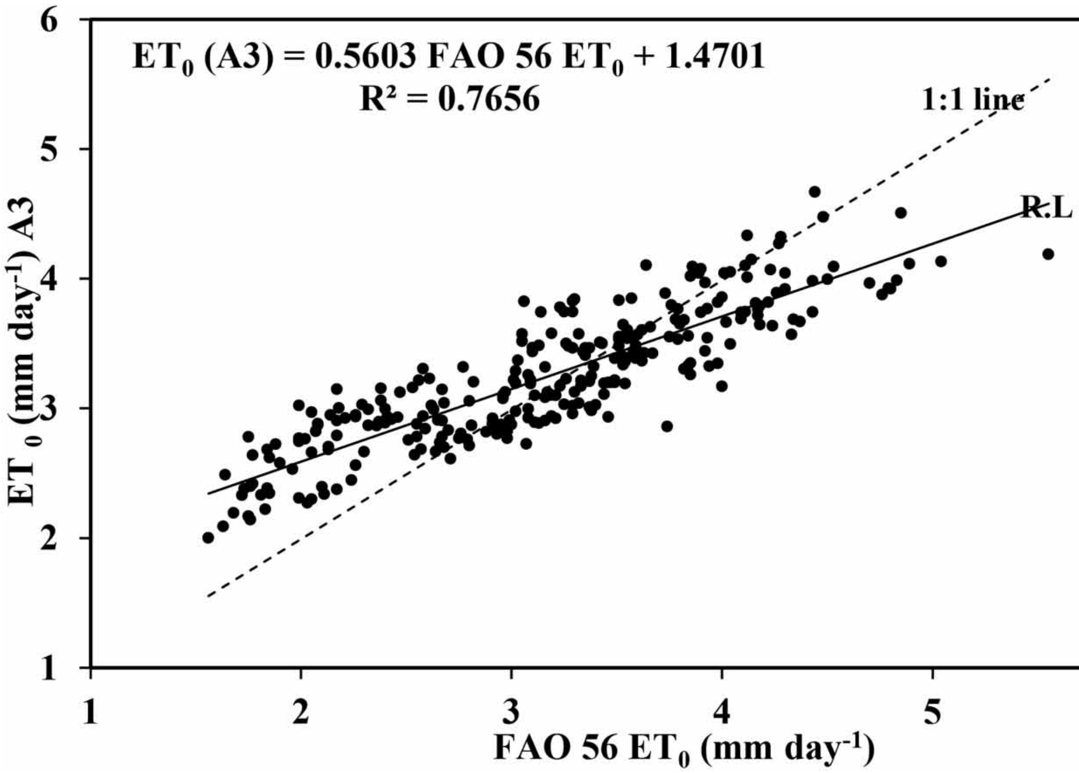


Figure 4 | 1:1 and R.L graph between FAO-56 ET_0 and evapotranspiration generated by the Hargreaves equation-based modified Abtew equation.

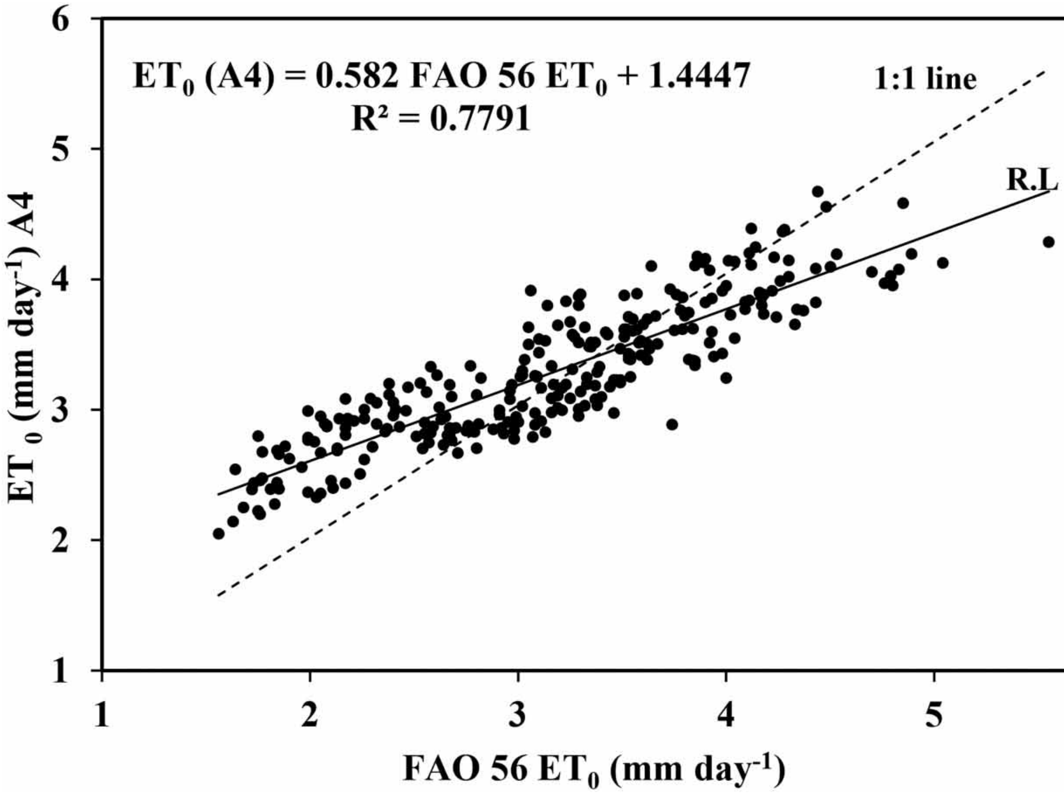


Figure 5 | 1:1 and R.L graph between FAO-56 ET_0 and evapotranspiration generated by the Chen equation-based modified Abtew equation.

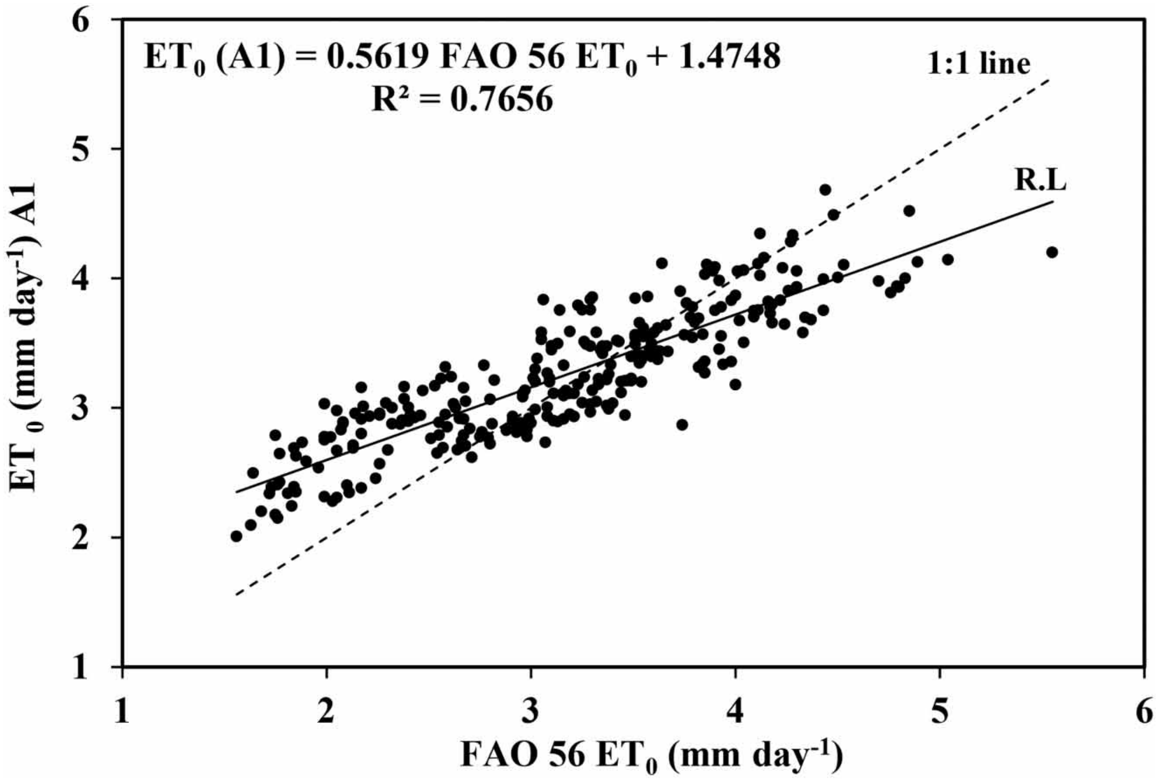


Figure 6 | 1:1 and R.L graph between FAO-56 ET_0 and evapotranspiration generated by the Allen equation-based modified Abtew equation.

high-accuracy estimations with similar MAE, RMSE, and SE values. Equation Mkk has the highest error estimation, the highest MAE, RMSE, and SE values, and the lowest r and R^2 values. Details of equations A1, A5, and A7 performance can be seen in Table 2.

Equation MT which is the Modified Turc equation with mean as 0.49 (mm/day) and MAE as 2.66 (mm/day), RMSE as 2.77 (mm/day), and SE as 1.8 (mm/day), index of agreement D is found as 0.497, and R^2 as 0.75. The highest MAE, RMSE, and SE values indicate that it has the highest error among all equations. However, it has a low accuracy estimation with the lowest rank (ranked 11).

The best equation among four selected physical models for monthly estimation ET_0 is found as Ir with mean as 3.314 (mm/day) and MAE as 0.2897 (mm/day), RMSE as 0.417(mm/day), and SE as 0.340 (mm/day), index of agreement D is found as 0.9170, and R^2 as 0.750 (Table 2).

In summary, Table 2 comprehensively compares different equations based on their error and accuracy estimation, which can help select the most appropriate equation for a particular application.

4. DISCUSSION

The Irmak model had the highest ET_0 performance among the four physical models assessed in this study. The Irmak model is based on temperature and radiation input data, which are the key factors influencing ET_0, and its conclusions are comparable to those of previous studies.

The results suggested that A6 had the most precise ET_0 estimation in Northeast India, followed by A2, A3, A4, and A1. The M6 was the enhanced Abtew model based on the Bristow–Campbell radiation model. Using data regarding air temperature, the Bristow–Campbell model estimated R_S. Pandey & Pandey (2020) examined the sensitivity of ET_0 in Northeast India. They discovered that the minimum temperature was the most sensitive variable, followed by a sunshine hour (relative sensitivity of 0.77 and 0.66, respectively). According to Djaman *et al.* (2017), the Abtew ET_0 equation, which utilizes solar radiation and maximum temperature, was found to have the best performance compared to other methods across all three climatic zones in Mali. Bourletsikas *et al.* (2018) evaluated 24 different reference evapotranspiration equations in a grass-covered ground in a Mediterranean forest environment in Greece and reported among the radiation-based models, and their analysis found that the Abtew model demonstrated the most robust performance. All the above-cited studies confirm that the Abtew model showed good performance under different climatic conditions across the globe.

In contrast, the wind speed had the most negligible effect; there was no improvement in model performance when wind speed was added as an input parameter. A2, A3, A4, and A1 also demonstrated an excellent performance for ET_0 estimation in Northeast India, while A6 inclusion of the minimum temperature effect was the primary factor in its superior accuracy.

The Bristow–Campbell, Goodin, and Chen models were used to calibrate four ET_0 models that can accurately estimate R_S based on temperature differences using exponential and logarithmic functions. The Allen, Annandale, and Hargreaves models were used with simple monomial expressions to increase the estimation precision of A5, A1, and A6 relative to A2 and A6. In addition, the seven enhanced Abtew models (A1–A7) were more precise than the four chosen physical models. As a result of the single input parameter, most basic empirical ET_0 models cannot accurately represent the changing mechanisms of ET_0, leading to ambiguity. Parameter localization is the fundamental method for reducing uncertainty and improving the computation accuracy of simple empirical models.

5. CONCLUSIONS

The calibrated solar radiation equations estimate the evapotranspiration using Abtew (A1–A7) models. In the present study, seven temperature-based solar radiation models were locally calibrated under climatic conditions for Dibrugarh, Assam, to improve the performance of the Abtew model (A1–A7). These modified Abtew models, along with the Mkk, SS, Ir, and MT models, are compared statistically against original FAO-56 PM evapotranspiration values on monthly average data for 23 years data. The performances of all the modified equations (A1–A7) and other selected ET_0 models have been compared statistically using indices MAE, RMSE, SE, r, R^2, and D.

The main conclusions of this study are shown as follows:

1. For ET_0 estimation at the Dibrugarh site, the seven Abi models ($R^2 = 0.69–0.79$) were more accurate than the other selected ET_0 models ($R^2 = 0.71–0.75$).
2. The A6, A2, A3, A4, and A1 models outperformed the others. The A6 model performed best at the Dibrugarh station and was thus suggested for estimating ET_0.
3. The improved Abtew (Abi) models outperformed the Mkk, SS, Ir, and MT models for ET_0 estimate in Dibrugarh.
4. Overall, the present investigation discovered that the Abi models outperformed the Mkk, SS, Ir, and MT models for ET_0 estimate in Northeast India (MT). It is strongly advised to use the A6, which needs air temperature as an input parameter, to estimate ET_0 in Northeast India.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abtew, W. 1996 Evapotranspiration measurements and modeling for three wetland systems in South Florida. *JAWRA Journal of the American Water Resources Association* **32** (3), 465–473.

Allen, R. 1997 Self-calibrating method for estimating solar radiation from air temperature. *Journal of Hydrologic Engineering* **2**, 56–67.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper, 56, Rome, p. 300.

Annandale, J. G., Jovanic, N. Z., Benade, N. & Allen, R. G. 2002 Software for missing data error analysis of Penman–Monteith reference evapotranspiration. *Irrigation Science* **21**, 57–67.

Bourletsikas, A., Argyrokastritis, I. & Proutsos, N. 2018 Comparative evaluation of 24 reference evapotranspiration equations applied on an evergreen-broadleaved forest. *Hydrology Research* **49** (4), 1028–1041.

Bristow, K. L. & Campbell, G. S. 1984 On the relationship between incoming solar radiation and daily maximum and minimum temperature. *Agricultural and Forest Meteorology* **31**, 159–166.

Chen, R. S., Ersi, K., Yang, J. P., Lu, S. H. & Zhao, W. Z. 2004 Validation of five global radiation models with measured daily data in China. *Energy Conversion and Management* **45**, 1759–1769.

Djaman, K., Koudahe, K., Akinbile, C. & Irmak, S. 2017 Evaluation of eleven reference evapotranspiration models in semiarid conditions. *Journal of Water Resource and Protection* **9**, 1469–1490. doi:10.4236/jwarp.2017.912094.

El-Sebaii, A. A., Al-Ghamdi, A. A., Al-Hazmi, F. S. & Faidah, A. 2009 Estimation of global solar radiation on horizontal surfaces in Jeddah, Saudi Arabia. *Energy Policy* **37**, 3645–3649.

Fan, J., Wu, L., Zhang, F., Xiang, Y. & Zheng, J. 2016 Climate change effects on reference crop evapotranspiration across different climatic zones of China during 1956–2015. *Journal of Hydrology* **542**, 923–937.

Feng, Y., Cui, N., Zhao, L., Hu, X. & Gong, D. 2016 Comparison of ELM, GANN, WNN and empirical models for estimating reference evapotranspiration in humid region of Southwest China. *Journal of Hydrology* **536**, 376–383.

Feng, Y., Jia, Y., Cui, N., Zhao, L., Li, C. & Gong, D. 2017 Calibration of Hargreaves model for reference evapotranspiration estimation in Sichuan basin of southwest China. *Agricultural Water Management* **181**, 1–9.

Gebhart, S., Radoglou, K., Chalivopoulos, G. & Matzarakis, A. 2013 Evaluation of potential evapotranspiration in central Macedonia by EmPEst. In: *Advances in Meteorology, Climatology and Atmospheric Physics* (Helmis, C. & Nastos, P., eds). Springer, Berlin, Heidelberg, pp. 451–456.

Gocic, M. & Trajkovic, S. 2014 Analysis of trends in reference evapotranspiration data in a humid climate. *Hydrological Sciences Journal* **59** (1), 165–180.

Goodin, D. G., Hutchinson, J. M. S., Vanderlip, R. L. & Knapp, M. C. 1999 Estimating solar irradiance for crop modeling using daily air temperature data. *Agronomy Journal* **91**, 845–851.

Goroshi, S., Pradhan, R., Singh, R. P., Singh, K. K. & Parihar, J. S. 2017 Trend analysis of evapotranspiration over India: observed from long-term satellite measurements. *Journal of Earth System Science* **126** (8), 1–21.

Hargreaves, G. H. & Samani, Z. A. 1982 Estimating potential evapotranspiration. *Journal of the Irrigation and Drainage Division* **108** (3), 225–230.

Irmak, S., Irmak, A., Allen, R. G. & Jones, J. W. 2003 Solar and net radiation-based equations to estimate reference evapotranspiration in humid climate. *Journal of Irrigation and Drainage Engineering* **129** (5), 336–347.

Liu, X., Xu, C., Zhong, X., Li, Y., Yuan, X. & Cao, J. 2017 Comparison of 16 models for reference crop evapotranspiration against weighing lysimeter measurement. *Agricultural Water Management* **184**, 145–155.

Lu, J., Sun, G., McNulty, S. G. & Amatya, D. M. 2005 A comparison of six potential evapotranspiration methods for regional use in the south eastern United States. *JAWRA Journal of the American Water Resources Association* **41** (3), 621–633.

Makkink, G. F. 1957 Testing the Penman formula by means of lysimeters. *Journal of the Institution of Water Engineers* **11**, 277–288.

Nandagiri, L. & Kovoor, G. M. 2006 Performance evaluation of reference evapotranspiration equations across a range of Indian climates. *Journal of irrigation and drainage engineering* **132** (3), 238–249.

Pandey, P. K. & Pandey, V. 2020 Development of reference evapotranspiration equations using an artificial intelligence-based function discovery method under the humid climate of Northeast India. *Computers and Electronics in Agriculture* **179**, 105838.

Pandey, V., Pandey, P. K. & Mahanta, A. P. 2014 Calibration and performance verification of Hargreaves Samani equation in a humid region. *Irrigation and Drainage* **63** (5), 659–667.

Pandey, P. K., Dabral, P. P. & Pandey, V. 2016 Evaluation of reference evapotranspiration methods for the northeastern region of India. *International Soil and Water Conservation Research* **4** (1), 52–63.

Pandey, P. K., Nyori, T. & Pandey, V. 2017 Estimation of reference evapotranspiration using data driven techniques under limited data conditions. *Modeling Earth Systems and Environment* **3**, 1449–1461.

Poddar, A., Gupta, P., Kumar, N., Shankar, V. & Ojha, C. S. P. 2021 Evaluation of reference evapotranspiration methods and sensitivity analysis of climatic parameters for sub-humid sub-tropical locations in western Himalayas (India). *ISH Journal of Hydraulic Engineering* **27** (3), 336–346.

Samani, Z. 2000 Estimating solar radiation and evapotranspiration using minimum climatological data. *Journal of Irrigation and Drainage Engineering* **126** (4), 265–267.

Stephens, J. C. & Stewart, F. H. 1963 A comparison of procedures for computing evaporation and evapotranspiration. *International Association of Hydrological Sciences* **62**, 123–133.

Tabari, H., Hossein zadehtalaei, P., Willems, P. & Martinez, C. 2016 Validation and calibration of solar radiation equations for estimating daily reference evapotranspiration at cool semiarid and arid locations. *Hydrological Sciences Journal* **61** (3), 610–619.

Teke, A. & Başak Yildirim, H. 2014 Estimating the monthly global solar radiation for Eastern Mediterranean Region. *Energy Conversion and Management* **87**, 628–635.

Tomar, A. S. 2015 Comparative performance of reference evapotranspiration equations at sub-humid Tarai region of Uttarakhand, India. *International Journal of Agricultural Research* **10** (2), 65–73.

Trajkovic, S. & Kolakovic, S. 2009 Estimating reference evapotranspiration using limited weather data. *Journal of Irrigation and Drainage Engineering* **135** (4), 443–449.

Wang, K. & Liang, S. 2008 An improved method for estimating global evapotranspiration based on satellite determination of surface net radiation, vegetation index, temperature, and soil moisture. *Journal of Hydrometeorology* **9** (4), 712–727.

Xing, Z., Chow, L., Meng, F. R., Rees, H. W., Monteith, J. & Lionel, S. 2008 Testing reference evapotranspiration estimation methods using evaporation pan and modeling in maritime region of Canada. *Journal of Irrigation and Drainage Engineering* **134** (4), 417–424.

Yao, Y., Zhao, S., Zhang, Y., Jia, K. & Liu, M. 2014 Spatial and decadal variations in potential evapotranspiration of China based on reanalysis datasets during 1982–2010. *Atmosphere* **5** (4), 737–754.

Zhang, K. X., Pan, S. M., Zhang, W., Xu, Y. H., Cao, L. G., Hao, Y. P. & Wang, Y. 2015 Influence of climate change on reference evapotranspiration and aridity index and their temporal-spatial variations in the Yellow River Basin, China, from 1961 to 2012. *Quaternary International* **380**, 75–82.

Zhang, Q., Cui, N., Feng, Y., Gong, D. & Hu, X. 2018 Improvement of Makkink model for reference evapotranspiration estimation using temperature data in Northwest China. *Journal of Hydrology* **566**, 264–273.

First received 20 December 2022; accepted in revised form 18 April 2023. Available online 28 April 2023