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Comparative Evaluation of Different Reference Evapotranspiration Estimation Methods for Lakhimpur District of Assam, India

Rukmini Sonowal[1], Mrinal Kumar Borah[2]

[1]Post Graduate Student, Civil Engineering Department, Assam Engineering College, Gauhati University, Guwahati-781013, Assam, India

[2]Professor, Department of Civil Engineering, Assam Engineering College, Guwahati-781013, Assam, India

Abstract: ***Evapotranspiration is very important component of hydrology, crop-water requirements and necessary step in water resources management. In May(1990), Food and Agricultural Organization(FAO) in FAO Irrigation and Drainage Paper No.56 recommended the adoption of FAO-56 PM as a new standard method for estimating reference evapotranspiration that can easily derived from commonly measured data. Nine popular methods such as Blaney-Criddle(BCM), Thornthwaite(THM), Christiansen(CSM), Hargreaves(HGM), Modified Penman(MPM), Priestley-Taylor(PTM), Jensen-Haise(JHM), Makkink(MKM) and Turc(TCM) are considered. Observations recorded at North Lakhimpur Meteorological Station (Assam) are used to calculate the*** ET_O ***by the selected methods and results obtained are compared with the standard method on monthly and seasonal basis. The comparative evaluation of error and regression analysis results indicate that HGM performed best with lowest RMSE(0.898), MAE(0.804) &*** (R^2***=0.7485) followed by BCM with under estimating MBE values on monthly basis. On seasonal basis with lowest RMSE & MAE value, THM is found to be the best for monsoon, MPM for post-monsoon, MPM &PTM for winter and BCM for summer. The MBE values of BCM are underestimated during all four season. The next best methods after FAO-56 PM obtained can be used as guideline for selection of alternative/less data required methods in case of non-availability of data.***

Keywords: Evapotranspiration, FAO-56 Modified Penman Monteith Method (FAO-56 PM), Blaney-Criddle Method, Hargreaves Method, Thornthwaite Method

1. Introduction

Evapotranspiration is one of the major element and most important aspects of water losses in the hydrologic cycle. Evapotranspiration is the aggregate process of evaporation and transpiration. Evapotranspiration is the apparent motion of water to the air from the soil, canopy interception and water bodies. Transpiration is the apparent motion of water inside a plant and the subsequent loss of water through the stomata in its leaf. Both the process occurs simultaneously and there is no comfortable way to distinguish between the two of them. At sowing or when the height of the crop is small nearly 100% of ET occurs due to evaporation, but when the crop is fully grown and the soil is completely hidden by the crop, then 90% of ET takes place due to transpiration. Evapotranspiration plays a major role in the changing global climate and hence there is a need to estimate continually updated evapotranspiration and is necessary for water resources management, irrigation scheduling and planning and for environmental assessment. "Reference evapotranspiration is the rate of evapotranspiration from a hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance (70 s/m) and albedo (0.23) which would closely resemble ET from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water" as defined by Allen et.al. (1998). Due to the difficulty of obtaining accurate field data by various methods of direct measurement, ET is commonly computed from meteorological data. There are numerous methods available for estimation of reference evapotranspiration (ET_O) based on weather data requirements. But every method is not suitable for all climatic areas. Large data requirement also limits the application of many of these methods. In the present study ten different ET_O estimation methods are selected based on the type of weather data required, which may be classified as temperature-based, radiation-based or combination-based type methods. The comparative study of evaluation of different reference evapotranspiration methods is done by several researchers in different climatic areas. As per Allen et.al. , physically based combination approach of FAO-56 version of Modified Penman-Monteith method has been established and accepted as a standard method for calculating reference evapotranspiration. As per Lakshman Nandagiri and Gicy M. Kovoor (2006) suggest that ET_O is the important part for estimation of evapotranspiration rate of agricultural crops. ET_O is calculated from different areas in India for different climatic conditions such as arid, semi-arid, sub-humid and humid and concluded that radiation and temperature based methods provided good comparison results with FAO-56 PM method. Superior accuracy of FAO-56 PM methods is also verified in Indian conditions by Kashyap and Panda over FAO-24 Penman method.

From several research studies done by several researchers declared that FAO-56 PM method (combination based method) for calculation of evapotranspiration is the sole standard method and gives very accurate results. All the other evapotranspiration estimation methods which requires less data for their calculations are also very popular and useful because of their traditional use, but cannot debate the standard method. Evapotranspiration varies according to area and their climatic conditions. Comparative study of all methods gives another best suitable method after FAO-56

PM methods. In the present study all the methods selected for estimation of evapotranspiration are selected based on the Indian climatic conditions.

2. Study Area

Monthly average weather data for the period 2013- 2016 of North Lakhimpur station are collected from the Regional Meteorological Centre, LGBI Airport, Guwahati (Assam, India) have been used for estimating and analyzing ET_O using different methods. The study is conducted for Lakhimpur district and is situated on the North East corner of Assam, India and at the north bank of the River Brahmaputra. The district lies between 26°48′ and 27°53′ Northern latitudes and 93°42′ and 94°20′ East longitudes (approx.). It lies at an altitude of 101 meters above the sea level. The district occupies a geographical area of about 2277 square kilometers. It is bounded on the north by Siang and Papumpare District of Arunachal Pradesh and on the East by Dhemaji district and Subansiri River. The River Brahmaputra along with Majuli district stands on the southern side and Gahpur sub division of Sonitpur district is on the West. Lakhimpur district consists of four major rivers of North-East India and they are the river Brahmaputra, Subansiri, Ranganadi and the Dikrong. The climate of the study area is subtropical and humid due to high rainfall. The annual rainfall is 3268 mm and relative humidity is 74 to 89 percent with a mean of 81 percent. The district receives South-West monsoon rainfall from the month of April and continues up to September/October, a pleasant post-monsoon or retreating monsoon from October to November and a cold pleasant winter from December to February. Summer runs concurrently with the later part of the pre-monsoon season and continues throughout the monsoon season. The highest rainfall areas of the district are located near the foothills of Arunachal Himalayas, i.e., in the northern part of the district. The maximum and minimum daily temperatures fluctuate throughout the year and sometime may be very large in the study area. The maximum temperature goes up to 35°C during June/July and minimum temperature falls to 8°C in December/January.

3. Methodology

3.1 Data collection

Monthly average meteorological data of maximum and minimum temperature, relative humidity, Wind-velocity at 2 m height and sunshine hours for North Lakhimpur station were available from the Regional Meteorological Centre, LGBI Airport, Guwahati (Assam, India) for the period from January, 2013 to December, 2016. The monthly climate data was used to estimate the monthly ET_O (mm/day). The average monthly values of climate data for the period 2013-2016 are given in Table 1.

Table 1: Average climate data of North-Lakhimpur Station.

Month	*Temperature min (°C)*	*Temperature max (°C)*	*Relative humidity (%)*	*Wind speed (Km/d)*	*Sunshine hour (h)*
Jan	8.80	27.5	83.5	51.12	10.50
Feb	10.9	27.8	82.5	61.44	11.16
Mar	15.7	31.0	75.0	69.84	11.90
Apr	18.6	28.6	85.0	78.24	12.73
May	22.0	30.0	84.5	80.88	13.41
Jun	23.5	30.7	89.5	80.64	13.72
Jul	25.0	34.2	81.0	68.40	13.53
Aug	24.9	31.7	90.5	90.00	12.92
Sep	24.1	32.8	88.5	80.64	12.10
Oct	20.1	32.8	80.0	100.56	11.27
Nov	14.2	29.4	82.0	87.36	10.60
Dec	9.70	25.2	86.0	73.44	10.28
Average	18.13	30.2	84.0	76.88	12.01

3.2 Methods

The choice of ET_O estimation method depends on its suitability in the particular region and available data. On the basis of available meteorological data, the methods selected for estimation of ET_O are temperature based, radiation based and combination based methods. As per the recommendation of the FAO expert consultation panel, FAO-56 PM method is used as the sole standard method for the computation of ET_O from meteorological data. Therefore, FAO-56 PM method is used to estimate ET_O as standard for comparison of results of other nine methods listed above. The reference evapotranspiration (ET_O) estimated using FAO-56 PM method will be termed as standard ET_O hereafter. Following are the ten methods used to estimate ET_O in the present study

3.2.1 FAO-56 PM method

In May 1990, Food and Agricultural Organization (FAO) in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization review the FAO methodologies on crop water requirements and update the procedures. The Penman-Monteith combination method is recommended as a new standard for reference evapotranspiration. The method overcomes the shortcomings of the previous FAO Penman method and provide values more consistent with actual crop water use data worldwide.

The FAO-56 PM method to estimate ET_O is as follows:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_a - e_d)}{\Delta + \gamma\left(1 + 0.34 U_2\right)} \qquad (1)$$

Where, ET_O is the reference evapotranspiration (mm/day), R_n is the net radiation (MJ $m^{-2}day^{-1}$), G is the soil heat flux (MJ $m^{-2}day^{-1}$), T is the average temperature at 2 m height in ^OC, U_2 is the average 24 hour wind speed measured at 2 m height (m/s), (e_a-e_d) is the vapor pressure deficit for measurement at 2 m height (k Pa) = (e_s-e_a), Δis the slope vapor pressure curve (k Pa°C^{-1}), γ = psychrometric constant (k Pa°C^{-1}), 900 is the coefficient for the reference crop ($1J^{-1}$kg K day^{-1}), 0.34 is the wind coefficient for the reference crop (s m^{-1}).

The FAO-56 PM method requires observations of maximum and minimum air temperature, maximum and minimum relative air humidity (or the actual vapor pressure), wind speed at 2 m height, and solar radiation for accurately estimating ET_O. Where radiation data are lacking, or not reliable, the solar radiation (R_n) can be estimated using bright sunshine hours records as suggested by Allen et.al. [1]

$$R_n = R_{ns} - R_{nl} \qquad (2)$$

Where, R_{ns} is net shortwave radiation ($MJ/m^2/day$) and R_{nl} is net longwave radiation ($MJ/m^2/day$)

$$R_{ns} = (1-\alpha)R_s \qquad (3)$$

Where, R_s is incoming solar or shortwave radiation ($MJ/m^2/day$) and α albedo or canopy reflectance coefficient (α = 0.23), for hypothetical grass reference surface.

$$R_s = a_s + b_s \frac{n}{N} R_a \qquad (4)$$

Where, R_a is the extra-terrestrial radiation ($MJ/m^2/day$), n is actual duration of sunshine (hours), N is maximum possible duration of sunshine, a_s is regression constant expressing the fraction of extra-terrestrial radiation that will reach the earth surface on overcast/cloudy days (n=0) and a_s+b_s is fraction of extra-terrestrial radiation that reaches earth surface on clear sky days (n=N)

$$R_s = \frac{1440}{\pi} G_s d_r [\omega_s \sin(\phi)\sin(\delta) + \sin(\omega_s)\cos(\phi)\cos(\delta)] \qquad (5)$$

$$d_r = 1 + 0.033\cos(\frac{2\pi}{365} J) \qquad (6)$$

$$\delta = 0.409\sin(\frac{2\pi}{365} J - 1.39) \qquad (7)$$

$$\omega_s = \arccos[-\tan(\phi)\tan(\delta)] \qquad (8)$$

Where, G_s is solar constant (0.0820 $MJ/m^2/day$), d_r inverse relative Earth-Sun distance, ω_s is sunset hour angle (rad), δ is solar declination angle (rad) and ϕ is latitude of station (rad), J is the number of day in calendar year.

$$R_{nl} = \sigma[\frac{T^4_{\max,K} - T^4_{\min,K}}{2}](0.34 - 0.14\sqrt{e_a})(1.35\frac{R_s}{R_{so}} - 0.35) \qquad (9)$$

Where, σ is Stefen-Boltzman constant (4.903×10-9 $MJ/K^4/m^2/day$), $T_{max,K}$ & $T_{min,K}$ are absolute maximum and minimum temperature value (^OK), ratio R_s/R_{so} is relative shortwave radiation (limited to ≤ 1.0) and R_{so} is clear sky radiation ($MJ/m^2/day$) estimated as

$$R_{so} = (a_s + b_s)R_a \qquad (10)$$

3.2.2 Blaney-Criddle Method (BCM)

Blaney and criddle developed a simplified formula in which the consumptive use of water is correlated with day time hour, by multiplying mean monthly temperature T_m by the mean monthly percentage p of the maximum possible day times hours of the year. The value p depends on latitude of the place and the period of the year. This method is useful where only the temperature data is available.

$$ETo = p(0.46T_m + 8.13) \qquad (11)$$

Where, ET_O is the Reference crop evapotranspiration in mm/day, p is the mean daily percentage of the maximum possible daytime hours of the year, T_m is the mean monthly temperature in ^OC

3.2.3 Thornthwaite Method (THM)

Thornthwaite (1948) using meteorological observations from the Eastern USA, found that under conditions of limited availability of water there is an explicit relation between the evapotranspiration and the temperature of the atmosphere, longitude and the season. Thornthwaite derived the following general equation for estimating evapotranspiration:

$$ETo = 1.6 L_a (\frac{10T_m}{I})^a \qquad (12)$$

Where, ET_O is the reference crop evapotranspiration in cm/month, L_a is the adjustment for the number of hours of daylight and days in the month, related to the latitude of the place = $(\frac{n}{12})(\frac{D}{30})$, where D is in number of days in the month, T_m is the mean monthly air temperature in ^OC, I is the heat index $=\sum(T_m/5)^{1.514}$, a is an empirical exponent $=6.75\times10^{-7}I^3 - 7.71\times10^{-5}I^2 + 1.792\times10^{-2}I + 0.49239$

3.2.4 Christiansen Method (CSM)

The Christiansen equation for the estimation of reference evapotranspiration is written as

$$ETo = K_{ev} Q_o C \qquad (13)$$

Where, Q_O is the daily solar radiation at the top of the atmosphere converted into equivalent depth of evaporation in mm, ET_O is the reference crop evapotranspiration in mm/day, C is the coefficient derived from a series of climatic measurements, where, C = C_T. C_H. C_W. C_S. C_E. C_m (C_T is the temperature coefficient, C_H the humidity coefficient, C_W the wind coefficient, C_S the sunshine coefficient and C_E the elevation coefficient respectively and C_m is a monthly coefficient). The value C_m of ranges from 0.90 to 1.10 and vary from latitude to longitude.

3.2.5 Hargreaves Method (HGM)

Hargreaves (1974) established that amongst all the climatological data, temperature and radiation give more accurate value of evapotranspiration. This method is comparatively very simple and requires only temperature data apart from latitude. The equation gives more accurate results at interior locations with plain topography where the growing season of the crops are frost free.

$$ETo = 0.0023 \times R_a (T_m + 17.8) \times TD^{0.5} \qquad (13)$$

Where, ET_O is the reference crop evapotranspiration in mm/day, R_a is the extraterrestrial radiation in $MJ/m^2/day$ as an indicator of the incoming global radiation, T_m is the mean monthly air temperature in ^{O}C and TD is the difference of maximum and minimum temperature in ^{O}C.

3.2.6 Modified Penman Method (MPM)

The original equation of Penman consisted of two terms viz. the energy or radiation term and the aerodynamic term. It gives the evaporation from an open water surface due to wind and humidity considered together. A modified method was presented by Doorenbos and Pruitt (1977) which introduced somewhat simplified and widely accepted form of equation along with correction factor considering day and night weather conditions and was considered to offer the best results with minimum possible errors in relation to a living grass reference crop. This method can be easily adopted and provides most satisfactory result where measured data on temperature, humidity, wind and sunshine hours are available. It is fairly accurate method for estimation of evapotranspiration as it utilizes almost all the meteorological parameters responsible for the process of evapotranspiration. The FAO Modified Penman formula is as below:

$$ETo = c[W.R_n + (1-W).F(U)(e_s - e_a)] \tag{14}$$

Where, ET_O is the reference crop evapotranspiration in mm/day, W is the temperature altitude related weighting factor for the effect of radiation on ET_O, R_n is the net radiation in equivalent evaporation expressed as mm/day, F(u) is the wind related function, $(e_s$-$e_a)$ is the difference between saturated vapor pressure at mean air temperature and mean actual vapor pressure of air (mbar) and c is adjustment factor to compensate for the day and night weather effect for RH maximum and for R_S respectively.

3.2.7 Priestley-Taylor Method (PTM)

Priestley and Taylor (1972) proposed a simplified version of the combination equation (Penman, 1948) for surface area generally wet, which is a condition required for potential evapotranspiration. The aerodynamic component was deleted and the energy component was multiplied by a co-efficient (α=1.26), when the general surrounding areas were wet or under humid conditions.

$$ETo = 1.26[\frac{\Delta}{(\Delta+\gamma)}]\times(\frac{R_n - G}{\lambda}) \tag{15}$$

Where, ET_O is the reference crop evapotranspiration in mm/day, Δ is the slope of saturation vapor pressure curve in kPa^oC^{-1}, Υ is the psychometric constant in kPa^oC^{-1}, R_n is the net radiation in MJ $m^{-2}day^{-1}$, λ the latent heat of vaporization in MJ kg^{-1} (= 2.45) and G is the heat flux density to the ground in MJ/m^2/day.

3.2.8 Jensen-Haise Method (JHM)

Jensen and Haise evaluated 3000 observations of ET as determined by soil sampling procedures over a 35-year period, and developed the following relation:

$$ETo = C_t.(T_m - T_x).R_s \tag{16}$$

ET_O is the reference crop evapotranspiration in mm/day and T_m is the mean monthly air temperature in ^{O}C. T_X is the intercept on the temperature axis [T_X = -2.5-0.14(e_2-e_1)-EL/550]. e_2 & e_1 is the saturation vapor pressure of water in mbar at the mean daily maximum and minimum temperature respectively for the warmest month of the year, EL is the altitude of the place in meters. R_S is the incident solar radiation in mm of evaporable water per day. C_t is the temperature co-efficient = 1/ (C_1+C_2.C_H), where C_1 = 38-($2^oC\times EL/305$), C_2 = 7.6°C and C_H = 50 mbar/ (e_2 - e_1).

3.2.9 Makkink Method (MKM)

Makkink method (1957) is based on the theory that much of the energy consumed for evapotranspiration almost entirely comes from two sources; radiation energy and energy of air which is warmer than the surface. These two energy sources are actually transformed into solar energy. So, evapotranspiration is correlated with solar radiation and moreover is dependent intensely on short-wave radiation in a linear manner. The dependence of evapotranspiration on radiation is not constant throughout the year as the climate and surface conditions change. It must be noted that in dry areas, the energy transfer on the horizontal level and its downward transfer form an important percentage of the respective evapotranspiration in subtropical and semiarid areas. In these case even though the transferred heat comes from the sun, it leads to a non-linear correlation of ET_O and short-wave radiation. For this reason, Makkink (1957) has suggested the following relationship for the estimation of ET_O (mm/day) from solar radiation measurements:

$$ETo = [0.61\times\frac{\Delta}{\Delta+\gamma}\times R_s] - 0.12 \tag{17}$$

Where, ET_O is the reference crop evapotranspiration in mm/day, Δ is the slope of saturation vapor pressure curve in kPa^oC^{-1}, Υ is the psychometric constant in $kPaoC^{-1}$and R_S is the solar radiation in MJ $m^{-2}day^{-1}$.

3.2.10 Turc Method (TCM)

Under general climatic conditions of Western Europe, Turc (1961) computed potential evapotranspiration in millimetres per day for 10 day periods as:

When $RH_{mean}\geq 50\%$

$$ETo = 0.013\frac{T_m}{(T_m+15)}(R_s+50) \tag{18}$$

When $RH_{mean}\leq 50\%$

$$ETo = 0.013\frac{T_m}{(T_m+15)}(R_s+50)[1+\frac{(50-RH_{mean})}{70}] \tag{19}$$

Where, ET_O is the reference crop evapotranspiration [mm/day], T_m is the mean daily temperature in °C, R_S is the total solar radiation [$cal.cm^{-2}day^{-1}$] and RH_{mean} is the mean relative humidity in %.

4. Evaluation Criteria

Using the available monthly climatological and physiographical data, monthly ET_O values and seasonal ET_O

values are estimated. The regression analysis of various forms are done to examine the performance of nine methods compared with the standard ET_O on monthly and seasonal basis. Regression analysis is performed by considering the FAO-56 PM value as the independent variable and ETO estimated by using the selected empirical formulae as dependent variable to investigate the suitability of the formula for computing ET of the region. And also the percentage variation of ETO of different empirical methods over FAO-56 PM are evaluated. Further statistical error analysis was carried out with the parameters; Root mean square error (RMSE), mean bias error (MBE) and mean absolute error (MAE).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Y_i - X_i)^2}{N}} \quad (20)$$

$$MBE = \frac{\sum_{i=1}^{N}(Y_i - X_i)}{N} \quad (21)$$

$$MAE = \frac{\sum_{i=1}^{N}(|Y_i - X_i|)}{N} \quad (22)$$

Where, N is the overall number of observation, Y_i is the estimated ET_O and X_i is the standard ET_O value.

MBE is a good measure of model bias and is simply the average of all differences in the set. This provides a measure of general bias, but not of average error that could be expected. But RMSE and MAE are the measures of average difference. RMSE involves the square of the departures and therefore become sensitive to extreme values. MAE uses the absolute difference, thus reducing the sensitivity to extreme differences.

5. Results

The monthly ET_O values estimated by each of the ten methods for the period of record from the available climatological data used in present study are shown in Figure 1 and their mean values are given in Table 2.

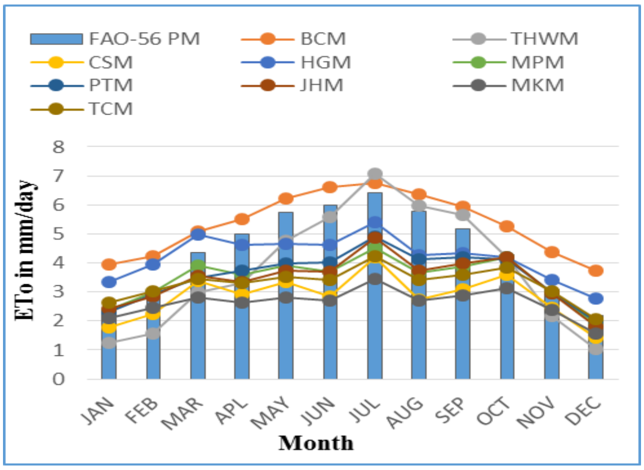

Figure 1: Estimated and Standard monthly ET_O values

To understand the influence of ET_O on crop water use, the ET_O need to be estimated on seasonal basis i.e. Monsoon (June-September), Post-monsoon (October-November), winter (December-February) and summer (March-May). Results obtained from the regression of ET_O estimated by each of the nine methods against standard FAO-56 PM method on monthly basis and the result obtained from the percentage variation evapotranspiration of the nine methods over FAO-56 PM method are presented in the Table 3 and Table 4 respectively. It is observed from Table 4, that FAO-56 PM method gives average 26.42% and 1.07% lower value of ET_O than by BCM and HGM while other selected methods gives lower value ET_O than FAO-56 PM method.

The regression and error analysis of these methods on monthly time scale shows that HGM performance as best among all the methods on monthly basis with lowest error (RMSE = 0.8958, MAE = 0.804) and high coefficient of determination (R^2 = 0.7485). The MBE values on annual basis indicate that all the methods except BCM are over estimating ET_O compared to the ET_O values of FAO-56 PM.

On seasonal basis, performance evaluation of each of the method was done using error analysis. In monsoon season THM performed better than all other methods with minimum RMSE (0.4709) and MAE (0.438). In post-monsoon season MPM performed best among all other methods with lowest errors (RMSE = 0.1061 & MAE = 0.105). During winter season RMSE & MAE value of PTM and MPM are lowest and during summer season BCM resulted least error and performed best. When MBE values are segregated season wise, the magnitude of errors are large in all the seasons with MKM, CSM, PTM, and MPM. BCM under-estimated during all four season. During monsoon, winter and summer season BCM performed better with least MBE. And the THM which under-estimated during monsoon season was found to over-estimated during the remaining three season.

Table 2: Standard and estimated mean monthly ET_O (mm/day), total annual ET_O (in mm and mm/day) and average ET_O (mm/day)

Month	*FAO-56PM*	*BCM*	*THM*	*CSM*	*HGM*
Jan	2.37	3.95	1.24	1.78	3.34
Feb	3.05	4.25	1.56	2.26	3.94
Mar	4.36	5.10	2.99	3.37	4.98
Apr	5.00	5.51	3.32	2.91	4.62
May	5.73	6.23	4.77	3.35	4.66
Jun	5.98	6.60	5.60	2.86	4.62
Jul	6.40	6.74	7.08	4.21	5.42
Aug	5.77	6.35	5.97	2.75	4.28
Sep	5.18	5.94	5.67	3.11	4.33
Oct	4.30	5.28	4.21	3.61	4.19
Nov	3.07	4.36	2.16	2.47	3.40
Dec	2.19	3.72	1.05	1.43	2.78
Annual mm/day	53.4	64.03	45.62	34.11	50.56
Annual in mm	1602	1920.9	1368.6	1023.3	1516.8
Average	4.45	5.336	3.802	2.843	4.214
Month	*MPM*	*PTM*	*JHM*	*MKM*	*TCM*
Jan	2.39	2.30	2.42	2.10	2.64
Feb	2.99	2.90	2.86	2.44	3.03
Mar	3.92	3.48	3.54	2.80	3.46
Apr	3.58	3.72	3.36	2.63	3.30

May	3.92	3.98	3.74	2.81	3.51
Jun	3.69	4.03	3.69	2.71	3.42
Jul	4.52	4.92	4.86	3.45	4.22
Aug	3.66	4.13	3.75	2.70	3.41
Sep	3.87	4.18	3.99	2.88	3.60
Oct	4.21	4.13	4.18	3.13	3.85
Nov	2.95	2.98	2.96	2.40	3.03
Dec	1.91	1.98	1.81	1.57	2.08
Annual mm/day	41.61	42.73	41.16	31.62	39.55
Annual in mm	1248.3	1281.9	1234.8	948.6	1186.5
Average	3.4675	3.561	3.43	2.64	3.295

Table 3: Regression analysis between monthly values of standard and estimated ET_O

	Regression equation	R^2	*R*
BCM	y = 0.722x + 2.119	0.989	0.9945
THM	y = 1.321x - 2.079	0.899	0.9482
CSM	y = 0.423x + 0.959	0.634	0.7966
HGM	y = 0.440x + 2.252	0.748	0.8652
MPM	y = 0.446x + 1.481	0.736	0.8579
PTM	y = 0.550x + 1.111	0.878	0.9373
JHM	y = 0.483x + 1.276	0.750	0.8660
MKM	y = 0.262x + 1.467	0.639	0.7998
TCM	y = 0.312x + 1.906	0.677	0.8234

Table 4: Percentage variation of Evapotranspiration of different empirical methods over standard FAO-56 PM method

Month	*BCM over FAO-56 PM*	*THM over FAO-56 PM*	*CSM over FAO-56 PM*	*HGM over FAO-56 PM*	*MPM over FAO-56 PM*
Jan	66.67	-47.68	-24.89	40.93	0.84
Feb	39.34	-48.85	-25.90	29.18	-1.97
Mar	16.97	-31.42	-22.71	14.22	-10.09
Apr	10.20	-33.60	-41.80	-7.60	-28.40
May	8.73	-16.75	-41.54	-18.67	-31.59
Jun	10.37	-6.35	-52.17	-22.74	-38.29
Jul	5.31	10.63	-34.22	-15.31	-29.38
Aug	10.05	3.47	-52.34	-25.82	-36.57
Sep	14.67	9.46	-39.96	-16.41	-25.29
Oct	22.79	-2.09	-16.05	-2.56	-2.09
Nov	42.02	-29.64	-19.54	10.75	-3.91
Dec	69.86	-52.05	-34.70	26.94	-12.79
Average	**26.42**	**-20.41**	**-33.82**	**1.070**	**-18.29**

Month	*PTM over FAO-56 PM*	*JHM over FAO-56 PM*	*MKM over FAO-56 PM*	*TCM over FAO-56 PM*
Jan	-2.95	2.11	-11.39	11.39
Feb	-4.92	-6.23	-20.00	-0.66
Mar	-20.18	-18.81	-35.78	-20.64
Apr	-25.60	-32.80	-47.40	-34.00
May	-30.54	-34.73	-50.96	-38.74
Jun	-32.61	-38.29	-54.68	-42.81
Jul	-23.13	-24.06	-46.09	-34.06
Aug	-28.42	-35.01	-53.21	-40.90
Sep	-19.31	-22.97	-44.40	-30.50
Oct	-3.95	-2.79	-27.21	-10.47
Nov	-2.93	-3.58	-21.82	-1.30
Dec	-9.59	-17.35	-28.31	-5.02
Average	**-17.01**	**-19.54**	**-36.77**	**-20.64**

Table 5: RMSE in the estimation of ET_O on annual as well as seasonal basis

Method	*Root mean square error (RMSE) of estimate for*			
	Annual	*Monsoon*	*Winter*	*summer*
BCM	0.9736	0.5946	1.1455	1.4465
THM	1.0058	0.4709	0.6467	1.2645
CSM	1.8560	2.6428	0.6465	0.7187
HGM	0.8958	1.1993	0.2459	0.8329
MPM	1.3083	1.9331	0.1061	0.1657
PTM	1.1279	1.5559	0.1360	0.1544
JHM	1.3116	1.8105	0.1152	0.2469
MKM	2.1082	2.9202	0.9534	0.5260
TCM	1.5354	2.2007	0.3195	0.1687

Table 5: MAE in the estimation of ET_O on annual as well as seasonal basis

Method	*Mean absolute error (MAE) of estimate for*			
	Annual	*Monsoon*	*Winter*	*summer*
BCM	0.886	0.575	1.437	0.584
THM	0.877	0.438	1.253	1.337
CSM	1.608	2.60	0.714	1.820
HGM	0.804	1.17	0.817	0.690
MPM	0.986	1.898	0.120	1.224
PTM	0.889	1.518	0.144	1.303
JHM	1.028	1.760	0.207	1.483
MKM	1.815	2.898	0.50	2.238
TCM	1.199	2.170	0.134	1.607

Table 5: MBE in the estimation of ET_O on annual as well as seasonal basis.

Method	*Mean bias error (MBE) of estimate for*			
	Annual	*Monsoon*	*Winter*	*summer*
BCM	-0.886	-0.575	-1.135	-1.437
THM	0.6483	-0.248	0.50	1.254
CSM	1.608	2.60	0.645	0.714
HGM	0.237	1.17	-0.11	-0.817
MPM	0.983	1.898	0.105	0.107
PTM	0.890	1.518	0.13	0.143
JHM	1.02	1.76	0.115	0.173
MKM	1.815	2.898	0.92	0.50
TCM	1.154	2.17	0.245	-0.047

6. Conclusion

Based on the objective of the present study, the comparative performance evaluation of nine ET estimation technique done is site specific and the results may vary site to site. The performance and accuracy of FAO-56 PM method can never be debated in theoretical or practical applications, yet the comparative evaluation performed in this study can be used as guideline for selection of alternative or less data dependent method in case of non-availability of data. BCM, HGM and THM are found to be the most suitable method with respect to data/cost constraints or accuracy constraints on monthly basis as well as seasonal basis for the Lakhimpur district of Assam (India), where unpredictable and erratic weather predominates most of the growing season.

References

[1] Anita Nag, Sirisha Adamala, N.S. Raghuwanshi, R. Singh, Arnab Bandyopadhyay, " Estimation and Ranking

of Reference Evapotranspiration for different spatial scales in India", Journal of Indian Water Resources Society, 34 (3), July, 2014.

[2] D.T. Meshram, S.D. Gorantiwar, H.K. Mittal, and R.C. Purohit, "Comparison of reference crop evapotranspiration methods in western part of Maharashtra state." Journal of Agrometeorology, 12(1):44-46, 2010.

[3] Daniel K. Fisher, H.C. Pringle III, "Evaluation of alternate methods for estimating reference evapotranspiration", Agricultural Sciences, 4(8A), 51-60, 2013.

[4] George H Hargreaves., (Fellow, ASCE), "Defining and Using Reference Evapotranspiration", Journal of Irrigation & Drainage Engineering, 120(6):1132-1139, 1990.

[5] H.V. Hajare, Dr. N.S. Raman, Er. Jayant Dharkar, "Evapotranspiration studies for Nagpur district", WSEAS Transaction on Environment & Development, 5(1), ISSN: 1790-5079, 2009.

[6] Hari Datta Paudel and Ashish Pandey, "Comparative study of ET_O estimation methods for the water balance estimation–a case study of Sikta irrigation project, Nepal" Journal of Indian Water Resources Society, 33(4), 2013

[7] J. Doorknobs, and W.O. Pruitt, "Crop Water Requirements", FAO Irrigation and Drainage Paper NO-24, 2nd Edition, Food and Agriculture of UN, Rome, Italy, 1977.

[8] L. Nandagiri and G.M. Kovoor, "Performance evaluation of Reference Evapotranspiration Equations across a Range of Indian Climates." Journal of Irrigation and Drainage Engineering, 132(2), 238-249, 2006.

[9] P.K. Pandey, Parmendra P. Dabral, and Vanita Pandey, "Evaluation of reference evapotranspiration methods for the North-Eastern region of India", International Soil and Water Conservation Research, 4, 52-63, 2016.

[10] R.G. Allen, L.S. Pereira, D. Raes, and M. Smith "Crop Evapotranspiration", Irrigation and Drainage Paper No. 56, Food and Agriculture Organization, Rome, Italy, 1998.

[11] R.G. Allen and W.O. Pruitt, "FAO-24 Reference Evapotranspiration Factor", Journal of Irrigation and Drainage Engineering, ASCE, 109(2), pp. 265-270, 1983.

[12] S. Chowdhury, M.K. Nanda, G. Saha, and N. Deka, "Evaluation of different methods for evapotranspiration estimation using automatic weather station data.", Journal of Agro-meteorology, 12(1):85-88, 2010.