

Evaluation of temperature-based Penman–Monteith (TPM) model under the humid environment

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Abstract In this study, an attempt is made to check the suitability of TPM approach and present software to estimate reference evapotranspiration based on TPM and Hargreaves–Samani (HS) method by using Visual Basic Environment. Considering the FAO-56 Penman–Monteith (FAOPM) as the standard model, the comparative performances of selected methods were evaluated under the climatic condition of Umaim, Meghalaya, India. Using the Root Mean Square Error (RMSE) and ‘correlation coefficient (r)’ as statistical measures of ‘goodness-of-fit’ the regression analysis was carried out. Based on the regression analysis TPM (RMSE = 0.014 mm day⁻¹, r = 0.92) was found better followed by HS (RMSE = 0.054 mm day⁻¹, r = 0.87). The average overestimate (e.g. 1.97 %) by TPM were found to be in close agreement with the FAOPM. These results support the use of the TPM approach under limiting climatic data conditions for Umaim.

Keywords Software · Temperature-based Penman–Monteith (TPM) · HS method

Introduction

Reference evapotranspiration (ET₀) is the most important index to represent evaporative demand of the atmosphere. It has a vital role in FAO recommended two-step approach of estimation of actual crop evapotranspiration (Pandey et al. 2016; Pandey and Pandey 2011). The FAO56 Penman–Monteith method (FAOPM) is the FAO and American Society of Civil Engineers (ASCE) Task Committee on Standardized Evapotranspiration Calculations (ASCE-Environmental and Water Resources Institute (EWRI), 2005) (ASCE-EWRI 2005) accepted and sole recommended method for reliable estimation of ET₀ in absence of directly lysimetric measured values (Pandey et al. 2014; 2016) but, its practical applicability is limited in many parts of world, because of non-availability of its least required input climatic limits mainly solar radiation and wind speed. There are many alternative approaches based on different input need are in practice to the estimation of ET₀ in a situation of non-applicability of FAOPM model. Among the various approaches, the temperature-based ET₀ models are the easiest and primary methods for estimating ET₀ (Xu and Singh 2002). According to Jensen et al. (1990), the temperature is the sole input of ET₀ process. These methods of estimating ET₀ are widely used because, the air temperature data are more readily available in most of the meteorological stations compared to other weather data such as solar radiation, sunshine hours; relative humidity and wind speeds that are required by models of the other groups. Moreover, in places where the data for other weather variables exist; they are always with a broad range of missing data, making the computation of daily ET₀ with those models difficult.

The main shortcoming of FAOPM equation is that it requires various weather data that are not always available

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for many locations (Droogers and Allen 2002). Additionally, computation procedure of missing variable is required exhaustive computation procedure. This limitation needs to be addressed especially in the limited data condition.

To discuss this issue, Allen et al. (1998) prescribed strategies to assess the limits of the FAOPM when the some of the climate variable are absent. The non-availability of climate information can likewise be overcome by utilizing ET_0 models with less climate information necessities. Allen et al. (1998) have suggested that when adequate information to apply the FAOPM model is not accessible, the Hargreaves Eqn. is prescribed for estimation of ET_0 .

According to Allen et al. (1998) that under conditions where the input variables of FAOPM are not available or observed with reasonable accuracy, the use of TPM approach is justified by the possible loss of precision due to parameters estimation, as referred by Allen (1997), these studies are relevant to assess the performance of ET_0 calculations when parameters related to a missing variable are replaced by an alternative calculation of the FAOPM equation. Results reported by studies quoted above revealed that the performance of TPM is superior to those obtained when using the HS equation.

Literature suggest that Several studies around the globe under different climate environment (e.g. Liu and Pereira 2001; Pereira et al. 2003; Popova et al. 2006; López-Moreno et al. 2009) have assessed the accuracy of the TPM equation using only maximum and minimum temperature data by comparing it with results of full data $PMET_0$ and with other ET_0 equations, mainly HS model, and reported that TPM give reliable estimates in accounting ET_0 values.

There is various software available to estimate ET_0 with the full input information while a few software is available that depends on temperature as fundamental data for processing reference evapotranspiration. DAILYET (Hess, 1999) is a Windows-based program, which could be used to day or month level reference evapotranspiration estimation. However, it requires most of the input data like that standard FAOPM. GSRad (Donatelli et al. 2006a; b) is software to estimate software component containing models to estimate extraterrestrial and ground level solar radiation from alternative methods. Gocic and Trajkovic 2010, developed the software for calculating ET_0 , feathered for limited weather data environment. Recently, Guo et al. 2016, developed an “R” Package for estimation of different types of evapotranspiration using 17 common methods, but it requires write a programme to estimate ET_0 values.

There is no software to best of author’s knowledge that estimate all other inputs based on only temperature input. So an attempt is made to develop software that can be easily used under limiting data conditions, only by knowing basic geographical parameters and temperature data.

Microsoft visual basic is a most productive tool for creating high-performance components and applications. It makes use of graphical user interface (GUI) for creating robust and powerful applications. Visual basic features such as easier comprehension, user-friendly, faster application development, etc.

A part of the crucial elements of visual basic 6.0 like make user interface utilizing design instruments, add drawings to structures, set properties for the individual article on the structure, fabricate an executable record, investigate the applications, analyze the items in the structures, work with data in the projects, and add more usefulness to the system by composing code. In the present study, an endeavor is made to gauge reference ET_0 in view of TPM method and Hargreaves system by utilizing Visual Basic Environment.

Methodology

Detail of study area

The study was conducted for Umaim (Meghalaya), India. The area comes under the temperate, tropical hill zone. The area falls under class VII land, and the soil belongs to regular peadalf series with clay loam texture with pH varying from 5.4 to 6.2 and is situated an $25^{\circ}41'21''N$ Latitude, $94^{\circ}55'25''E$ Longitude and at an altitude of 1010 m above mean sea level. The study site depicted in Fig. 1.

The daily data were collected for the period of 11 years (January 2000–December 2010) from, ICAR Research Complex at Umaim in Meghalaya (Barapani), India.

Penman–Monteith FAO-56 Model (FAOPM)

The standard universally accepted FAO-56 Penman–Monteith combination equation (FAOPM) has been recommended by FAO as the standard equation for estimating ET_0 Allen et al. 1998,

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

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n the net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G the soil heat flux ($\text{MJ m}^{-2} \text{day}^{-1}$), T the mean air temperature at 2 m height ($^{\circ}\text{C}$), u_2 the wind speed at 2 m height (m s^{-1}), e_s the saturated vapour pressure (kPa), e_a the actual vapour pressure (kPa), $e_s - e_a$ the vapour pressure deficit (kPa), Δ the slope vapour pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

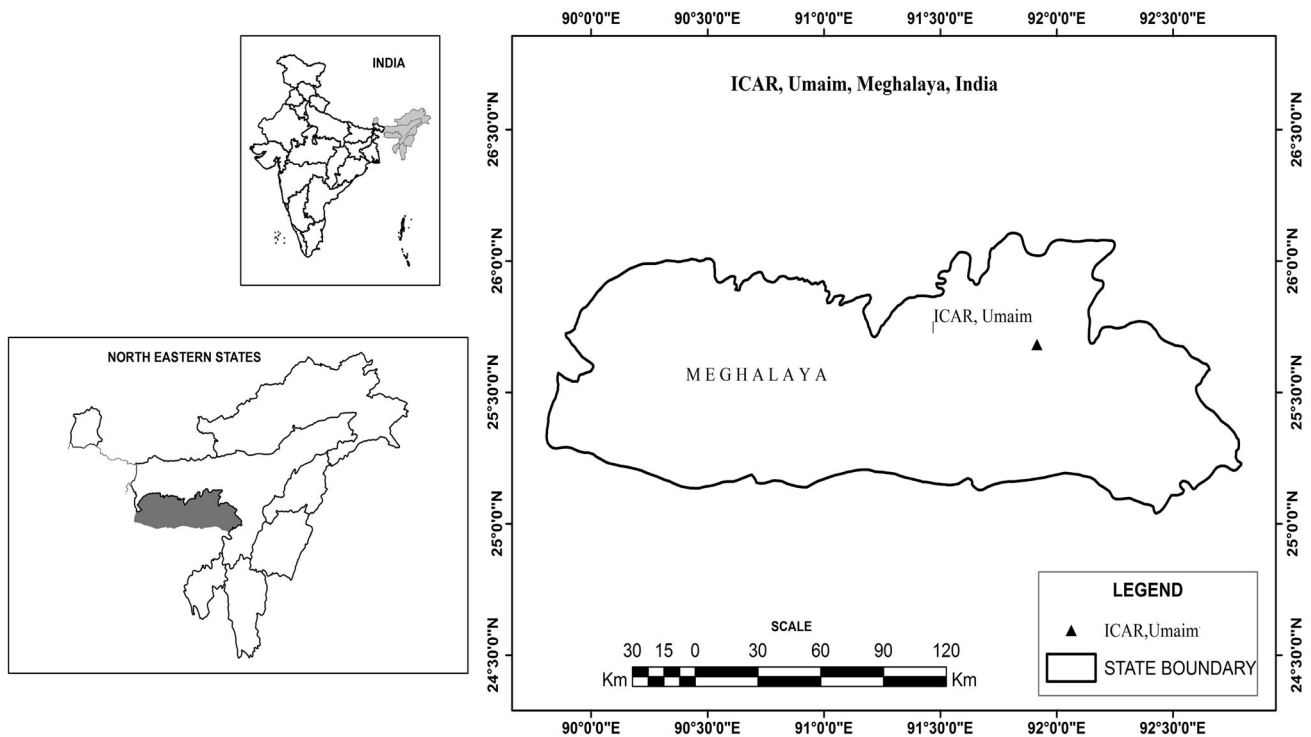


Fig. 1 Location map of study site, showing selected meteorological station

Temperature-based Penman–Monteith model (TPM)

TPM was utilized to calculate ET_0 from the temperature data taking after the proposals of (Allen et al. 1998; Allen 2002; Kra 2010). In the TPM the daily values of e_s , e_a , R_n , G , Δ , γ , data and associated intermediate parameters were estimated from maximum, and minimum temperatures T_{max} and T_{min} , the altitude of the station (z), the latitude of the location (ϕ). The detail of all the inputs parameters of FAOPM and their associated parameters are stated in Table 1.

The accompanying parameters were estimated daily basis from temperature data for a climate station utilizing the following eqs: average temperature, T , using Eq. (14); Slope of the saturation vapour pressure versus temperature curve, Δ , using Eq. (13); latent heat of vapourization of water, λ , using Eq. (17); Psychrometric constant, γ , using Eq. (15); Actual vapour pressure, e_a , using Eq. (2); Saturation vapour pressure, e_s , using Eq. (3); Extraterrestrial radiation, R_a , using Eq. (7); Solar radiation, R_s , using Eq. (6); Clear sky radiation, R_{so} , using Eq. (12); Net longwave radiation, R_{nl} , using Eq. (11); Net shortwave radiation, R_{ns} , using Eq. (6); Net radiation, R_n , using Eq. (4); TPM reference grass evapotranspiration, ET_0 using Eq. (1). The detail of the formula used for calculations of each eqns. including references depicted in Table 1.

Hargreaves–Samani (HS) method

The HS eqn. as presented by Hargreaves and Samani (1985), Allen (1997) and Pandey et al. (2009):

$$ET_0 = 0.0135(KT)(T + HT)(T_{max} - T_{min})^{HE} R_a \quad (18)$$

where ET_0 is the reference evapotranspiration in $MJ\ m^{-2}\ day^{-1}$, KT the empirical coefficient, T the mean air temperature in $^{\circ}C$, HT the Hargreaves Temperature Coefficient, T_{max} the maximum air temperature in $^{\circ}C$, T_{min} the minimum air temperature in $^{\circ}C$, HE the Hargreaves’s Exponent, R_a the extraterrestrial radiation in $MJ\ m^{-2}\ day^{-1}$, HE the 0.5, HT is the 17.8 (Hargreaves 1994).

ET_0 is converted to $mm\ day^{-1}$ by a conversion factor of 0.408. According to Hargreaves (1994) the suitable values may be used as ($KT = 0.162$ for “interior” regions and $KT = 0.19$ for coastal regions). Further, Allen (1996), prescribed a condition to figure observational coefficient as $KT = 0.17$ (mean monthly atmospheric pressure of the site (P)/mean monthly atmospheric pressure at sea level (P_0)^{0.5} for “interior” sites, and $KT = 0.2(P/P_0)^{0.5}$ for “seaside” locales to suit region to a substantial water body and altitude impact on the volumetric warmth limit of the atmosphere.

Development of software

A computer program was developed to estimate reference evapotranspiration (ET_0) based on TPM and HS models in

Table 1 Details of calculation formula of intermediate parameters of TPM including their references

Parameters (abbreviation)	Unit	References	Formula	Eq. no.
Actual vapor pressure, (e_a)	kPa	Allen et al. (1998)	$e_a = 0.611 \exp\left[\frac{17.27T_{\min}}{T_{\min}+237.3}\right]$	2
Saturated vapor pressure, (e_s)	kPa	Allen et al. (1998)	$e_s = 0.611 \left(\exp\left(\frac{17.27T_{\max}}{T_{\max}+237.3}\right) + \exp\left(\frac{17.27T_{\min}}{T_{\min}+237.3}\right) \right)$	3
Net radiation, (R_n)	MJ m ⁻² day ⁻¹	Allen et al. (1998)	$R_n = R_{ns} - R_{nl}$	4
Net shortwave radiation,	MJ m ⁻² day ⁻¹	Allen et al. (1998)	$R_{ns} = 0.77R_s$	5
Solar radiation (R_s)	MJ m ⁻² day ⁻¹	Allen et al. (1998)	$R_s = k_{R_s} \cdot R_a (T_{\max} - T_{\min})^{0.5}$ where, $k_{R_s} = 0.16$ for other locations (Hargreaves and Allen 2003)	6
Extraterrestrial radiation (R_a)	MJ m ⁻² day ⁻¹	Duffie and Beckman (1991)	$R_a = \frac{24 \times 60}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \sin(\delta)]$	7
Solar declination (δ)	radians	Allen (2002)	$\delta = 0.4093 \sin\left(\frac{2\pi(284+J)}{365}\right)$ where, J is the Julian day (is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December))	8
Relative Earth–sun distance (d_r)		Allen et al. (1998)	$d_r = 1 + 0.033 \cos\left(\frac{2\pi J}{365}\right)$	9
Sunset hour angle (ω_s)	radians	Allen et al. (1998)	$\omega_s = \cos^{-1}(-\tan(\varphi) \tan(\delta))$	10
Net long-wave radiation, R_{nl}	MJ m ⁻² day ⁻¹	Allen et al. (1998)	$R_{nl} = \sigma \frac{(T_{\max}+273.16)^4 + (273.16+T_{\min})^4}{2} (0.34 - 0.14\sqrt{e_a}) \left(\frac{1.35}{R_{so}} - 0.35\right)$	11
Clear sky solar radiation (R_{so})	MJ m ⁻² day ⁻¹	Allen et al. (1998)	$R_{so} = (0.75 + 2 \times 10^{-5}z)R_a$, where z = altitude above sea level (m).	12
Slope of vapor pressure–temperature curve (Δ)	kPa °C ⁻¹	(Murray 1967; Tetens 1930)	$\Delta = \frac{2503 \exp\left(\frac{17.27T}{T+237.3}\right)}{(T+237.3)^2}$, where, T is the mean temperature (°C)	13
Mean temperature(T)	(°C)	Allen et al. (1998)	$T = \frac{T_{\max}+T_{\min}}{2}$	14
psychrometric constant, γ	kPa °C ⁻¹	Allen et al. (1998)	$\gamma = 0.000665P$ where, P is the atmospheric pressure (kPa)	15
P at elevation, z m above sea level	(kPa)	Allen et al. (1998)	$P = 101.3 \left[\frac{293-0.0065z}{293}\right]^{5.26}$ where z is the elevation(m)	16
Latent heat of vaporization (λ)	MJ kg ⁻¹	Allen et al. (1998)	$\lambda = 2.501 - (2.361 \times 10^{-3})T$	17

visual basic 6.0 using Eqs. (1–18) and the process flowchart (Fig. 2) of the program.

Input data

The essential input data for developed software are the name of station & location, date (dd/mm/yy), daily maximum temperature (°C, T_{\max}), daily minimum temperature (°C, T_{\min}), latitude (° or rad), long-term average wind velocity (ms⁻¹), and elevation (m). The minimum necessary data for the software are latitude, elevation, temperature, and day or month information for the weather station. A sample screen printout of input parameters as shown in Fig. 3.

Output data

The desired output parameters are reference evapotranspiration (ET₀) in mm day⁻¹ using following methods: temperature-based Penman–Monteith (TPM) and Hargreaves–Samani (HS) method. A screen printout of sample output parameters as shown in Fig. 4.

Graphical user interface

The GUI based on a mouse drove approach and provides a connection between data and user. The window of the interface consists of six parts. The window includes information about the weather station (latitude and

Fig. 2 Process flow chart of model developed for estimation of reference evapotranspiration using TPM and HS equation

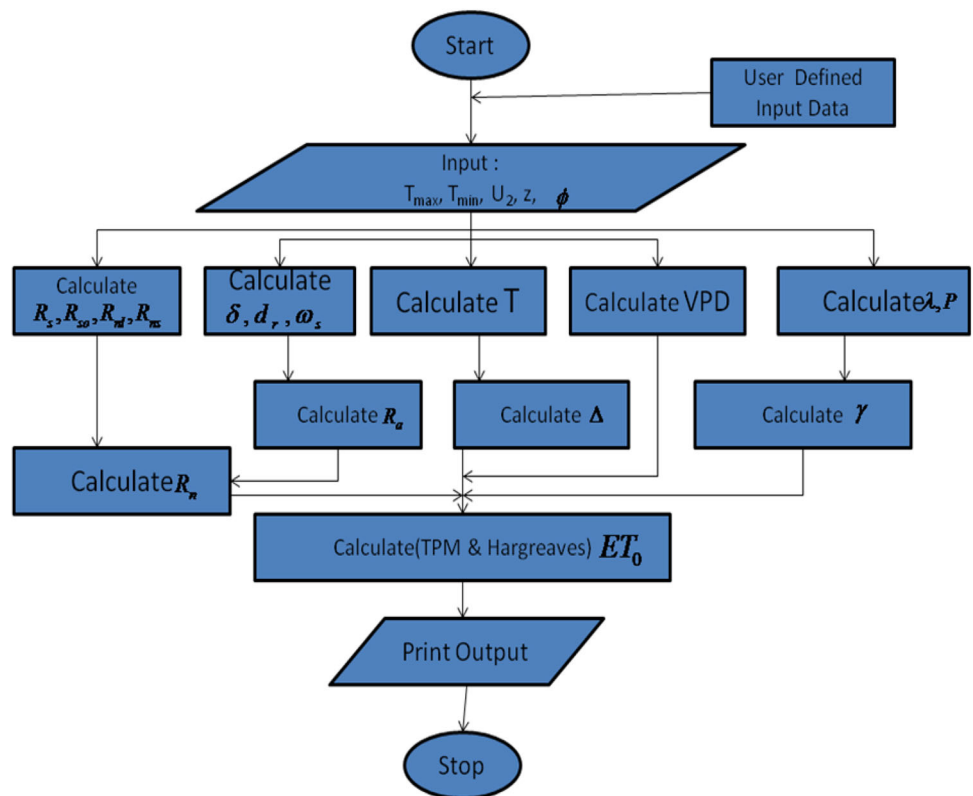
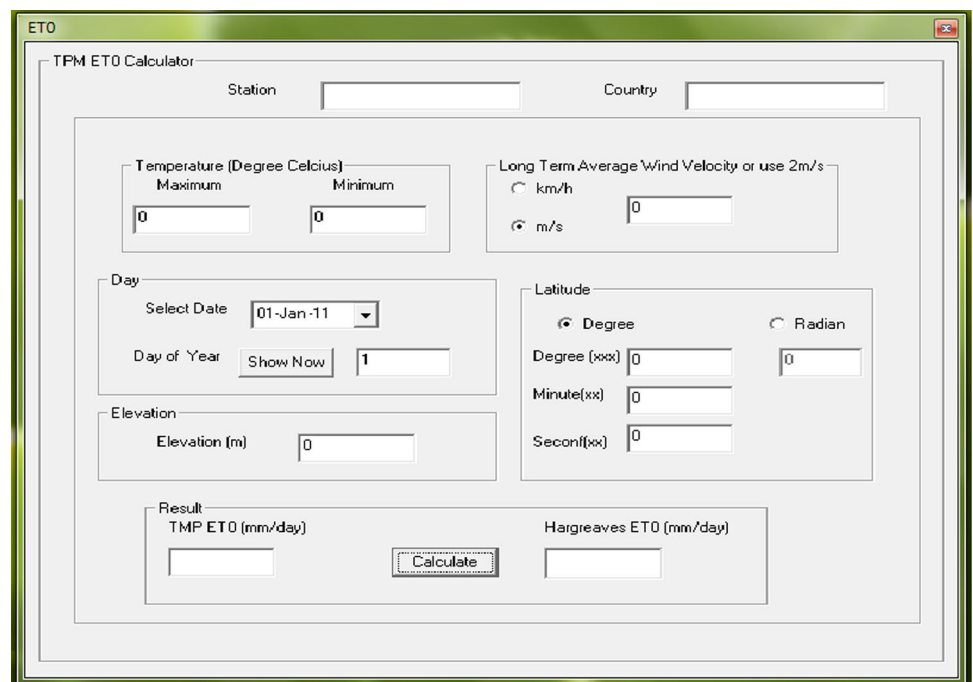


Fig. 3 Input parameters and initial window of developed software



elevation), daily maximum and minimum temperatures, the long-term average wind speed, and date. When the user clicks the command button, the ET_0 is calculated by TPM and HS model.

Overview of the developed software

The software developed using visual basic 6.0 environments has a window serving specific purposes in the ET_0

Fig. 4 Sample output of the developed software

The screenshot shows a software window titled "ET0" with a subtitle "TPM ETO Estimator". It features several input sections:

- Station:** Umiam, **Country:** India
- Temperature (Degree Celcius):** Maximum: 27.35, Minimum: 19.41
- Long Term Average Wind Velocity or use 2m/s:** Radio buttons for km/h and m/s (selected), with a value of 0.67.
- Day:** Select Date: 16-Sep-11, Day of Year: Show Now, 259
- Latitude:** Radio buttons for Degree and Radian (selected), with a value of 0.4479. Sub-fields for Degree (xxx), Minute(xx), and Second(xx) are all set to 0.
- Elevation:** Elevation (m): 1010
- Result:** TPMET0 (mm/day): 3.2587783843, Hargreaves ETO (mm/day): 3.87272358732

 A "Simulate" button is located between the two result boxes.

estimation process. The window consists of weather station input parameters, data input parameters, and the result.

Functioning of the software

The software starts by showing the ET_0 estimation window. It contains all the input parameters. The window is designed in such a way that there is a minimum error in entering the data, for example, a user cannot enter decimal twice and cannot input any alphabets in data input box. After the user had entered all the input parameters in their respective text box, he can go to simulate button provided in the bottom portion of window

Simulation of the program

When all the specification is entered then to obtain the results, the simulated button is to be clicked. In the simulation, all the values of the standard selected are extracted from the windows and used to calculate the required output. When the output values are calculated, they are displayed in the result box.

Statistical approach

For regression curve fits, the error is assessed using the RMSE, 1:1 line criteria and correlation coefficient. They give a helpful evaluation in comparison between two

methods. RMSE used as the main parameter for evaluating the reliability of TPM and HS methods in predicting ET_0 in comparison with FAOPM at the location. Therefore, RMSE parameter was used to show the goodness-of-fit of ET_0 estimates as compared to FAOPM. The RMSE of the estimate is defined as follows:

$$RMSE = \sqrt{\left(\frac{\left(\sum_{i=1}^N ET_{FAO56PM,i} - ET_{Eq,i} \right)^2}{n} \right)} \quad (19)$$

where $ET_{FAO56PM,i}$ is the ET_0 estimated by standard FAOPM, ET_{Eq} the ET_0 estimated by other selected methods, n is a total number of observations.

Another measure of goodness-of-fit is the correlation coefficient (r), the slope of the regression and the absolute deviation was also computed. The best fit method is the one with the lowest absolute deviation 'a' value closest to zero and 'b' value closest to one and smallest RMSE (Amatya et al. 1995).

Results

Evapotranspiration can be seen as a combined effect of various climatic parameters. The relationship of evapotranspiration with different climatic factor helps in identification of specific parameter to be used for estimation. In

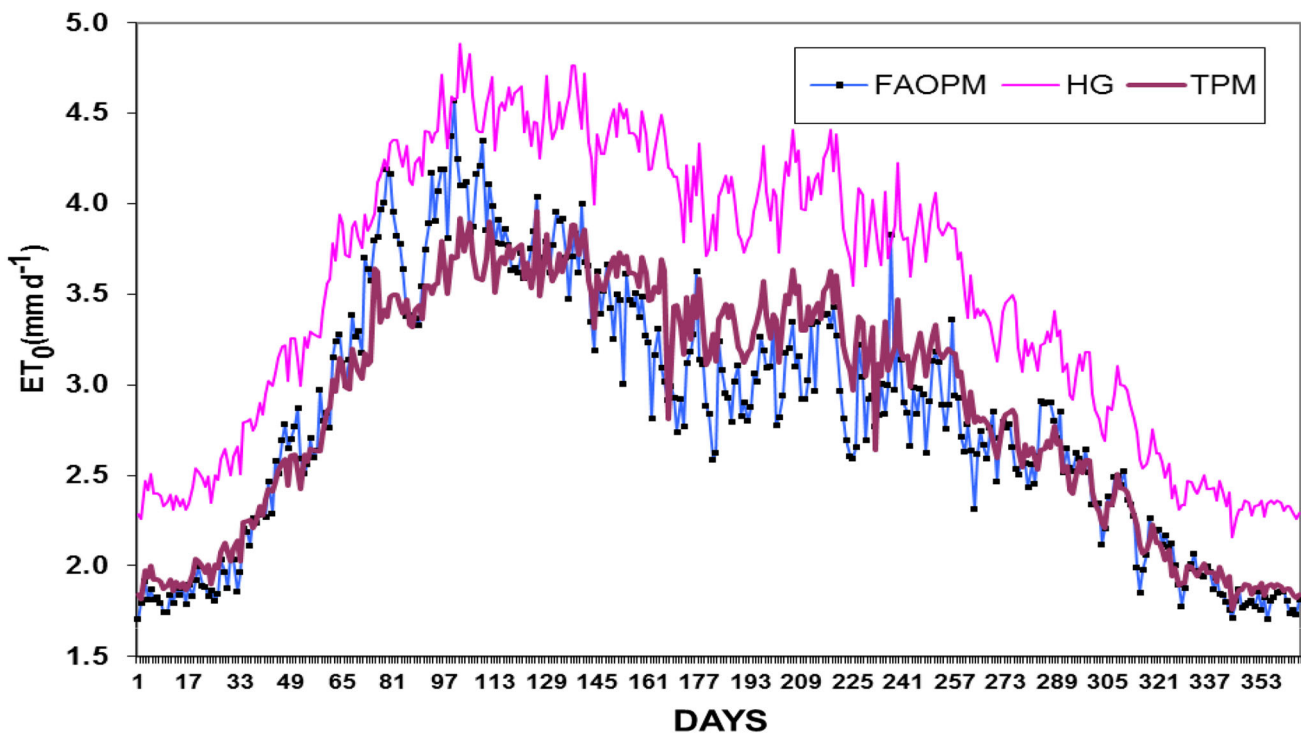


Fig. 5 Variation of reference evapotranspiration (ET_0) with time using FAOPM, HS, and TPM models

Table 2 Average statistical indices between selected models of ET_0 estimation with FAOPM

Methods		Values of the constants of the equation ($Y = a + bX$)		Root mean square error, RMSE (mm day^{-1})	Correlation coefficient, r^*	Average overestimation
X	Y	a	b			
FAOPM	TPM	0.8664	0.4297	0.014	0.92	+1.75
FAOPM	HS	1.042	0.5772	0.054	0.87	+19.74

* Significant at 1 % level

the present study, an attempt is made to check the validity of temperature-based approach for estimation of ET_0 .

Output of developed software

The developed software can be suitably used to estimate reference evapotranspiration under poor data condition when sufficient data to solve FAOPM are not available. When the required input parameters (T_{max} , T_{min} , and U_2) and weather station information are entered, then to obtain the results the simulated button is to be clicked. In the simulation, all the values of the specifications selected are extracted from the windows and used to calculate the required output. When the output values are calculated, they are displayed in the result box. A sample result screen printout of the ET_0 applications is shown in Fig. 4.

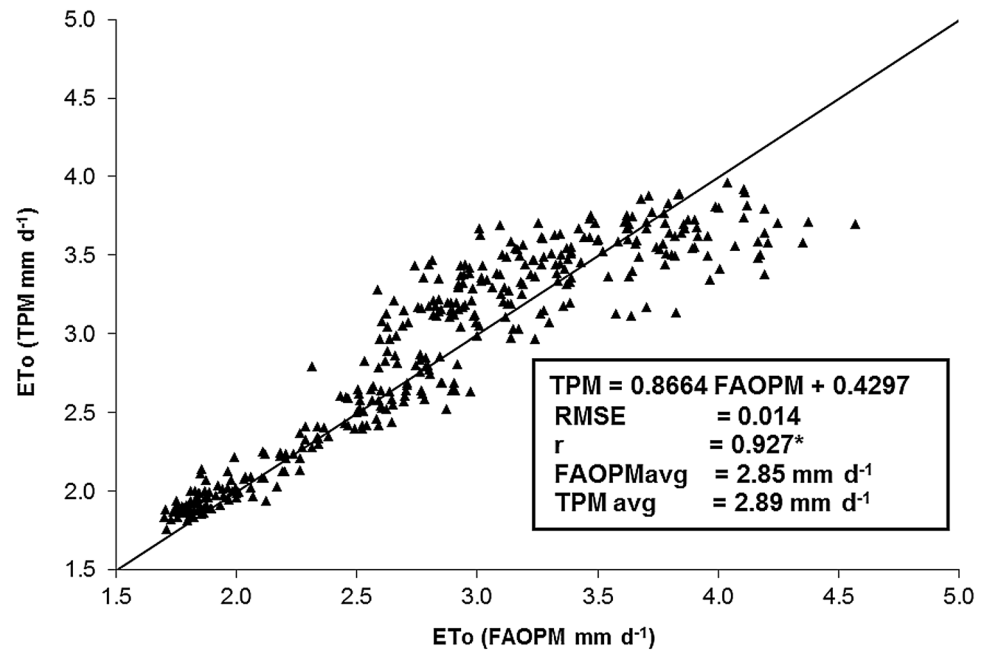
Comparison and inter-relationships among various ET_0 models

The daily reference evapotranspiration values obtained from different reference evapotranspiration models for Umaim are shown in Fig. 5 and Table 2. There is a strong deviation between the reference evapotranspiration values obtained from different methods.

Penman–Monteith FAO-56 model (FAOPM)

It is worth mentioning that FAO has recommended universal use of FAO56 Penman–Monteith method (FAOPM) (Allen et al. 1998). The estimated daily values of reference evapotranspiration computed by Penman–Monteith FAO-56 method are presented in Table 2. It was observed that

Fig. 6 Comparison between the estimated ET_0 by TPM and FAOPM model



the lowest value of reference evapotranspiration (1.70 mm day^{-1}) occurred in day number 1 and 355, and the highest value of reference evapotranspiration (4.57 mm per day) took place in day's number 100. The average daily reference evapotranspiration value obtained for Umaim was observed to 2.85 mm day^{-1} .

Temperature Penman–Monteith model (TPM)

The estimated daily values of reference evapotranspiration computed by TPM method are presented in Fig. 5. It was observed that the lowest value of reference evapotranspiration (2.56 mm day^{-1}) occurred in day number 350, and the highest value of reference evapotranspiration (4.08 mm day^{-1}) took place in day number 80. The average daily reference evapotranspiration value obtained from TPM model for Umaim (Barapani) was observed to be 3.26 mm per day . The lowest daily mean temperature ($11.7 \text{ }^\circ\text{C}$) and the highest daily mean temperature ($24.84 \text{ }^\circ\text{C}$) were recorded in day numbers 25 and 216, respectively. Therefore, the lowest value of reference evapotranspiration and the highest value of reference evapotranspiration were observed to be in day numbers 350 and 80, respectively. A comparison was made between ET_0 estimated by TPM model and FAOPM model. The relationship is depicted in Fig. 6 which show that there exists a linear relationship between and TPM model and FAOPM model with $RMSE = 0.014 \text{ mm day}^{-1}$, and $r = 0.927$, which is significant at 1 % level (Table 1). TPM model overestimated the standard FAOPM by 1.75 % at the site (Fig. 6).

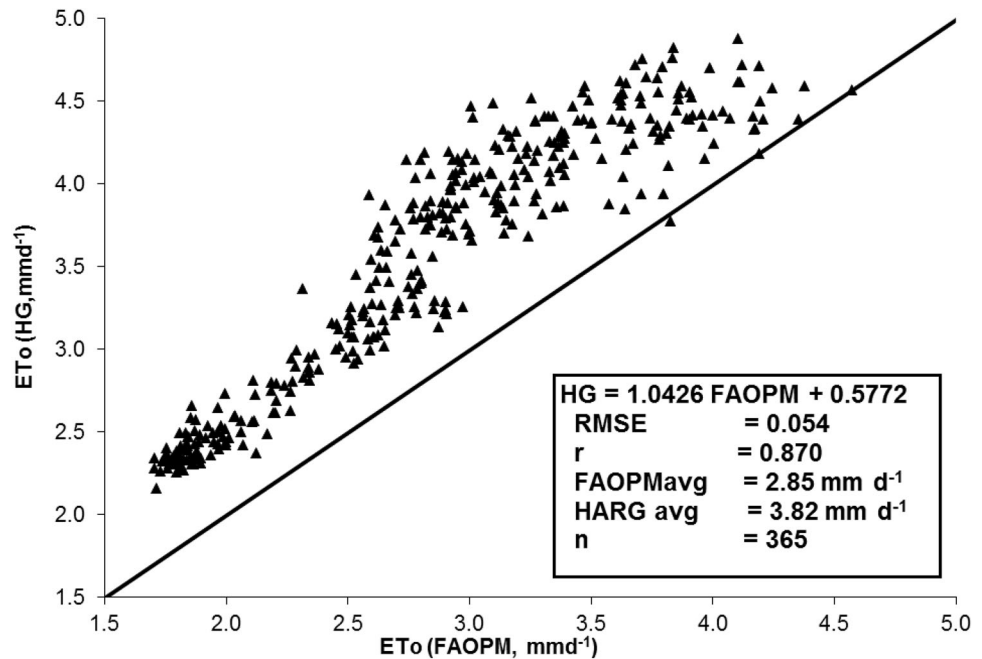
Hargreaves–Samani (HS) method

It was observed that the lowest value of reference evapotranspiration (3.23 mm day^{-1}) occurred in day's number 177, and the highest value of reference evapotranspiration (4.61 mm day^{-1}) took place in day number 102. The average daily reference evapotranspiration value obtained from HS model over Umaim was observed to be 3.82 mm day^{-1} . A comparative study shows that there exists a linear relationship between HS model and FAOPM model with $RMSE = 0.054 \text{ mm day}^{-1}$, and the $r = 0.87$, which is significant at 1 % level (Table 2). The relationship is depicted in Fig. 7. Hargreaves method overestimates the standard FAOPM by 19.74 %. From Table 2 it is clear that TPM method is related more closely to FAOPM method in comparison to HS method with the value of 'r' as 0.92 followed by Hargreaves's with 'r' value of 0.87.

Discussion and conclusions

There is an advantage of using TPM approach compared to combination equations, which is regularly neglected, that is the fewer data necessity since just extreme air temperatures are required. This is imperative in areas where solar radiation, humidity, and wind speed information are missing or are of low or faulty quality. Truth be told, air temperature can be measured with less fault and by less skilled people than the other atmosphere variables required by FAOPM.

Fig. 7 Comparison between the estimated ET_0 by HARG and FAOPM model



In this study, the software for estimating reference evapotranspiration using only temperature weather data has been presented. It is based on FAO reduced data set methodology for estimating reference evapotranspiration and a user-friendly software based on two limited data approach (e.g. TPM, and HS model), and provides estimates of daily/monthly ET_0 values. The developed software may a suitable alternative of FAOPM under non-availability of inputs data such as solar radiation, wind speed, relative humidity. All the selected temperature-based models; TPM, and HS overestimated the FAO PM values. The average daily ET_0 value obtained by the TPM is 2.89 mm day^{-1} , which is close to the mean daily ET_0 value (2.85 mm day^{-1}) obtained from the FAOPM method. Based on the regression analysis the alternative methods to the FAO56 Penman–Monteith, for estimation of reference evapotranspiration, is TPM, HS, methods in order of superiority for Umam.

According to Allen 1996 and Hargreaves and Allen 2003 the limit of deviation (i.e. 15 %) for calibrated models against FAO56PM. In the study suggested TPM model overestimated 1.75 % is well within the suggested limit under humid environment. The overall deviation of FAO suggested HS model was +19.74 are too high over the recommended limit. Similar finding reported by Lu et al. 2005 on evaluation of HS equation in Sothern eastern US. However, the deviation in the arid region was not tested, but the author may say TPM will perform equally well in arid or semi-arid regions also. In another study in North and Central Tunisia by (Jabloun and Sahli 2008) reported similar results that HS equation

overestimated ET_0 whereas the TPM method produced better estimates.

Findings of present study leads to conclude that the HS has larger overestimation compared to TPM against standard FAOPM, is well correlated with other reported studies in humid environment (e.g. Yoder et al. 2005; Martinez and Thepadia 2010; Tabari 2010; Todorovic et al.2013). The developed software could be successfully used to estimate reference evapotranspiration under the limiting data conditions when the use of FAOPM is limited due to nonavailability of required meteorological data.

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