Comparative evaluation of reference evapotranspiration estimation models in New Bhupania Minor Command, Jhajjar, Haryana, India

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Accurate quantification of reference crop evapotranspiration (ET_o) plays a significant role in determining crop water requirements in irrigated agriculture. A plethora of methods for the estimation of ET_o are available. However, the regional suitability of these methods needs to be assessed given the limited availability of meteorological data. In this study, daily estimates of 11 ET_o models were selected and compared with the FAO-Penman–Monteith equation (FAO-PM). The selected methods were Blaney–Criddle (BC), Jaisen–Haise (JH), Hargreaves method (HM), McGuinness–Borndne (MB), Chapman (CM), Abtew model (AM), Turc method (TM), FAO-PM equation, Penman equation (PM), Priestley–Taylor (PT) and Matt–Shuttleworth (MS). Evaluation of these models was carried out during 2016–20 in the New Bhupania Minor Command of the Dulhera distributary, Western Yamuna Canal Command (WYCC), Haryana, India. The selected models were evaluated to find a substitute for the FAO-PM equation based on different statistical indices. It was observed that the PT method performed best and was in line with the FAO-PM equation with correlation coefficient, root mean square error, mean absolute error, Nash–Sutcliffe coefficient and mean bias error as 0.92, 0.74, 0.48, 0.83, 0.171 respectively. Based on this study and statistical error indices values, the models can be ranked as PT > CM > TM > JH > AM > PM > MS > HM > BC > MB. Thus, we recommend using the PT model for the estimation of ET_o in the study area with available meteorological parameters for irrigation scheduling.

Keywords: Canal command, climatological data, comparative evaluation, evapotranspiration estimation models, irrigated agriculture.

WATER is one of the major components of agriculture, which is becoming scarce due to increased demand pertaining to population growth, besides urbanization and industrialization[1,2]. The unplanned and non-scientific development of water resources, mostly driven by individual initiatives, has led to increased stress on the available resources[3]. Therefore, an accurate estimation of crop water requirements is important. This can be achieved by measuring soil moisture, evapotranspiration, plant-based indicators and the use of surface energy balance components through remote sensing[4]. Evapotranspiration (ET) is the main source of water loss (90% of precipitation) in arid and semi-arid regions. It is one of the important parameters under hydrological, agricultural and environmental studies[5]. Direct measurement of actual ET (AET) is laborious, time-consuming and costly on a mega-scale[6]. So, reference crop evapotranspiration (ET_o) is being used to estimate AET. ET is the ability of the atmosphere to remove water from the soil and plants through the processes of evaporation and transpiration respectively. It depends on meteorological factors such as temperature, solar radiation, wind speed and humidity. ET_o is the rate of evapotranspiration from a well-watered grass surface with specific characteristics[6], and the terms 'potential evapotranspiration' and 'reference evapotranspiration' are used interchangeably.

Various methods such as empirical, remote sensing approaches, field measurements, water balance equation, lysimeter and artificial neural network (ANN) are used to estimate ET_o. However, the developed models are not suitable for all climatic regions due to spatial and temporal variability, data requirement, complexity and reliability[3,5,7]. Besides, most of these models are only applicable where they are developed. The Food and Agricultural Organization (FAO), Rome, Italy, and World Meteorological Organization, Geneva (Switzerland) have recommended a standard model called FAO–Penman–Monteith Equation (FAO-PM), which is universally applicable[6]. Besides its complex calculation procedure, FAO-PM requires exhaustive meteorological parameters, which are generally not available in many weather stations in developing countries[8]. Therefore, it is essential to find alternative models for the calculation of

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ET with limited and available meteorological data. Moreover, the developed models need to be verified with the FAO-PM estimate before being recommended for use in a region[8,9]. In view of the above, the present study was undertaken to compare the performance of eleven different ET_o models for the New Bhupania minor canal command region, Western Yamuna Canal Command (WYCC), Jhajjar district, Haryana, India.

Materials and methods

The study area is situated between 28°38′25″–28°40′22″N lat. and 76°48′28″–76°49′25″E long. with an altitude varying between 212 and 220 m amsl. During the years 2016–20, climatological data were obtained from India Meteorological Department (IMD), New Delhi. The data include daily maximum and minimum temperatures, maximum and minimum relative humidity, wind speed and bright sunshine hours. Figure 1 shows Pearson's correlation coefficient (r) between climatic factors and ET_o. The study area is part of the agro-climatic region known as the 'Trans-Gangetic Plain region'[10]. Summer season is usually dry and hot while winter is chilly. The temperature begins to increase from March and continues untill the end of June. The hottest months are May and June, with the mean daily maximum temperature exceeding 40°C. During winter season, the temperature starts decreasing from November and January is the coldest month. The average annual precipitation of the Jhajjar district is 577 mm. The wettest months are July and August, and about 74% of the total rainfall is received during monsoon season[11]. Agricultural land, fallow land, water bodies, wasteland and settlements were all classified as part of the land use/cover map (LULC). The maximum land use pattern of the catchment was found under agricultural land. The major crops in the command area are rice, wheat, cotton, bajra, mustard and jowar. The soil texture of the study region varies from clay loam to sandy soil.

ET_o models

In this study, 11 models were chosen to estimate ET_o based on meteorological data available in the study region. These models are FAO-PM, Priestley–Taylor method (PT), Blaney–Criddle method (BC), Abtew method (AM), Jaisen–Haise method (JH), Hargreaves equation (HE), Turc method (TM), Penman Method (PM), Matt–Shuttleworth approach (MS), Chapman method (CM) and McGuinness and Bordne (MB).

FAO-Penman–Monteith (FAO-PM) method: The FAO-PM equation requires a total of nine inputs for the calculation of reference evapotranspiration (ET_o). Detailed guidelines for the estimation are discussed in Allen *et al.*[6]. This method is used as the standard for comparison with other methods.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.3u_2)}, \quad (1)$$

where R_n is net solar radiation (MJ m^{-2} day^{-1}), γ the latent heat of evaporation (MJ kg^{-1}), T the daily mean temperature (°C), u_2 the mean daily wind speed at 2 m height (m/s), e_s and e_a are the saturation and actual vapour pressure (kPa) respectively, G the soil heat flux (MJ m^{-2} day^{-1}) and Δ is the slope of the saturated water vapour pressure curve (kiloPascal/degree centigrade).

Priestley–Taylor method: In 1972, Priestley and Taylor developed a semi-empirical, radiation-based model to compute ET_o. It is a simplified form of the Penman equation[12]. The vapour pressure and convection components of the PT technique are combined into a single term, viz. α. Details to calculate ET_o have been presented by Doorenbos and Pruitt[12].

Abtew method: In 1996, Abtew[13] proposed an empirical equation to estimate ET_o. The proposed equation requires only two input parameters, viz. solar radiation and maximum temperature to compute ET_o.

Jensen–Haise equation: This equation employs solar radiation and temperature to estimate ET_o. The equation was developed based on 3000 observations made over 35 years in the arid region of the Western United States[14].

Hargreaves equation: This is an energy-based approach that estimates ET_o using input variables like maximum and minimum temperature and solar radiation[15]. In 1985, Hargreaves and Samani[15] provided a detailed procedure for the calculation of ET_o.

Turc method: This method takes into account minimum and maximum air temperature as well as solar radiation as input parameters for the estimation of ET_o. Turc[16] has discussed the detailed methodology for the same.

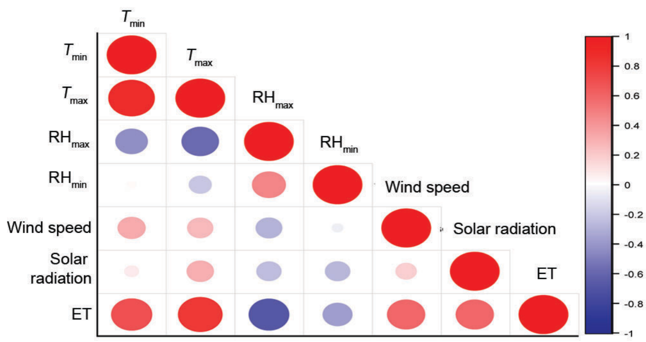

Figure 1. Correlation between climatic factors and reference evapotranspration (ET_o).

Penman equation: This is a modified version of the initial Penman equation (1948). It can be adopted when data on temperature, humidity, wind speed and solar radiation or sunshine hours are available[12,17,18]. The aerodynamic and radiation components are taken into account in the modified equation.

FAO-24 Blaney–Criddle (1977) method: Blaney and Criddle developed a simplified equation for the consumptive use of water that involves multiplying the mean monthly temperature and mean monthly percentage of daytime hours. This approach can be used when there is insufficient meteorological data. Besides, it is mainly based on temperature data and the detailed ET_o estimation procedure is provided in the literature[12,19,20].

Chapman equation: This method is used to estimate the ET_o using temperature, relative humidity, elevation, latitude and some other constants like soil heat flux and latent heat of evaporation. The detailed procedure for the estimation of ET_o is given by Chapman[21].

Matt–Shuttleworth approach: This is a simple and feasible approach for estimating potential ET. This method involves transforming crop coefficients from FAO publications into equivalent surface resistances, and using the Penman–Monteith equation to perform a one-step calculation for estimating crop water requirements. The MS approach to ET_o calculation is based on the relationship between crop coefficient and crop surface resistance, with the simplifying assumption that ET_o equals the Priestley–Taylor estimate of 1.26. The methodology for estimating ET_o was followed as provided in the literature[22–24].

McGuinness–Bordne equation: In 1972, McGuinness and Bordne developed an equation that requires solar radiation as well as daily temperature as input parameters for the estimation of ET_o (refs 25, 26).

Performance evaluation of the ET_o models

The performance of the ET_o methods were compared with the standard FAO-PM approach. The FAO-PM equation was used as an independent variable, and ET_o computed by other methods/formulae as the dependent variables, to determine the model appropriateness for determining ET_o of the study region. Equations (2)–(6) were utilized to evaluate the model using several statistical indices, viz. root mean square error (RMSE), mean absolute error (MAE), Nash–Sutcliffe model efficiency coefficient (E_{NSC}) and mean bias error (MBE)[2,27–30].

$$R^2 = \left\{ \frac{n(\sum x_i y_i) - (\sum x_i)(\sum y_i)}{\sqrt{[n\sum x_i^2 - (\sum x_i)^2][n\sum y_i^2 - (\sum y_i)^2]}} \right\}^2, \tag{2}$$

$$\text{MAE} = \frac{\sum_{i=1}^{n} |y_i - x_i|}{N}, \tag{3}$$

$$\text{MBE} = \frac{\sum_{i=1}^{n} (x_i - y_i)}{N}, \tag{4}$$

$$E_{\text{NSC}} = 1 - \frac{\sum_{i=1}^{n} (y_i - x_i)^2}{\sum_{i=1}^{n} (y_i - \overline{y}_i)^2}, \tag{5}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (y_i - x_i)^2}{N}}, \tag{6}$$

where y_i is the observed ith value, x_i the predicted ith value and $\overline{y}_i$ is average of observed values and N is the total number of observations.

The coefficient of determination (R^2) is the proportion of variance predicted by ET_o estimated by the models and the FAO-PM equation. The difference between the FAO-PM equation and the other models used in this study was computed using RMSE. The lower the RMSE, the better the fit of models-estimated ET_o values with the FAO-PM-estimated value. MAE is a measure of the average magnitude of the errors in ET_o values when comparing FAO-PM equations and other methods without considering their direction. The aim of MBE was to find the average bias in the anticipated model ET_o values from the standard method. Positive and negative values of MBE imply overestimation and underestimation of the ET_o values respectively. In hydrological models, E_{NSC} is widely used to assess the accuracy of the simulated model with observed data. However, E_{NSC} was used in this study to compute the estimation accuracy of other ET_o methods compared to the FAO-PM method.

Results and discussion

The mean monthly, total, and average ET_o values from 2016 to 2020 were estimated employing 11 different models and available climatic data (Table 1). Moreover, it was observed that temperature is the most influential factor in ET_o estimation, followed by sunshine hours, wind speed and relative humidity (Figure 1). Similar findings were also reported by Patle and Singh[31]. Figure 2 shows the trend of ET_o estimation by different models in the study area during 2016–20. The FAO-PM approach predicted the highest ET_o value in April (194.80 mm) and the lowest value in December (46.30 mm). In addition, the highest monthly

Table 1. Mean monthly reference evapotranspration (ET_o) estimated using different models

	Methods										
Months	FAO-PM	BC	HE	JHE	MS	TM	AM	MB	PT	PM	CM
January	47.40	35.09	41.25	48.63	33.72	51.64	60.58	78.73	45.30	71.24	35.55
February	71.84	122.80	97.32	80.56	49.66	74.18	82.65	103.34	67.48	99.11	55.04
March	116.31	142.71	129.51	138.76	82.68	111.54	114.98	164.95	111.28	158.60	89.74
April	164.87	186.29	175.58	199.21	109.32	138.10	130.63	224.27	145.90	215.56	131.53
May	195.80	195.10	195.45	231.99	124.62	151.13	138.30	266.93	165.65	247.71	156.29
June	172.73	154.66	163.70	205.58	115.67	133.04	119.30	221.73	154.26	213.02	136.09
July	122.75	81.47	102.11	159.29	99.86	110.04	98.29	194.78	131.86	159.17	93.08
August	109.76	75.09	92.42	142.99	90.73	101.42	90.37	173.31	119.73	143.56	83.07
September	115.15	123.46	119.30	156.36	92.88	110.01	100.26	180.39	121.23	156.81	89.25
October	95.07	179.72	137.39	131.37	74.76	99.94	94.03	161.43	96.04	143.70	77.60
November	56.56	32.04	44.30	63.01	38.90	58.89	57.53	106.32	50.61	89.53	45.77
December	46.30	34.59	40.45	51.96	32.48	53.51	59.81	78.70	42.73	76.14	36.94
Total	1314.57	1363.04	1338.80	1609.71	945.27	1193.44	1146.74	1954.89	1252.08	1774.17	1029.96
Average	109.55	113.59	111.57	134.14	78.77	99.45	95.56	162.26	104.34	147.85	85.76

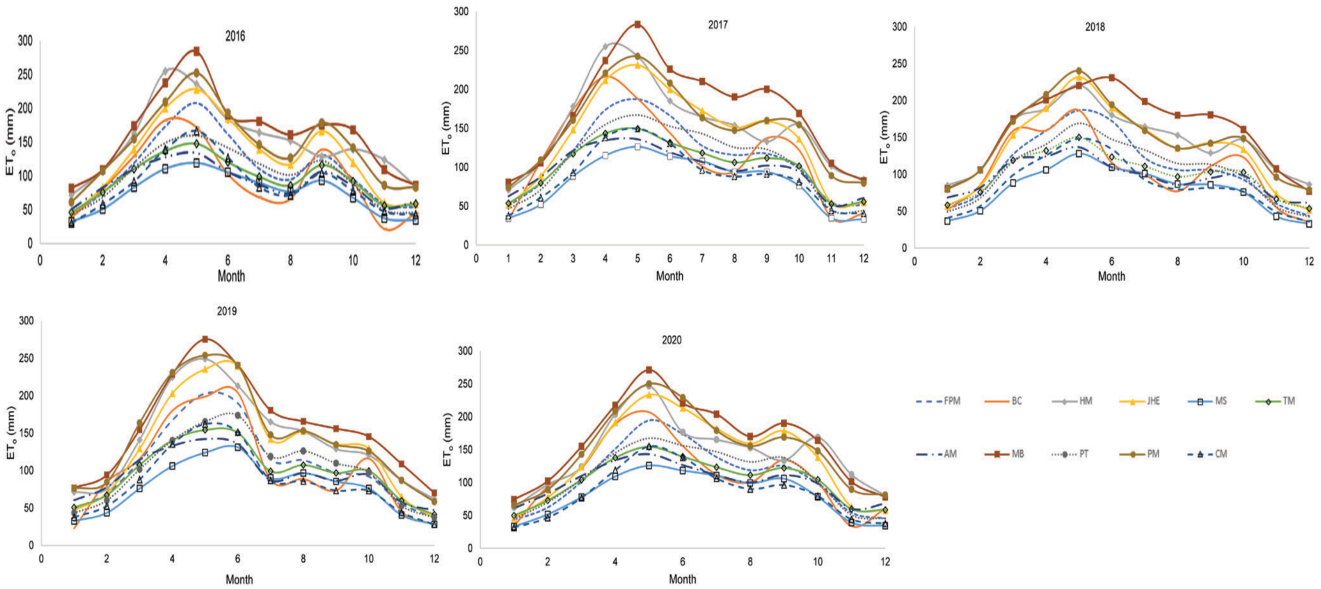

Figure 2. Trend of ET_o over the study area during 2016–20.

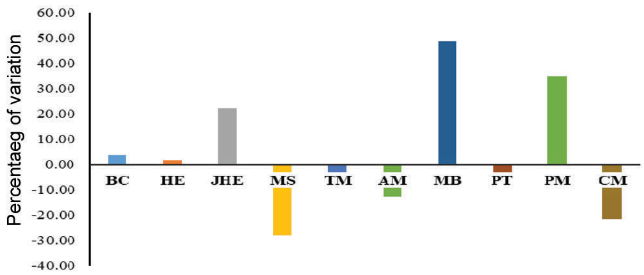

Figure 3. Percentage of variation of ET_o models compared to FAO-PM method.

ET_o (266.6 mm) was predicted by the MB model for April, and the lowest value (32.04 mm) was estimated by the BC model for November (Table 1). It can be observed from Table 1 that the FAO-PM equation has estimated the annual average ET_o to be 109.55 mm, which was used as the standard method. In addition, the highest and lowest annual average ET_o values were estimated by the MB model and MS model respectively. Figure 2 shows ET_o estimated from 11 different models for the years 2016–20. It can be observed that none of the ET_o models generated identical ET_o values as the FAO-PM method. However, in this analysis, ET_o value was either overestimated or underestimated. The MB technique overestimated ET_o as compared to the other models (Figure 2). For the period 2016–20, the percentage of variation (PV) was computed for several models using the FAO-PM technique as a standard (reference) method. The BC, HE, JHE, MB and PM models overestimated ET_o, whereas the MS, TM, AM, PT and CM models underestimated the same (Figure 3). This estimation of ET_o by the MB model had the highest PV (+48%) compared to the other

Table 2. Ranking of ET_o models based on prediction error statistics

Model	MAE	MAPE	MBE	RMSE	Rank
BC	1.95862	57.842	0.1654	2.24	9
HM	1.4396	50.44	2.4694	1.83	8
JH	0.9656	26.282	0.8076	1.26	4
MS	1.0114	26.26	–1.0102	1.34	7
TM	0.5426	14.94	–0.3308	0.86	3
AM	0.7914	22.28	–0.4586	1.10	5
MB	2.527	81.38	2.4854	2.91	10
PT	0.4832	12.82	–0.171	0.74	1
PM	1.2968	42.18	1.2576	1.44	6
CM	0.7786	22.06	–0.7784	0.86	2

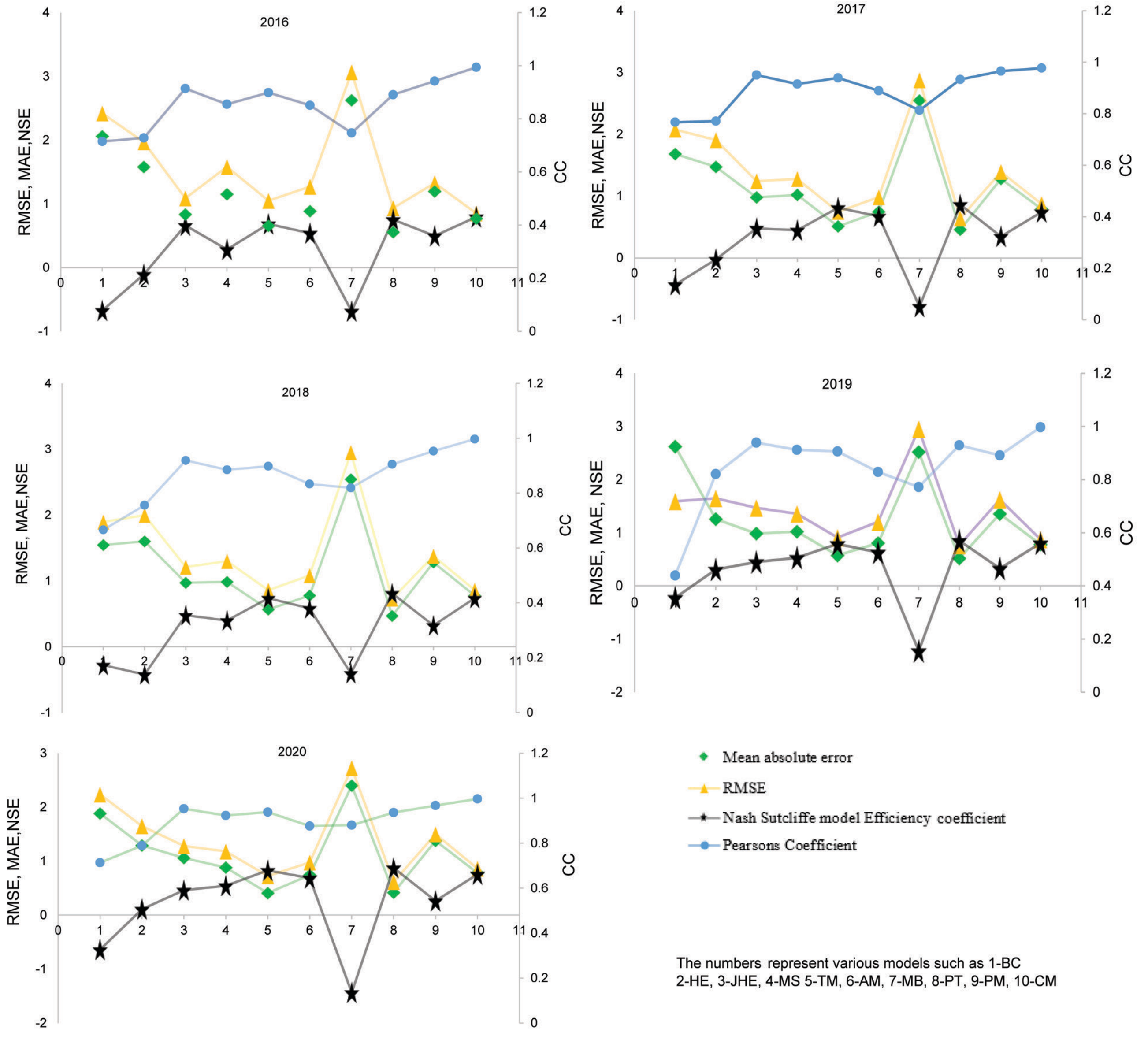

Figure 4. Root mean square error (RMSE), mean absolute error (MAE), Nash–Sutcliffe efficiency (NSE) of ET_o models over the study area during 2016–20.

models, followed by MB (Figure 3). In contrast, the HE model yielded the lowest PV, followed by the PT model.

Evaluation of ET_o using different models during 2016–20

Prediction error statistical indices were used to analyse the accuracy and reliability of different ET_o models. A comparison of the daily reference evapotranspiration value of the FAO-PM model with the remaining 10 models for the years 2016–20 revealed that none of them was expected to produce identical results with the FAO-PM method. ET_o estimation of the PT model, on the other hand, was close to that of the FAO-PM model. The PT and MB models were found to be the most and least acceptable respectively (Table 2). The highest correlation coefficient was exhibited by the CM, PM and JH models, while the lowest was by the BC model with the FAO-PM model. The RMSE values for several ET_o models ranged from 0.73 to 2.96 (Figure 4). The MB and the PT models had the highest and lowest RMSE values respectively. The Nash–Sutcliffe model efficiency ranged from –1.65 to 0.83 for several models. The BC model had the lowest correlation coefficient and higher standard deviation (Figure 5). In contrast, the PT and Chapman methods were (i.e. lower standard deviation and higher Pearson's correlation coefficient) to the reference model. However, 90% of the selected models in the study had a correlation coefficient in the range of 0.90–1.0. For 2016–20, the CC, coefficient of determination, MAE, MBE, RMSE, Nash–Sutcliffe efficiency coefficients for the PT model were 0.92, 0.83, 0.48, –0.17, 0.74, 0.83 respectively (Table 2). In contrast to the PT model, the CC, R^2, MAE, MBE, RMSE and Nash–Sutcliffe efficiency coefficients of the MB model were 0.81, 0.65, 2.53, 2.49, 2.91, –1.65

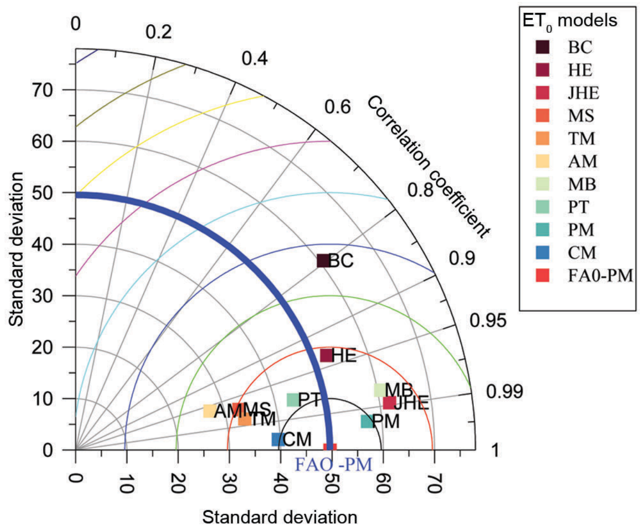

Figure 5. Correlation coefficient and standard deviation among ET_o models.

respectively, for the period 2016–20. The Chapman and Turc models ranked second and third respectively, and can be recommended as alternative best-performing models for the study region. Similar findings have been reported in the literature[2,29,32–34].

Ranking of ET_o estimation method

The ET_o estimation methods were ranked according to their accuracy compared to the FAO-PM model. In Table 2, the prediction of ET_o is ranked in decreasing order as PT, CM, TM, JH, AM, PM, MS, HM, BC and MB. Due to its lower RMSE, MBE, and greater CC and E_{NSC} values, the PT model is best for the study region. However, because of its larger RMSE value and poorer CC and E_{NSC}, the MB model is ranked last. Similar results have also been reported by Liu *et al.*[35].

Conclusion

In this study, we estimated the reference evapotranspiration using climatological data from 2016 to 2020, employing 11 models to identify the most suitable one in the cropped area of the New Bhupania minor command of WYCC. Results reveal that the performance of models differs in the estimated ET_o values. Moreover, the mean monthly estimation of ET_o by all models exhibits a similar trend. However, the BC, HE, JHE, MB, and PM models overestimate the ET_o value, whereas the MS, AM, TM, PT and CM models underestimate the same with reference to the standard FAO-PM method. The PT approach was observed to be the most reliable and ranked first. It can be used as an alternative to FAO-PM for data-scarce semi-arid regions. The MB model, on the other hand, underpredicts the ET_o value. The radiation-based models (PT and TM) which are generally developed for warm and humid climatic conditions, performed well in the study area, as expected. Besides, they required less data and were closely related to evapotranspiration estimated by the FAO-PM method. Therefore, we recommend the use of the PT model for estimating ET_o in the study area compared to other models, viz. MB, HM and JH. The PT model has demonstrated superior performance, especially in situations with limited availability of meteorological data. In addition, this method can also be used for irrigation scheduling.

Conflict of interest: The authors declare that they have no conflict of interest.

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Received 19 March 2022; accepted 10 February 2023

doi: 10.18520/cs/v124/i10/1181-1187