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Intercomparison of Estimates of Reference Evapotranspiration of Surat Region of Gujarat, India

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ABSTRACT

Evapotranspiration is a vital parameter for irrigation planning and management, and for hydrological and climatological studies. This can be estimated by using Blaney-Criddle (BC), Thornthwaite (TW), Hargreaves (HG) and Penman-Monteith (PM) methods. Out of these methods, BC and TW are known as temperature based whereas HG is radiation based and PM is based on Food and Agriculture Organization (FAO) report on crop water requirements. This paper illustrates a study on comparison on estimates of reference evapotranspiration (ETo) obtained from temperature, radiation and FAO based methods for Surat region. The meteorological data such as air temperature, relative humidity and sunshine hours observed at Surat region for the period 2001 to 2016 is used. In addition, the wind speed and solar radiation data is downloaded from the International Water Management Institute website and used in estimation of ETo using PM. The performance of the methods used in estimation of ETo is evaluated through regression analysis by developing a linear regression between the observed and estimated values of ETo using BC, TW and HG, and FAO based PM. The results of linear regression analysis indicated that there is a good line of agreement between the observed and estimated ETo using PM with CC of 0.968 when compared with those values of BC, TW and HG. The study show that the PM is better suited amongst four methods applied in estimating the ETo for Surat region, Gujarat.

Keywords: Blaney-Criddle, Correlation Coefficient, Evapotranspiration, Hargreaves, Linear Regression, Penman-Monteith, Thornthwaite

INTRODUCTION

Evapotranspiration (ET) is one of the important parameters for irrigation planning and management, and for various climatological studies. Most of the regions throughout the world do not have vegetation reference sites or installed reference evapotranspiration (ETo) networks because of the high installation and maintenance costs. This results in systematic use of improper weather data for ETo calculations from non-ideal sites. During the past half century, empirical and/or physically based equations have been developed to estimate ETo in various climatic regimes (Alexandris et al., 2006). Crop consumptive water is usually obtained by using a two-step approach. In the first step, an atmospheric demand indicator is calculated, namely ETo, in which the reference crop indicates an extensive surface of actively growing green grass with uniform height, completely shading the ground and not short of water. In the second step, ETo is turned into actual evapotranspiration (ET) (viz., ET=K_c*ETo) by considering a crop coefficient (K_c) depending on the crop type, stage of growth, canopy cover, and density and soil moisture (Marti et al., 2011).

A number of methods are available for estimation of ETo. Out of these methods, Blaney-Criddle (BC), Hargreaves (HG), Priestley and Taylor (PT), Thornthwaite (TW) and FAO based Penman-Monteith (PM) are generally used for estimation of ETo (Hargreaves and Samani, 1985; Trajkovic and Kolakovic, 2009; Tabari et al., 2013; Afandi and Abdrabbo, 2015; Guan et al., 2021). BC and TW methods are known as temperature based whereas HG is radiation based and PM is based on Food and Agriculture Organization (FAO) report on crop water requirements (Valiantzas, 2013). George et al. (2002) evaluated ETo equations at three sites in India and Davis, California. They found that PT method underestimated the ETo in two sites in India that have humid climates. Dehghani Sanij et al. (2004) examined the ETo estimates obtained by using PM, Wright–Penman, BC, PT and HG methods against experimentally determined values. They found that the PM method gave the most reliable estimates compared to lysimeter data.

Lopez-Urrea et al. (2006) examined the accuracy of seven empirical methods for calculating the average daily ETo in a semiarid climate of Spain and indicated that Hargreaves method was the most accurate. Trajkovic and Kolakovic (2009) examined the methods of HG and Samani, TW, Turc and PT for estimating ETo under humid conditions. They found that the Turc was the most suitable method for estimation of ETo. Tabari et al. (2013) investigated the accuracy of four ETo equations with small weather data requirements in four different climates. He concluded that the Turc method performed the best in estimating ETo for cold humid and arid climates.

Murugappan et al. (2011) compared the results of ETo for Annamalai Nagar obtained from HG, calibrated HG and PM methods. They found that both HG and calibrated HG equations provided better ETo estimates for longer time steps. Paparrizos et al. (2014) compared the results of ETo obtained from 13 different approaches using the daily and monthly data of Lamia which is located within Sperchios river valley in central Greece. Mashru and Dwivedi (2016) applied seven different methods for estimation of ETo for the Junagadh city of Gujarat, India. They found that the BC, Modified PM, Jensen-Haise and PT are the alternative methods to PM for better estimate of ETo. Studies on estimation of ETo by Hsin-Fu Yeh (2017) revealed that the radiation-based methods are better than temperature-based methods, as temperature is most likely to be the only meteorological parameter required in empirical formula of temperature-based methods. Djaman et al. (2019) expressed that the PM method showed good performance under missing solar radiation, relative humidity and wind speed and could still be adapted under limited data conditions across New Mexico. Ferreira and da Cunha (2020) made an attempt to estimate the daily ETo by employing random forest, extreme gradient boosting, artificial neural network and convolution neural network models with available hourly meteorological data (temperature and relative humidity or only temperature). Study by Juan Pinos (2022) revealed that the quality of input data and direct measurements play a key role for estimation of ETo using empirical, regression and machine learning models. Moreover, when number of methods used in estimation of ETo, a common problem that arises is how to determine which method fits best for a given set of data. This possibly could be evaluated by regression (REG) analysis by developing a linear regression between the observed and estimated ETo with correlation coefficient (CC).

This paper presents the procedures applied in estimation of ETo using BC, TW, HG and PM methods, identify the best method for estimation of ETo of Surat region using REG, and the results obtained thereon.

MATERIALS AND METHODS

The effort made in this study is to evaluate the performance of the methods applied in estimation of ETo. For this, the method of approach consists various steps viz., (i) pre-processing and validates the meteorological data; (ii) apply various selected methods for estimation of ETo; (iii) evaluate the performance of the methods applied in ETo through REG and (iv) analyze the results for selection of best suitable method. The methods based on temperature, radiation and FAO applied in estimation of ETo are briefly described in the following sections.

Blaney-Criddle method

Blaney-Criddle (BC) proposed an empirical relation (Manikumari, 2016), which is largely used by irrigation engineers to calculate crop water requirement of various crops. Estimation of ETo (consumptive use) is carried out by correlating it with sunshine temperature. The general form of the equation involved in estimation of ETo for a crop during its growing season is given by:

$$ETo = \sum KF \text{ and } F = P(0.457T_m + 8.128)$$

Where, K is the monthly crop efficient to be determined from experimental data, F is the monthly consumptive use factor, ETo is the reference evapotranspiration (in mm), T_m is the mean monthly temperature (in ^oC) and P is the monthly percentage of bright sunshine hours in a year.

Thornthwaite method

Thornthwaite (TW) developed an exponential relationship between mean monthly temperature and mean monthly consumptive use (T_e) (Thornthwaite, 1948; Pereira and Pruitt, 2004), which is given by:

$$ETo = 1.62 R_f \frac{(10\,T_m)^a}{T_e}$$

Where, R_f is the reduction factor and a the constant factor that can be computed from:

$$a = 0.4923 + (0.01792)T_e - (0.0000771)T_e^2 + +(0.000000675T_e^3)$$

Where, T_e is the annual temperature efficiency index and given by $T_e = \sum_{j=1}^{12}\left(\frac{T_m}{5}\right)^{1.514}$

For the period of one month, T_e is calculated as

$$T_e = \left(\frac{T_m}{5}\right)^{1.514}$$

Hargreaves method

Hargreaves (HG) developed an equation (Manikumari, 2016) for estimating ETofor varying periods from days to month using solar radiation and mean temperature, which is given as below:

$$ETo = (0.0075)\,R_S T$$

Where, R_s is the solar radiation at surface in equivalent water evaporation, T is the mean temperature (°C) for the period. This equation was further improved by including relative humidity and corrections to other climatic factors, and given by:

$$ETo = (0.0075) T K_t R_a T_d^{0.5}$$

Where, R_a is extra-terrestrial radiation (in mm) of water evaporation, T_d is the mean maximum minus mean minimum temperature (°F) and K_t is the coefficient for temperature (°F) that is given as below:

$$K_t = 0.035(100 - RH)^{0.333}$$

Where, RH is the relative humidity (in %).

Penman-Monteith method

Penman developed a theoretical formula based on the principles of both energy budget and mass-transfer approaches to calculate ETo (FAO, 1977). A simple energy budget neglecting all minor losses can be written as:

$$ETo = \frac{(HA + \alpha E_a)}{(A + \alpha)}$$

Where, H is the heat budget of an area with crops which is the net radiation (in mm) of evaporable water per day, ETo is the daily evapotranspiration from free water surface (in mm/day), α is a constant (called psychometric constant whose value is 0.49 mmHg/°C or 0.66 mb/°C), A is the slope of the saturated vapour pressure versus temperature curve at mean air temperature, E_a is the drying power of air which includes wind velocity and saturation deficit, which is estimated from the following relation

$$E_a = 0.002187\ (160 + u_2)(e_s - e_a)$$

Where, u_2 is the mean wind speed (in km/day) measured at 2m above the ground, e_s is the saturation vapour pressure at mean air temperature (in mmHg) and e_a is the actual vapour pressure in the air (in mm of mercury).The daily net radiation (H in mm) of evaporable water and is estimated from the energy budget theories using the relation

$$H = H_a(1 - r)(0.29\cos\phi + 0.55(n/N) - \sigma T_a^4(0.56 - 0.092\sqrt{e_a})(0.10 + 0.9(n/N))$$

Where, H_a is the extra-terrestrial solar radiation received on a horizontal surface (in mm) of evaporable water per day, ϕ is the latitude of the place where ETo is to be computed, r is the reflection coefficient whose values for close crops may be taken as 0.15 to 2.5 whereas 0.05 to 0.45 for barren land and 0.05 for water surface, n is the actual duration of bright sunshine which is a function of latitude and is an observed data at a place, N is the maximum possible hours of bright sunshine available at different location, σ is the Stefan-Boltzman constant (viz., 2.01 x 10^{-9} mm/day), T_a is the mean air temperature (in °F=(273+°C)) and e_a is the actual vapour pressure (in mm of Hg). The wind speed measured at any other height (z) can be reduced to 2 m height by the relation

$$u_2 = u(2/z)^{0.143}$$

Regression analysis

In this paper, the performance of the methods applied in estimation of ETo using BC, TW, HG and PM methods is analyzed through REG analysis with Correlation Coefficient (CC). The general form of the REG (Paparrizos et al., 2014; Mashru and Dwivedi, 2016; Hsin-Fu Yeh, 2017) between the observed (X) and estimated (Y) values of ETo is defined by:

$$Y = a + Xb$$

Where, X is the independent variable, Y is the dependent variable, a and b are regression coefficients that are computed by using method of least square.

$$b = \frac{\sum_{i=1}^{N} Y_i \sum_{i=1}^{N} X_i - N\sum_{i=1}^{N} X_i Y_i}{\left(\sum_{i=1}^{N} X_i\right)^2 - N\sum_{i=1}^{N} X_i^2}$$

$$a = \overline{Y} - b\overline{X}$$

Where, X_i is the observed ETo for i^{th} sample, Y_i is the estimated ETo for i^{th} sample, $\overline{X}$ is the average of observed ETo, $\overline{Y}$ is the average of estimated ETo and N is the number of samples. The CC between the observed and estimated ETo using four methods (viz., BC, TW, HG and PM) can be computed from:

$$CC = \left[\frac{\sum_{i=1}^{N}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{N}(X_i - \overline{X})^2\left(\sum_{i=1}^{N}(Y_i - \overline{Y})^2\right)}}\right]$$

Selection criteria: The method with good line of agreement between the observed and estimated values and high CC is considered as better suited for estimation of ETo.

Application

In this paper, a study on comparison of estimates of ETo using BC, TW, HG and PM methods for Surat region was carried out. Figure 1 shows the index map of the study region. The monthly maximum temperature (T_{max}), monthly minimum temperature (T_{min}), mean monthly temperature (T_{mean}), monthly relative humidity (RH) and actual hours of bright sunshine for the period 2001 to 2016 observed at Surat IMD observatory was collected from India Meteorological Department (IMD) and used in the study. By using the observed data, the average of T_{max}, T_{min}, T_{mean} and RH for the months from January to December was computed and is presented in Table 1. Data on wind speed and solar radiation were not available for the climatic stations in lower Tapi basin. Hence, the wind speed and solar radiation data wascollected from International Water Management Institute and used in computing the ETo by PM.

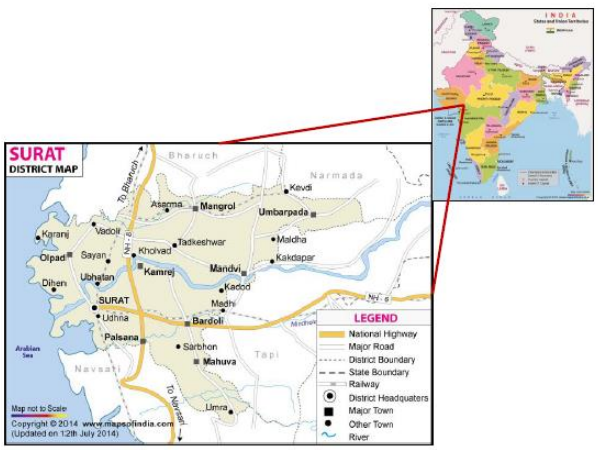

Figure 1. Index Map of the Study Region

Table 1. Monthly maximum, minimum and mean temperature and relative humidity with descriptive statistics

Month	T_{max} (°C)	T_{min} (°C)	T_{mean} (°C)	RH (%)
January	30.1	14.7	22.4	60
February	32.2	16.6	24.4	55
March	35.4	20.2	27.8	50
April	36.5	24.1	30.3	40
May	35.2	27.6	31.4	40
June	33.4	27.5	30.5	60
July	31.0	26.3	28.7	85
August	30.2	25.8	28.0	80
September	31.8	25.5	28.6	70
October	34.8	22.9	28.9	45
November	34.2	19.4	26.8	60
December	31.6	16.3	23.9	58
Descriptive statistics				
Average	33.0	22.2	27.6	58.6
Standard Deviation	2.174	4.634	2.793	14.318
Minimum	-	14.7	22.4	40.0
Maximum	36.5	-	31.4	85.0

From Table 1, it is noticed that the monthly T_{max} of the study region vary between 30.1 °C and 36.5 °C while the monthly T_{min} varies from 14.7 °C to 27.6 °C. The mean monthly temperature (T_{mean}) in the month of May is found as maximum with a value of 31.4 °C. The RH for the period of four months from June to September varies between 60 % and 85%.

RESULTS AND DISCUSSION

By applying the procedures, as described above, the monthly ETo was computed by using BC, TW, HG and PM methods, and the results are presented with observed ETo in Table 2.

From Table 2, it is noted that the estimated ETo using TW is closer to those values of PM for the months of April and May. The results showed that there is a little difference between the observed and estimated ETo using TW for the months from April to June and October. Also, from Table 2, it is noted that the percentage of variations between the average ETo obtained from BC and TW methods with reference to the average observed ETo are about 4% and 5% respectively. The coefficient of variance on the estimated ETo by BC, TW, HG and PM methods vary between 13.3% and 59.6%. Figure 2 presents the time series plots of the observed and estimated monthly ETo using BC, TW, HG and PM methods.

Table 2. Observed and estimated monthly ETo with descriptive statistics

Month	Observed	Estimated ETo (mm)			
	ETo (mm)	BC	TW	HG	PM
January	124.7	141.5	63.3	69.5	72.5
February	136.6	139.3	85.3	78.4	95.8
March	199.9	174.9	165.1	112.8	148.8
April	242.9	186.9	236.2	124.4	207.0
May	296.4	205.3	293.3	127.3	307.5
June	222.7	198.1	256.2	116.4	172.8
July	129.6	196.0	205.7	109.1	55.8
August	125.4	187.2	183.0	103.0	39.7
September	136.9	175.7	182.1	98.9	79.2
October	189.8	174.0	183.8	101.1	137.0
November	190.9	154.1	128.0	82.5	102.0
December	166.2	145.5	81.5	69.9	94.9
Descriptive statistics					
Average	180.2	173.2	172.0	99.4	126.1
Standard Deviation	54.3	23.1	71.9	20.2	75.2
Minimum	124.7	139.3	63.3	69.5	39.7
Maximum	296.4	205.3	293.3	127.3	307.5

BC: Blaney-Criddle; TW: Thornthwaite; HG: Hargreaves; PM: Penman-Monteith

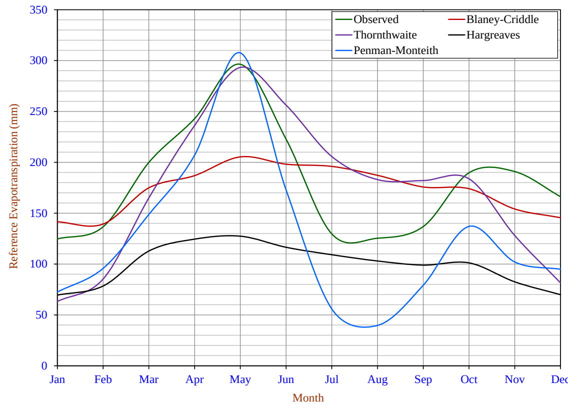

Figure 2. Observed and estimated ETo using BC, TW, HG and PM methods

Analysis of results based on regression analysis

By applying the procedure of REG, as described above, the linear regression between the observed and estimated ETo using BC, TW, HG and PM methods were developed and are shown in Figure 3. By using the observed and estimated ETo, a cross correlation matrix was formulated and is presented in Table 3. From Table 3 and Figure 3(d), it can be seen that there is a good line of agreement between the observed and estimated ETo using PM with CC value of 0.968. Based on the results of regression analysis, the PM is found to be a good choice for estimation of ETo for the region under study.

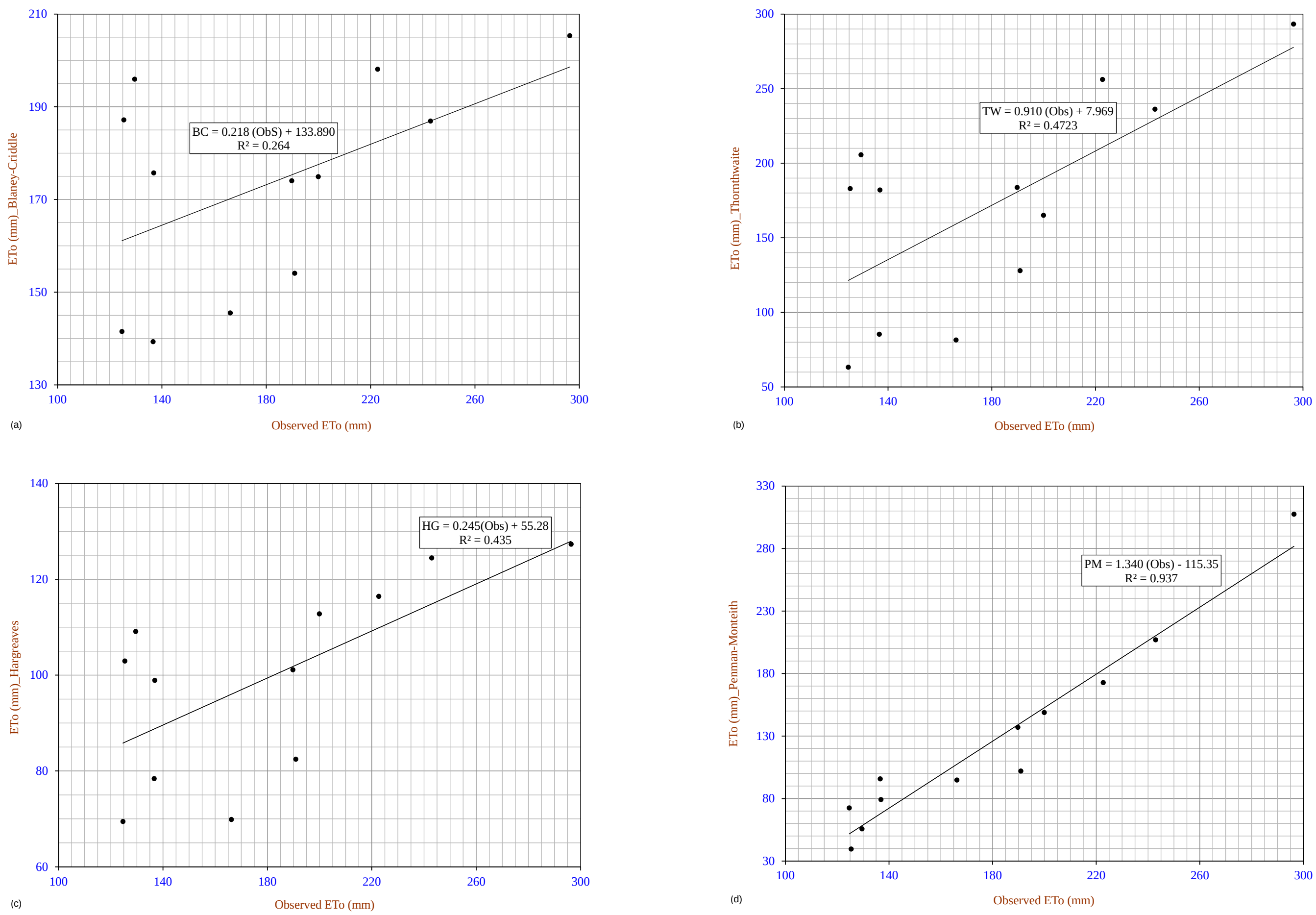

Figure 3. Regression between observed and estimated ETo using BC, TW, HG and PM

Table 3. Cross correlation matrix between observed and estimated ETo using BC, TW, HG and PM methods

Reference Evapotranspiration (ETo)	Observed	BC	TW	HG	PM
Observed	1.000	-	-	-	-
Blaney-Criddle (BC)	0.514	1.000	-	-	-
Thornthwaite (TW)	0.687	0.962	1.000	-	-
Hargreaves (HG)	0.660	0.930	0.648	1.000	-
Penman-Monteith (PM)	0.968	0.486	0.666	0.648	1.000

CONCLUSIONS

This paper presented a study on comparison of BC, TW, HG and PM methods applied in estimation of ETo of Surat region, Gujarat. The selection of best method was evaluated through regression analysis with correlation coefficient. On the basis of the results, some of the conclusions drawn from the study were summarized and are given as below:

i) Analysis based on estimates of ETo:
   a) Estimated monthly ETo using TW is nearer to the observed data from April to June and October whereas the estimated value of PM is closer to the observed values for April and May.
   b) Estimated ETo using HG is found to be lower than those values of BC and TW for the months from February to December.

ii) The CC obtained from the estimated ETo using BC, TW, HG and PM vary between 0.514 and 0.968.

iii) Results of regression analysis indicated that there is a good line of agreement between observed and estimated ETo using PM with CC value of 0.968, which is closer to the perfect correlation value of 1.000.

iv) The study identified that PM is better suited amongst four methods studied in estimation of ETo. The results showed that the estimated monthly ETo using PM vary from 39.7 mm to 307.5 mm.

The study suggested that the estimated ETo values using PM method could be considered as the design parameter for irrigation planning and management, and for hydrological and climatological studies of the region.

DECLARATIONS

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Conflict of interest

The authors hereby confirm that there is no conflict of interest.

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