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A COMPARISON OF FIVE POTENTIAL EVAPOTRANSPIRATION METHODS FOR BILIGIHOLE WATERSHED IN WESTERN GHATS OF INDIA

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ABSTRACT: Evapotranspiration is an important component in water-balance and irrigation scheduling models. While the FAO-56 Penman-Monteith method has become the de facto standard for estimating reference evapotranspiration (ETo), it is a complex method requiring several weather parameters. Required weather data are oftentimes unavailable, and alternative methods must be used. Four alternative ETo methods, the Hargreaves, Turc method, Makkink method and Preistley-Taylor method were evaluated for use in Biligihole watershed with the available data using only measurements of air temperature. The Hargreaves equation, developed for use with measured temperature was tested and found to provide better estimates of FAO-56 ETo than the other methods.

Index terms: Reference Evapotranspiration; FAO-56; Penman-Monteith; Turc; Hargreaves; Reduced Set; Irrigation Scheduling

1. INTRODUCTION

Evapotranspiration (ET) is an important component in water-balance models and irrigation scheduling, and is often estimated in a two-step process. The evaporative demand of the environment is estimated based on weather conditions, and is often estimated as the evapotranspiration from a theoretical, reference grass crop (ETo) with the crop defined as an actively growing, uniform surface of grass, completely shading the ground, and not short of water [1]. The ETo value is then adjusted to estimate the evapotranspiration of the particular crop of interest using a crop-specific crop coefficient [2].

Many methods have been proposed for estimating *ETo* based on weather data, and range from locally developed, empirical relationships to physically based energy- and mass-transfer models. To allow for greater understanding, sharing, and intercomparison of

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evapotranspiration information worldwide, under varying climatic and agronomic conditions, a standardized method of estimating *ETo* was developed [2], referred to as the *FAO*-56 Penman-Monteith method. While the *FAO*-56 method has become the de facto standard worldwide for estimating *ETo*, it is a complex method requiring several weather parameters, including air temperature, humidity, solar radiation, and wind speed, to be measured under strict instrumentation and maintenance conditions.

While there is no consensus on the most appropriate method to use when required data are not available [3], two methods are recommended [2]. One method involves using a reduced set of weather data, estimating missing weather parameters, and inputting these to the standard *FAO*-56 method. Air temperature is commonly measured, and procedures are outlined for estimating missing humidity, solar radiation, and wind speed data. A second recommendation is to use the Hargreaves equation [4], an empirical model based on air temperature and extraterrestrial radiation. This method requires only air temperature as input, estimating the radiation term from air temperature data.

Researchers from many parts of the world have compared available reference *ET* equations to the *FAO*-56 method to determine suitable alternatives for use in their regions, including the *FAO*-56 reduced-set method [5-7]. A number of these efforts have been aimed at identifying methods suitable for use in humid regions [8-12]. One method which has consistently performed well under humid conditions is that of Turc [13]. The Turc method is an empirical equation which uses only air temperature and solar radiation as inputs, and is simple to implement. While the Turc method was originally developed with solar radiation as an input, the radiation term could be estimated in a manner similar to that used in the Har- greaves method, making it possible to use this method based only on air temperature.

The objective of this study was to evaluate alternative methods of estimating reference *ET* (*ETo*) under humid conditions when weather data are limited to only air temperature. Three alternative methods were tested: 1) the *FAO*-56 method with a reduced set of weather data as input, 2) the Hargreaves equation, and 3) the Turc equation with estimated solar radiation. *ETo* estimates from these alternative methods and limited weather data were evaluated by comparing the estimates to those made us- ing the *FAO*-56 method and a complete set of weather data.

2. MATERIALS AND METHODS

2.1. *ETo* Estimation Methods

2.1.1. *FAO*-56 Method

The *FAO*-56 Penman-Monteith method [2] for estimat- ing reference evapotranspiration on a daily time scale is written as

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T_{mean} + 273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where *ETo* = reference evapotranspiration (mm·day−1), *Rn* = net radiation (MJ·m−2), *G* = soil heat flux (MJ·m−2), *T*mean = average air temperature (°C), *u*2 = wind speed at 2-m height (m·s−1), *es* = saturation vapor pressure (kPa), *ea* = actual vapor pressure (kPa), Δ = slope of vapor pressure curve (kPa·°C−1), and *γ* = psychrometric constant (kPa·°C−1). Supporting equations, tables, and descriptive information for determining each of the terms in the equation are extensive, and are detailed in [2]. To simplify the implementation of the *FAO*-56 method, computer software, such as RefET: Reference Evapotranspiration Calculator [14], are available. RefET, which was used in this study, performs all calculations based on weather data input by the user.

2.1.2. Reduced-Set Method

When the complete set of weather data required for the *FAO*-56 method are not available, procedures are described for using a reduced set of weather data as input [2]. While air temperature measurements are almost always available, reliable measurements of solar radiation, relative humidity, and wind speed may not be. Extensive discussion and methods for estimating missing values are presented based on temperature measurements and historical and general knowledge of local environmental conditions. The reduced set of values, consisting of mea- sured data and estimated values, is then input to the *FAO*-56 equation, **Eq.1**. In this study, this method (hereafter referred to as the *FAO*-56 RS method) was used to estimate *ETo* assuming the availability of maximum and minimum air temperatures only.

2.1.3. Hargreaves Method

The Hargreaves method [4] estimates *ETo* based on maximum and minimum air temperature, and is written as

$$ET_0 = 0.0023R_a\left(\frac{T_{max} + T_{min}}{2} + 17.8\right)\sqrt{T_{max} - T_{min}} \quad (2)$$

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where *T*max = maximum air temperature (°C), *T*min = minimum air temperature (°C), *Ra* = extraterrestrial radiation (MJ·m−2), and 0.408 is a factor to convert MJ m−2 to mm. Extraterrestrial radiation, *Ra*, is estimated based on the location's latitude and the calendar day of the year by

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s) \right] \tag{3}$$

where *Gsc* = solar constant (0.0820 MJ·m−2·min−1), φ = latitude (radians), converted from degrees latitude to radians (radians = degrees(π/180)), and the term 24(60) is a factor to convert min to day.

Based on the calendar day of the year, remaining factors are determined:

$$d_r = 1 + 0.33\cos\left(\frac{2\pi}{365} J\right) \tag{4}$$

where *dr* = inverse relative distance from earth to sun, and *J* = calendar day of the year,

$$\delta = 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{5}$$

where δ = solar declination (radians), and

$$\omega_s = \arccos\left(-\tan(\varphi)\tan(\delta)\right) \tag{6}$$

where ωs =sunset hour angle (radians).

2.1.4. Turc Method

The Turc method [13] estimates monthly *ETo* based on measurements of maximum and minimum air temperature and solar radiation using the equation

$$ET_o = 0.40\left(\frac{T_{\text{mean}}}{T_{\text{mean}} + 15}\right)(R_s + 50) \tag{7}$$

where *ETo* = reference evapotranspiration (mm·mon−1), *Rs* = solar radiation (MJ·m−2), and *T*mean = average air temperature (°C) calculated as (*T*max + *T*min)/2. To esti- mate *ETo* on a daily basis, the factor 0.40 is divided by 30 (average days per month), and **Eq.7** becomes

$$ET_o = 0.0133\left(\frac{T_{\text{mean}}}{T_{\text{mean}} + 15}\right)(R_s + 50) \tag{8}$$

where ET_o = reference evapotranspiration (mm·day^{-1}).

To estimate ET_o using the Turc equation with only air temperature as input, measurements of solar radiation, *Rs*, in **Eq.8** are replaced with estimates made using the method developed by Hargreaves and Samani [15] and used in the Hargreaves equation (**Eq.2**):

$$R_s = 0.16(T_{max} - T_{min})^{0.5} R_a . \qquad (9)$$

2.1.5. Priestly-Taylor Method

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

$$ET = \alpha \frac{\Delta}{\Delta + \gamma} \frac{R_n}{\lambda} \qquad (10)$$

where Rn is the net radiation (cal/cm2 day), and other notations have the same meaning and units as in Equation (4). In this study, owing to a lack of observation data, Rn is estimated using an equation proposed by Linsley et al. (1982)

$$R_n = 7{\cdot}14 \times 10^{-3} R_s + 5{\cdot}26 \times 10^{-6} R_s (T + 17{\cdot}8)^{1{\cdot}87} - 3{\cdot}94 \times 10^{-6} R_s^2 - 2{\cdot}39 \times 10^{-9} R_s^2 (T - 7{\cdot}2)^2 - 1{\cdot}02 \qquad (11)$$

where Rn is in equivalent millimetres of evaporation per day.

2.1.6. Makkink Method

Makkink (1957) estimated ET in millimetres per day over 10-day periods for grassed lands under cool climatic conditions of the Netherlands as:

$$ET = 0{\cdot}61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{58{\cdot}5} - 0{\cdot}012 \qquad (12)$$

where Rs is solar radiation in equivalent millimetres of evaporation per day. D is the slope of the saturation vapour pressure curve (in mbar/ 8C), g (in mbar/ 8C) is the psychromatic constant. These quantities are calculated as (see also Singh, 1989):

$$\Delta = 33{\cdot}8639[0{\cdot}05904(0{\cdot}00738\,T + 0{\cdot}8072)^7 - 0{\cdot}0000342] \qquad (13)$$

$$\gamma\ (\text{mbar}/^\circ\text{C}) = \frac{c_p P}{0{\cdot}622\lambda} \qquad (14)$$

$$\lambda\ (\text{cal/g}) = 595 - 0{\cdot}51\,T \qquad (15)$$

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$$P = 1013 - 0{\cdot}1055EL \tag{16}$$

where EL is elevation (in meters), λ (in calories per gram) is latent heat, and P (in mbar) is atmospheric pressure. The specific heat of air c_p (in cal/g/ 8C) varies slightly with atmospheric pressure and humidity, ranging from 0.2397 to 0.260. An average value of 0.242 is reasonable.

3. STUDY AREA

The Western Ghats, locally called as ‘Sahayadri Mountains’, is a range of mountains in the peninsular India running approximately parallel to the West coast and home to the largest tracts of moist tropical forests in the country. Uttara Kannada district in Karnataka state has the biggest share of moist tropical forests. The district straddles the Ghats, which are at their lowest elevation here (<600m) and are about 20-25 km inland. East of the crest line of the Ghats are rolling hills with forested slopes and shallow valleys with cultivation. This region, locally known as the Malnad, covers most of the Siddapur, Sirsi and Yellapur talukas. The selected watersheds are located in Siddapur taluk.

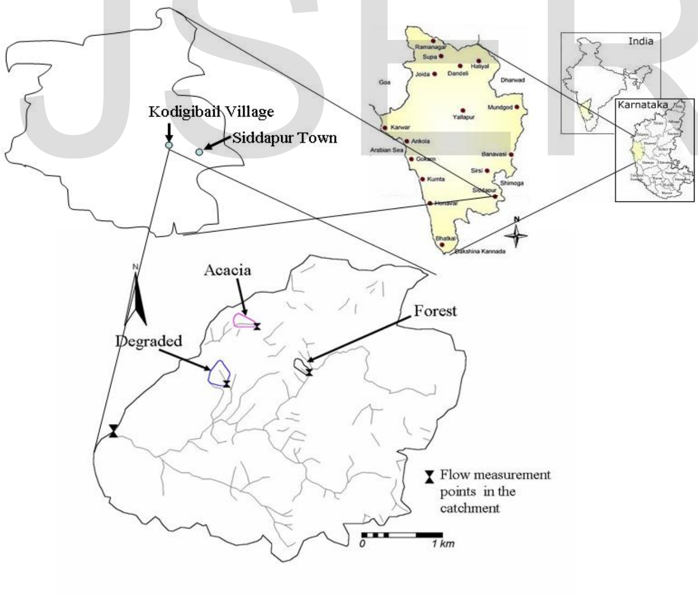

Figure 1. : Index map of the study area

The Biligihole watershed is of 28 km^2 area and possesses a complex land-use system. The major landuses in the watershed are forest, plantation forest, Soppinabetta and garden plantation mainly with arecanut. A number of instruments such as minimum and maximum temperature thermometer, dry and wet bulb temperature and pan evaporimeter were used for observation from 2004 to 2014. Theses available data are being used in the present analysis.

4.0 Comparison of the performance of different methods relative to FAO-56 PM

The performances of the tested methods were analysed by computing the standard error of estimate SEE of the ET_o between the FAO-56 PM and other methods. The SEE is computed following the equation presented by Irmak et al. (2003) as;

$$SEE = \sqrt{\frac{1}{n(n-2)}\left[n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2 - \left[\frac{[n\sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)]^2}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}\right]\right]}$$

Where x_i ET_o estimated using FAO-56 PM (mm/day); y_i ET_o estimated using other equation (mm/day) and "n" is the sample size.

In addition to SEE, the following statistics were used in this paper to evaluate the performance of various methods against the FAO-56 PM method. The statistics such as maximum absolute different (MXE), mean absolute difference (MAE), root mean square difference (RMSD), adjusted root mean square different (ARMSD), weighted root mean square difference (WRMSD), slope of the regression equation (b) and coefficient of determination (r^2) were computed.

The MXE and MAE values are defined as;

$$MXE = max\left(\left|ET_{PM,i} - ET_{eq,i}\right|\right)_{i=1}^{n}$$

$$MAE = \frac{\sum_{i=1}^{n}\left(\left|ET_{Pm,i} - ET_{eq,i}\right|\right)}{n}$$

The root mean square difference (RMSD) was calculated as follows;

$$RMSD = \left[\frac{\sum_{i=1}^{n}\left(ET_{PM,i} - ET_{eq,i}\right)^2}{n}\right]^{0.5}$$

Where ET_{pm} = ET_o estimated by the Standard (FAO-56 PM) equation (mm day^{-1}); ET_{eq} = corresponding ET_0 estimated by the comparison equation (mm day^{-1}), and "n" is the total number of observations. The root mean square difference (RMSD) is used when comparing two estimates rather than comparing an estimate with a measurement as with the standard error of estimate (SEE).

Liner regression analyses were made between the ET_0 estimates by the standard and comparison equation as follows;

$$ET_{pm} = b * ET_{eq}$$

Where, b is regression coefficient (slope). Regression through the origin was used to evaluate the goodness of the fit between ET_0 values estimated by the comparison equation and the standard equation because both values should theoretically approach the origin when the actual ET_0 is zero. The regression coefficient were used to adjust ET_0 estimates and RMSD were recalculated for the 'adjusted' values as follows;

$$ARMSD = \left(\frac{\left(\sum_{i=1}^{n}\left(ET_{PM,i} - ET_{eq,i}\right)^2\right)}{n}\right)^{0.5}$$

Where ARMSD is adjusted root mean square difference (mm day-1). The adjusted root mean square difference indicates the potential accuracy of the each equation in estimating ET_0 when a constant bias has been removed. The use of these two RMSDs (RMSD and ARMSD) provide information on both accuracy of unadjusted ET_0 values and ease with which the comparison equations can be corrected with a simple coefficient to fit ET_0. The RMSD values were calculated for all months. Then these values were used to compute the Weighted RMSD as follows (Jensen et al 1990);

$$WRMSD = 0.67*RMSD + 0.33* ARMSD$$

Where WRMSD is weighted root mean square difference (mm day^{-1}). RMSDs were weighted by two thirds weight was placed on the unadjusted RMSD and one third weight was placed on the RMSD of regression adjusted estimates. The resulting values of the weighted RMSD indicate the ability of equations to accurately estimate reference evapotranspiration during all the months and the ability to be adjusted using a liner multiplier.

5.0 Ranking of Equations

The final ranking of the equations was based on the weighted RMSD (Jensen et al. 1990) and the Standard Error of estimate (SEE). The weighted RMSD was selected as the appropriate ranking criterion because of the fact that this statistical parameter indicates the ability of equations and adjust equations to accurately estimate reference evapo-transpiration during all months. The Standard Error of Estimate (SEE) values provide the reliability of the estimates of the methods considered for the study. The average ranking from all the criterion was used to arrive at the best model, i.e., the best model is the one which has the lowest average ranking obtained by averaging the rankings.

6.0 RESULTS AND DISCUSSIONS

The data available from 2004 to 2015 for the study were used to estimate the Evapo-transpiration by five ET_0 methods on daily basis. In order to compare the results, the mean daily ET0 values were obtained by averaging daily results across the period of record and are tabulated in Table 1.

Table 1: Mean Daily ET_0 Estimates

Methods	Mean Daily ET_0 Estimates (mm/day)
Penman-Monteith Method (PMM)	4.52
Hargreaves Method (HM)	4.81
Turc Method (TM)	4.18
Preistley-Taylor Method (PTM)	3.76
Makkink Method (MM)	3.51

The mean monthly values of ET_0 are also calculated and tabulated in Table.2.

Table 2: Mean Monthly ET_0 Estimates

Methods	Mean Monthly ET_0 Estimates (mm/month)											
	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
PMM	4.57	5.54	5.95	6.06	4.66	3.69	3.44	2.89	4.26	4.35	4.34	4.26
HM	4.64	5.42	6.01	6.38	5.86	4.37	3.63	3.64	4.3	4.63	4.25	4.19
TM	4.13	4.7	5.08	5.29	4.9	3.83	3.28	3.29	3.79	4.03	3.78	3.77
MM	3.5	4.01	4.32	4.5	4.15	3.17	2.68	2.69	3.15	3.36	3.14	3.16
PTM	3.5	4.19	4.81	5.21	4.78	3.41	2.73	2.73	3.34	3.66	3.27	3.16

Comparison of different PET estimation methods are based on both temporal and spatial similarities. Among the methods studied, Hargreaves and Turc method show a similarity in temporal variation with FAO 56 PM method (Figure 2).

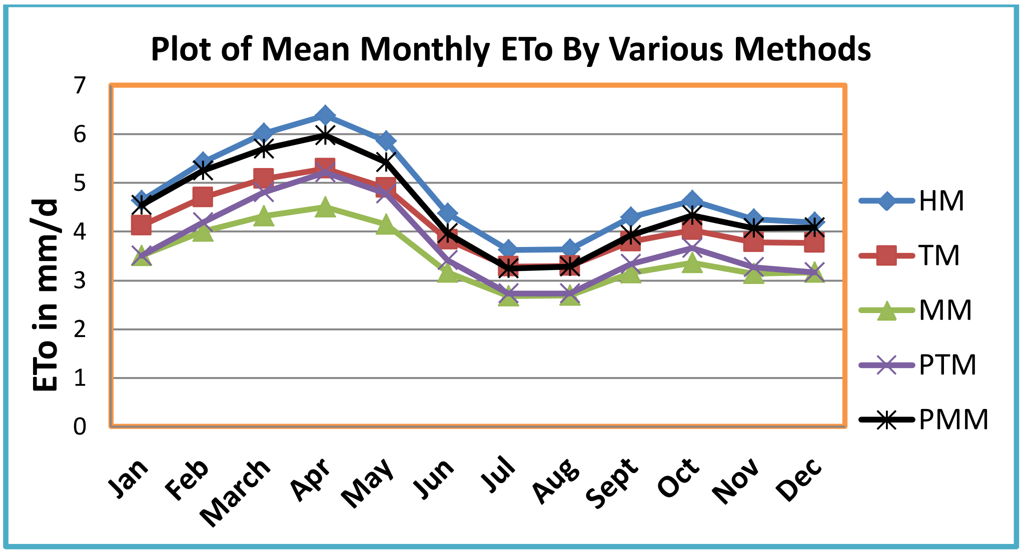

Figure 2: Plot of mean monthly ET_o values by various methods

Comparisons between the FAO 56 PM method and the other methods are particularly relevant given the popularity of the latter methods among Indian practitioners. This is more clearly evident from the scatter plots shown in figures 3 to 6 in which the daily comparisons for the individual days of record are shown.

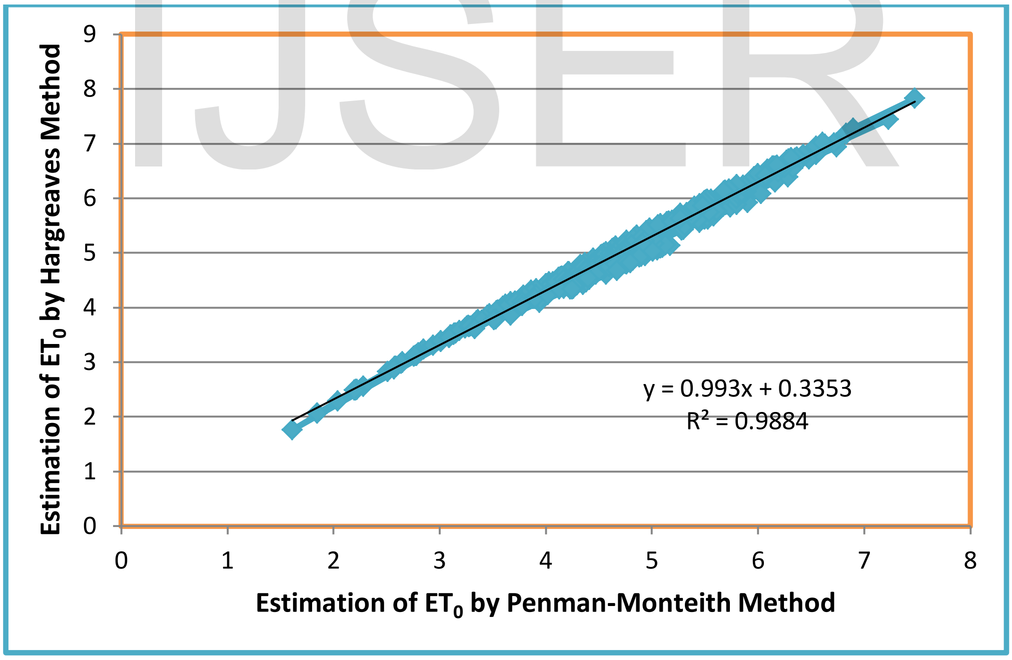

Figure 3: Scatter plot of ET_o values of PM method with Hargreaves method

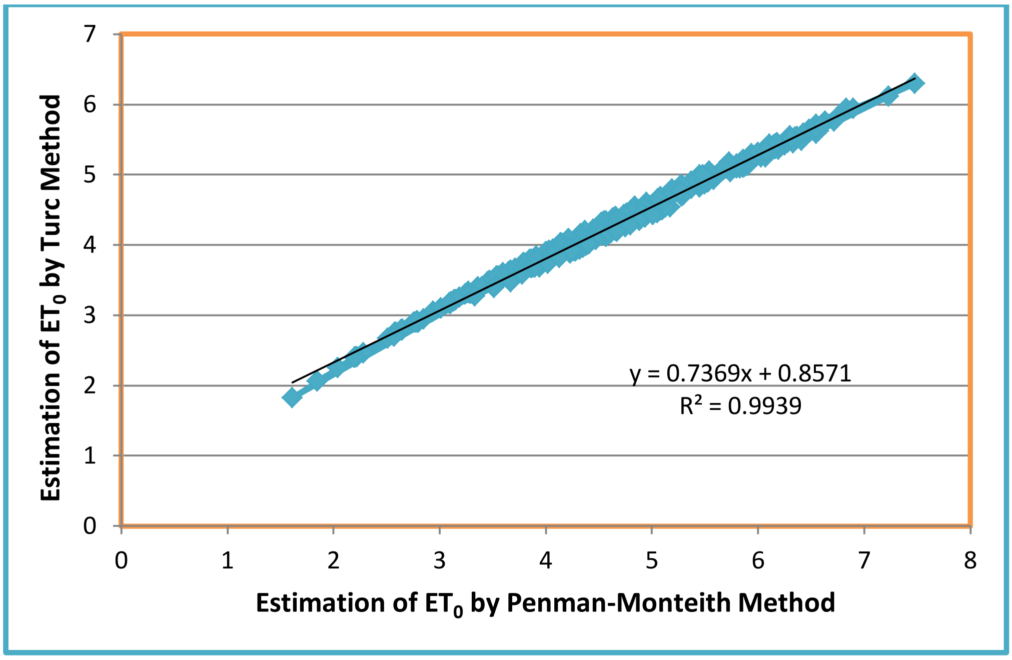

Figure 4: Scatter plot of ET_o values of PM method with Turc method

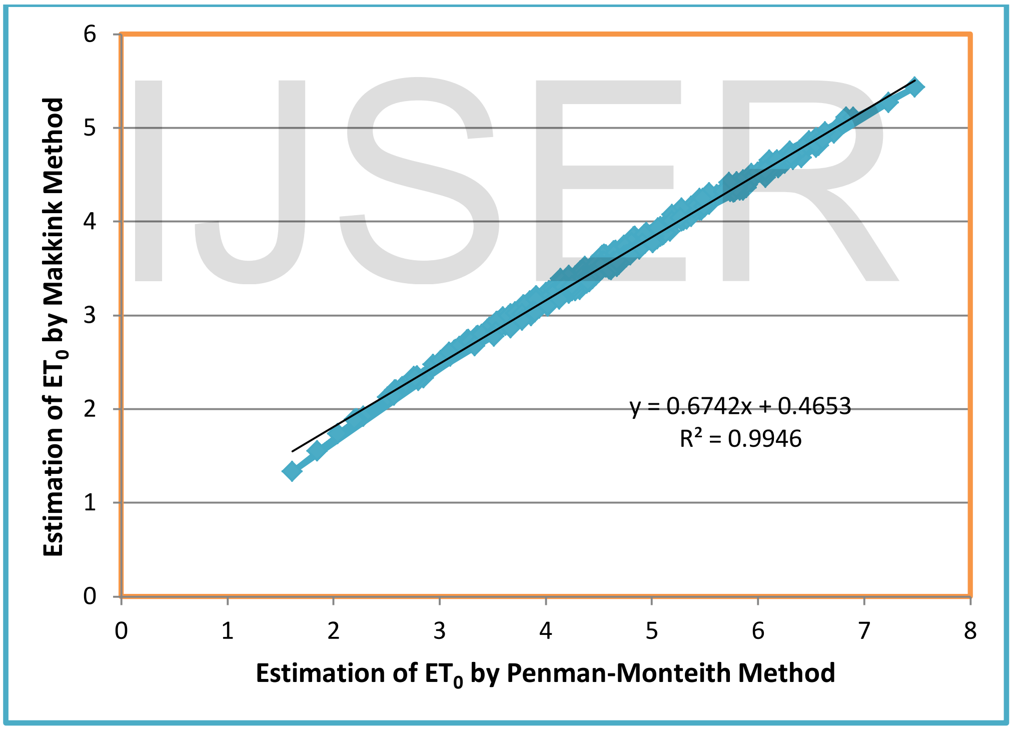

Figure 5: Scatter plot of ET_o values of PM method with Makkink method

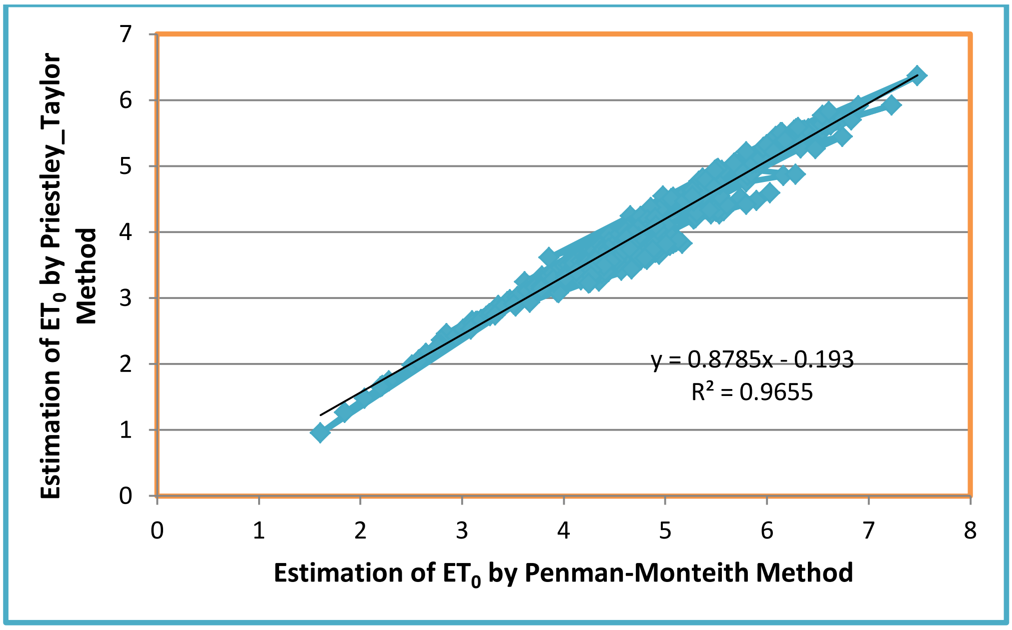

Figure 6: Scatter plot of ET_o values of PM method with Preistley-Taylor method

The coefficient of determination was calculated for each individual method with the FAO56 PM method. It is seen that all the the methods have noticeable correlation with the PM method. Hence various performance statistics were computed on the basis of individual comparisons between daily ET_o estimated by the FAO 56 PM method and each of the other methods. Methods were ranked separately on the basis of SEE, MXE, MAE, RMSD, R^2, ARMSD and WRMSD values. Since each statistic highlights a different aspect of model performance, an overall rank number calculated as the average of rank numbers from all the statistics computed for each method. From these results (Table 3), it is evident that for a given ETo method, considerable differences exist in rank numbers derived from the performance statistics and therefore the overall rank may prove useful in selecting the best method.

Table 3: Regression statistics of daily ETo comparisons by various methods with FAO 56 PM method

Methods	SEE	MXE	MAE	RMSD	R^2	ARMSD	WRMSD	Rank
Hargreaves	0.31(1)	0.47 (1)	0.29 (1)	0.101(1)	0.988(3)	0.304(1)	0.168(1)	1
Turc	0.592(4)	1.118 (2)	0.38 (2)	0.203(2)	0.993(2)	0.453(2)	0.255(2)	2
Makkink	0.384(2)	2.05 (4)	1.01 (4)	1.156(4)	0.994(1)	1.076(4)	1.129(4)	4
Preistley Taylor	0.441(3)	1.62 (3)	0.76 (3)	0.641(3)	0.965(4)	0.757(3)	0.678(3)	3

From the analysis, it is found that Hargreaves method performs better and therefore it is recommended as the empirical method for estimating the ETo values for the study area considered.

7.0 CONCLUSIONS

The present study was aimed at identifying an effective method of ET_0 estimation using the observed data of Biligihole in Karnataka. The observed data for the years from 2004 to 2014 were used to estimate the ETo values using four different methods and were compared with FAO-56 PM method. Following observation is made based on the results obtained through the analysis;

1. The Hargreaves method forms the upper bound and Makkink method formed the lower bound of ET_0 values.
2. The performance statistics shows that, the Hargreaves method performed better for the study area. However, the temporal variation indicates that, the method always estimated higher value in comparison of FAO-56 PM method

In conclusion, it can be stated that, considering the data requirement and the performance of different methods for estimating the ET_0 values, the Hargreaves method is best suited for the study area considered.

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