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Comparison of Different Methods to Estimate Mean Daily Evapotranspiration from Weekly Data at Patna, India

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Abstract

Estimation of evapotranspiration is necessary for efficient water management and crop planning. Fifteen different methods of ET_0 estimation were employed to compute daily reference evapotranspiration for the period 2010 to 2014. In the absence of reliable open pan evaporimeter data, FAO-56 Penman Monteith method was considered as one of the reliable method of ET_0 estimation. The results showed that mean weekly evapotranspiration values obtained from Penman-Monteith method were very closer to FAO-56 Penman-Monteith method and values from all the other methods except FAO- 24 Pan, Christiansen Pan and Hargreaves methods generally predicted higher values of mean weekly daily ET_0 in comparison to FAO-56 Penman-Monteith method. The analysis shows that mean weekly daily ET_0 estimates of combination methods resulted better ET_0 estimates than radiation, and temperature and evaporation methods. Weekly ET_0 values estimated by FAO-56 Penman-Monteith method were found to vary in the range of 1.3 mm/day to 6.7 mm/day. Average annual reference evapotranspiration was found as 1517.1 mm.

Keywords: Evapotranspiration; Penman-Monteith method; Pan evaporation; Crop water requirement

Acronyms

Δ=slope of vapor pressure versus air temperature curve (KPa °C^{-1})

R_n=mean daily net radiation (MJm^{-2}d^{-1})

G=soil heat flux (MJm^{-2}d^{-1})

γ=psychometric constant (0.0671 Kpa °C^{-1})

T=mean daily air temperature at 2 m height

U_2=wind speed at 2 m height (ms^{-1})

e_s=saturation vapor pressure (Kpa)

e_a=actual vapor pressure (Kpa)

e_s-e_a=vapor pressure deficit VPD (KPa)

TD=difference between mean monthly maximum and mean monthly minimum temperatures in °C

RA=extraterrestrial solar radiation in MJ m^{-2} d^{-1}

T_{mean} is mean monthly air temperature in °C

R_s'= solar radiation in cal cm^{-2} d^{-1}

R_s'=R_s/0.041869

R_s=Total incoming solar radiation (MJ m^{-2} d^{-1})

RH=Mean relative humidity

Λ=latent heat of vaporization (MJ kg^{-1})

T_{mean}=mean air temperature in °C

Δ=slope of saturation vapour pressure-temperature curve (kPa °C^{-1})

$e°_{mean}$ (kPa)=saturation vapour pressure at mean temperature

γ=psychometric constant (kPa °C^{-1})

C_p=specific heat at constant pressure in kJ kg^{-1} °C^{-1}

P=atmospheric pressure at elevation in kPa

R_n=net radiation (MJ m^{-2}d^{-1})

α=albedo as 0.23

R_s=short wave or solar radiation received at earth surface

R_b=the net outgoing thermal radiation

$E_{v=}$class A pan evaporation (cm/d)

$T_{mean=}$ mean air temperature in °C

W=wind speed in km/hr

RH_{mean}=the mean relative humidity in %

S=ratio of actual to maximum possible sunshine hours

$E_{pan=}$class A pan evaporation in mm/d

k_p=pan coefficient

$(e_z^0 - e_z)^{VPD\#1}$=vapour pressure deficit #1 (kPa) and equal to (e^0_{mean}- e^o_d)

e^0_{mean}=saturation vapour pressure at mean temperature

$e^o_{d=}$saturation vapour pressure at dew point temperature

W_f^{P1}=wind function for Penman (1963) VPD#1 method

u_2=wind speed measured at 2 m above the ground surface in ms^{-1}

k=von-Karman's constant and its value is equal to 0.41

u_z=horizontal wind speed at height z cm (m s^{-1})

d=zero plane displacement of wind profile in cm

Z_0=roughness length (cm) and it is set at arbitrary values of about 1/100 of crop height

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P=atmospheric pressure (kPa)

ρ=air density (kg m^{-3})

$W_f^{P3}=W_f^{P1}$

$(e_z^0 - e_z)^{VPD\#3}$=vapour pressure deficit #3 (kPa) and equal to 0.5 $(e^0_{min}+ e^o_{max}) - e_0^d$

u_d=day time wind speed

u_n=night time wind speed

Introduction

Crop water requirement mainly depends upon crop sowing date, crop growth stages, crop duration and climatic conditions during the growing season of an individual crop. A good estimate of evapotranspiration is essential for water balance irrigation scheduling and water resource planning and management. Since, direct measurement of ET_0 is difficult and time consuming, so most common practice is to estimate ET_0 from meteorological data available for the area employing empirical equations. There are numerous evapotranspiration equations developed and used by researchers but still there is confusion in selecting the reliable evapotranspiration estimation method for the area concerned. Some authors compared estimates of different ET_0 estimation methods for different regions of the world. Al-Ghobari compared five different methods: FAO-Penman, Jensen- Haise, Blaney and Criddle, Pan Evaporation and calibrated FAO-Penman for four areas under local conditions of Saudi Arabia [1]. The results showed that estimated ET values were highly correlated with measured evapotranspiration values. George et al. used DSS model for estimation of reference evapotranspiration for three climatic conditions: Davis, Jagdalpur, and Kharagpur by different applicable methods [2]. Comparison of the estimates of different methods with the Penman- Monteith ET_0 estimates showed that Hargreaves, FAO-24 Blaney Criddle and 1982 Kimberley- Penman methods ranked first, respectively for the Davis, Jagdalpur and Kharagpur stations. They recommended that DSS model is a user- friendly tool for estimating ET_0 under different data availability and climatic conditions. Itenfisu et al. made comparison between various methods of reference evapotranspiration with ASCE-Penman-Montieth equations in the United States [3]. Results showed that the ASCE standardized equation agreed best with full form of ASCE Penman-Montieth. The International Commission for Irrigation and Drainage and the Food and Agriculture Organization of the United Nations experts' consultation on revision of FAO methodologies for crop water requirements. Smith et al. recommended the use of FAO56-Penman-Monteith method as the standard method to estimate ET_0 [4]. Irmark et al. in north-central Florida, compared ET_0 values obtained from two equations derived from FAO56-PM (first equation was solar radiation (R_s) based and second net radiation (R_n) based) against FAO56-Penman-Monteith method and results were found correlated very well with the standard FAO56-Penman-Monteith method in all the locations [5]. Irmark et al. compared the estimates of 21 evapotranspiration methods with the estimate of FAO56- PM Method in humid climate of Florida [6]. The 1948 Penman method daily estimates were closest to the FAO56- PM method followed by 1963 Penman on the basis of standard error of estimate. Krishan et al. computed evapotranspiration rate for Pusa area in Bihar by various estimation methods [7]. They concluded that FAO-24 Penman(c=1) is the closest whereas Hargreaves method is the farthest. The objective of this study is to compare the estimates of various methods with the FAO56-Penman Montieth Method estimates and evaluate the performance of these methods for Patna canal command.

Methodology

Collection of meteorological parameters

In order to estimate daily reference evapotranspiration, available daily meteorological data for the period from 2010 to April 2015 were collected from automatic weather station located at 25° 27' North latitude and 85° 10' East Longitude in Indian Council of Agricultural Research- Research Complex for Eastern Region, (ICAR-RCER) Patna. These meteorological data include minimum and maximum temperature, minimum and maximum relative humidity, wind velocity, and solar radiation. Mean weekly meteorological parameters are presented below in Table 1.

It may be observed from the Table that mean maximum temperature varied from 18.9°C (1st week) to 37.4°C (17th week) and mean minimum temperature varied from 7.3°C (2nd week) to 26.8°C

Week No.	Max. Temp. (ºC)	Min. Temp. (ºC)	Relative Humidity Max. (%)	Relative Humidity Min. (%)	Wind Speed (m/s)	Solar Radiation, MJ/m²/ day
1	18.9	8.2	96.0	57.9	0.7	12.34
2	20.1	7.3	95.4	57.4	0.5	13.08
3	20.2	7.8	94.7	60.6	0.6	12.98
4	22.3	9.2	91.9	53.3	0.9	13.88
5	21.9	10.4	91.0	53.0	0.7	14.20
6	23.5	11.4	90.4	54.3	0.7	14.23
7	25.6	12.1	89.7	47.7	0.8	15.96
8	26.9	13.4	90.6	49.6	0.7	15.32
9	28.0	14.1	84.8	43.3	0.8	16.99
10	29.6	13.6	81.0	32.3	0.8	18.98
11	30.4	15.3	76.3	33.7	0.8	19.33
12	32.8	16.1	73.4	27.6	0.7	21.34
13	34.7	18.5	72.2	26.1	0.8	23.16
14	36.6	20.1	63.2	24.5	1.1	24.29
15	36.4	21.5	64.1	28.7	1.3	23.20
16	36.7	22.6	73.5	31.5	1.2	24.80
17	37.4	23.3	68.8	35.7	1.4	24.70
18	35.6	24.3	76.5	46.5	2.0	28.78
19	34.8	24.9	72.5	46.0	1.3	28.03
20	34.8	24.9	76.0	48.4	1.4	28.83
21	35.3	25.6	77.9	49.4	1.5	29.94
22	35.2	25.7	79.5	49.2	1.2	30.95
23	35.2	25.9	78.0	50.7	1.4	27.32
24	33.9	26.0	85.1	62.3	1.4	26.85
25	32.5	25.5	88.4	69.6	1.5	21.45
26	32.9	26.3	87.5	66.0	1.3	22.56
27	33.0	26.6	89.3	70.1	1.1	23.73
28	32.7	26.5	86.4	70.6	1.3	20.18
29	32.6	26.7	89.8	73.4	1.3	22.20
30	33.0	26.5	86.2	62.7	1.1	22.55
31	32.5	25.0	89.0	67.2	1.1	26.47
32	32.9	26.8	90.8	75.8	1.2	24.57
33	31.5	26.2	91.8	73.0	1.4	21.18
34	31.9	26.6	91.0	73.1	1.4	22.71
35	31.6	25.9	90.7	74.8	1.3	22.17
36	31.4	26.3	89.1	73.6	1.1	21.57
37	31.8	26.0	90.2	71.4	1.2	23.64
38	31.3	25.5	90.3	70.3	1.3	25.06
39	32.0	24.9	87.6	70.1	1.0	25.63
40	32.4	24.6	87.3	70.0	1.0	22.96
41	32.8	24.1	89.1	62.4	0.9	22.87
42	32.1	23.2	89.6	62.5	0.9	20.58
43	31.2	20.8	88.1	51.3	0.9	19.65
44	31.4	20.7	91.2	56.4	0.7	20.30
45	30.9	17.9	91.6	52.3	0.4	19.10
46	29.7	15.7	91.2	49.3	0.4	16.53
47	28.8	14.5	90.4	48.4	0.4	14.02
48	26.8	11.6	89.3	49.9	0.5	13.02
49	25.8	10.8	91.4	54.0	0.5	10.78
50	24.4	10.1	91.3	60.7	0.4	9.14
51	23.1	9.9	93.8	59.0	0.5	8.85
52	22.9	10.1	94.3	49.2	0.5	10.65

Table 1: Mean meteorological parameters as observed at ICAR-RCER, Patna.

(32nd week). Mean maximum relative humidity ranged from 63.2 percent (14th week) to 96.0 percent (1st week) whereas mean minimum relative humidity from 24.5 percent (14th week) to 75.8 percent (32nd week). Wind velocity varied in the range of 0.4 m/s to 2 m/s. Mean solar radiation was observed to be minimum of 8.85 $MJm^{-2}day^{-1}$ in the 51st week and maximum of 30.95 $MJm^{-2}day^{-1}$ in the 22nd week, respectively.

Computation of evapotranspiration

Computation of crop water requirement needs estimation of reference evapotranspiration (ET_0). Direct measurement of ET_0 is difficult and time consuming, so most common practice is to estimate ET_0 from meteorological data available for the area employing empirical equations. Daily reference evapotranspiration (ET_0) values for the period from 2010 to 2014 were estimated using thirteen different methods. All the methods used in this study are cited and described in DSS-ET model of ET_0 estimation. The methods used were grouped according to their classification as (1) combination methods such as FAO-56. Penman-Monteith Allen et al. [8] Penman-Monteith Monteith, [9] Kimberley Penman Wright, [10] FAO-PPP-17 Penman Frere and Popov, [11] Penman VPD#1, Penman VPD#3 Kimberley Penman Wright and Jensen, [12] FAO-24 Penman c=1 Doorenbos and Pruitt [13,14], Businger-van-Bavel, [15,16] and CIMIS Penman Snyder and Pruitt [17] (2) Radiation methods such as Turc [18] and Priestly-Taylor, [19] and (3) Temperature method such as Hargreaves [20]. The list of data requirement for each method is given below in Table 2.

The ICID and the FAO expert consultation on revision of FAO methodologies for crop water requirements have recommended that FAO-56 Penman-Monteith method be used as the standard method to estimate ET_0. In this study also FAO-56 Penman-Monteith method was used as an index to estimate daily ET_0. The FAO-56 Penman-Monteith is a grass reference equation that was derived from the ASCE equations by fixing grass height=0.12 m for clipped grass using latent heat of vaporization (λ)=2.45 MJ kg^{-1}; bulk surface resistance of 70 sm^{-1}, and albedo of 0.23. The equation to estimate daily ET_0 (mm/d) is given as:

$$ETo = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,U_2)} \quad (1)$$

Methods to calculate evapotranspiration (ET_0)

ET methods recommended by ASCE are classified into four categories, namely, temperature, radiation, evaporation and combination methods. Description of each ET method is given below:

Hargreaves and Samani recommended estimation of solar radiation from extraterrestrial radiation and used temperature difference term [20]. Net solar radiation, relative humidity and wind parameters were not considered in the proposed equation mentioned below.

$$E_{to} = 0.0023\,R_A\,\sqrt{TD}\,\,(T_{mean} + 17.8) \quad (2)$$

Among the radiation methods, Turc proposed two equations of ET_o estimation as a function of daily mean air temperature and total incoming solar radiation (R_s) for the mean relative humidity (RH) >50% and (RH) <50% as given below [18].

When RH_{mean} > 50%

$$E_{to} = 0.013\,\frac{T_{mean}}{(T_{mean} + 15)}\,(R_s^{'} + 50)\,\frac{1}{\lambda} \quad (3)$$

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

$$E_{to} = 0.013\,\frac{T_{mean}}{(T_{mean} + 15)}\,(R_s^{'} + 50)\,\frac{1}{\lambda}\left(1 + \frac{(50 - RH_{mean})}{70}\right) \quad (4)$$

Priestly and Taylor proposed an equation for surface area generally wet, which is a condition, required for potential evaporation [19]. The aerodynamic component was deleted and energy component was multiplied by a coefficient, α=1.26. The final equation is as below

$$E_p = \alpha\,\frac{1}{\lambda}\,\frac{\Delta}{(\Delta + \gamma)}\,(R_n - G) \quad (5)$$

Where Δ is expressed as

$$\Delta = \frac{4098\,e^0_{mean}}{(T_{mean} + 237.3)^2} \quad (6)$$

e^0_{mean} (kPa) is expressed as

$$e^0_{mean} = 0.6108\,\exp\left[\frac{17.27\,T_{mean}}{T_{mean} + 237.3}\right] \quad (7)$$

Christiansen and Hargreaves developed equation for estimating reference evapotranspiration from USWB class 'A' pan evaporation and several weather parameters.

$$E_{to} = 0.755\,E_v\,C_{T2}\,C_{w2}\,C_{H2}\,C_{s2} \quad (8)$$

Methods	Temperature		Relative Humidity		Wind Velocity	Solar Radiation	Pan Evaporation
	Min.	Max.	Min.	Max.			
FAO-56Penman-Monteith	√	√	√	√	√	√	-
Penman-Monteith	√	√	√	√	√	√	-
1982Kimberley Penman	√	√	√	√	√	√	-
FAO-PPP	√	√	√	√	√	√	-
Penman 1963 VPD#1	√	√	√	√	√	√	-
Penman 1963 VPD#3	√	√	√	√	√	√	-
1972Kimberley Penman	√	√	√	√	√	√	-
FAO-24 Penman c=1	√	√	√	√	√	√	-
Hargreaves	√	√	-	-	-	-	-
Businger-van-Bavel	√	√	√	√	√	√	-
FAO-24 Pan	-	-	√	√	√	-	√
Christiansen Pan	√	√	√	√	√	-	√
Turc	√	√	√	√	-	√	-
Priestly-Taylor	√	√	√	√	√	√	-
CIMIS Penman	√	√	√	√	√	√	-

Table 2: Input parameters for different methods of ETo estimation.

C_{T2}, C_{w2}, C_{H2} and C_{s2} are estimated by following set of equations:

$$C_{T2}=0.862 + 0.179\,(T_{mean}/20) - 0.041((T_{mean}/20)^2 \quad (9)$$

$$C_{w2}=1.189 - 0.240\,(W/6.7) + 0.051(W/6.7)^2 \quad (10)$$

$$C_{H2}=0.499 + 0.620\,(RH_{mean}/60) - 0.119\,(RH_{mean}/60)^2 \quad (11)$$

$$C_{s2}=0.904 - 0.0080\,(S/0.80) + 0.088\,(S/0.80)^2 \quad (12)$$

Doorenbos and Pruitt suggested *FAO-24* pan method in which, ET_o depends on two different conditions for estimating the pan coefficient values, one is for vegetation while other is for bare soil [13].

$$E_{to}=k_p\,E_{pan} \quad (13)$$

Frevert et al. has mentioned polynomial equations for estimating k_p.

Penman in Vapor pressure deficit (*VPD) #1,* combined the two components i.e., radiation and aerodynamic components and defined general form of resulting equation for a well-watered grass reference as [21]:

$$E_{to} = \frac{1}{\lambda}\frac{\Delta}{(\Delta+\gamma)}(R_n - G) + \frac{1}{\lambda}\frac{\gamma}{(\Delta+\gamma)}6.43\,W_f^{P1}\,(e_z^0 - e_z)^{VPD\#1} \quad (14)$$

Here,

$W_f^{P1}=1.0 + 0.537\,u_2$

Businger, Monteith and van Bavel adopted a more theoretical vapour pressure function based on earlier work of resulting the following Businger Bavel equation for a wet surface with zero resistance to vapour transfer [9,15,16].

$$E_{to} = \frac{1}{\lambda}\frac{\Delta}{(\Delta+\gamma)}(R_n - G) + \frac{1}{\lambda}\frac{\gamma}{(\Delta+\gamma)}\frac{0.622\rho\lambda k^2}{P}\frac{u_z}{[\ln((z-d)/z_0)]^2}(e_z^0 - e_z)^{VPD\#1} \quad (15)$$

Here 0.622 is the ratio of the molecular mass of water to the apparent molecular mass of dry air. Penman suggested to use VPD#3 in place of VPD#1 in his proposed equation, the resulting equation becomes [15]:

$$E_{to} = \frac{1}{\lambda}\frac{\Delta}{(\Delta+\gamma)}(R_n - G) + \frac{1}{\lambda}\frac{\gamma}{(\Delta+\gamma)}6.43\,W_f^{P3}\,(e_z^0 - e_z)^{VPD\#3} \quad (16)$$

$(e_z^0 - e_z)^{VPD\#3} = 0.5\,(e^0_{min} + e^o_{max}) - e_0^d$

Penman-Monteith equation proposed by Monteith [9] was employed to estimate ET_o for clipped crop surface condition considering crop height as 0.12 for humidity and temperature measurement at the height of 2 m. The equation used variable daily value of latent heat of vaporization and bulk surface resistance and aerodynamic resistance. The equation is available in many text books.

Wright and Jensen recommended more common wind function for the Penman method. The revised method is referred as 1972 Kimberly Penman method and is given below [12]:

$$E_{to} = \frac{1}{\lambda}\frac{\Delta}{(\Delta+\gamma)}(R_n - G) + \frac{1}{\lambda}\frac{\gamma}{(\Delta+\gamma)}6.43\,W_f^{72KP}\,(e_z^0 - e_z)^{VPD\#3} \quad (17)$$

Here $W_f^{72KP}=0.75 + 0.993\,u_2$.

Doorenbos and Pruitt [13,14] presented a modified Penman equation for estimating reference ET for grass which is known as FAO-24 corrected Penman [15]. If value of c is set to 1.0 in FAO 24 corrected Penman equation, then the resulting equation is called FAO-24 Penman (c=1) method.

$$E_{to} = c\,[\frac{\Delta}{(\Delta+\gamma)}(R_n - G) + \frac{\gamma}{(\Delta+\gamma)}2.7\,W_f^{F24CP}\,(e_z^0 - e_z)^{VPD\#i}] \quad (18)$$

Here W_f^{F24CP} is wind function for FAO Corrected Penman method and it can be calculated by $W_f^{F24CP}=1 + 0.864\,u_2$ and c is adjustment factor and expressed as:

$c=0.68 + 0.0028\,RH_{max} + 0.018\,R_s - 0.068\,u_d + 0.013\,(u_d/u_n) + 0.0097\,u_d(u_d/u_n) + 0.430 \times 10^{-4}\,RH_{max}\,R_s\,u_d$. If c=1, it becomes FAO 24 Penman (c=1) method.

Frere and Popov suggested the different wind functions for various ranges of temperatures and used VPD#1 for estimating vapour pressure deficit. The equation can be written as below [11]:

$$E_{to} = \frac{1}{\lambda}\frac{\Delta}{(\Delta+\gamma)}(R_n - G) + \frac{1}{\lambda}\frac{\gamma}{(\Delta+\gamma)}6.43\,W_f^{FP17P}\,(e_z^0 - e_z)^{VPD\#1} \quad (19)$$

Here W_f^{FP17P} is wind function for FAO-PPP Penman method. The suggested wind functions depend upon temperature difference.

Wright presented variable wind function coefficients for E_{tr} using fifth order polynomials with calendar day D as independent variable at Kimberly, Idaho, Kimberly Penman equation used variable value of wind function coefficients using fifth order polynomials with calendar day as independent variable [10]. Simplified equation for wind function is expressed as:

$$W_f^{82KP} = a_w + b_w\,u_2 \quad (20)$$

Where,

$a_w=0.4 + 1.4\exp\{-[(D-173)/58]^2\}$ and $b_w=0.605 + 0.345\exp\{-[(D-243)/80]^2\}$

D is calendar Day (i.e., day of the year). For southern latitude use D' in place of D and take D'=(D-182) for D≥ 182 and D'=(D+182) for D <182. Keeping all other parameters same, the 1982 Kimberly Penman may be written as follows:

$$E_{to} = \frac{1}{\lambda}\frac{\Delta}{(\Delta+\gamma)}(R_n - G) + \frac{1}{\lambda}\frac{\gamma}{(\Delta+\gamma)}6.43\,W_f^{82KP}\,(e_z^0 - e_z)^{VPD\#3} \quad (21)$$

Results and Discussion

Daily reference evapotranspiration were computed by the above mentioned methods and converted into mean weekly ET_0 (mm/day). The results are presented below in Figure 1.

The weekly reference evapotranspiration (ET_0) estimates in year 2010, 2011, 2012 and 2013, and 2014 computed using FAO 56 Penman Monteith method varied from 1.4 mm/day (3rd week) to 8.0 mm/day (22nd week), 1.4 mm/day (50th and 51th weeks) to 7.2 mm/day (22nd week), 1.1 mm/day (51st weeks) to 6.6 mm/day (18th week), and 1.3 mm/day (51st week) to 6.6 mm/day (16th week), respectively. The average of five years weekly ET_0 values ranged from 1.3 mm/day (51st week) to 6.7 mm/day (21st and 22nd weeks), respectively. Annual reference evapotranspiration in these years were computed as 1535.4 mm, 1523.5 mm, 1485.2 mm, 1501.6 and 1539.9 mm, respectively, and average annual reference evapotranspiration was found as 1517.1 mm.

It may be observed from Figure 1 that all the methods except Hargreaves, FAO 24 Pan and Christiansen Pan methods, follow the same trend of variation of ET_0 values in different weeks. ET_0 values computed by FAO 24 Pan and Christiansen Pan methods are always lower than ET_0 values computed by all other methods in all the weeks. ET_0 values computed by Hargreaves method are lower during 18th to 43rd week and higher during 44th week to 17th week compared to ET_0 values obtained from FAO 56 Penman-Monteith method. In rest of the methods the difference in ET_0 values obtained from Penman-Monteith and FAO 56 Penman-Monteith method is very less as compared to other methods.

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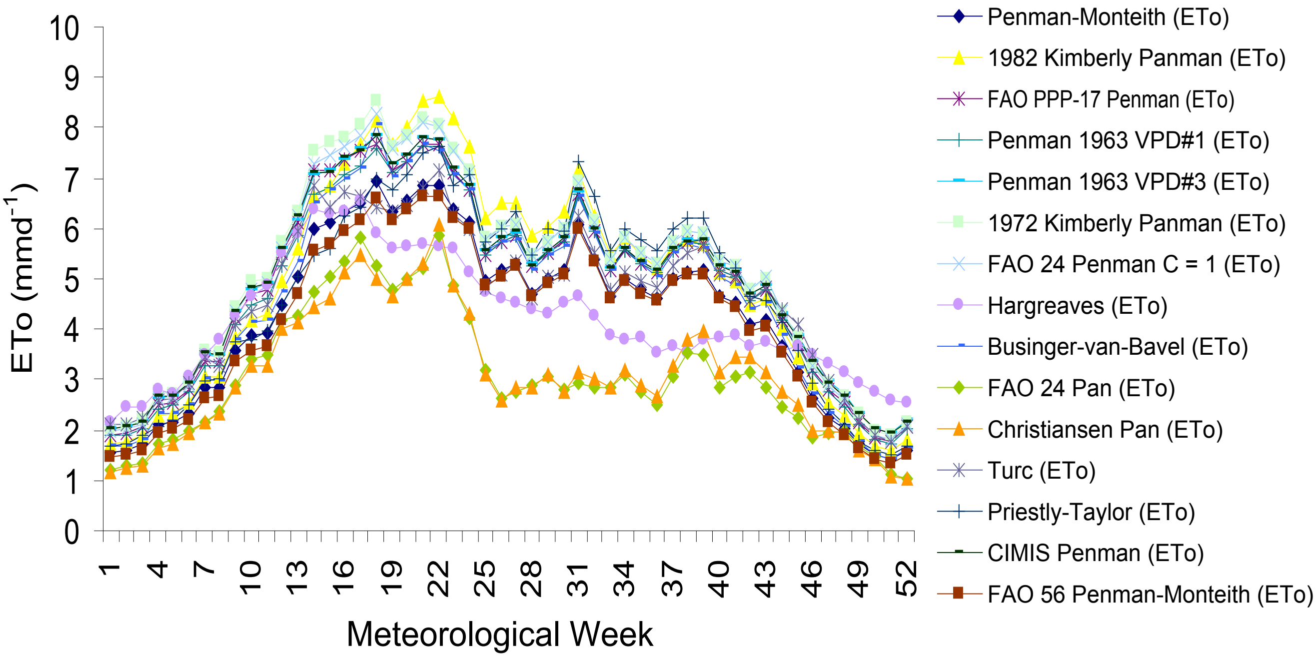

Figure 1: Variation of ET_0 values as estimated by various methods.

Methods	Average ratio of ETo(method)/ ETo(FAO56-PM)	Slope	Intercept	Coefficient of determination	Rank
Penman-Monteith	1.04	1.023	0.065	0.996	1
1982 Kimberly Penman	1.20	1.263	-0.251	0.986	10
FAO-PPP	1.19	1.107	0.344	0.977	4
Penman1963 VPD#1	1.17	1.093	0.329	0.990	2
Penman1963 VPD#3	1.21	1.089	0.513	0.978	3
1972 Kimberley Penman	1.26	1.176	0.325	0.971	9
FAO-24 Penman C=1	1.24	1.168	0.290	0.980	8
Hargreaves	1.03	0.591	1.795	0.657	14
Businger-van-Bavel	1.13	1.163	-0.126	0.990	7
FAO-24 Pan	0.76	0.681	0.305	0.719	13
Christiansen Pan	0.76	0.694	0.260	0.769	12
Turc	1.13	0.927	0.817	0.934	11
Priestly-Taylor	1.14	1.118	0.081	0.961	6
CIMIS Penman	1.22	1.090	0.511	0.976	5

Table 3: Various statistical parameters and rank of ET0 estimation methods.

The relationships between the ET_0 (mm/day) computed by fourteen various methods with ET_0 obtained from FAO56-Penman-Montetith method are given below in Figure 2a to 2n.

The ratio of Five years average of ET_0 (method) and ET_0 (FAO56-PM), slope (m), intercept (c) and coefficient of determination (r^2) were computed in order to know the over and under estimation of all the methods with respect to the FAO-56 Penman-Monteith method are given below in Table 3.

In the above Table, the average ratios above and below 1.0 indicate over and under estimation of ET_0 compared to ET_0 values computed by FAO-56 Penman-Monteith method. The average ratios lie in the range of 0.76 to 1.26, which indicates that Christiansen Pan and FAO-24 Pan under estimate, whereas other methods overestimate ET_0 values compared to ET_0 estimated by FAO-56 Penman-Monteith method [22]. Coefficient of determination represents the closeness of relationship of other ET_0 estimation methods with FAO-56 Penman Monteith method and can be considered good indicator for deciding the rank. Penman Monteith with coefficient of determination of 0.996 was observed having 1st rank and Hargreaves with coefficient of determination 0.657 at 14th rank. The methods having rank between 1 and 5 were Penman Monteith, Penman1963 VPD#1, Penman1963 VPD#3, FAO-PPP, and CIMIS Penman, respectively and the methods having rank between 10 and 14 were 1982 Kimberley Penman, Turc, Christiansen Pan, FAO-24 Pan, and Hargreaves, respectively.

Conclusion

Fifteen different methods of ET_0 estimation were employed for climatic data of the period 2010 to 2014 and daily estimates of reference evapotranspiration were computed and converted into mean weekly daily values. The mean weekly daily ET_0 estimates from all the methods were compared against the ET_0 values obtained using FAO-56

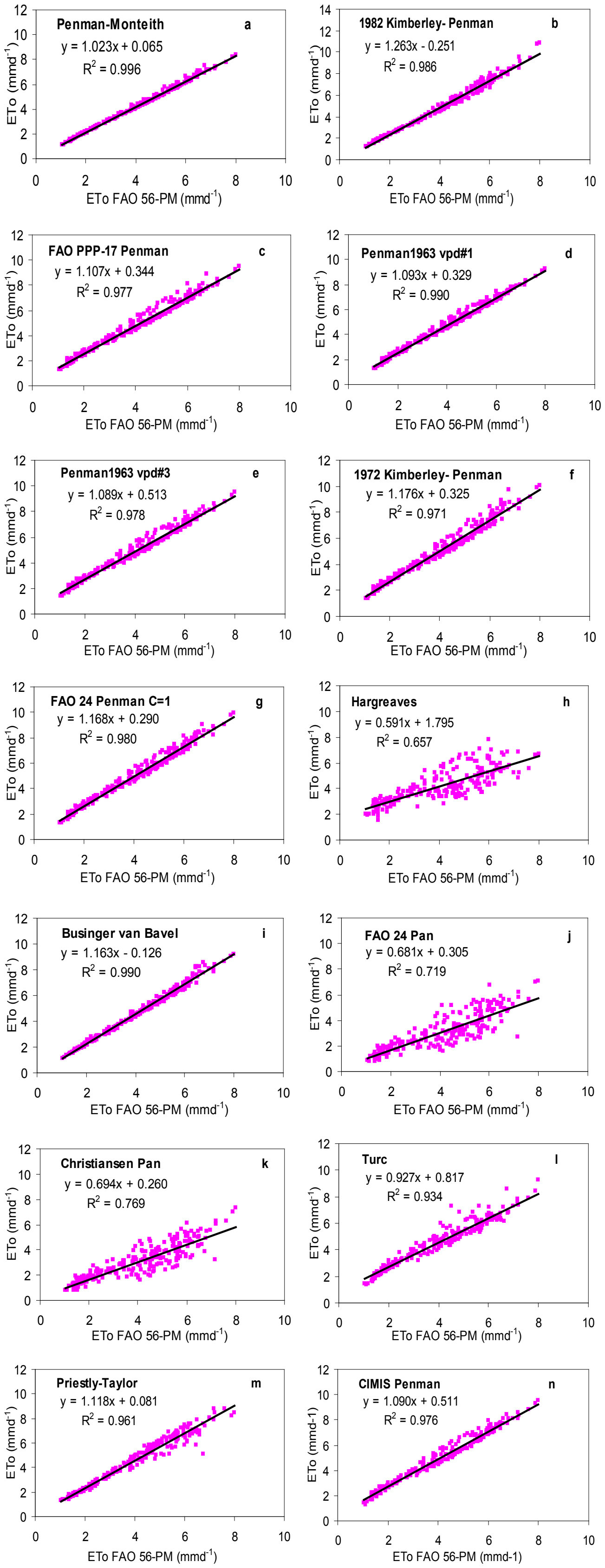

Figure 2: (a to n): Comparison of ET_0 (mm/day) estimated by various methods with FAO 56 Penman-Monteith method.

Penman-Monteith method. On the basis of results, it can be said that all the methods produced significantly different evapotranspiration estimates than the FAO-56 Penman-Monteith method. Mean weekly daily evapotranspiration rates obtained from Penman-Monteith method were found very closer to FAO-56 Penman-Monteith method and values from all the other methods except Christiansen Pan, FAO-24 Pan and Hargreaves methods, generally predicted higher values of mean weekly daily ET_0 in comparison to FAO-56 Penman-Monteith method. The performance of all the methods against FAO 56 Penman-Monteith was evaluated by assigning rank on the basis of coefficient of determination. The analysis shows that mean weekly daily ET_0 estimates of combination methods resulted better ET_0 estimates than radiation, temperature and evaporation methods. Penman-Monteith method produced best ET_0 estimate against FAO-56 Penman-Monteith estimated ET_0. Among the combination methods its performance followed by Penman VPD#1, PenmanVPD#3, FAO-PPP-17 Penman, CIMIS Penman, Businger-van-Bavel, FAO-24 Penman (c=1), 1972 Kimberley Penman method, 1982 Kimberley Penman. The performance of Turc radiation methods was less reliable than combination methods. Among the radiation methods Priestley-Taylor method performed much better than Turc method which may be due to consideration of wind parameter in its equation. The poorest estimates of temperature and evaporation methods were observed because these methods do not account for net radiation, vapor pressure deficit, solar radiation, or other important parameters, which have greater impact on ET_0 estimation.

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