Performance Evaluation of Calibrated Hargreaves Method for Estimation of Ref-ET in a Hot and Humid Coastal Location in India

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Abstract:

The FAO-56 Penman-Monteith equation is recommended as the standard for estimating reference evapotranspiration (Ref-ET), and for evaluating other Ref-ET estimation methods. The main hindrance to use the FAO-56 Penman-Monteith (FAO-56 P-M) equation is the non-availability of requisite weather data in most of the observatories. In such situations, one has to resort to a method that employs minimum number of observed weather data. The Hargreaves equation which employs only maximum and minimum temperature data could be used to estimate reference evapotranspiration. But, this method yields poor results, generally overestimating Ref-ET, in humid locations worldwide. The main objective of the present study is to evaluate the performance of the original Hargreaves equation (Har) and the calibrated Hargreaves equation (cHar) for a hot and humid location near to east coast in Tamilnadu State, India. The original Hargreaves equation underestimated Ref-ET on more than two-thirds (68%) of the time period considered in the study and overestimated only during less than one-third (32%) of the period. The Hargreaves equation was calibrated using the FAO-56 P-M equation. The calibrated Hargreaves equation (cHar) provided better estimates of Ref-ET compared to original Hargreaves equation (Har). The mean standard error of estimate (SEE) in estimation of weekly mean daily Ref-ET were found to be 0.845 mm day^{-1} and 0.958 mm day^{-1} for calibrated Hargreaves equation and original Hargreaves equation respectively. The SEE worked out to be lesser at 0.573 mm day^{-1} and 0.737 mm day^{-1} for calibrated Hargreaves equation and original Hargreaves equation respectively, in estimation of monthly mean daily Ref-ET underlying the fact that both Hargreaves and calibrated Hargreaves equations provided better Ref-ET estimates for longer time steps.

Keywords: Evapotranspiration; Temperature; FAO-56 PM method; Hargreaves equation.

1. Introduction

Evapotranspiration is one of the important processes in the hydrological cycle. Its reliable estimation is vital to water resources planning and management. Common practices for estimating crop evapotranspiration are to first estimate reference evapotranspiration (ET_0) and then relate a corresponding crop coefficient. Reference evapotranspiration is defined in Allen et al. (1998) as 'the rate of evapotranspiration from hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance (70 s m^{-1}) and albedo (0.23) which would closely bear a resemblance to evapotranspiration from a widespread surface of green grass cover of identical height, aggressively growing, wholly shading the ground and not short of water'.

The International Commission for Irrigation and Drainage and Food and Agriculture Organization of the United Nations have proposed using the Penman–Monteith method as the standard method for estimating reference evapotranspiration, and for evaluating other methods (Allen et al. 1994a, b). In the FAO-56 Penman–Monteith method (Allen et al. 1998), ET_0 is computed as:

$$ET_{0,PM} = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where $ET_{0,PM}$ = Reference evapotranspiration estimated by FAO-56 Penman-Monteith equation (mm day^{-1}); Δ = slope of the saturation vapor pressure function (kPa°C^{-1}); R_n = net radiation (MJ m^{-2} day^{-1}); G = soil heat flux density (MJ m^{-2} day^{-1}); γ = psychometric constant (kPa°C^{-1}); T = mean daily air temperature (°C); U_2 = mean 24-h wind speed at 2-m height (m s^{-1}); and (e_s-e_a) = vapor pressure deficit (kPa).

When there is no measured lysimeter data on reference evapotranspiration, the FAO 56 P-M method is recommended as the standard procedure for accurate estimation of reference ET (Irmak et al. 2003; Utset et al. 2004; Gavilan et al. 2006; Nandagiri and Kovoor 2006; Trajkovic 2007; Martinez and Thepadia, 2010).

The Penman–Monteith method is ranked as the best method for estimating daily and monthly ET_0 in all the climates. This has been confirmed by many researches in the last decade (Todorovic 1999; Ventura et al. 1999; Hussein 1999; Abdelhadi et al. 2000; Beyazgul et al. 2000; Hargreaves and Allen 2003; Tyagy et al.2003; DelghaniSanij et al. 2004; Berengena and Gavilan, 2005; Trajkovic 2005; Lopez-Urrea *et al.*, 2006; Gavilan *et al.*, 2007; Trajkovic 2007; Trajkovic and Kolakovi 2009).

The FAO-56 PM is a physically based approach that requires measurements of a number of meteorological parameters namely, air temperature, relative humidity, solar radiation, and wind speed. The number of stations where there are reliable data for these parameters is limited (Martinez and Thepadia, 2010).

This lack of data motivated Hargreaves and Samani (1985) to develop a simpler approach where only air temperatures are required. The Hargreaves equation can be written as

$$ET_{O,Har} = 0.0023R_a(T_{\max} - T_{\min})^{0.5} - \left(\frac{T_{\max} + T_{\min}}{2} + 17.8\right) \quad (2)$$

where $ET_{o,Har}$ = Ref-ET estimated by the Hargreaves equation (mm day^{-1}); R_a = extraterrestrial radiation (mm day^{-1}); T_{max} = daily maximum temperature (C°); 0.0023 = empirical Hargreaves coefficient; 0.5 = empirical Hargreaves exponent; and 17.8 = empirical temperature coefficient.

The Hargreaves equation is an attractive alternative due to its simplicity and minimum data requirements. The Hargreaves equation ranked highest among temperature-based equations compared to lysimeter measurements at the 11 locations studied by Jensen et al. (1990). Allen et al. (1998) have proposed that when sufficient data to solve the FAO-56 PM equation are not available then the Hargreaves equation can be used. Several studies have shown the Hargreaves equation may provide reliable estimates of Reference evapotranspiration for five days or longer time steps (Hargreaves 1989; Jensen et al. 1997; Droogers and Allen 2002; Hargreaves and Allen 2003). However, this equation generally overestimates ET_o at humid locations (Jensen et al. 1990, Amatya et al. 1995, Itenfisu et al. 2003, and Temesgen et al. 2005 and Trajkovic 2005) and underestimates in arid locations (Jensen et al. 1990; Allen et al. 1998; Droogers and Allen 2002). The average overestimation of annual ET_o was found to be 15% at three sites in North Carolina in the study by Amatya et al. (1995). Similar results were obtained by Yoder et al. (2005) in Cumberland Plateau. Similar results were obtained in several recent studies such as by Popova et al. (2006) in the Trace Plain in Bulgaria, Jabloun and Sahli (2008) in Tunisia and Martinez and Thepadia (2010) in Florida. Allen et al. (1998) noted that the Hargreaves equation should be calibrated if necessary for obtaining reliable estimates of reference evapotranspiration. The basic objective of this paper is to investigate the performance of Hargreaves method calibrated using the standard FAO-56 P-M method in estimating reference evapotranspiration in a hot and humid coastal location in India.

2. Materials and Methods

The India Meteorological Observatory selected for this study is located at Annamalainagar in Tamilnadu State, India. The Latitude and Longitude of the weather station are respectively 11° 24' N and 79° 42' E. Annamalainagar is located 8 km interior from the East Coast of India. Measured daily meteorological data on maximum and minimum temperature (T_{max} and T_{min}), maximum and minimum relative humidity (RH_{max} and RH_{min}), actual hours of bright sunshine (n) and wind speed at 3 m height (U_3) for a period of 22 years (1977 to 1998) were obtained from India Meteorological Department, Pune. Table 1 shows the details of the meteorological observatory at Annamalinagar.

Table 1 Details of India Meteorological Observatory at Annamalainagar, Tamilnadu State, India

Name of Observatory	Latitude	Longitude	Altitude (m)	Mean Weather Data					
				T_{max} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)	u_3 (km h^{-1})	SSH(n)
Annamali nagar	11° 24′	79° 42′	+ 5.79	32.4	22.4	83.4	64.3	7.7	7.86

The mean annual maximum and minimum temperatures were respectively 32.4°C and 22.4°C. The mean annual maximum and minimum relative humidity were respectively 83.4% and 64.3%. The mean annual wind speed (measured at 3 m height) was 7.7 km h^{-1} and actual hours of bright sunshine was 7.86.

Out of the 22 years of data, the first 14 years (1977 to 1990) were used in deriving the calibrated Hargreaves equation and the last 7 years (1992 to 1998) were used evaluating the performance of the calibrated Hargreaves equation in reference evapotranspiration estimation. As the data were missing for a few months in year 1991, it was not considered in the study. The Hargreaves equation given by (2) was verified by comparing with the FAO-56 P-M method given by (1). Then, equation (2) is calibrated on a daily, weekly and monthly basis as follows:

$$ET_{o,PM} = a + b.ET_{o,Har} \quad (3)$$

where $ET_{o,PM}$ = grass reference ET defined by the FAO-56 PM equation

$ET_{o,Har}$ = reference ET estimated by the Hargreaves equation; and

a and *b* = empirical coefficients determined be regression analyses

The performance of the calibrated Hargreaves equation, was analyzed as follows:

Reference evapotranspiration in the test period 1992 to 1998 was estimated using the calibrated Hargreaves equation as:

$$ET_{o,cHar} = a + b.ET_{o,Har} \quad (4)$$

where $ET_{o,cHar}$ = ET_0 estimated by the calibrated Hargreaves equation; and $ET_{o,Har}$ = ET_o estimated by the Hargreaves method. Then, $ET_{o,Har}$ and $ET_{o,cHar}$ evaluated using equations (2) and (4) respectively were compared with $ET_{o,PM}$ evaluated using equation (1) and the statistics namely, Mean Absolute Error (*MAE*), Minimum Absolute Error (*MinAE*), Maximum Absolute Error (*MaxAE*), Mean Percent Absolute Error (*MPAE*), Mean Bias Error (*MBE*), Minimum Bias Error (*MinBE*), Maximum Bias Error (*MaxBE*) and Standard Error of Estimate (*SEE*) were determined to speak of the ability of calibrated Hargreaves equation to reliably estimate reference evapotranspiration close to those estimated by FAO 56 P-M method. These statistical criteria were estimated as follows:

$$MAE_{Har} = \frac{\sum_{i=1}^{N} \left| ET_{O,PM}^{i} - ET_{O,Har}^{i} \right|}{N} \tag{5}$$

$$MinAE_{Har} = \text{minimum} \left| ET_{o,PM}^{i} - ET_{o,Har}^{i} \right|, \; i = 1, 2, \ldots\ldots, N \tag{6}$$

$$MaxAE_{Har} = \text{maximum} \left| ET_{o,PM}^{i} - ET_{o,Har}^{i} \right|, \; i = 1, 2, \ldots\ldots, N \tag{7}$$

$$MAPE_{Har} = \frac{\sum_{i=1}^{N} \left| \frac{ET_{O,PM}^{i} - ET_{O,Har}^{i}}{ET_{O,PM}^{i}} \text{ x } 100 \right|}{N} \tag{8}$$

$$MBE_{Har} = \frac{\sum_{i=1}^{N} \left(ET_{o,Har} - ET_{o,PM} \right)}{N} \tag{9}$$

$$MinBE_{Har} = \text{minimum} \left(ET_{o,Har}^{i} - ET_{o,PM}^{i} \right), \; i = 1, 2, \ldots\ldots, N \tag{10}$$

$$MaxBE_{Har} = \text{maximum} \left(ET_{o,Har}^{i} - ET_{o,PM}^{i} \right), \; i = 1, 2, \ldots\ldots, N \tag{11}$$

$$SEE_{Har} = \left[\frac{\sum_{i=1}^{N} \left(ET_{O,PM}^{i} - ET_{O,Har}^{i} \right)^{2}}{N-1} \right]^{0.5} \tag{12}$$

where MAE_{Har}, $MinAE_{Har}$, $MaxAE_{Har}$, $MAPE_{Har}$, MBE_{Har}, $MinBE_{Har}$, $MaxBE_{Har}$ and SEE_{Har} are respectively the Mean Absolute Error, Minimum Absolute Error, Maximum Absolute Error, Mean Percent Absolute Error, Mean Bias Error, Minimum Bias Error, Maximum Bias Error and Standard Error of Estimate, when employing Hargreaves equation for estimation of Ref-ET. The symbol '*N*' represents the number of samples.

$$MAE_{cHar} = \frac{\sum_{i=1}^{N} \left| ET_{O,PM}^{i} - ET_{O,cHar}^{i} \right|}{N} \tag{13}$$

$$MinAE_{cHar} = \text{minimum} \left| ET_{o,PM}^{i} - ET_{o,cHar}^{i} \right|, \; i = 1, 2, \ldots\ldots, N \tag{14}$$

$$MaxAE_{cHar} = \text{maximum} \left| ET^{i}_{o,PM} - ET^{i}_{o,cHar} \right|, \; i = 1, 2, \ldots\ldots, N \qquad (15)$$

$$MAPE_{cHar} = \frac{\sum_{i=1}^{N} \left| \frac{ET^{i}_{O,PM} - ET^{i}_{O,cHar}}{ET^{i}_{O,PM}} \text{ x } 100 \right|}{N} \qquad (16)$$

$$MBE_{cHar} = \frac{\sum_{i=1}^{N} \left(ET_{o,cHar} - ET_{o,PM} \right)}{N} \qquad (17)$$

$$MinBE_{cHar} = \text{minimum} \left(ET^{i}_{o,cHar} - ET^{i}_{o,PM} \right), \; i = 1, 2, \ldots\ldots, N \qquad (18)$$

$$MaxBE_{cHar} = \text{maximum} \left(ET^{i}_{o,cHar} - ET^{i}_{o,PM} \right), \; i = 1, 2, \ldots\ldots, N \qquad (19)$$

$$SEE_{cHar} = \left[\frac{\sum_{i=1}^{N} \left(ET^{i}_{O,PM} - ET^{i}_{O,cHar} \right)^{2}}{N-1} \right]^{0.5} \qquad (20)$$

where MAE_{cHar}, $MinAE_{cHar}$, $MaxAE_{cHar}$, $MAPE_{cHar}$, MBE_{cHar}, $MinBE_{cHar}$, $MaxBE_{cHar}$ and SEE_{cHar} are respectively the Mean Absolute Error, Minimum Absolute Error, Maximum Absolute Error, Mean Percent Absolute Error, Mean Bias Error, Minimum Bias Error, Maximum Bias Error and Standard Error of Estimate, when employing calibrated Hargreaves equation for estimation of Ref-ET.

3. Results and Discussion

3.1 Comparison of Ref-ET estimated by Hargreaves method with those estimated by FAO P-M method

Figures 1, 2 and 3 show the comparison of daily Ref-ET, weekly mean daily Ref-ET and monthly mean daily Ref-ET estimated by Hargreaves method with those estimated by FAO 56 P-M method in the 14 year period from 1977 to 1990.

The Hargreaves method underestimated Ref-ET on 3477 days and overestimated Ref-ET on 1636 days. That is, the Hargreaves method has underestimated Ref-ET on more than two-thirds (68%) of the time period considered in the study and has overestimated only during less than one-third (32%) of the period. The maximum underestimation and maximum overestimation of daily Ref-ET by Hargreaves method is found to be 4.82 mm and 3.94 mm respectively. Table 2, 3 and 4 show the fundamental statistics of daily Ref-ET, weekly mean daily Ref-ET and monthly mean daily Ref-ET computed by Hargreaves method and FAO 56 P-M method for the period 1977-1990.

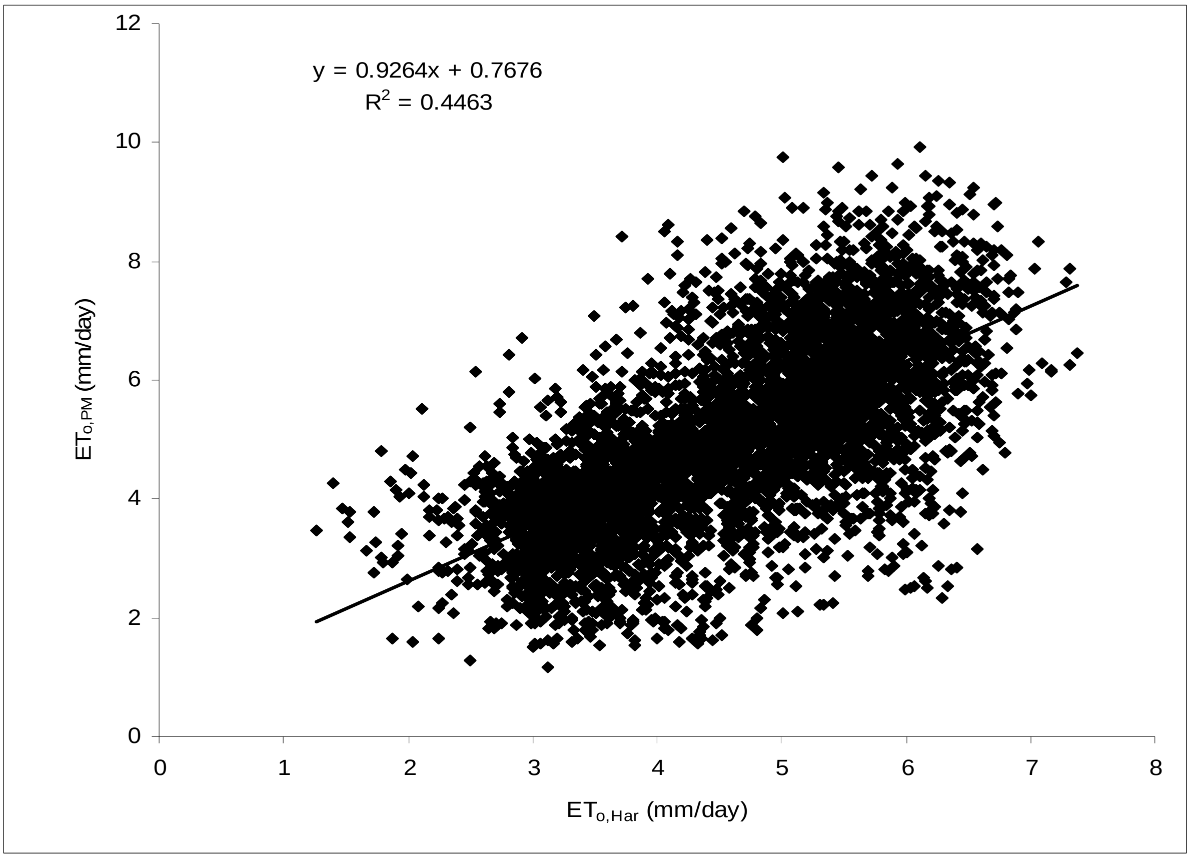

Fig. 1. Comparison of daily Ref-ET (Hargreaves vs. FAO-56 P-M) – 1977-1990

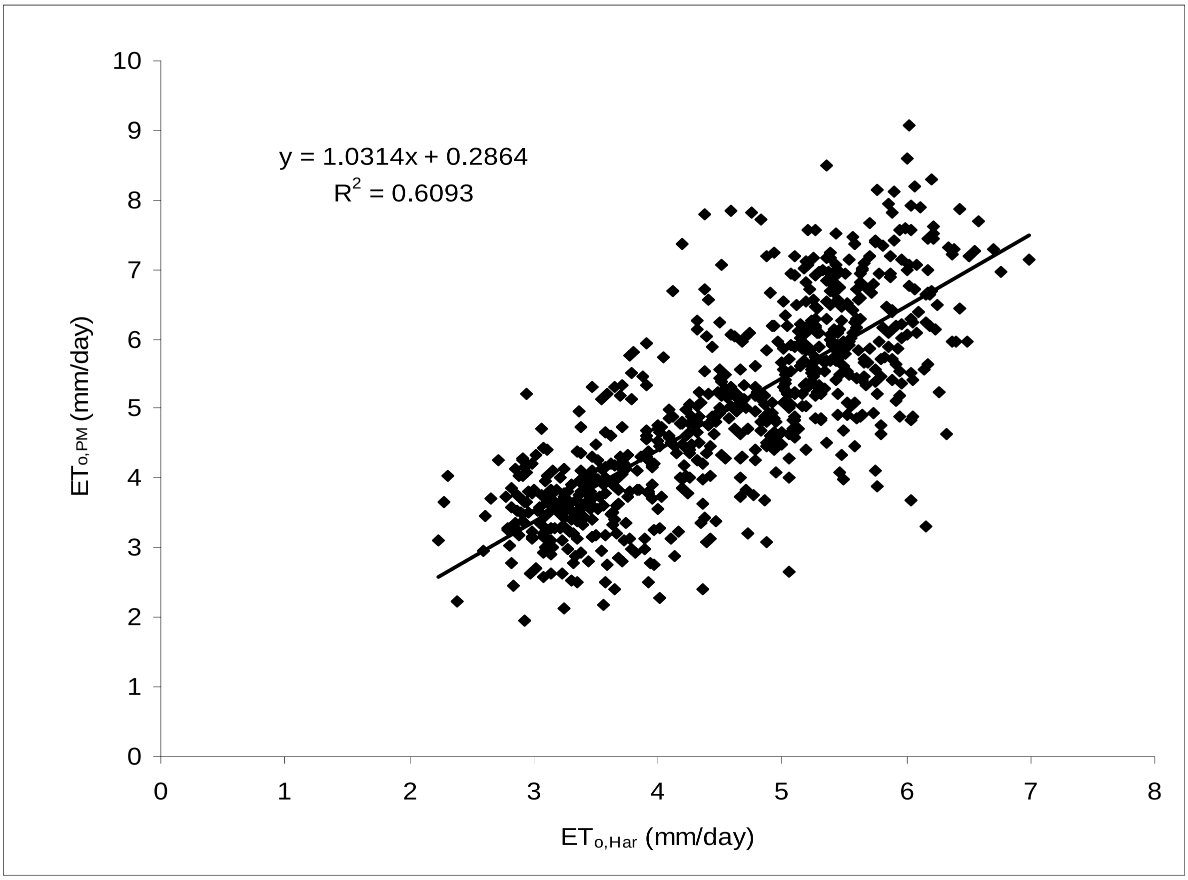

Fig. 2. Comparison of weekly mean daily Ref-ET (Hargreaves vs. FAO-56 P-M) – 1977 – 1990

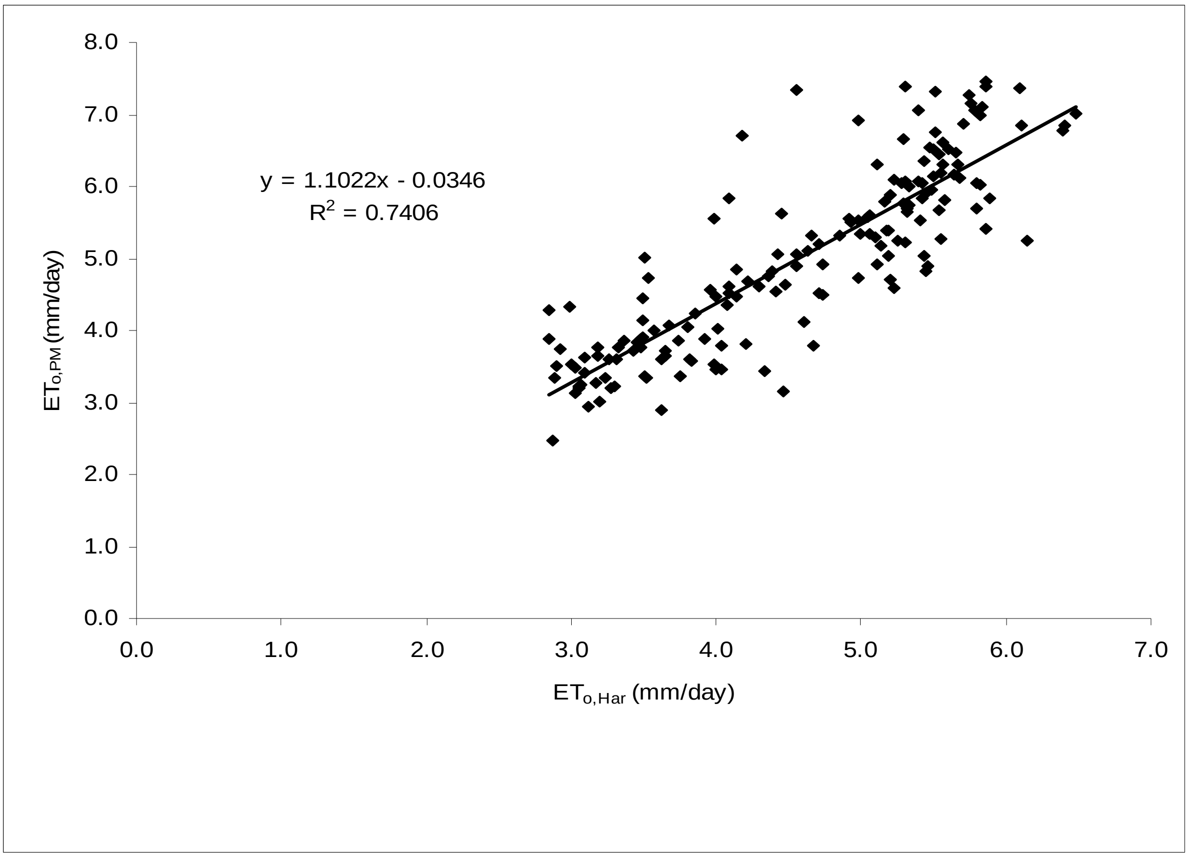

Fig. 3. Comparison of monthly mean daily Ref-ET (Hargreaves vs. FAO-56 P-M) – 1977 – 1990

Table 2. Fundamental statistics of daily Ref-ET (1977-1990)

Statistical Parameter	FAO 56 P-M (mm/day)	Hargreaves (mm/day)	$ET_{o,Har} - ET_{o,PM}$ (mm/day)
Minimum	1.16	1.26	- 4.82
Maximum	9.93	7.37	3.94
Mean	5.00	4.57	- 0.43

Table 3. Fundamental statistics of weekly mean daily Ref-ET (1977-1990)

Statistical Parameter	FAO 56 P-M (mm/day)	Hargreaves (mm/day)	$ET_{o,Har} - ET_{o,PM}$ (mm/day)
Minimum	1.96	2.23	- 3.43
Maximum	9.06	7.00	2.85
Mean	5.00	4.57	- 0.43

Table 4. Fundamental statistics of monthly mean daily Ref-ET (1977-1990)

Statistical Parameter	FAO 56 P-M (mm/day)	Hargreaves (mm/day)	$ET_{o,Har} - ET_{o,PM}$ (mm/day)
Minimum	2.46	2.84	- 2.79
Maximum	7.46	6.48	1.33
Mean	5.00	4.57	- 0.43

The Hargreaves method, by and large, underestimates Ref-ET. The mean difference between Hargreaves and FAO 56 P-M methods yielded a value of – 0.43 mm pointing to the general underestimation of Ref-ET by Hargreaves method. The quantum of underestimation was found to be high during hot and humid days during summer period. The minimum daily Ref-ET estimated by Hargreaves method during the period 1977-1990 is found to be 1.26 mm which is slightly higher than that obtained by FAO 56 P-M method (1.16 mm). The Hargreaves method has overestimated daily Ref-ET in cold and windy weathers during rainy and winter periods.

The minimum weekly mean daily Ref-ET is found to be higher for both FAO 56 P-M and Hargreaves methods at 1.96 mm/day and 2.23 mm/day respectively compared to daily Ref-ET of 1.16 mm/day and 1.26 mm/day. However, the maximum weekly mean daily Ref-ET is found to be lower by 0.87 mm at 9.06 mm/day for FAO 56 P-M method and lower by 0.37 mm at 7.00 mm/day for Hargreaves method compared to the maximum daily Ref-ET obtained by both methods. The performance of Hargreaves method in estimation of weekly mean daily Ref-ET is improved from the fact that the quantum of underestimation and overestimation of Ref-ET has significantly reduced. The maximum underestimation of Ref-ET got reduced to 3.43 mm/day compared to 4.82 mm/day obtained for daily Ref-ET and the maximum overestimation of Ref-ET too got reduced from 3.94 mm/day to 2.85 mm/day obtained for daily Ref-ET.

From Table 4, it is evident that, the minimum monthly mean daily Ref-ET is found to be highest for FAO 56 P-M and Hargreaves methods at 2.46 mm/day and 2.84 mm/day respectively compared to minimum daily Ref-ET depicted in Table 2 as well as minimum weekly mean daily Ref-ET depicted in Table 3. The maximum monthly mean daily Ref-ET is found to be the lowest at 7.46 mm/day and 6.48 mm/day respectively for FAO 56 P-M method and Hargreaves method compared to maximum daily Ref-ET and maximum monthly mean daily Ref-ET estimated by both methods. When the daily Ref-ET values are averaged over a longer period of a month compared to a week, the underestimation or overestimation of Ref-ET by Hargreaves method compared to FAO 56 P-M method got reduced significantly. The maximum underestimation and maximum overestimation of Ref-ET by Hargreaves method got decreased to 2.79 mm/day and 1.33 mm/day respectively compared to those obtained for weekly mean daily Ref-ET. To summarize, the Hargreaves method performed better in estimating daily Ref-ET when averaged over longer time frames such as a week or a month, as the underestimation or overestimation of Ref-ET got reduced considerably with longer time steps.

From the above discussions, the degree of reliability of estimates of Ref-ET by Hargreaves method can be stated as: monthly mean daily Ref-ET > weekly mean daily Ref-ET > daily Ref-ET. This endorses the studies made by Hargreaves (1989), Jensen et al. (1997), Droogers and Allen (2002) and Hargreaves and Allen (2003) which have shown that Hargreaves equation provided reliable estimates of Reference evapotranspiration for five days or longer time steps.

3.2 Calibration of Hargreaves Method

The Hargreaves method defined by equation (2) was calibrated on a daily, weekly and monthly basis using equation (3) with the objective of evaluating its performance in reliable estimation of Ref-ET close to that estimated by FAO 56 P-M method. The coefficients ‘a’ and ‘b’ were determined by linear regression analysis. Equations (21), (22) and (23) present the calibrated Hargreaves equations obtained for estimating daily Ref-ET, weekly mean daily Ref-ET and monthly mean daily Ref-ET.

Daily Ref-ET: $$ET_{o,cHar} = 0.7676 + 0.9264 ET_{o,Har} \quad (21)$$

Weekly mean daily Ref-ET: $$ET_{o,cHar} = 0.2864 + 1.0134 ET_{o,Har} \quad (22)$$

Monthly mean daily Ref-ET: $$ET_{o,cHar} = -0.0346 + 1.1022 ET_{o,Har} \quad (23)$$

The R-squared values of the calibrated Hargreaves equations (21), (22) and (23) obtained by linear regression are respectively 0.446, 0.609 and 0.741 respectively. The R-squared values of the linear fits obtained indicate the degree of closeness of estimates of Ref-ET obtained by the calibrated Hargreaves equations with those obtained by FAO 56 P-M method. The high R-squared values of 0.741 and 0.609 obtained for the calibrated Hargreaves equations obtained for estimating monthly mean daily Ref-ET and weekly mean daily Ref-ET are indicative of the high degree of closeness with those obtained by FAO 56 P-M method.

3.3 Daily Ref-ET estimation

The Hargreaves equation showed positive bias in the years 1992 to 1996 with the maximum MBE of 0.681 mm/day observed in the year 1995, while in the years 1997 and 1998, the bias was negative equal to – 0.312 mm/day and – 0.283 mm/day respectively. The MBE of calibrated Hargreaves equation worked out to be less than those of Hargreaves equation in terms of magnitude in all the test years (1992 – 1998). The calibrated Hargreaves equation showed positive bias in the years 1993 – 1995, 1997 and 1998 with the MBE ranging from 0.044 mm/day to 0.285 mm/day, while the bias was negative in the years 1992 and 1996 with MBE equal to – 0.005 mm/day and – 0.186 mm/day respectively. These indicate that both the Hargreaves and calibrated Hargreaves methods showed positive bias in most of the years. Martinez and Thepadia (2010) indicated that the Hargreaves method showed significant positive bias except in the east coast and the southernmost portion of the Florida state.

The MAE derived when employing Hargreaves equation for predicting Ref-ET estimates ranged between a low of 0.809 mm/day in the year 1997 to a high of 1.057 mm/day in the year 1998. The mean MAE for all the test years (1992 – 1998) put together worked out to be 0.952 mm/day. The MAE derived when using calibrated Hargreaves equation was comparatively lower in most of the test years. The mean MAE for all the test years put together worked out to be 0.888 mm/day which is less that that of Hargreaves Equation. The MAPE in estimation of Ref-ET using calibrated Hargreaves method in most of the test years are found to be marginally lower than those of Hargreaves method. The mean MAPE worked out to be 23.66 for calibrated Hargreaves method compared to 25.92 for Hargreaves method.

The SEE of calibrated Hargreaves method is found to vary from a low of 1.008 mm/day in the year 1997 to a high of 1.363 mm/day in the year 1996, while the SEE of Hargreaves method varies from 1.044 mm/day in the year 1997 to 1.370 mm/day in the year 1996. The mean SEE for calibrated Hargreaves method and Hargreaves method are found to be 1.180 mm/day and 1.252 mm/day respectively in estimation of daily Ref-ET. Table 5 shows the statistical summary of daily Ref-ET estimates for the test years.

Table 5. Statistical summary of daily Ref-ET estimates for the test years (1992 -1998)

Year	Hargreaves				Calibrated Hargreaves			
	MBE	MAE	MAPE	SEE	MBE	MAE	MAPE	SEE
1992	0.399	0.927	23.233	1.215	-0.005	0.862	20.310	1.152
1993	0.547	0.955	29.808	1.279	0.153	0.856	25.008	1.155
1994	0.447	0.951	26.383	1.246	0.044	0.889	22.781	1.161
1995	0.681	0.950	26.127	1.269	0.285	0.831	22.103	1.120
1996	0.250	1.013	30.038	1.370	-0.186	1.081	29.352	1.363
1997	-0.312	0.809	19.077	1.044	0.121	0.746	19.620	1.008
1998	-0.283	1.057	26.759	1.340	0.153	0.950	26.461	1.303
1992-1998 Mean	0.247	0.952	25.918	1.252	0.081	0.888	23.662	1.180

3.4. Weekly Mean Daily Ref-ET estimation

Even though there is no reduction in the bias of weekly mean daily Ref-ET estimates by Hargreaves equation, the calibrated Hargreaves equation has shown reduction in the bias compared to those of daily Ref-ET estimates by both methods. There has been reduction in MAE of estimates by both methods for all the test years. The MAE varied from a low of 0.585 mm/day in year 1997 to a high of 0.861 mm/day in year 1995 with a mean of 0.753 mm/day for estimates by Hargreaves equation. In case of calibrated Hargreaves equation, the MAE varied in the range 0.486 mm/day to 0.802 mm/day with a mean of 0.637 mm/day. The calibrated Hargreaves equation resulted in a reduction in mean MAE by 0.116 mm/day compared to Hargreaves equation. This reduction in mean MAE is higher than that obtained for calibrated Hargreaves equation in estimation of daily Ref-ET. The reduction in mean MAE while employing calibrated Hargreaves equation for estimation of daily Ref-ET was found to be only 0.064 mm/day.

The mean MAPE in estimation of weekly mean daily Ref-ET worked out to be 18.22 and 15.18 respectively for Hargreaves and calibrated Hargreaves equations. These are much lower than 25.92 and 23.66 obtained respectively for Hargreaves and calibrated Hargreaves equations in estimation of daily Ref-ET. The SEE ranged from 0.766 mm/day to 1.046 mm/day with a mean of 0.958 mm/day for Hargreaves equation while the SEE ranged from 0.702 mm/day to 1.006 mm/day with a mean of 0.845 mm/day for calibrated Hargreaves equation. The performance of both Hargreaves and calibrated Hargreaves equations in estimation of Ref-ET are found to be better for weekly time steps than for daily periods. Table 6 shows the statistical summary of weekly mean daily Ref-ET estimates for the test years.

Table 6. Statistical summary of weekly mean daily Ref-ET estimates for the test years (1992 -1998)

Year	Hargreaves				Calibrated Hargreaves			
	MBE	MAE	MAPE	SEE	MBE	MAE	MAPE	SEE
1992	0.442	0.700	16.098	0.900	0.000	0.580	12.648	0.783
1993	0.602	0.760	19.902	0.991	0.156	0.606	14.937	0.808
1994	0.486	0.765	18.628	0.978	0.044	0.657	14.893	0.850
1995	0.733	0.861	20.670	1.046	0.288	0.615	14.715	0.789
1996	0.243	0.760	19.773	0.993	-0.185	0.802	19.104	0.978
1997	-0.315	0.585	12.992	0.766	0.115	0.486	11.905	0.702
1998	-0.281	0.840	19.490	1.032	0.147	0.712	18.042	1.006
1992-1998 Mean	0.273	0.753	18.222	0.958	0.081	0.637	15.178	0.845

3.5. Monthly Mean Daily Ref-ET estimation

Both the Hargreaves and calibrated Hargreaves equations provide their best performances in estimating Ref-ET for monthly time steps. The MBE ranged from -0.316 – 0.765 mm day^{-1} with a mean of 0.228 mm day^{-1} while employing the Hargreaves method, while it ranged from -0.002 – 0.283 mm day^{-1} with a mean of 0.139 mm day^{-1} for calibrated Hargreaves method. These values are generally well within the range found for monthly estimates in Florida (Martinez and Thepadia, 2010) (−1.232 – 0.863 mm d^{-1} with a mean of 0.301 mm d^{-1}). In case of Hargreaves equation, the mean MAE reduced from 0.753 mm/day (Table 6) to 0.583 mm/day (Table 7). The mean MAE decreased from 0.637 mm/day (Table 6) to 0.428 mm/day (Table 7) for calibrated Hargreaves equation. On the average, the estimates of Ref-ET by both Hargreaves and calibrated Hargreaves equations got significantly improved and were close to FAO 56 P-M estimates by 0.17 mm/day and 0.209 mm/day respectively for monthly time-steps compared to weekly time-steps. The mean MAPE of estimates by both Hargreaves and calibrated Hargreaves equations too got significantly reduced to 13.24 and 9.76 respectively for monthly time steps compared to 18.22 and 15.18 respectively for weekly time steps. The mean SEE for both Hargreaves and calibrated Hargreaves equations were the lowest at 0.737 m/day and 0.573 mm/day respectively for monthly time steps compared to 0.958 mm/day and 0.845 mm/day respectively obtained for weekly time steps. Values of SEE ranged from 0.557 – 1.005 mm day^{-1} for Hargreaves equation while it ranged from 0.498 – 0.651 mm day^{-1} for calibrated Hargreaves equation. The range of values obtained for SEE is similar to the range obtained by Martinez and Thepadia (2010) for Florida State (0.294–1.307 mm d^{-1} with a mean of 0.616 mm d^{-1}), the western Balkans (Trajkovic 2007) (0.45–0.8 mm d^{-1}), southern Iran (Fooladmand et al. 2008) (0.58–1.43 mm d^{-1}), and worldwide (Droogers and Allen 2002) (0.8 mm d^{-1}). Table 7 shows the statistical summary of monthly mean daily Ref-ET estimates for the test years.

Table 7. Statistical summary of monthly mean daily Ref-ET estimates for the test years (1992 -1998)

Year	Hargreaves				Calibrated Hargreaves			
	MBE	MAE	MAPE	SEE	MBE	MAE	MAPE	SEE
1992	0.469	0.557	12.561	0.698	-0.002	0.400	8.621	0.498
1993	0.636	0.636	16.155	0.844	0.152	0.464	10.896	0.592
1994	0.513	0.556	13.131	0.755	0.042	0.381	8.322	0.553
1995	0.765	0.856	19.311	1.005	0.283	0.502	11.554	0.651
1996	-0.186	0.412	8.427	0.557	0.240	0.406	9.126	0.548
1997	-0.316	0.541	11.769	0.689	0.115	0.415	10.173	0.603
1998	-0.285	0.528	11.288	0.614	0.140	0.429	9.617	0.567
1992-1998 Mean	0.228	0.583	13.235	0.737	0.139	0.428	9.759	0.573

Figures 4, 5 and 6 respectively show the daily Ref-ET, weekly mean daily Ref-ET and monthly mean daily Ref-ET of Hargreaves and calibrated Hargreaves equations compared to FAO 56 P-M method at Annamalainagar for the years 1992-1998. A close observation of the trends of both the Ref-ET curves obtained by Hargreaves and calibrated Hargreaves equations compared to those of the FAO-56 P-M equation in all Figures 4, 5 and 6 reveal that the performance of calibrated Hargreaves equation is better than that of original Hargreaves equation in estimating Ref-ET values close to those of FAO-56 P-M equation during the summer months of April and May and during the windy months of June and July in all test years. In other months in any test year, the Ref-ET estimates provided by the original Hargreaves equation are much closer to those of FAO-56 P-M equation than those estimated by calibrated Hargreaves equation. Hence, even though, statistically speaking, the performance of calibrated Hargreaves equation was better than that of Hargreaves equation in estimating Ref-ET estimates close to those of FAO-56 P-M equation, the Hargreaves equation also performs well in many of the months of all test years except during the summer months of April and May and windy months of June and July when the Ref-ET values attain their peaks.

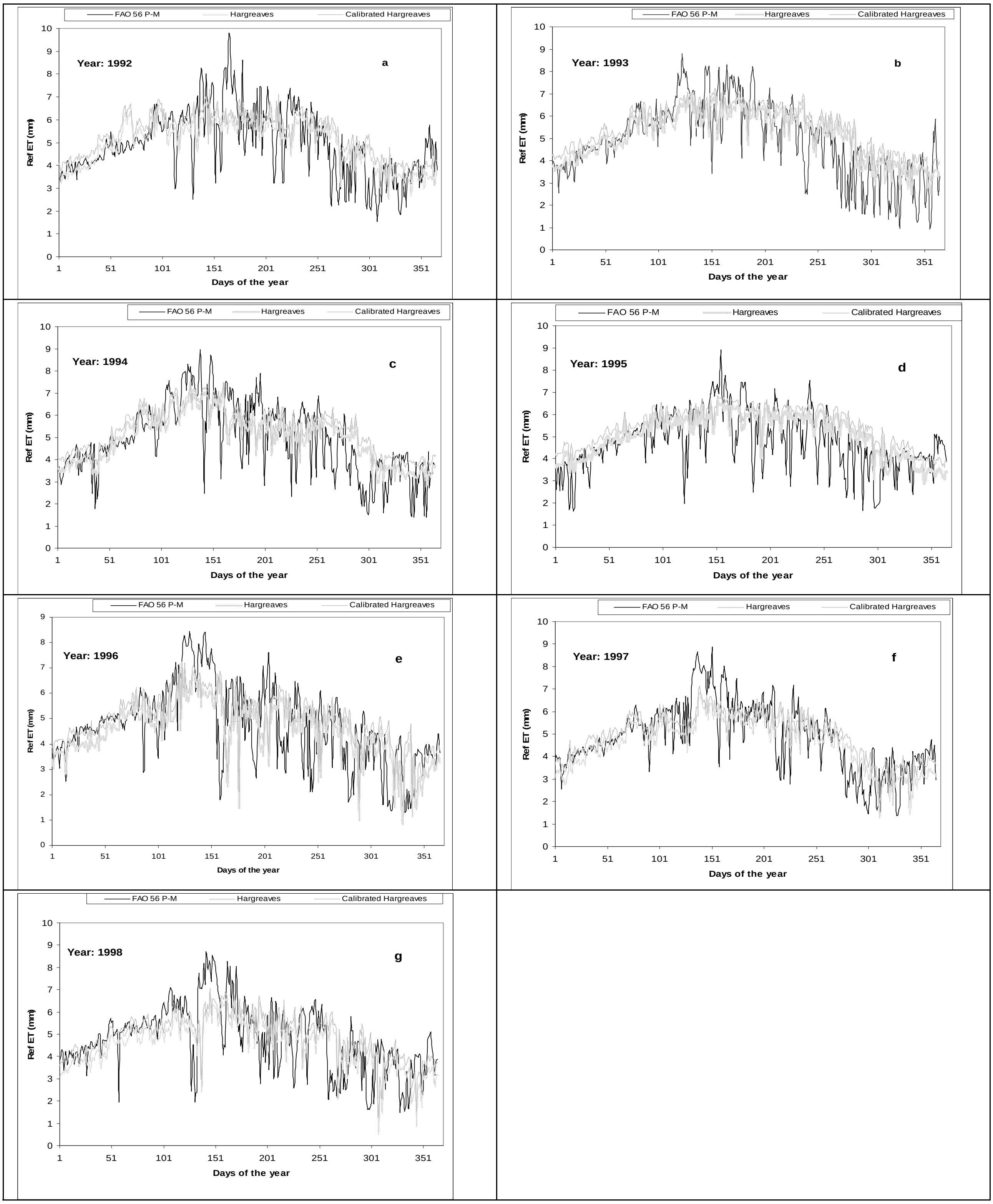

Fig. 4. Daily Ref-ET of Hargreaves and calibrated Hargreaves equations compared to FAO 56 P-M method: (a) 1992 (b) 1993 (c) 1994 (d) 1995 (e) 1996 (f) 1997 and (g) 1998

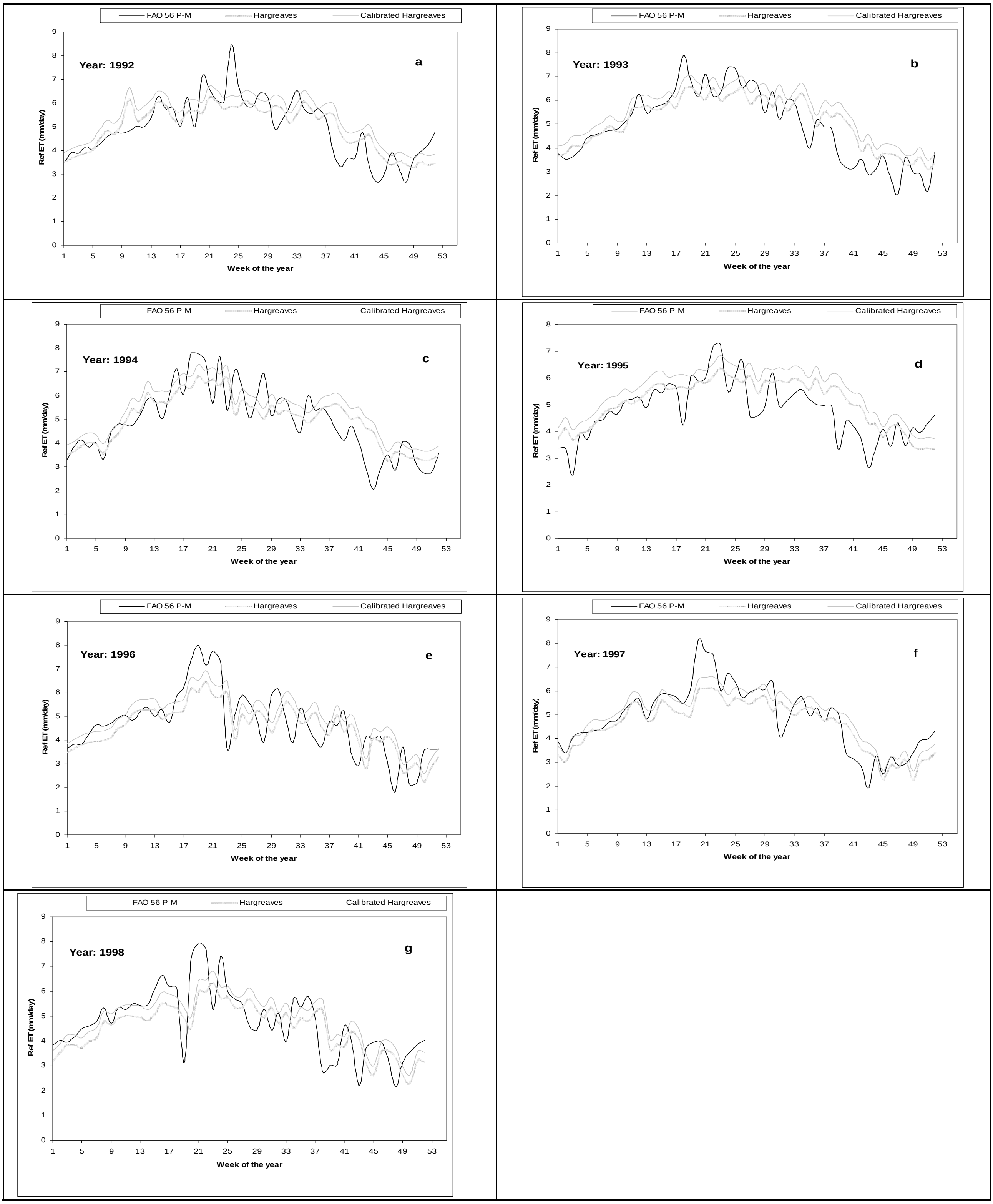

Fig. 5. Weekly mean daily Ref-ET of Hargreaves and calibrated Hargreaves equations compared to FAO 56 P-M method: (a) 1992 (b) 1993 (c) 1994 (d) 1995 (e) 1996 (f) 1997 and (g) 1998

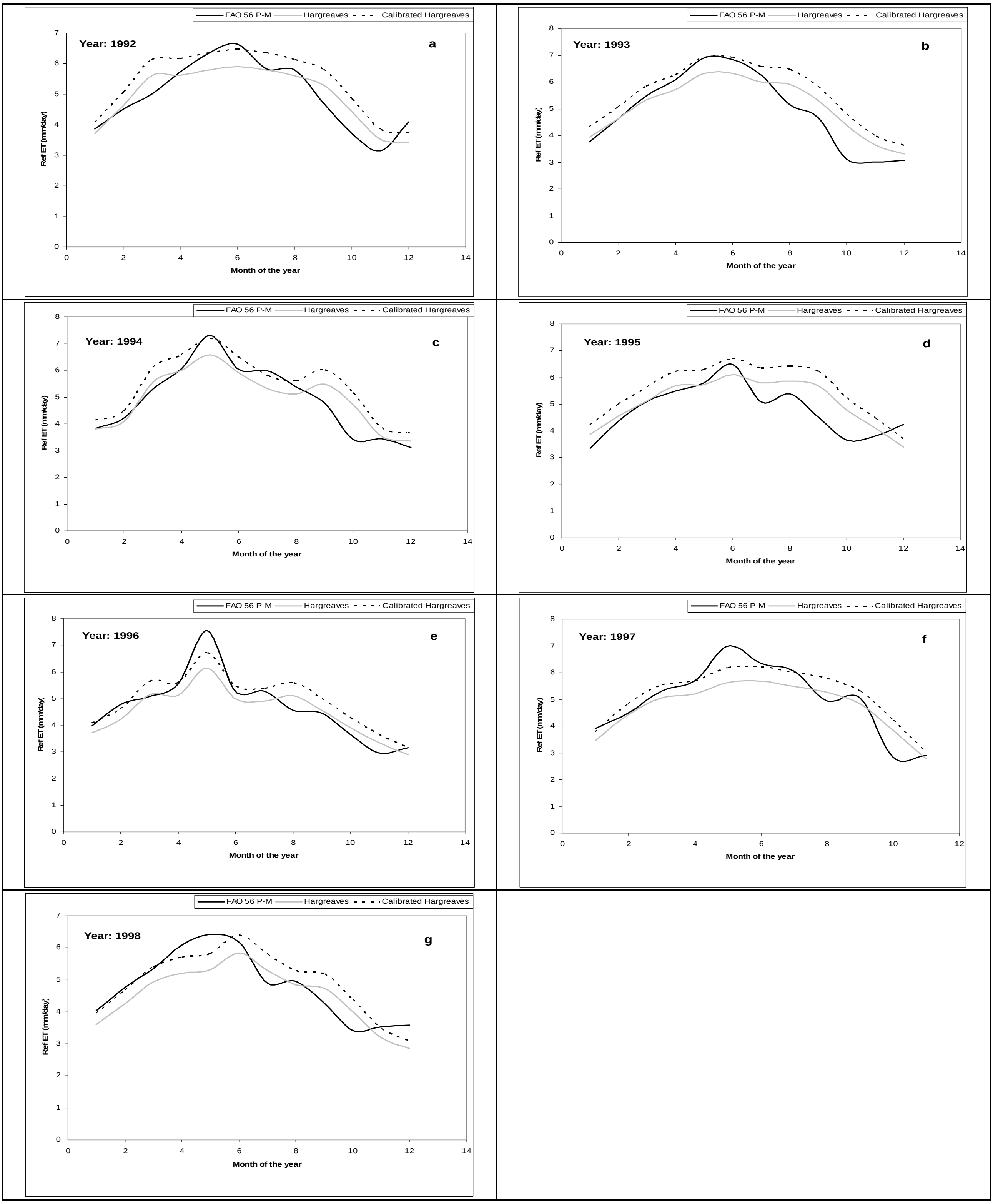

Fig. 6. Monthly mean daily Ref-ET of Hargreaves and calibrated Hargreaves equations compared to FAO 56 P-M method: (a) 1992 (b) 1993 (c) 1994 (d) 1995 (e) 1996 (f) 1997 and (g) 1998

4. Summary and Conclusion

- The Hargreaves method underestimated Ref-ET in more than two-thirds (68%) of the time period considered in the study and overestimated only during less than one-third (32%) of the period. The quantum of underestimation was found to be high during hot and humid days during summer period.

- The maximum underestimation by Hargreaves equation compared to FAO-56 P-M eqaution were foud to be 4.82 mm, 3.43 mm and 2.79 mm respectivley for daily Ref-ET, weekly mean daily Ref-ET and monthly mean Ref-ET, while the maximum overestrimation of Ref-ET were respectively 3.94 mm, 2.85 mm and 1.33 mm. The Hargreaves method performed better in estimating daily Ref-ET when averaged over longer time frames such as a week or a month, as the underestimation or overestimation of Ref-ET got reduced considerably with longer time steps.

- Both the Hargreaves and calibrated Hargreaves methods showed positive bias in most of the years. The MBE of calibrated Hargreaves equation worked out to be less than those of Hargreaves equation in terms of magnitude in all the test years. The MBE ranged from - 0.316 – 0.765 mm day^{-1} with a mean of 0.228 mm day^{-1} while employing the Hargreaves method, while it ranged from - 0.002 – 0.283 mm day^{-1} with a mean of 0.139 mm day^{-1} for calibrated Hargreaves method.

- The mean SEE for both Hargreaves and calibrated Hargreaves equations were the lowest at 0.737 m/day and 0.573 mm/day respectively for monthly time steps compared to 0.958 mm/day and 0.845 mm/day respectively obtained for weekly time steps. Values of SEE ranged from 0.557 – 1.005 mm day^{-1} for Hargreaves equation while it ranged from 0.498 – 0.651 mm day^{-1} for calibrated Hargreaves equation.

- The lower MBE and lower SEE in estimation of Ref-ET by calibrated Hargreaves equation compared to original Hargreaves equation are indicative of the better performance of the former equation in estimating Ref-ET values close to those of FAO-56 P-M method.

- The performance of calibrated Hargreaves equation is better than that of original Hargreaves equation in estimating Ref-ET values close to those of FAO-56 P-M equation during the summer months of April and May and during the windy months of June and July in all test years.

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