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Performance Evaluation of Monthly Reference Evapotranspiration Estimation Methods in Nellore Region

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Abstract

Many reference evapotranspiration (ET_0) estimation methods have been developed for different types of climatic data, and the accuracy of these methods depends on climatic conditions of that area. In the present study, the monthly ET_0 values estimated from nine different ET_0 equations are evaluated with ET_0 estimated by FAO-56 Penman-Monteith (PM) equation in order to select an appropriate ET_0 equation in the semi-arid Nellore region of Andhra Pradesh, India. The evaluation is based on performance criteria, namely, Root Mean Square Error (RMSE), Coefficient of Determination (R^2) and Efficiency Coefficient (EC). Then the ET_0 equations were recalibrated with respect to the PM method for improving their monthly ET_0 estimation capability in the region selected for the present study. The recalibrated Modified Penman and Blaney-Criddle methods showed satisfactory performance in the monthly ET_0 estimation. However, the recalibrated Blaney-Criddle method may be suggested because of its simpler data requirements with a reasonable degree of accuracy.

Keywords: Recalibration, Reference evapotranspiration, Performance evaluation.

1.0 INTRODUCTION

Reference crop evapotranspiration (ET_0) computation forms an integral part of agriculture and regional water balance studies. The ET_0 equations developed are used according to the availability of historical and current weather data.

Most of the studies have shown that the FAO-56 Penman-Monteith (Allen et al.1998)[1] equation gives very accurate ET_0 estimates in different environments. However, if climatic data availability is not sufficient to use this equation, the simple empirical methods yielding results comparable with PM ET_0 may be selected for reasonable estimation of ET_0.

Berengena and Gavilan (2005)[2] evaluated several ET_0 estimation methods for hourly and daily estimates. Penman locally adjusted and ASCE PM performed the best, followed by the FAO PM method. FAO 24 methods showed a strong tendency to overestimate throughout the whole range of evaporation. The methods showed a tendency to underestimate more with increasing advective intensities except ASCE PM and FAO PM methods. Nandagiri and Kovoor (2006)[4] evaluated the performance of several ET_0 methods in the major climate regimes of India with a view to quantify the differences in ET_0 estimates as influenced by climatic conditions. Among the ET_0 methods evaluated the FAO 56 Hargreaves method yielded ET_0 estimates closest to the FAO 56 PM method both for daily and monthly time steps. Singh. V et al., (2006)[6] evaluated Priestley-Taylor, Turc, Blaney-Criddle, Hargreaves-Samani, Christiansen and pan evaporation ET_0 estimation methods, choosing the Penman-Monteith method as the standard of comparison for the Kashmir valley. Radiation and temperature based methods correlated well with the Penman-Monteith method.

The present study reports the performance evaluation of commonly used nine empirical methods, namely, Blaney-Criddle, Jensen-Haise and Hargreaves (temperature based), Priestley-Taylor, Radiation and Makkink (radiation based), Modified Penman (physically based), Pan Evaporation and Christiansen (pan evaporation based) methods with respect to FAO-56 Penman-Monteith (PM) method for estimating monthly ET_0. All these empirical methods are recalibrated with FAO-56 Penman-Monteith method for improving their performance in ET_0 estimation for the Nellore region of Andhra Pradesh.

2.0 MATERIAL AND METHODS

Nellore region, located in Nellore district of Andhra Pradesh, India, with global coordinates of 14^0 22′ N latitude and 79^0 59′ E longitudes, has been chosen as the study area. Meteorological data in the region for the period 1983-2003 was collected from India Meteorological Department (IMD), Pune. A part of the data (1983-1997) was used for developing recalibrated equations, while the rest of the data (1998-2003) was used to verify the performance of the recalibrated equations. The brief descriptions of the methods selected for the study are presented in Table 1.

Table1: Details of reference evapotranspiration estimation methods

Method	Equation	Input data	
		Primary	Secondary
Temperature based 1. FAO-24Blaney-Criddle(BC) method	$ET_0 = a + b\,[p\,(0.46T + 8.13)]$ Where $a = 0.0043\,(RH_{min}) - n/N - 1.41$ $b = 0.82 - 0.0041\,(RH_{min}) + 1.07\,(n/N)$ $+ 0.066\,(u_d) - 0.006\,(RH_{min})\,(n/N)$ $-0.0006\,(RH_{min})\,(u_d)$	T_{max}, T_{min}	RH_{min}, n, u_2, u_d/u_n
2.Jensen-Haise (JH) method	$ET_0 = R_s\,(0.025\,T_{mean} + 0.08)$	T_{max}, T_{min}, n	---
3.FAO-56 Hargreaves(HR) method	$ET_0 = 0.0023\,R_a\,(T_{mean} + 17.8) \times (TD)^{0.5}$	T_{max}, T_{min}, n	---
Radiation based 1. Priestley-Taylor (PT) method	$ET_0 = 1.26 \frac{\Delta}{\Delta + \gamma}(R_n - G)$	T_{max}, T_{min}, n	---
2.FAO-24 Radiation (RA) method	$ET_0 = c\,(W.R_s)$ Where $c = 1.066 - 0.00128\,RH_{mean} + 0.045\,u_d$ $- 0.0002 RH_{mean} u_d + 0.0000315\,(RH_{mean})^2$	T_{max}, T_{min}, n	RH_{max}, RH_{min}, u_2, u_d/u_n

3.Makkink(MK) method	$-\ 0.00103\ (u_d)^2$ $ET_0 = 0.65 \frac{\Delta}{\Delta + \gamma} R_s$	T_{max}, T_{min}, n	---
Physically based 1.FAO-24 Modified-Penman(MP) method	$ET_0 = C\ x$ $\left[\frac{\Delta}{\Delta+\gamma} R_n + \frac{\gamma}{\Delta+\gamma}(0.27)(1.0+0.01U_2)(e_s - e_a)\right]$ Where $C = 0.68 + 0.0028\ (RH_{max}) + 0.018\ (R_s)$ $-\ 0.068\ (u_d) + 0.013\ (u_d/u_n)$ $+\ 0.0097\ (u_d)(u_d/u_n)$ $+\ 0.000043\ (RH_{max})\ (R_s)\ (u_d)$	T_{max}, T_{min}, RH_{max}, RH_{min}, n	u_2, u_d/u_n
2.FAO-56 Penman-Monteith(PM) method	$ET_0 = \frac{0.408\Delta^1(R_n^1 - G^1) + \gamma^1 \frac{900}{T_{mean}+273} u_2 (e_s^1 - e_a^1)}{\Delta^1 + \gamma^1(1+0.34u_2)}$	T_{max}, T_{min}, RH_{max}, RH_{min}, u_2, n	---
Pan Evaporation based 1. FAO-56 Pan Evaporation(PE) method	$ET_0 = K_p\ E_{pan}$ where $K_p = 0.108 - 0.0286\ u_2 + 0.0422\ \ln(FET)$ $+\ 0.1434\ \ln(RH_{mean}) - 0.000631\ [\ln(FET)]^2\ \ln(RH_{mean})$	E_{pan}	FET, RH_{max}, RH_{min}, u_2
2.Christiansen(CS) method	$ET_0 = 0.473\ R_a\ C_T\ C_W\ C_H\ C_S\ C_E\ C_M$ where $C_T = 0.393 + 0.5592\ (T/T_m) + 0.04756\ (T/T_m)^2$ $C_W = 0.708 + 0.3276\ (U_2/U_{2m}) - 0.036\ (U_2/U_{2m})^2$	---	T_{max}, T_{min}, u_2, RH_{max}, RH_{min}, n, E

	$C_H = 1.25 - 0.212(RH/RH_m) - 0.038(RH/RH_m)^5$ $C_S=0.542+0.64(s_p/s_{pm})-0.4992(s_p/s_{pm})^2$ $+0.3174(s_p/s_{pm})^3$ $C_E = 0.970 + 0.030(E/E_m)$ C_M = ranges from 0.9 to 1.1depending on the latitude		

3. PERFORMANCE EVALUATION CRITERIA

The performance evaluation criteria used in the present study are, namely, the coefficient of determination, the root mean square error, systematic RMSE, unsystematic RMSE and the efficiency coefficient.

3.1 Coefficient of Determination (R^2)

It is equivalent to the square of the correlation coefficient (R). Mathematical formula of 'R' is

$$R = \frac{\sum_{i=1}^{n} (o_i - \bar{o})(p_i - \bar{p})}{\left[\sum_{i=1}^{n}(o_i - \bar{o})^2 \sum_{i=1}^{n}(p_i - \bar{p})^2\right]^{1/2}}$$

Where, O and P are observed and estimated values, $\overline{O}$ and $\overline{P}$ are the means of observed and estimated values and n is the number of observations. It indicates the strength of the linear association between O and P. It evaluates performance of the model.

3.2 Root Mean Square Error (RMSE)

It measures the residuals between observed and estimated values and is expressed as

(Yu et al., 1994)[7]

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (p_i - o_i)^2}{n}}$$

3.3 Systematic RMSE ($RMSE_s$)

It shows the room available for local adjustment. It is represented as

$$RMSE_s = \sqrt{\frac{\sum_{i=1}^{n} (\hat{p}_i - o_i)^2}{n}}$$

Where, $\hat{p}_i = a + bo_i$, a and b are the liner regression coefficients

3.4 Unsystematic RMSE ($RMSE_u$)

It a measure of scatter about the regression line and it shows the noise level in the model. It is represented as

$$RMSE_u = \sqrt{\frac{\sum_{i=1}^{n} (p_i - \hat{p}_i)^2}{n}}$$

3.5 Efficiency Coefficient (EC)

It is used to assess the predictive power of hydrological models (Nash and Sutcliffe, 1970)[5]. It is a better choice than RMSE statistic when the calibration and verification periods have different lengths (Liang et al., 1994)[3]. It measures directly the ability of the model to reproduce the observed values and is expressed as

$$EC = 1 - \frac{\sum_{i=1}^{n} (o_i - p_i)^2}{\sum_{i=1}^{n} (o_i - \bar{o})^2}$$

A value of EC of 90% generally indicates a very satisfactory model performance while a value in the range 80-90%, a fairly good model. Values of EC in the range 60-80% would indicate an unsatisfactory model fit.

3.0 RESULTS AND DISCUSSION

The monthly ET_0 values estimated by different methods with original empirical coefficients were compared with those estimated by PM method. The percentage deviations with reference to the PM method are shown in Table 2. The positive deviation represents overestimation and negative deviation indicates underestimation of ET_0 values. It is observed that the deviations are significant for all the methods in ET_0 estimation. The performance of BC, CS and MP methods are relatively better than the other methods in the study region. The performance indicators of the methods with original coefficients are presented in Table 3. The relatively more unsystematic RMSE components with the ET_0 estimation methods except MP and BC methods indicate more noise level in the methods and scatter about the regression line.

The temperature, radiation, physically and pan evaporation based methods selected for the present study were recalibrated with respect to the PM method as presented in Table 4. The performance indicators of these empirical models with original and recalibrated coefficients in the estimation of ET_0 are given in Table 5. The improved R^2, EC and reduced RMSE (Table 5) indicate the closeness of estimated monthly ET_0 values and thereby reflect the appropriateness of recalibration. Though an improvement in the performance of ET_0 estimation methods with recalibrated coefficients over these methods with original coefficients, in general, has been observed (Table 5), a significant improvement has been found in case of recalibrated MP and BC methods. However, out of these methods, recalibrated BC method may be adopted in the reasonable monthly ET_0 estimation in the regions because of simpler data requirements. The scatter plots as shown in Figs.1 & 2 also depict similar observations.

Table 2 Percentage deviations in the estimated monthly reference evapotranspiration with original coefficients

Method	BC	JH	HR	PT	RA	MK	MP	PE	CS
Percentage deviation	-19.0 to 17.4	-21.4 to 59.6	-21.6 to 36.3	-38.0 to 22.9	-10.2 to 96.5	-49.7 to 11.3	-14.3 to 39.6	-44.2 to 53.8	-18.2 to 22.7

Table 3 Performance indicators of various methods with original coefficients against PMM

Method	Slope(m)	Intercept(c)	R^2	RMSE (mm)	$RMSE_S$ (mm)	$RMSE_U$ (mm)	EC (%)
BC	0.9543	0.3728	0.9398	0.27	0.07	0.26	93.98
JH	0.7540	– 0.0575	0.7315	0.57	0.29	0.48	73.15
HR	0.9936	0.0364	0.8079	0.48	0.21	0.43	80.79
PT	1.0492	– 0.3339	0.6545	0.64	0.38	0.52	65.45
RA	0.6534	– 0.0973	0.5203	0.76	0.52	0.55	52.03
MK	1.2097	– 0.1152	0.5327	0.75	0.51	0.55	53.27
MP	0.7603	0.0910	0.9695	0.19	0.03	0.19	96.95
PE	0.5901	2.2014	0.5076	0.77	0.54	0.55	50.76
CS	0.9235	0.2314	0.9244	0.30	0.08	0.29	92.44

Table 4 ET_0 estimation methods with original and recalibrated coefficients

Method	Original equation	Recalibrated equation
BC	$ET_0 = a + b\,[p\,(0.46T + 8.13)]$ where $a = 0.0043\,(RH_{min}) - n/N - 1.41$ $b = 0.82 - 0.0041\,(RH_{min})$ $+ 1.07\,(n/N) + 0.066\,(u_d)$ $- 0.006\,(RH_{min})\,(n/N)$ $- 0.0006\,(RH_{min})\,(u_d)$	$ET_0 = a + b\,[p\,(0.46T + 8.13)]$ where $a = -0.1237(RH_{min}) - 6.4(n/N) + 9.01$ $b = -0.96 + 0.0179\,(RH_{min})$ $+ 0.99\,(n/N) + 0.234\,(u_d)$ $+ 0.009\,(RH_{min})(n/N)$ $- 0.0029\,(RH_{min})\,(u_d)$
JH	$ET_0 = R_s\,(0.025\,T + 0.08)$	$ET_0 = R_s\,(0.031\,T - 0.30)$
HR	$ET_0 = 0.0023\,R_a\,(T + 17.8) \times (TD)^{0.5}$	$ET_0 = 0.0021\,R_a\,(T + 21.8) \times (TD)^{0.5}$
PT	$ET_0 = 1.26\frac{\Delta}{\Delta+\gamma}(R_n - G)$	$ET_0 = 1.22\frac{\Delta}{\Delta+\gamma}(R_n - G)$
RA	$ET_0 = c\,(W.R_s)$ where $c = 1.066 - 0.00128\,RH + 0.045\,u_d$ $-0.0002RH\,u_d + 0.0000315\,(RH)^2$ $- 0.00103\,(u_d)^2$	$ET_0 = c\,(W.R_s)$ where $c = 0.705 - 0.0021\,RH + 0.374\,u_d$ $- 0.0045\,RH\,u_d + 0.000015\,(RH)^2$ $+ 0.00305\,(u_d)^2$
MK	$ET_0 = 0.65\frac{\Delta}{\Delta+\gamma}R_s$	$ET_0 = 0.76\frac{\Delta}{\Delta+\gamma}R_s$
MP	$ET_0 = C \times$ $\left[\frac{\Delta}{\Delta+\gamma}R_n + \frac{\gamma}{\Delta+\gamma}(0.27)(1.0+0.01U_2)(e_s-e_a)\right]$ where $C = 0.68 + 0.0028(RH_{max}) + 0.018\,(R_s)$ $- 0.068\,(u_d) + 0.013\,(u_d / u_n)$ $+ 0.0097\,(u_d)(u_d/u_n)$ $+ 0.000043\,(RH_{max})\,(R_s)\,(u_d)$	$ET_0 = C \times$ $\left[\frac{\Delta}{\Delta+\gamma}R_n + \frac{\gamma}{\Delta+\gamma}(0.27)(1.0+0.01U_2)(e_s-e_a)\right]$ where $C = 0.66 + 0.0010\,(RH_{max}) + 0.011\,(R_s)$ $- 0.013\,(u_d) + 0.013\,(u_d / u_n)$ $+ 0.0097\,(u_d)(u_d/u_n)$ $- 0.000038(RH_{max})\,(R_s)\,(u_d)$

PE	$ET_0 = K_p\ E_{pan}$ where $K_p = 0.108 - 0.0286\ u_2$ $+ 0.0422\ \ln(FET)$ $+ 0.1434\ \ln(RH)$ $- 0.000631[\ln(FET)]^2 \ln(RH)$	$ET_0 = K_p\ E_{pan}$ where $K_p = -3.667 + 0.1536\ u_2$ $+ 0.0422\ \ln(FET)$ $+ 0.9766\ \ln(RH)$ $- 0.000631[\ln(FET)]^2 \ln(RH)$
CS	$ET_0 = 0.473\ R_a C_T C_W C_H C_S C_E C_M$ where $C_T= 0.393+0.02796T+0.0001189(T)^2$ $C_W=0.708+0.00339W-0.0000038(W)^2$ $C_H=1.25-0.00369RH - 6.1x10^{-11} (RH)^5$ $C_S=0.542+0.80s_p-0.78(s_p)^2 + 0.62(s_p)^3$ $C_E =0.970 + 0.0000984\ E$ C_M = ranges from 0.9 to 1.1depending on the latitude	$ET_0 = 2.45\ R_a C_T C_W C_H C_S C_E C_M$ where $C_T = 1.066 - 0.06495\ T + 0.001315\ (T)^2$ $C_W=0.768+0.004556W-0.0000094\ (W)^2$ $C_H=1.01-0.00242\ RH - 51.1x10^{-11} (RH)^5$ $C_S =1.143-1.53s_p + 2.62\ (s_p)^2 - 1.25\ (s_p)^3$ $C_E = 0.970 + 0.0000984\ E$ C_M = ranges from 0.9 to 1.1depending on the latitude

Table 5 Performance evaluation of ET_0 estimation methods with original and recalibrated coefficients against PM method

Method	Slope (m)			Intercept (c)			R^2			RMSE (mm)			EC (%)		
	Original	recalibrated		Original	recalibrated		Original	recalibrated		Original	recalibrated		Original	recalibrated	
		training	testing		training	testing		training	testing		training	testing		training	testing
BC	0.9543	0.9997	1.0256	0.3728	-0.0002	-0.1506	0.9398	0.9844	0.9875	0.27	0.13	0.14	93.98	98.44	98.75
JH	0.7540	0.8258	0.9708	–0.0575	0.8438	0.1828	0.7315	0.7618	0.9280	0.57	0.50	0.33	73.15	76.18	92.80
HR	0.9936	0.9176	1.2089	0.0364	0.3357	-0.7676	0.8079	0.7871	0.8813	0.48	0.47	0.42	80.79	78.71	88.13
PT	1.0492	0.9619	1.3444	–0.3339	0.1892	-1.4641	0.6545	0.5810	0.8186	0.64	0.66	0.52	65.45	58.10	81.86
RA	0.6534	0.8738	0.7786	–0.0973	0.5597	0.9357	0.5203	0.9345	0.9668	0.76	0.26	0.22	52.03	93.45	96.68
MK	1.2097	0.8862	1.3363	–0.1152	0.5398	-1.4641	0.5327	0.4330	0.7456	0.75	0.77	0.61	53.27	43.30	74.56
MP	0.7603	1.0059	1.0129	0.0910	-0.0291	-0.0764	0.9695	0.9966	0.9976	0.19	0.06	0.06	96.95	99.66	99.76
PE	0.5901	0.5822	0.9369	2.2014	1.8370	1.0652	0.5076	0.6058	0.8290	0.77	0.64	0.50	50.76	60.58	82.90
CS	0.9235	0.9240	0.8974	0.2314	0.2408	0.5313	0.9244	0.9130	0.9332	0.30	0.30	0.31	92.44	91.30	93.32

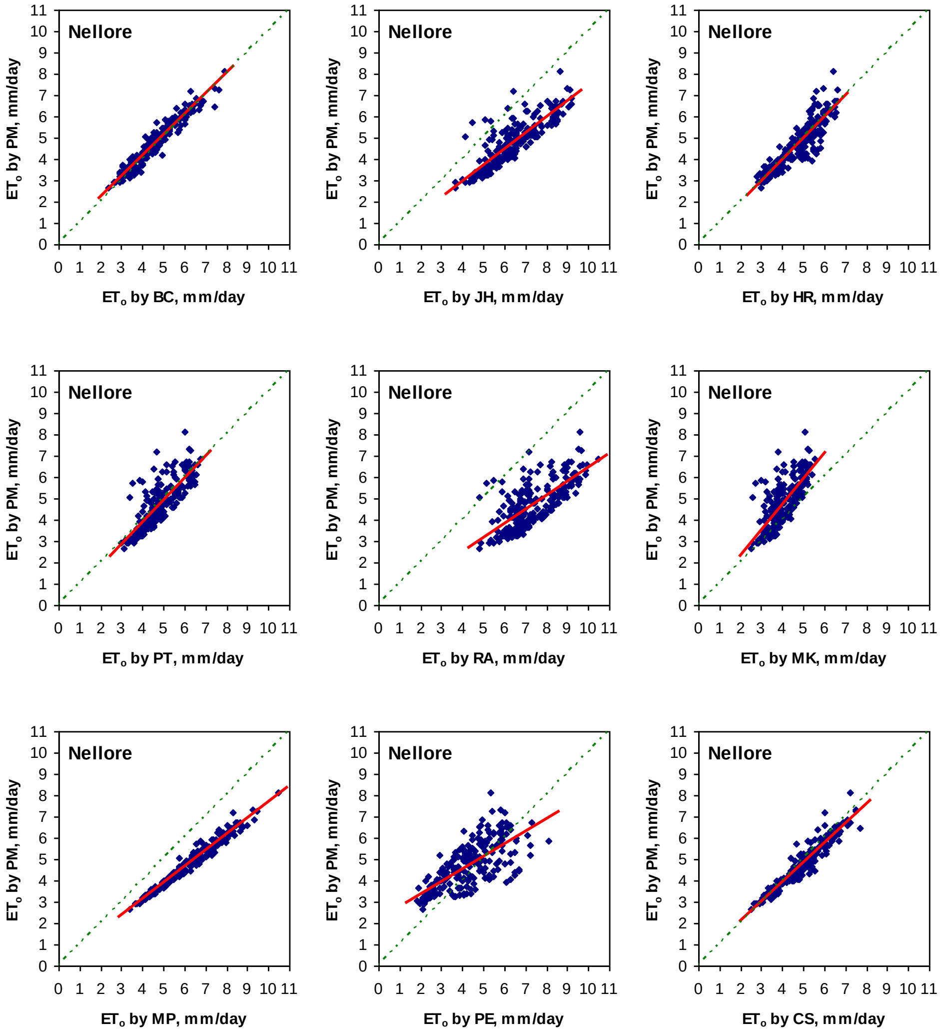

Fig. 1 Scatter plots of monthly ET_0 estimated by various methods with original coefficients against ET_0 estimated using PM method

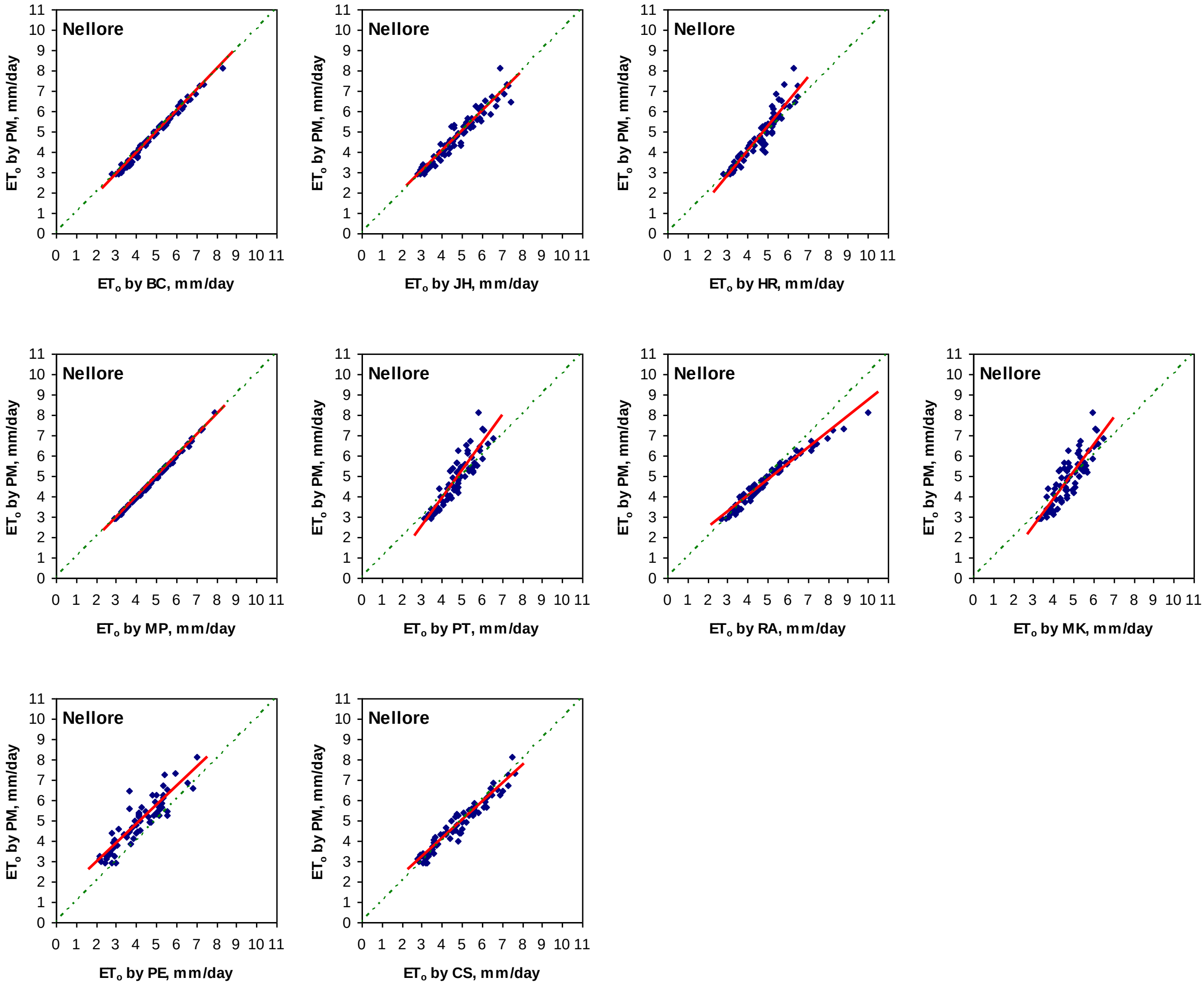

Fig. 2 Scatter plots of monthly ET_0 estimated by various methods with recalibrated coefficients against ET_0 estimated using PM method during testing period

4.0 CONCLUSIONS

The BC, JH and HR (temperature based), PT, RA and MK (radiation based), MP(physically based), PE and CS (pan evaporation based) reference evapotranspiration estimation methods have been recalibrated with respect to FAO-56 Penman-Monteith method and their performance in the monthly reference evapotranspiration (ET_0) estimation was evaluated based on the performance criteria. All these ET_0 estimation methods, in general, showed an improved performance with recalibrated coefficients. The recalibrated MP method and BC method have performed well in the monthly ET_0 estimation. However, recalibrated Blaney-Criddle (BC) method may be applied for the reasonable estimation of monthly ET_0 in the region because of simpler data requirements.

5.0 ACKNOWLEDGEMENT

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