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Comparison of various methods for estimating reference crop evapotranspiration

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Abstract

The reference crop evapotranspiration (ET_0) was estimated for three locations of Bangladesh using the standard Penman-Monteith (P-M) method as recommended by the Food and Agriculture Organization of the United Nations (FAO). The same was also estimated using four other emperical methods and compared with the standard method. The regression equations developed were evaluated with independent data sets. The superiority order were found as: FAO temperature, Radiation, Hargreaves and pan evaporation, respectively. It is revealed from the study that the regression equation developed herein with FAO temperature method can be used to estimate ET_0 more accurately than the original FAO temperature method, as well as regression equations with other methods.

Keywords: Evapotranspiration, Crop water requirement, ET_0 methods

Introduction

Management practices for optimal utilization of water have been increasingly emphasized because of unevenly distributed rainfall, high evapotranspiration and excessive depletion of groundwater resources. Thus practical methods for the accurate estimation of water use in irrigated agriculture are essential. The estimation of crop water requirement is one of the principal steps in the planning, design and operation of irrigation and water resources systems. Crop water requirements vary with crop characteristics and local condition. Relationships between the evapotranspiration of a pre-selected crop (the reference crop), which is referred to as reference evapotranspiration (ET_0), and other crops are established by multiplying ET_0 by crop coefficients. The ET_0 depends on local meteorological conditions, whereas the actual evapotranspiration (ET) of a crop depends on its characteristics, time of planting or sowing and stage of crop development.

Models for predicting ET_0 range from deterministically-based combined energy balance-vapor transfer approaches to empirical relationships based on climatological variables, or to evaporation from a standard evaporation pan. Updated procedures for calculating ET_0 were established by FAO. According to FAO-1992 (Smith *et al.*, 1992), Penman-Monteith method gives more consistent ET_0 estimates and has been shown to perform better than other ET_0 methods when compared with lysimeter data. FAO-1992 also suggested to compare and validate other methods of ET_0 estimates with respect to Penman–Monteith (P-M) method. The P-M method takes into account almost all the factors which are known to influence ET_0, such as temperature, humidity, sunshine hour, wind speed. But these weather variables are not available at different locations in developing countries like Bangladesh. Air temperature is available at most of the weather stations worldwide, the remaining variables are only collected at relatively very few locations and those recordings are not always very reliable (Droogers and Allen, 2002). This lack of reliable weather data lead to suggest to use simpler ET_0 estimation equations, and compare and calibrate the same with standard P–M equation (Smith *et al.*, 1992; Allen *et al.*, 1998; Walter *et al.*, 2000; Drooger and Allen, 2002). A relationship of other methods (which requires limited data) with P-M method will facilitate to increase accuracy of this method. The purpose of this study was to compare a few of the most popular (FAO suggested) ET_0 equations against the FAO P–M equation, which is considered the standard approach to define and compute reference crop evapotranspiration (Walter et al., 2000), and to correlate the same with P-M equation.

Materials and Methods

Selection of Meteorological Stations and Data Collection

Three different stations located at different representative regions (and also agro-ecological zones) of the country were selected for study. The stations were namely: Mymensingh (24 ^{0} 43 $''$ N, 90 ^{0} 26 $''$ E, and 19 m above Mean Sea Level (MSL)), Ishurdi (Pabna) (24 ^{0} 8$''$ N, 89 ^{0} 3$''$ E, 34 m above MSL), and Rangpur (25 ^{0} 45 $''$ N, 89 ^{0} 15 $''$ E, 34 m above MSL). Daily data of different climatic parameters such as, maximum temperature, minimum temperature, humidity, wind speed and bright sunshine hour for the period from 2001 to 2003 were collected and used in this study. Monthly average values of the climatic parameters are presented in Table 1.

Selection of ET_0 estimation methods

The methods for estimating ET_0 from the numerous methods reported in the literature were chosen based on the report of Smith *et al.* (1992). They reported that the P-M method gives the best estimation of ET_0, but also recommended the Blaney-Cridle (referred as FAO temperature), Radiation (FAO radiation), Hargreaves method and Class-A pan evaporation. A summary definition of each equation is given below:

FAO temperature (Blaney – Criddle) equation

The recommended relationship is expressed as:

$$ET_0 = c\,[p(0.46T + 8)] \quad \text{...} \quad (1)$$

where: ET_0 = reference crop evapotranspiration in mm/d
T = mean daily temperature in ^{0}C
p = daily percentage of total annual daytime hours
c = adjustment factor

Radiation method

The relationship recommended is expressed as:

$$ET_0 = c\,(W/R_s) \quad \text{...} \quad (2)$$

Where: ET_0 = reference crop evapotranspiration in mm/d
R_s = solar radiation in equivalent evaporation in mm/day
W = weighing factor which depends on temperature and altitude
c = adjustment factor

When R_s is not available, it is obtained from measured sunshine duration record as follows:

$$R_s = (0.25 + 0.50\ n/N)\ R_a \qquad (3)$$

Where n/N is the ratio between actual measured bright sunshine hours and maximum possible sunshine hours, and R_a is the amount of radiation received at the top of the atmosphere.

Hargreaves method

Hargreaves & Samani (1985) suggested a method involving only temperature and radiation data. Their equation is given by:

$$ET_0 = (0.0023\ R_a)\ (T_{mean} + 17.8)\ TD^{0.5} \qquad (4)$$

In which R_a is extra-terrestrial radiation in equivalent mm of water evaporation for the period, T_{mean} is the mean temperature in ^0C, and TD is the difference between maximum and minimum temperatures.

Pan evaporation

Reference crop evapotranspiration (ET_0) can be obtained from :

$$ET_0 = K_p\ .E_{pan} \qquad (5)$$

Where: E_{pan} = pan evaporation in mm/d
K_p = adjustment factor

Penman-Monteith equation

The Penman-Montheith (P-M) equation is expressed in the form;

$$ET_0 = \frac{0.0864}{\lambda} . \frac{\Delta(R_n - G) + c_p p_a DPV / r_a}{\Delta + \gamma(1 + r_c / r_a)} \qquad (6)$$

Where λ is the latent heat of vaporization ($MJkg^{-1}$); Δ the slope of the vapor pressure versus temperature curve (kPa $^0C^{-1}$); γ the psychrometric constant (kPa $^0C^{-1}$); R_n the net radiation (Wm^{-2}); G the soil heat flux (Wm^{-2}); c_p the specific heat of air (1013 Jkg^{-1} C^{-1}); ρ_a the atmospheric density (kgm^{-3}); DPV the vapour pressure deficit (kP_a); r_a the aerodynamic resistance (sm^{-1}); r_c the bulk canopy resistance (sm^{-1}); and the ratio $0.0864/\lambda$ was used to transform Wm^{-2} to mm per day.

Calculation of ET_0

The daily values of the meteorological variables were used to compute reference crop evapotranspiration (ET_0) with Penman-Monteith (ET_{P-M}), FAO temperature (ET_{BC}), Hargreaves (ET_{HAR}) equations. The ET_0 values were calculated using a software package 'ET_0', developed by Katholic University of Leuven, Belgium. In P-M method, the model parameter angstrom coefficients $\boldsymbol{a_s}$ and $\boldsymbol{b_s}$ were taken as 0.25 and 0.50, respectively.

Correlating the methods with standard (P-M) method

The computed daily ET_0 values for three years (2001-03) from the different methods were analyzed to find the components of the following linear regression equations:

$$y = mx + c$$
$$y = mx$$

Where y represents ET_{PM} and x is the ET_0 estimates from the FAO temperature, FAO radiation, Hargreaves methods and pan evaporation; and m and c are constants representing the slope and intercept respectively.

Validation/evaluation of the regression model

Validation is essentially an independent test of the model, where the model predictions are compared with data not used in the calibration/development process. Evaluation of model performance should include both statistical criteria and graphical display. A model is a good representation of reality only if it can be used to predict an observable phenomenon with acceptable accuracy and precision (Loague and Green, 1991).

Bias (Retta *et al.*, 1996); root mean square error (RMSE) (Gabrielle and Kengni, 1996), which quantifies the dispersion between simulated and measured data; and relative error (RE) (Cob and Juste, 2004; Willmott, C. J., 1982) were used to indicate overall simulation performance:

$$\text{Bias} = \frac{1}{N}\sum_{i=1}^{N}(S_i - M_i) \quad \text{.................................} \quad (7)$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - M_i)^2} \quad \text{.................................} \quad (8)$$

$$\text{RE} = \frac{\text{RMSE}}{\bar{y}}.100 \quad \text{.................................} \quad (9)$$

Where S and M are the simulated and measured values for the ith observation and N is the number of observations, y is the average of ET_{PM} estimates.

Results and Discussion

Comparison of methods

Daily ET_0 values for the month of January using different methods (including pan evaporation) are shown in Fig.1. From the figure it can be seen that Hargreaves method overestimated ET_0 at highest level. For the other months of the year (not shown in figure), the Radiation method overestimated at highest level and the Hargreaves method showed the 2nd highest tendency. FAO temperature, Radiation, and Hargreaves method follow the trend as that of P-M method. But the deviation is higher in Hargreaves and Radiation method compared to temperature method. Pan evaporation sometimes follows the same trend as that of P-M method, but abrupt fluctuation in most of the period. This may be due to erroneous reading of the pan. It is clear that for the Mymensingh station, estimates by FAO temperature (ET_{BC}) are somewhat closer to P-M estimates (ET_{PM}) than other estimates; and Radiation (ET_{RAD}) and Hargreaves (ET_{HAR}) methods overestimated ET_0.

At Ishurdi, the Hargreaves method clearly dominates over Radiation method. But the FAO temperature, Hargreaves and Radiation method followed the same trend as that of P-M method.

At Rangpur, the tendency of Radiation and Hargreaves method to overestimate ET_0 value compared to P-M method is apparent. The superiority of FAO temperature method for closer estimation of ET_0 with P-M method is also clear.

Correlation between the methods

The slope (m), intercept (C), and the coefficient of determination (R^2) of the regression equation between P-M and other methods for two contrasting season (dry and wet) are summarized in Table 2. FAO temperature and radiation method showed a close relation ($r = 0.92$ to 0.96) with P-M than the Hargreaves method in all locations and in both the seasons. The FAO temperature method showed better result in dry season at Mymensingh and Ishurdi, but reverse at Rangpur. The radiation method showed better performance in wet season than that of dry season. The performance of Hargreaves equation is worse in wet season than the dry season. This may be due to the reason that the Hargreaves equation use temperature difference between maximum and minimum which did not reflect accurately the available energy for ET in wet season because of frequent rainfall. Pan evaporation showed scattered distribution, may be due to erroneous pan reading, as mentioned earlier. Overall, the FAO temperature and Radiation methods showed consistent good performance in both the seasons.

The slope (m), intercept (C), and the coefficient of determination (R^2) of the regression model irrespective of the season were summarized in Table 3. The FAO temperature and Radiation method showed their superiority than the others in all locations studied (not shown). When the intercept of the regression equations were forced to pass through zero ($y = mx$), the R^2 value for the above mentioned methods were almost similar, indicating the consistent better performance.

Table 1. Climatic parameters of the stations

Location	Weather variables	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Mymensingh	Max^{m} temp. (^{0}C)	24.8	27.3	31.1	32.8	31.8	31.3	31.2	31.7	31.5	31.1	29.2	26.3
	Min^{m} temp. (^{0}C)	13.7	11.7	13.7	17.9	21.7	24.1	24.9	25.5	25.6	25.2	23.3	28.5
	RH (%)	75	69	67	72	80	86	87	86	86	84	78	77
	Rainfall (mm)	15.1	20.2	39.4	114.3	305.0	417.9	416.1	360.4	321.0	201.6	19.3	5.2
	Wind speed (km/d)	92.2	122.6	171.4	253.2	286.6	289.2	283.2	245.0	186.0	116.9	79.9	73.4
	Bright sunshine(hr/d)	6.47	7.30	7.36	6.92	5.59	3.82	3.52	4.22	4.31	6.55	7.57	7.13
Ishurdi	Max^{m} temp. (^{0}C)	24.6	27.9	33.1	35.9	34.7	33.2	31.9	31.9	32.0	31.3	29.3	25.9
	Min^{m} temp. (^{0}C)	10	12.9	17.1	12.7	24.2	25.5	25.8	25.9	25.5	22.7	17.4	12.7
	RH (%)	73	66	58	63	74	83	87	86	86	82	77	75
	Rainfall (mm)	19.1	47.6	74.0	147.9	200.6	292.0	258.6	211.5	191.0	90.9	12.1	14.7
	Wind speed (km/d)	72.0	79.2	120.0	182.4	201.6	177.6	168.0	144.0	115.2	76.8	55.2	139.2
	Bright sunshine(hr/d)	8.7	9.2	8.7	8.4	8.5	4.3	5.0	4.9	6.9	7.6	9.0	8.8
Rangpur	Max^{m} temp. (^{0}C)	25.4	27.9	32.1	33.9	33.4	33.1	32.6	32.9	32.3	31.6	29.2	26.2
	Min^{m} temp. (^{0}C)	10	11.6	14.9	19.1	21.4	23.2	24.4	24.7	23.7	20.8	16.3	12.1
	RH (%)	84	80	72	75	81	85	84	86	87	87	84	84
	Rainfall (mm)	14.2	12.8	31.8	95.4	292.9	490.5	440.1	343.2	318.8	175.8	10.6	2.9
	Wind speed (km/d)	45.6	55.2	79.2	115.2	129.6	115.2	108.0	98.4	79.2	139.2	40.8	36.0
	Bright sunshine(hr/d)	4.97	7.99	7.49	6.40	9.5	3.49	5.07	4.56	6.5	7.3	6.9	6.1

Table 2. The slope (m), intercept (C) and R^2 value of regression equations (different ET_0 equations regressed with P-M method) for dry and wet season

Location	Method	For dry period			For wet period		
		m	C	R^2	m	C	R^2
Mymensingh	FAO temp.	0.9342	-0.083	0.888	0.8931	0.4717	0.86
	Radiation	0.7492	0.3619	0.877	0.7332	0.9116	0.934
	Hargrives	1.096	-0.8537	0.773	1.1011	-0.2133	0.417
	Pan evapo.	0.6256	1.235	0.579	0.4809	2.0009	0.571
Ishurdi	FAO temp.	0.9049	0.0232	0.931	1.0175	0.1259	0.932
	Radiation	0.7632	0.3212	0.911	0.7776	0.7719	0.958
	Hargrives	0.8291	-0.3591	0.716	0.6632	0.9879	0.178
	Pan evapo.	0.6026	1.0749	0.546	0.4693	1.9637	0.286
Rangpur	FAO temp.	0.815	0.6428	0.905	0.9025	0.5865	0.968
	Radiation	0.7708	0.5327	0.912	0.7476	0.9949	0.969
	Hargrives	1.036	-0.2745	0.849	0.9259	0.1011	0.637
	Pan evapo.	0.4339	1.9582	0.430	0.3477	2.5816	0.358

Table 3. Slope, intercept and R^2 of regression equation irrespective of season

Location	Method	Form: y = mx + C			Form: y = mx	
		m	C	R^2	m	R^2
Mymensingh	FAO Temp.	0.9400	0.0641	0.857	0.9563	0.857
	Radiation	0.7590	0.5285	0.869	0.8810	0.844
	Hargreaves	1.1076	-0.7712	0.630	0.9128	0.609
	Pan evapo.	0.5662	1.5228	0.614	1.0024	0.324
Ishurdi	FAO Temp.	1.0147	-0.1715	0.916	0.9589	0.913
	Radiation	0.8382	0.2173	0.907	0.9030	0.900
	Hargreaves	0.9355	-0.5701	0.607	0.7782	0.589
	Pan evapo.	0.6550	1.0406	0.592	1.0045	0.387
Rangpur	FAO Temp.	0.8777	0.5805	0.933	1.0170	0.907
	Radiation	0.7659	0.7752	0.928	0.9360	0.875
	Hargreaves	0.9643	-0.0436	0.732	0.9540	0.732
	Pan evapo.	0.4059	2.2102	0.387	0.8570	0.196

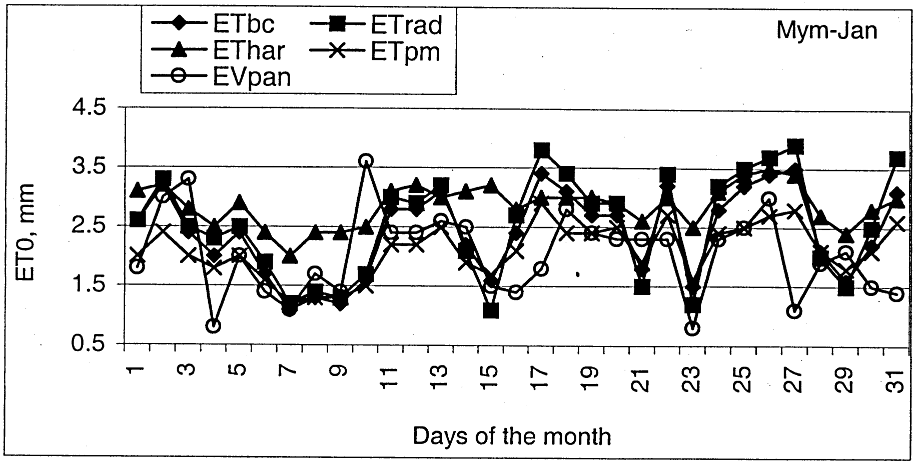
A relation of the methods with P-M irrespective of the season and location (combined) was also tried (Fig. 2). Here also, the FAO temperature and Radiation method exhibited better performance.

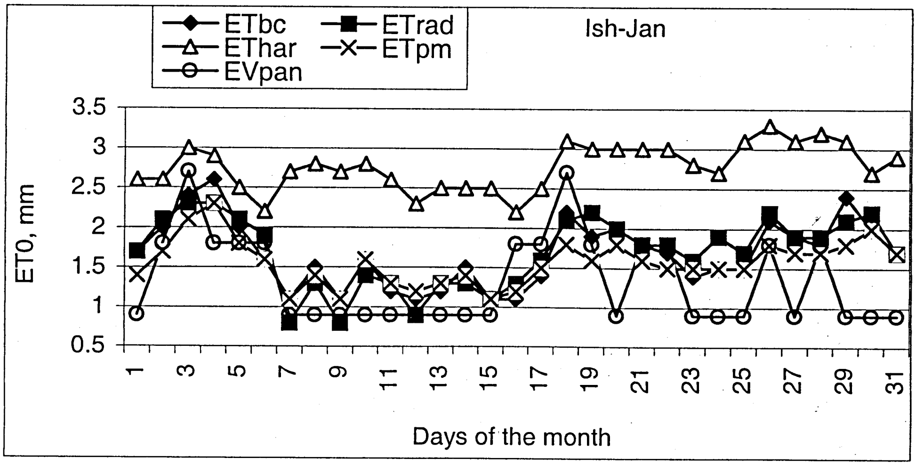
For simulation performance evaluation, equations irrespective of the season were used, since the FAO temperature and Radiation method performed well in both the seasons. The observed (P-M) versus simulated (from regression equation) ET_0 values for Mymensingh location are shown in Fig. 3. The simulation of FAO temperature method fall close to 1: 1 line at all locations (not shown), indicating good simulation. The statistical indicators of simulation performance are summarized in Table 4. The FAO temperature showed lowest bias, root mean square error (RMSE) and relative error (RE) than the other methods. From the simulation graph (Fig. 3) and performance indicator (Table 4), it can be concluded that FAO temperature method is best over other methods studied in simulating actual ET_0. Radiation method showed second position and the Hargreaves method showed third position in superiority judgement. The pan evaporation method ranked fourth.

Table 4. Statistical indicators of simulation performance

Methods	Statistical indicators	Locations		
		Mymensingh	Ishurdi	Rangpur
FAO temperature	R^2	0.857	0.916	0.934
	Bias	- 0.003	- 0.022	- 0.052
	RMSE (mm/d)	0.274	0.164	0.183
	RE (%)	10	3.6	4.42
Radiation	R^2	0.869	0.907	0.928
	Bias	0.071	- 0.409	- 0.076
	RMSE (mm/d)	0.387	0.440	0.511
	RE (%)	14	9.75	12.34
Hargreaves	R^2	0.630	0.60	0.732
	Bias	0.038	- 0.19	- 0.208
	RMSE (mm/d)	0.571	0.610	0.64
	RE (%)	21	13.41	15.4
Pan evaporation	R^2	0.615	0.59	0.399
	Bias	0.292	0.07	0.03
	RMSE (mm/d)	0.884	1.1	1.14
	RE (%)	32	24.5	27.5

From the study, it is revealed that the regression equation developed herein with FAO temperature method can be used to estimate ET_0 more accurately than the original FAO temperature method, as well as regression equations with other methods.





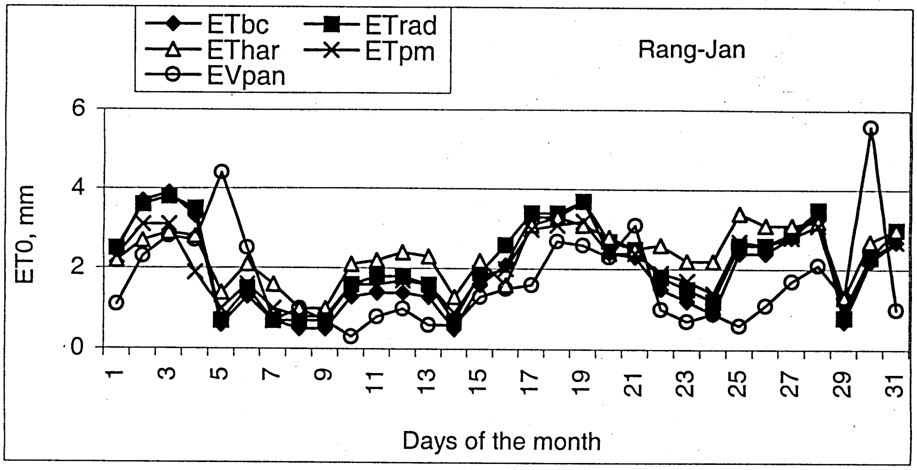


Fig. 1. Daily ET0 by different methods and Pan evaporation at Mymensingh, Ishurdi and Rangpur

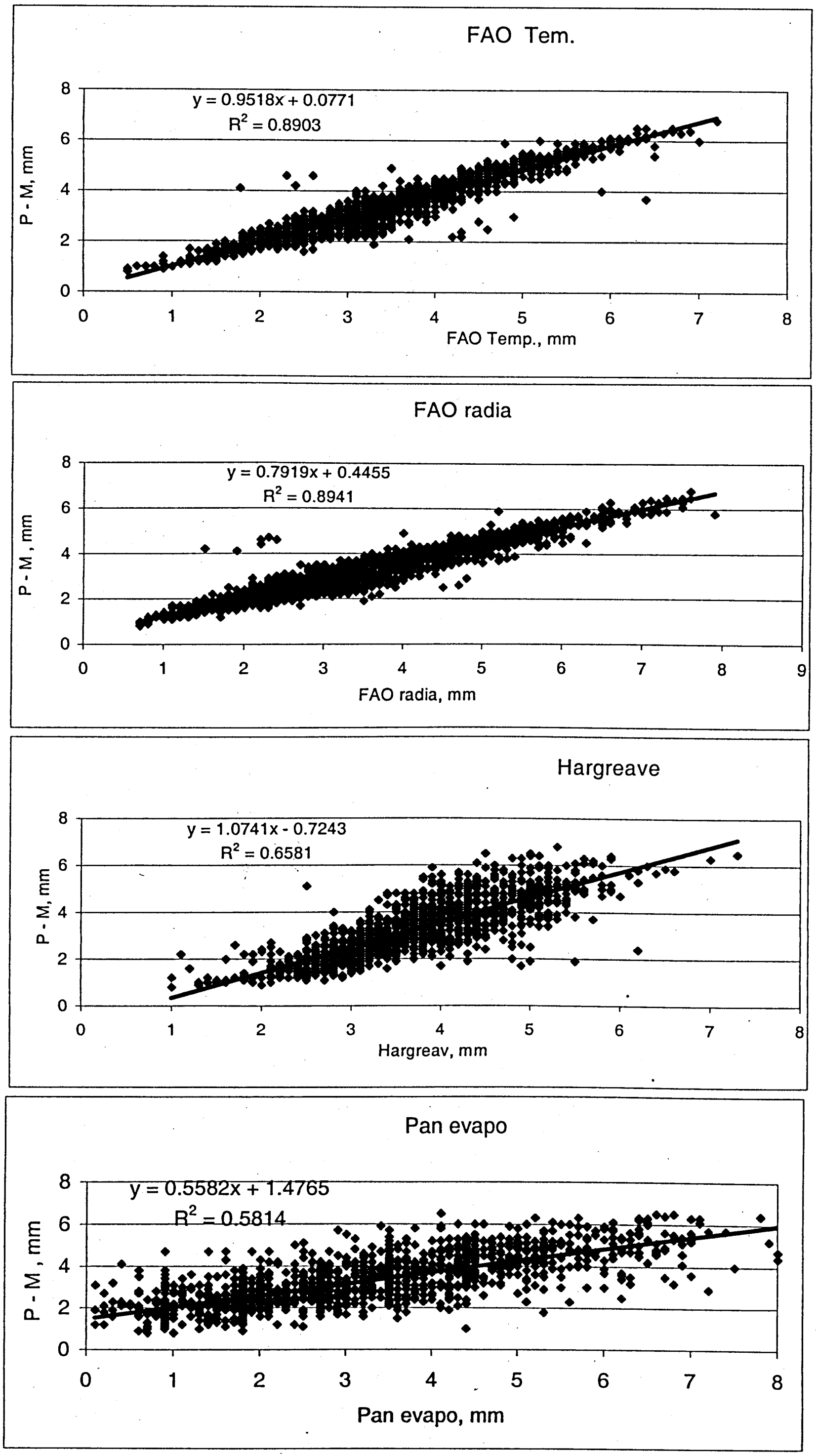


Fig. 2. Relation of different methods with P-M method (irrespective of season and location)

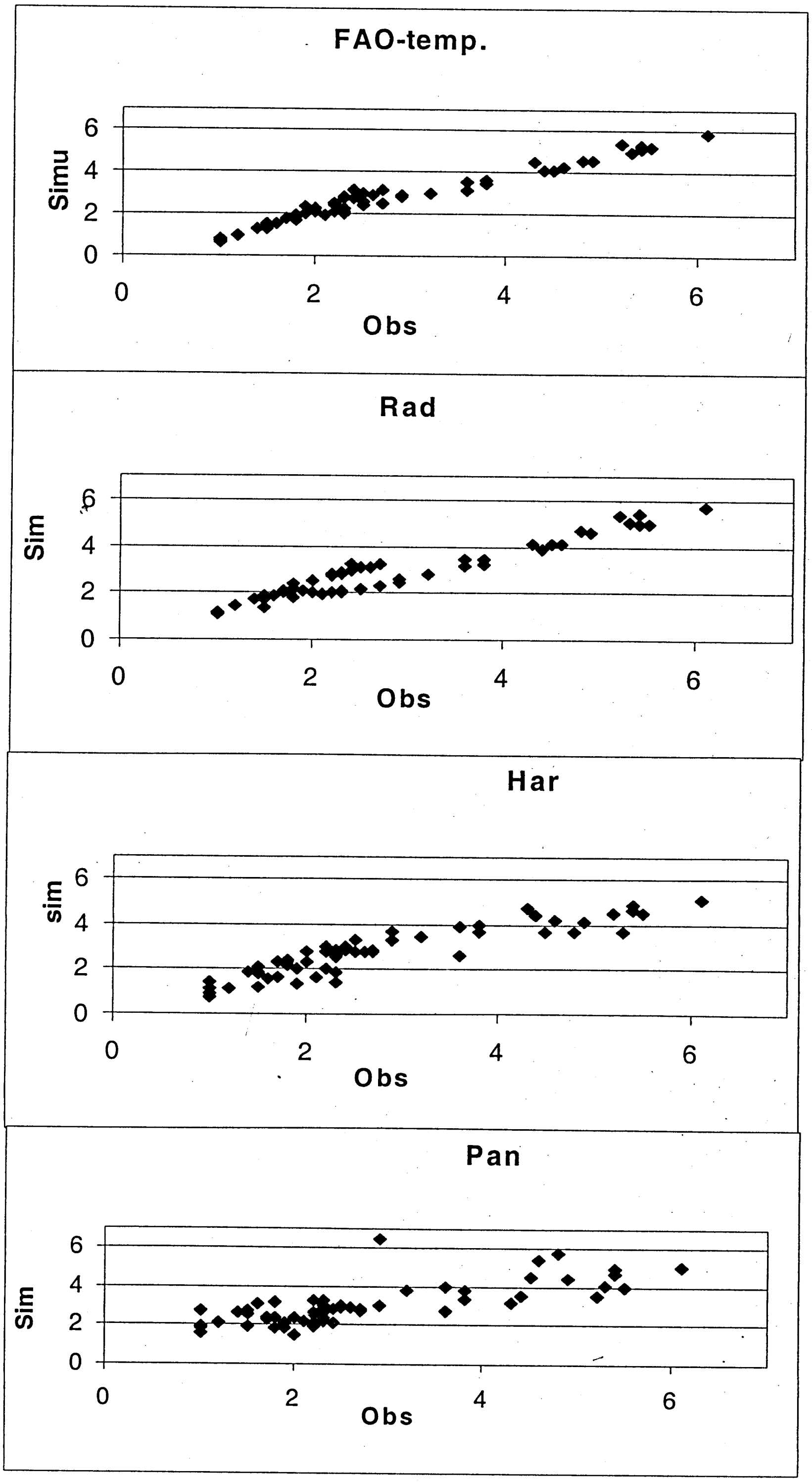


Fig.3. Comparison of simulated (from regression eqn.) and observed (P-M) ET_0 at Mymensingh

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