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Evaluation of empirical models for estimating reference-evapotranspiration (RET-ET) in humid semi-hot equatorial coastal climate

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The performances of five empirical models, namely: Hargreaves-Samani, Makkink1 (1957), Makkink2 (1984), Priestley-Taylor and FAO 56-PM in estimating reference evapotranspiration (REF-ET) were separately compared with Epan data and FAO 56-PM, respectively. Based on statistical analysis, Hargreaves-Samani method compared best with daily and monthly Epan data, while Makkik2 (1984) ranked first with FAO 56-PM. In terms of regression analysis, Priestley-Taylor performed best with daily FAO 56-PM method while Hargreaves-Samani ranked first with daily Epan data. Hargreaves-Samani also correlated best with mean monthly Epan data. The quantitative evaluation of cumulative daily and monthly reference-evapotranspiration (RET-ET) values showed that Makkink (1984) produced the least overestimation and percent relative error against FAO 56-PM while Hargreaves-Samani performed best with Epan data with the least overestimation and percent relative error. In terms of cumulative monthly ET_o totals for the farming season (Dec-April) over the study period, Hargreaves-Samani ranked best with Epan data with the least overestimation and percent relative error while Priestley–Taylor ranked best with FAO 56-PM producing the least overestimation. Overall, Hargreaves-Samani with its original coefficient was adjudged best, capable of approximating FAO 56-PM and Epan data in the Lower Niger River Basin, followed by Makkink (1984) and Priestley-Taylor. Penman-Monteith estimates were used to develop monthly correction factors for adjusting Empirical models for their potential use in Lower Niger Basin. A comparative study such as this has not been undertaken in the Lower Niger River Basin. The models recommended in this study are economical, lesser-data demanding and can be applied to predicting REF-ET in remote agricultural areas.

Key words: Reference-evapotranspiration (RET-ET), empirical models, radiation-based methods, temperature-based methods, FAO 56 –PM, Lower Niger River Basin.

INTRODUCTION

The accurate knowledge of evapotranspiration and consumptive use of water is an index of successful food production programme. The availability of water and efficiency of its economic use are dominant factors controlling or limiting food production and a better understanding of water requirements can, therefore result in large benefits (Hargreaves and Samani, 1981). Irrigation water demand is usually determined through evapotranspiration estimation procedures, namely; (i) direct field measurement methods such as Lysimeter apparatus and US weather Bureau Standard Class A pan and (ii) empirical relationships and mathematical model based on weather data to determine Reference Evapotranspiration (REF-ET) (Jensen et al., 1990; Allen et al., 1998). The Lysimeter apparatus, and Evaporation pans with associated automated measurement devices are rather expensive and are located at a limited number of weather stations around the United States and the world (William et al., 2008). In developing countries like Nigeria, there are additional problems of poor staffing, lack of regular site visitation, improper equipment calibration and instrument.

In view of the human resources and costs implications of using direct measurement methods, empirical and mathematical models based on weather data have become an attractive alternative.

The concept of reference evapotranspiration, REF-ET was introduced to model the evaporative demand of the atmosphere independent of crop type, crop development and management practices. Consequently, REF-ET values measured or calculated at different locations or in different seasons are comparative as they refer to the evapotranspiration (ET_o), from the same reference surface (Allen et al., 1998). The empirical models for evaluation of REF-ET can be grouped into five categories namely: i) water budget, ii) Mass-transfer, iii) Combination, iv) Radiation-based, and v) Temperature based.

The availability of numerous equations for determination of ET, the wide range of data types needed, and the wide range of expertise needed to use the various equations correctly make it difficult to select the most appropriate evaporation method for a given study location (Xu and Singh, 2002). Therefore, the most appropriate method for a given geographical location is to be found by research on comparative studies. In the humid semi-hot equatorial climate of the lower Niger basin, comparative studies with the objective of selecting the best ET_o model are lacking. The aim of this study, therefore, was to evaluate five frequently referred ET_o models (Table 1) and compare them first against Epan data and secondly against FAO 56-PM (where PM stands for Penman-Monteith equation). The daily and monthly REF – ET values were calculated following examples 17 and 18, of Allen et al. (1998) on pages 70 to 73 as guide. The calculation procedures outlined in examples 17 and 18 with the sample data were first programmed in Excel spreadsheet. After the Excel calculations had accurately reproduced the results of example problems, then the example data were replaced with the study data. The study data were the routinely measured variables, maximum temperature (T_{max}), minimum temperature (T_{min}), mean temperature (T_{mean}), measured solar radiation (Rs), relative humidity (RH), wind speed (u_2), and z only (where z is the elevation of the site in metres).

This study will be of great economic benefits to Nigeria, in view of the declining oil and gas revenues and the shift to agricultural economy. Most of the agricultural and allied industries are situated in remotest area without weather stations. The result of this study would be the recommendation of an empirical and less weather-data demanding REF-ET equation to FAO 56-PM which can easily be applied to such locations.

MATERIALS AND METHODS

Weather station

The weather station used in this study is located at the Port Harcourt International Airport, Omagwa, Rivers State, Nigeria. The station is located at latitude 04°51'N and longitude 05°35'E, elevation of 24 m (above sea level). The Nigerian Meteorological Agency (NIMET) station is equipped with the mercury and alcohol thermometers, a cup anemometer, a Campbell sunshine recorder, and a wet-bulb thermometer and some other meteorological instruments. All the instruments were checked for proper installation and operation during observations by NIMET. Figure 1 is the map of Lower Niger River Basin showing Port Harcourt while Table 2 shows the mean monthly weather characteristics for the study period. The climate of Port Harcourt may be classified as Humid Semi – Hot Equatorial Type (Salau and Lawson, 1986), with tropical wet and dry season and pronounced seasonal reversal of wind directions. The annual rainfall is greater than 3000 mm. The wet season occurs between March and October and dry season from November to February, sometimes with occasional rainfall.

Description of empirical equations

Penman-Monteith method

The FAO Penman-Monteith method is physically based, and explicitly incorporates both physiological and aerodynamic parameters (Allen et al., 1998). The form of FAO 56-PM equation for predicting ET_o on a daily basis is:

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

Where ET_o is the reference evapotranspiration (mmday^{-1}), Δ is slope of the vapour pressure curve (kPa °C^{-1}), R_n is net radiation at the crop surface (MJm^{-2}day^{-1}); G is soil heat flux density (MJm^{-2}day^{-1}); T is air temperature (°C) at 2 m height, U_2 is wind speed at 2 m height (ms^{-1}), e_s = saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), γ is psychometric constant (kPa °C^{-1}), and e_s – e_a is saturation vapour pressure deficit (kPa). The complementary parameters λ, P, e_s, e_a, Δ, and γ have been calculated following the procedures given in Chapter 3 of FAO 56 (Allen et al., 1998). For

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Table 1. Characteristics of REF-ET methods (adapted from Amatya et al., 1995).

Empirical models	Main parameter required ±	Recommended time period	Reference crop	Location developed for	Principal reference
FAO 56-PM Penman Monteith	Temp., rel.hum., Net solar rad., Rn	Hourly, daily, weekly, monthly	Any Crop	All Locations	Jensen et al. (1990); Allen et al. (1994a, b; 1998)
Makkink1 (1957) Makkink2 (1984)	Temperature, incoming solar Rad (R_S)	10 days, monthly	Grass	Cool climate, the Netherlands, Australia	Jensen (1974), Jensen et al. (1990); Xu and Singh (2000)
Priestley-Taylor (1972)	Temperature (T) net radiation (R_n)	10 days, monthly	Rain – fed Land	Australia, United States	Jensen et al. (1990); Xu and Singh (2000)
Hargreaves-Samani	T_{max}, T_{min}, T_{mean} extraterrestrial Radiation (Ra)	Weekly, Monthly	Cool – season grass	Semiarid Western US	Jensen et al. (1990); Xu and Singh (2001)

± The appropriate units for the main parameters are given in Equations 1 – 10.

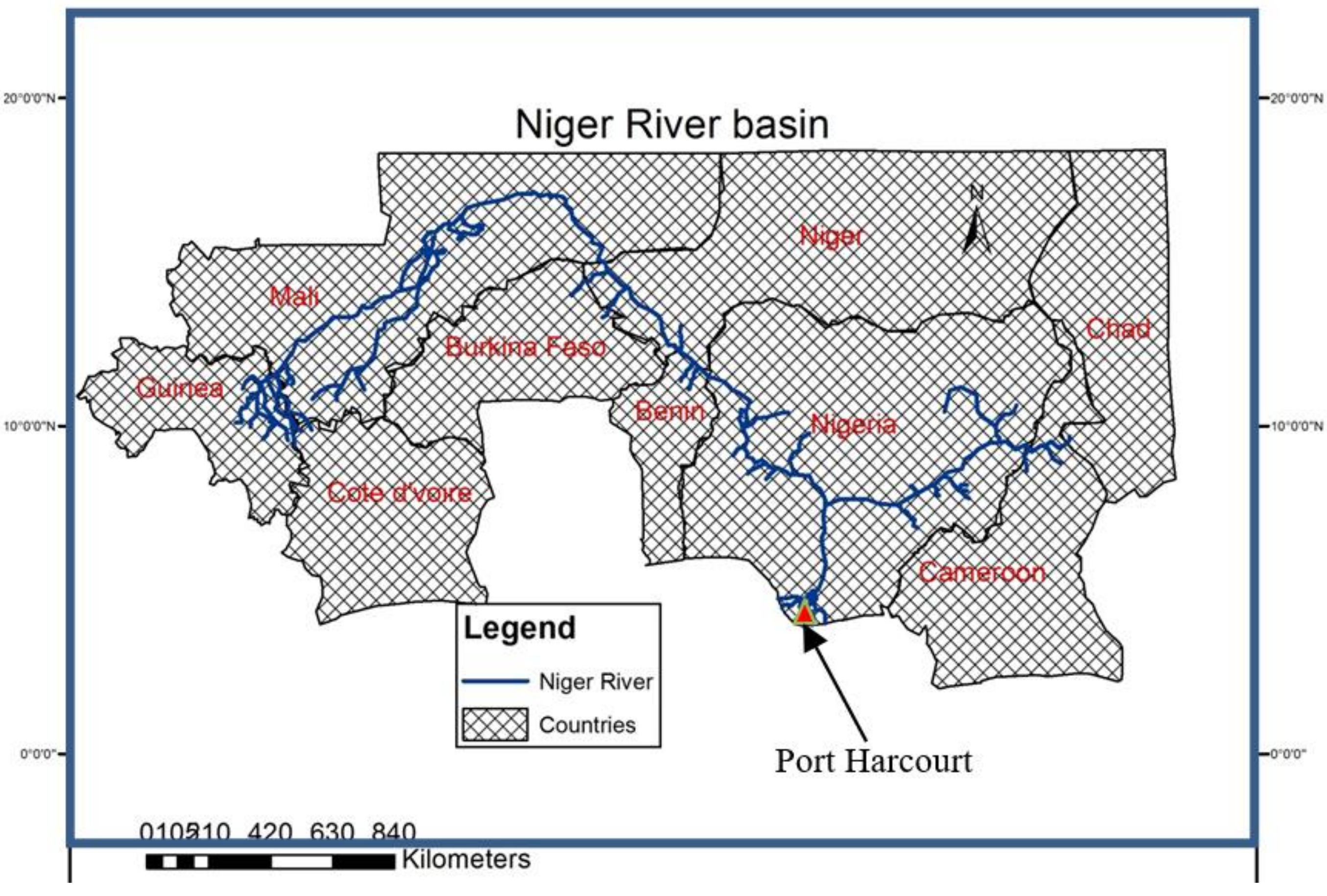

Figure 1. Map of the Niger River Basin Showing Port Harcourt.

the sake of completeness, other important parameters are briefly summarized below:

Net longwave radiation ($R_{n\ell}$): The rate of longwave energy emission may be expressed quantitatively by the Stefan-Boltzman constant due to the absorption and downward radiation from the sky as:

$$R_{n\ell} = \sigma\left[\frac{T_{\max},K^4 + T_{\min},K^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad (2)$$

Table 2. Daily averages of selected climatic parameters (2000-2010).

Month \ Parameters	U_2 (m/s)	Tmax (°C)	Tmean (°C)	Mean RH	Solar Rad.	Barometer pressure
Jan.	3.00	30.8	20.32	25.55	67.8	94.19
Feb.	3.30	31.1	20.93	26.01	67.57	92.03
Mar.	4.00	34.4	24.28	29.36	81.57	103.1
April	3.76	31.9	23.07	27.49	80.12	98.26
May	3.75	31.3	23.00	27.16	82.63	98.55
Jun	3.75	29.02	22.03	25.52	84.06	96.67
July	4.07	29.80	23.32	26.55	90.33	103.52
Aug.	3.91	29.3	23.28	26.28	90.5	103.06
Sept.	3.81	30.6	23.71	27.17	91.61	104.56
Oct.	3.21	30.1	22.57	26.34	85.00	99.20
Nov.	2.54	27.3	19.72	23.52	71.89	86.56
Dec.	2.38	27.92	18.95	23.44	65.61	86.06

Where $R_{n\ell}$ is net outgoing longwave radiation ($MJm^{-2}day^{-1}$), σ is Stefan-Boltzmann (4.903×10^{-9} $MJk^{-4}m^{-2}day^{-1}$); T_{max} is maximum absolute temperature during the 24 h period [K = °C + 273.16]; T_{min} is minimum absolute temperature during the 24 h period e_a is actual vapour pressure (kPa), $\frac{R_s}{R_{so}}$ is relative short wave radiation (limited to ≤ 1.0); R_s is measured or calculated solar radiation ($MJm^{-2}day^{-1}$), R_{so} is calculated (Equation 3) clear-sky radiation ($MJk^{-4}m^{-2}day^{-1}$).

Short wave radiation on a clear-sky day (R_{so}): A good approximation for R_{so} according to FAO (Allen et al., 1998), for daily and hourly periods is given by Equation (3).

$$R_{so} = (0.75 + 2 \times 10^{-5} z) R_a \quad (3)$$

Where z is station elevation [m], R_a is extraterrestrial radiation [$MJm^{-2}day^{-1}$] and R_{so} is clear – sky solar radiation [$MJm^{-2}day^{-1}$].

Extraterrestrial radiation for daily periods (Ra): The extraterrestrial radiation (R_a), for each day of the year and for different latitude can be estimated from solar constant, the solar declination and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} \left[\omega_s Sin(\varphi) Sin(\delta) + Cos(\varphi) Cos(\delta) Sin(\omega_s) \right] \quad (4)$$

Where R_a = extraterrestrial radiation [$MJm^{-2}day^{-1}$], G_{sc} = solar constant = 0.0820 [$MJm^{-2}min^{-1}$], dr = Inverse relative distance Earth – sun, ω_s = sunset hour angle, φ = latitude (rad.), δ = Solar declination. The complimentary equations for calculating dr, ω_s, φ and δ are given in Allen (1996) or any standard text in hydrology.

Net short wave radiation (R_{ns}): The net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - \alpha) R_s \quad (5)$$

Where R_{ns} = net shortwave radiation [$MJm^{-2}day^{-1}$]; α is = albedo, which is 0.23 for the hypothetical grass reference crop [dimensionless]; R_s = incoming solar radiation [$MJm^{-2}day^{-1}$] and R_{ns} is expressed in the above equation in $MJm^{-2}day^{-1}$.

Net radiation (R_n): The net radiation (R_n) is the difference between the incoming net short wave radiation (R_{ns}) and the outgoing net longwave radiation $(R_{n\ell})$.

$$R_n = (R_{ns} - R_{n\ell}) \quad (6)$$

Temperature-based equation

FAO-56 (Allen et al., 1998) recommended Hargreaves method as alternative approach when solar radiation, relative humidity and or wind speed data are missing. In the temperature-based category, the Hargreaves' equation has been selected.

$$ET_o = 0.0023\,(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a \quad (7)$$

Where ET_o = reference evapotranspiration (mmd^{-1}); R_a is extraterrestrial radiation [$MJm^{-2}day^{-1}$].

Radiation-based equations

Given Makkink (1984) and Priestley-Taylor (1972), two models have been selected in this study to represent the radiation-based method. Also, the lower Niger Delta region is similar to the Netherlands, where Makkink equation was found to give good results (Hansen, 1984); the two forms of Makkink equation and Priestley-Taylor are next discussed.

Makkink Method (1957) (Makkink1): The reference evapotranspiration (ET_o) according to Makkink (1957) is:

$$ET_o = 0.61\,\frac{\Delta}{\Delta + \gamma} \cdot \frac{Rs}{\lambda} - 0.12 \quad (8)$$

Where R_s is solar radiation ($MJm^{-2}day^{-1}$); Δ is slope of saturation vapour pressure curve at the temperature T (kρa $°C^{-1}$), γ is psychrometric constant (kρa $°C^{-1}$), λ is latent heat of vapourization, 2.45 ($MJkg^{-1}$).

Makkink Method (1984) (Makkink 2):

$$ET_o = 0.7 * \frac{\Delta}{\Delta + \gamma} \frac{Rs}{\lambda} \quad (9)$$

ET_o, Δ, γ, Rs and λ are as defined under Equation 1.

Priestley-Taylor Method: The Priestley-Taylor method (1972) replaces the aerodynamic term of Penman-Monteith equation by a dimensionless empirical multiplier, called the Priestley- coefficient (α). The Priestley-Taylor equation is useful for the calculation of daily ET_o for conditions where weather input for the aerodynamic term (relative humidity, wind speed) are unavailable.

$$ET_o = \alpha \cdot \frac{\Delta}{\Delta + \gamma} \cdot \frac{(R_n - G)}{\lambda} \quad (10)$$

Where ET_o is reference evapotranspiration (mm/day); α = 1.26, λ is the latent heat of vapourization [λ = 2.45 $MJkg^{-1}$ at 20°C]; and all other terms are the same as in Equation 1.

EVALUATION OF EMPIRICAL MODEL PERFORMANCE

Quantitative methods listed in Equations 11 to 18 have been used to test the strength of and/or weakness of the different models. These methods are indicators of model performance according to Fox (1981), Willmott (1982), Douglas et al. (2009), Berengena and Gavilan (2005), Alexandris et al. (2008), Pogen et al. (2016), and Dash and Khatua (2016). These statistical measures and the regression equations were evaluated using their optimal values as benchmarks.

i) Mean Absolute Error (MAE) = $N^{-1}\sum_{i=1}^{N}|P_i - O_i|$ (11)

ii) Root Mean Square Error (RMSE) = $\left[N^{-1}\sum_{i=1}^{N}\left(P_i - O_i\right)^2\right]^{0.5}$ (12)

iii) Root Mean Square Error (Systematic)(RMSEs)

$$\left[N^{-1}\sum_{i=1}^{N}\left(\hat{P}_i - O_i\right)^2\right]^{0.5} \quad (13)$$

iv) Root Mean Square Error (unsystematic) (RMSEu) =

$$\left[N^{-1}\sum_{i=1}^{N}\left(Pi - \hat{P}i\right)^2\right]^{0.5} \quad (14)$$

v) Model efficiency (EF) = $1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(\bar{O} - O_i)^2}$; 0<=EF<= 1.0 (15)

vi) Mean Bias Error (MBE) = $N^{-1}\sum_{i=1}^{N}\left(Pi - O_i\right)$ (16)

vii) Variance of the distribution of differences $\left(S_d^2\right)$ =

$$N-1\sum_{i=1}^{N}\left(P_i - O_i - MBE\right)^2 \quad (17)$$

viii) Index of Agreement (d) = 1 - $\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i| + |O_i|)^2}$; $0 \le d \le 1.0$ (18)

The notations and indices used in Equations 11 to 18 are as follows:

O_i is observed values (estimated by FAO 56-PM or Epan), P_i is value predicted by any of the empirical equations used in the study, $\hat{P}_i = aO_i + b, P'_i = P_i - \bar{O}$ and, $O'_i = O_i - \bar{O}$.

RESULTS

The results of the study are summarized in Appendix A (Tables A1 and A2), Tables 3 and 4 and Figures 2 to 7. The first stage of analysis involved the estimation of mean daily and mean monthly evapotranspiration based on Equations (1, 7, 8, 9 and 10) with their original constants. Subsequent analyses involved evaluation of REF – ET methods against FAO 56-PM and Epan data using: i) statistical measures represented by Equations (11-18), ii) statistical regression analysis, and iii) total accumulated daily and monthly ET_o values and graphical plots. Tables A1 and A2 show the results of evaluation using Equations (11 to 18). In Tables A1 and A2, R represents the daily rank number for each statistical index while R^* represents the corresponding monthly rank number for each statistical index. The score for each ET_o method was obtained by adding the rank numbers under R or R^*.

The evaluation of daily and monthly ET_o estimates against Epan data are as presented in Table A1. The computed ET_o values for FAO 56-PM, Hargreaves-Samani, Makkink-1, Makkink-2, and Priestley – Taylor were ranked for each of the nine indices (see column 1, Appendix A, Table A1). The cumulative ranked values of R and R* are as shown in Figure 2. Apparently, the order of ranked performance are 1st Hargreaves-Samani, 2nd Makkink-2, 3rd Priestley-Taylor, 4th FAO 56-PM and 5th Makkink-1, respectively.

For the comparison of estimated ETo against ETo-PM for daily and monthly values (Appendix A, Table A2) The cumulative ranked values of R and R* (Figure 3) are 1st Makkink-2 with the lowest aggregate score; 2nd Epan; 3rd Makkink-1; 4th Priestley-Taylor; and 5th Hargreaves-Samani.

The summary of regression models of daily and monthly data are presented in Table 3. The goodness of fit of the correlation was adjudged by R^2, in addition to the slope (b) and intercept (c) of the regression line. The applicable linear probability model was obtained by

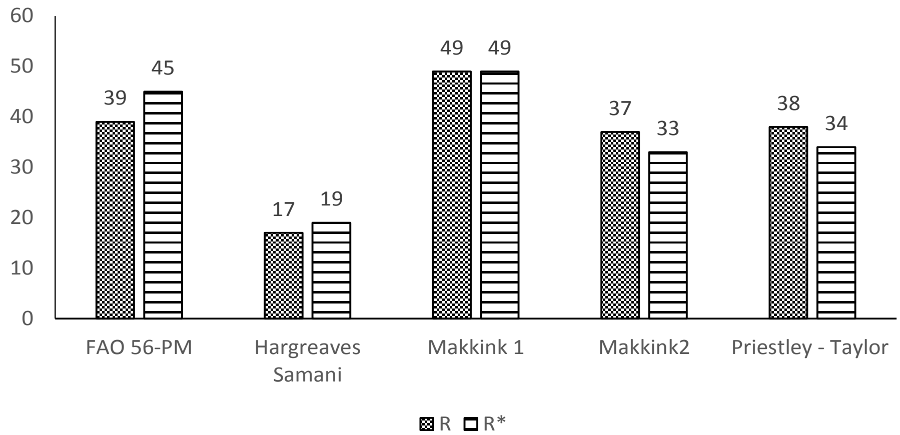

Figure 2. Comparison of cummulative ranking values of R & R* for estimated ET_o against Epan daily and monthly values.

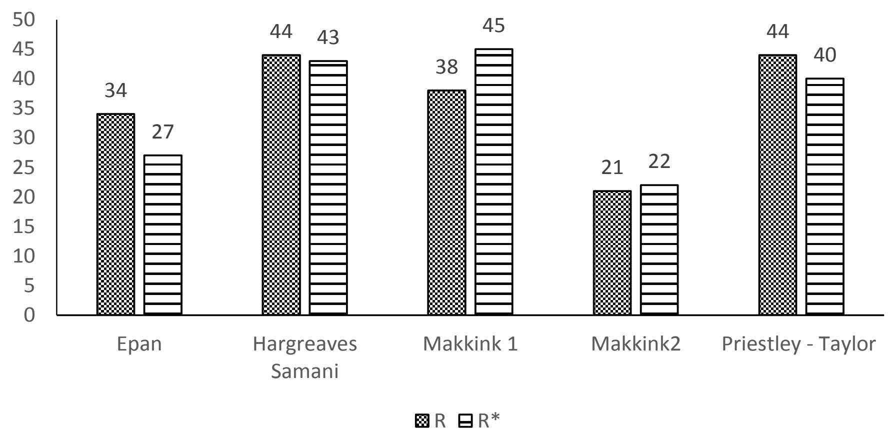

Figure 3. Comparison of cummulative ranking values of R & R* for estimated ET_o against ETo-PM daily and monthly values).

Table 3. Summary of linear regression equation against Epan/ET_o-PM.

S/N	a) Based on Daily Data		b) Based on Monthly Data		% Improvement on R^2 (daily and monthly)
	Equation Form	R^2	Equation Form	R^2	
1	ETo-PM = 0.636 Epan + 1.0663	0.443	ETo-PM = 0.948Epan - 0.188	0.785	77.2
2	ETo-PM = 0.644 ETo_{Harg} + 0.975	0.408	ETo-PM = 0.947ETo_{Harg} - 0.309	0.808	98.1
3	ETo-PM = 1.483 ETo_{MKK2} - 2.04	0.519	ETo-PM = 1.203ETo_{MKK2} - 0.84	0.771	25.2
4	ETo-PM = 1.075ETo_{RT} - 0.675	0.281	ETo-PM = 1.042 ETo_{P-T} - 0.484	0.636	126.3
5	ETo-PM = 1.702 ETo_{MKK1} - 1.84	0.519	ETo-PM = 1.416ETo_{MKK1} - 0.798	0.778	49.9
1	Epan = 0.696ETo_{PM} + 1.64	0.442	Epan = 0.827ETo_{PM} + 0.963	0.785	22.5
2	Epan = 0.9644 ETo_{Harg} + 0.0677	0.836	Epan = 0.945ETo_{Harg} + 0.078	0.922	10.3
3	Epan = 1.335 ETo_{MKK2} - 0.971	0.384	Epan = 1.050 ETo_{MKK2}+ 0.0752	0.674	43.0
4	Epan = 1.634 ETo_{Harg} - 0.545	0.30	Epan = 0.956 ETo_{P-T} + 0.2156	0.614	51.1
5	Epan = 1.532 ETo_{MKK1} – 0.788	0.384	Epan = 1.234 ETo_{MKK1} + 0.1186	0.678	43.4

regressing: (i) mean daily and mean monthly, ET_o-PM values against ET_o values, and (ii) mean daily and monthly Epan values against ET_o values. Both ET_o-PM and Epan data were used as comparison criteria. A

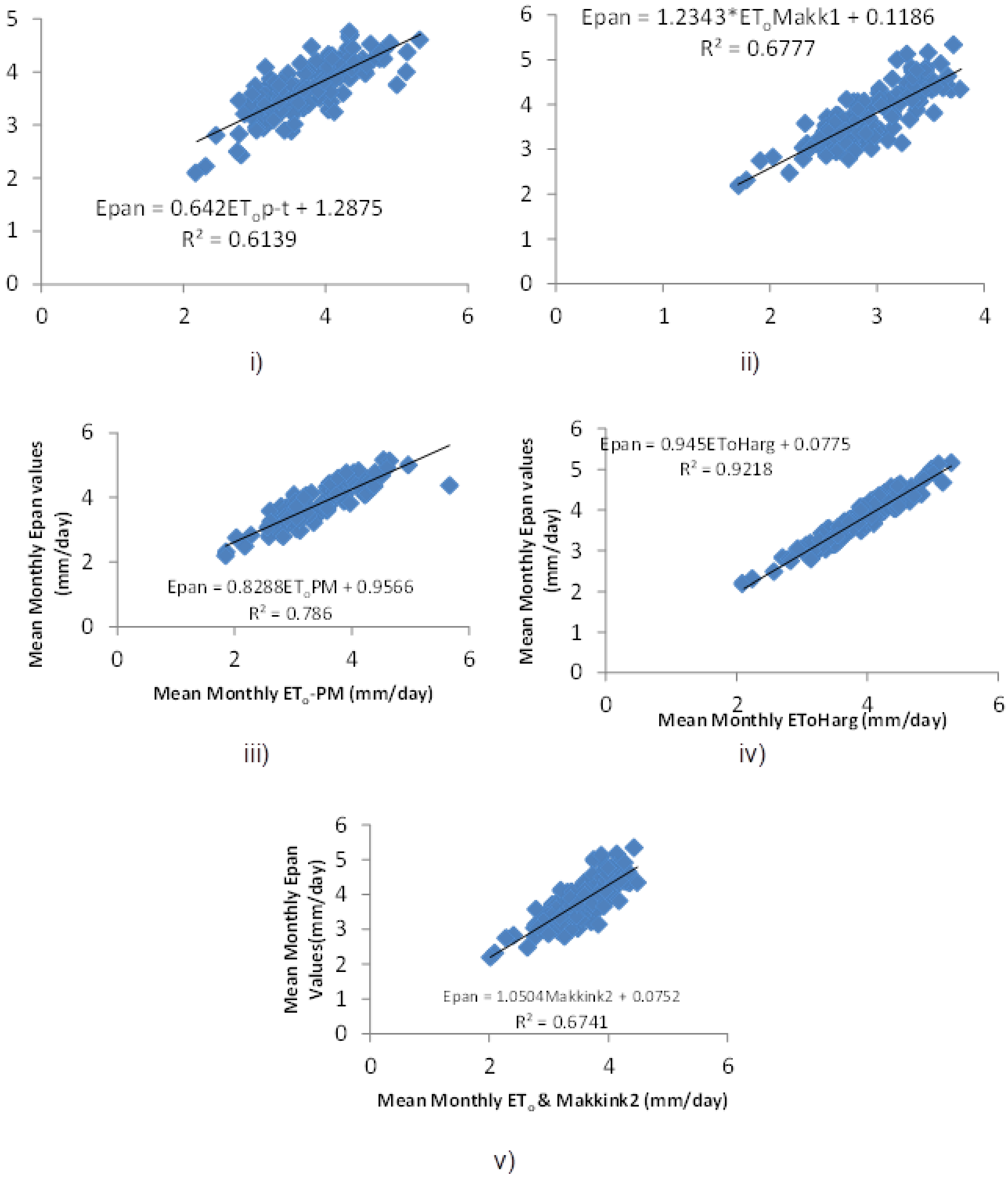

Figure 4. Regression of mean monthly Epan data against mean monthly ET_o models i) Epan versus ET_o-PT (Priestley-Taylor) ii) Epan versus Makkink-1 iii) Epan versus ET_o -PM iv) Epan versus Hargreaves-Samani and v) Epan versus Makkink-2.

regression equation of slope (b) of 1, an intercept (c) close to zero (0) and coefficient of determination (R^2) of 1, produces a perfect fit. Figures 4 and 5 show typical mean monthly plots of ET_o-PM against mean monthly ET_o values and mean monthly Epan values against mean monthly ET_o values, respectively.

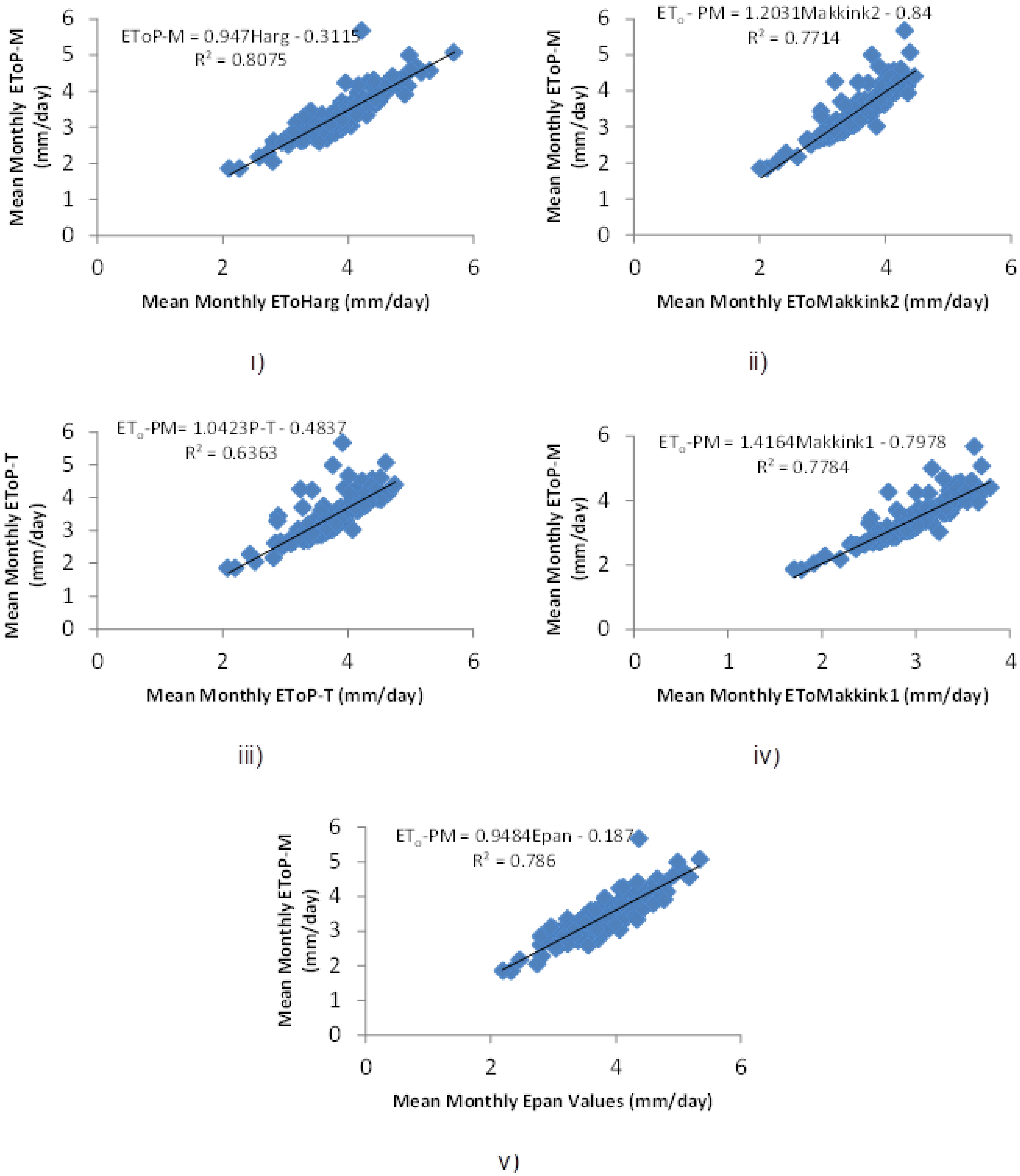

Figure 5. Regression of mean monthly ET_O - PM against mean monthly ET_o models i) ET_o - PM versus Hargreaves-Samani ii) ET_o - PM versus Makkink 2 iii) ET_o - PM versus PT (Priestley-Taylor) iv) ET_o - PM versus Makkink 1 and v) ET_o - PM versus Epan.

The cumulative ranked values of goodness of fit, R^2, slope, b and intercept, c for the regression models (Figures 4 and 5) of daily and monthly ET_o against ET_o-PM or Epan values are shown in Figures 6 and 7 and Tables A1 and A2, respectively. The correlation of daily ET_o values showed the following order of "best fit" (Figure 6):

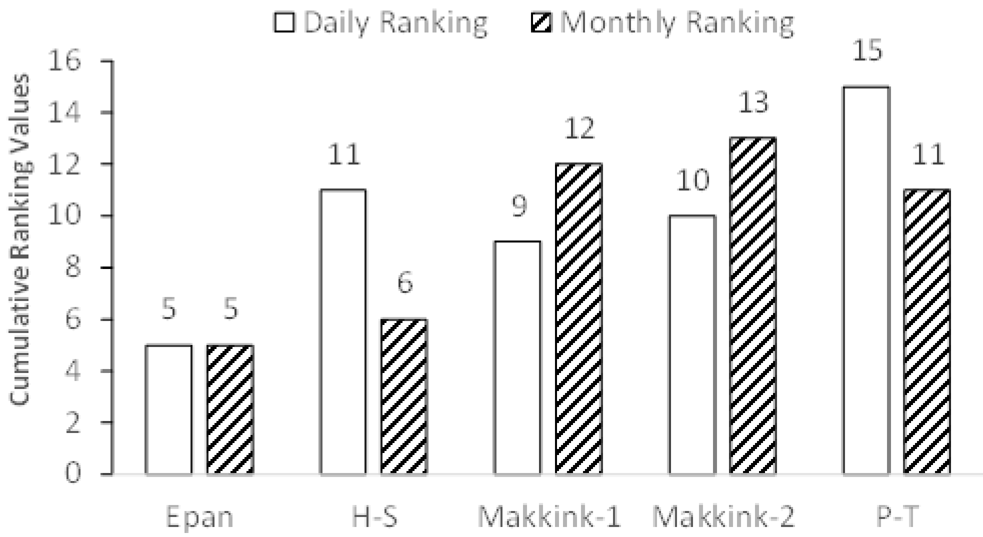

Figure 6. Comparison of best fit regression models of daily and monthly ET_o against ET_o-PM values.

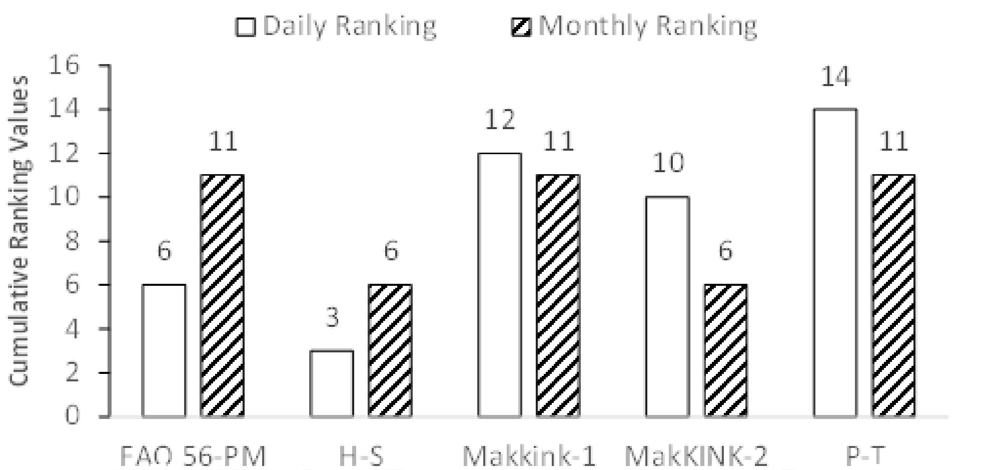

Figure 7. Comparison of best fit regression models of daily and monthly ET_o against Epan values.

1st Epan, 2nd Makkink-1, 3rd Makkink-2, 4th Hargreaves-Samani, 5th Priestly-Taylor, respectively. For the monthly ET_o against ET_o-PM linear regression models, we have: 1st Epan, 2nd Hargreaves-Samani, 3rd Priestly-Taylor, 4th Makkink-1 and 5th Makkink-2, respectively. Figure 7 shows the distribution of "best fit" regression models of daily and monthly ET_o against Epan values with respect of cumulative ranking of R^2, b and c values. For daily ET_o against Epan, the order of best fit are: 1st Hargreaves-Samani and Makkink-2, 2nd FAO 56-PM and Makkink-1, and 3rd Priestly-Taylor, respectively.

The distribution of the goodness of fit, R^2 as bench mark for the various regression models are as follows: i) 0.281 - 0.519 for daily ET_o versus ET_o-PM; ii) 0.299 – 0.836 for daily ET_o versus Epan values; iii) 0.613 – 0.922 for monthly ET_o versus Epan; and iv) 0.636 – 0.808 for monthly ET_o against ET_o-PM values, respectively.

Figure 9 shows the cumulative monthly ET_o totals for the farming season (December-April) during the study period (2000-2010). The cumulative monthly total estimated by Hargreaves-Samani was 7,136.19 mm, FAO 56-PM produced 6,448.5 mm, Priestly-Taylor-6,538.23 mm, Makkink1- 5,298.43 mm; Makkink2-6,280.9 mm and Epan- 7,124.32 mm.

In terms of absolute values of over/under estimation and percent relative error with Epan as benchmark, Hargreaves-Samani with original coefficient over estimated by 11.87mm and percent error of 0.17%

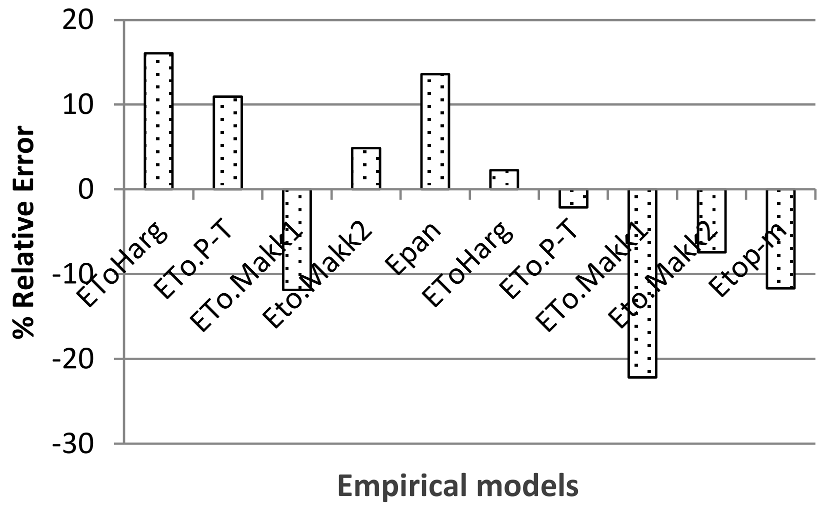

Figure 8. Percent relative error versus Epan & ET_o- PM monthly data.

ranked first, while Priestly-Taylor; 586.1 mm and 8.23%, FAO 56-PM; 675.77 mm and 9.49%, Makkink-2; 843.38 mm and 11.84% and Makkink-1; 1825.9 mm and 25.63% ranked second, third, fourth and fifth positions, respectively. With FAO 56-PM as benchmark, Priestly-Taylor ranked best by 89.68 mm and 1.39%, Makkink-2 ranked second by 167.6 mm and 2.60%, while Epan data (675.77 mm and 10.48%), Hargreaves-Samani (687.65 mm and 10.66%), Makkink-1(1,150.1 mm and 17.84%) ranked a distant third, fourth and fifth positions, respectively.

DISCUSSION

One of the objectives of this study is to find the best and approximate alternative to the standard FAO 56-PM method. The quest for the best ET_o model has prompted a global research in different climatic regions. For example, Tomar (2015) found FAO 56-PM model most appropriate for sub- humid Tarai region of Ultarakhand, India. Tabari (2010) found the Makkink model performed best in cold humid climates like the Netherlands. Amatya et al. (1995) found Turc model the best prediction method for the humid coastal plains of the United States and so on. In this study, the results of the statistical measures showed Hargreaves-Samani method ranked best for both daily and monthly evaluation with Epan data as benchmark. For the daily and monthly evaluation with FAO 56-PM as benchmark, Makkink2 (1984) ranked best while Epan data compared reasonably well with FAO 56-PM in the second position.

In terms of statistical regression analysis, Epan correlated best for daily and monthly FAO 56-PM values. Similarly, Hargreaves-Samani method correlated best with daily and monthly Epan data.

In terms of quantitative evaluation of total cumulated ET_o values for the study period (2000-2010) and cumulative monthly ET_o totals for the farming season (Dec-April) against both Epan data and FAO 56-PM, the results were in agreement with those of the statistical measures and regression analysis. Generally, Hargreaves-Samani method correlated best with Epan data, which is more evident in Figure 8 for the monthly ET_o totals for the farming season. Hargreaves-Samani scored the overall least over estimation of 11.78 mm (11 years) and percent relative error of 0.17%. With respect to FAO56-PM, both Priestly-Taylor and Makkink-2 compared best with FAO 56-PM.

The farming season is a period of high water demand and the best performance model was Hargreaves-Samani, a plausible model for the Lower Niger basin. Similar performance of the Hargreaves-Samani has been reported by Ramirez et al. (2011) for Colombian coffee zone, although in the said study, Hargreaves-Samani was evaluated against FAO 56-PM. Also Amatya et al. (1995) found Makkink and Priestly-Taylor methods in closest agreement with FAO 56-PM. The close agreement between FAO 56-PM and the radiation-based method (Makkink and Priestly-Taylor) is probably due to the prevalent low advective conditions in the Lower Niger River basin. The study agreed with Allen et al. (1998) who recommends an alternative ET_o equation to FAO Penman-Monteith equation.

The results of Equations 11 to 18 shown in Tables A1 and A2 have been used to assess the strength and weakness of the statistical measures. All the statistical measures were calculated on the basis of the relationship between observed and predicted mean deviations. The index “D” is a measure of cross-comparison between the models. Fox (1981) recommended that at least RMSE, MAE, RMSEs and RMSEu be applied in evaluating model performances and that RMSE and MAE are among the best overall measures of model performance

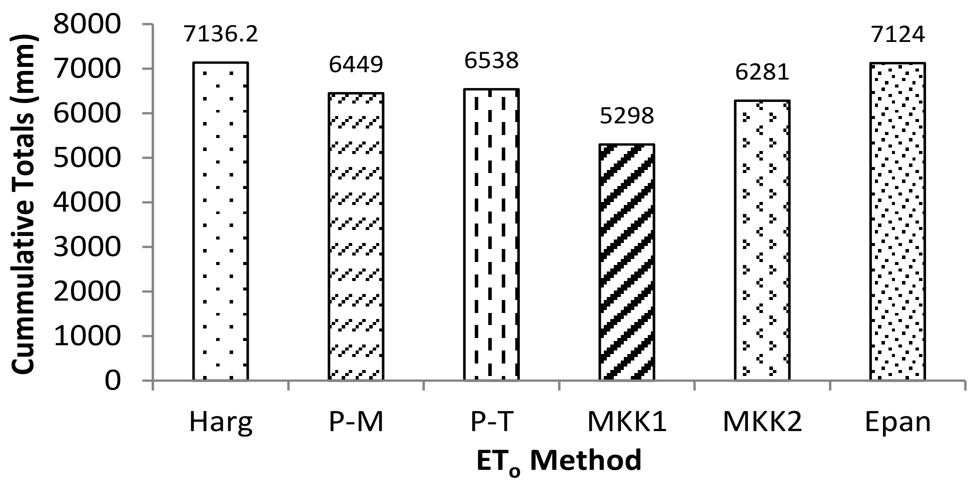

Figure 9. Cummulative totals against ET_o methods during farming season.

because they summarize the mean difference between observed(O) and predicted(P) values. The criteria adopted for assessment is that values of MAE and RMSE that are very close to zero are considered better models. According to Alexandris et al. (2008), Fox (1981) and Greenwood et al. (1985) a good model is one that has very low RMSEu and RMSEs values which are close to RMSE. From Table A1, Hargreaves–Samani has the least MBE, MAE, Sd, RMSE, RMSEs values with the exception of RMSEu, thus showing the best performance against Epan, seconded by Priestly-Taylor and thirdly by Makkink2. From Table A2, Makkink2 performed best against FAO-56 PM, seconded by Epan.

The general improvement for monthly estimates in R^2, MBE, MAE, and RMSE values indicated that the regression equations and statistical analyses for daily REF-ET values were less accurate than the monthly estimates. This greater error of prediction was due to the wide variation in daily weather parameters as compared to the mean monthly data where variability was reduced by the averaging effect.

In order to improve the accuracy of the REF-ET models against FAO 56-PM, monthly correlation factors have been computed as ratio of monthly total of PM REF-ET to the monthly total for each model as shown next.

Recalibration of model constants

From the evaluation of ET_o models against Epan data as benchmark, only Hargreaves-Samani and Priestly-Taylor methods over estimated/under estimated with a small margin of 313.4 mm and 452.3 mm in 11 years (2000-2010). With FAO 56-PM as a bench mark, only Makkink-2 (1984) method over estimated with a small margin of 512.4 mm, the other empirical models produced large margins. The existence of large margins support the need to adjust the models in a calibration process. The adjustment was achieved with the use of mean monthly correction factors. The mean monthly correction factors for ET_o models were computed as the ratio of the monthly total of FAO 56-PM to the monthly total for each method averaged over the record period (Amatya et al., 1995). Table 4 contains the estimated monthly correction factors for adjusting the ET_o models against FAO 56-PM. These adjustment factors can be used for prediction of RET- ET beyond year 2010.

Conclusion

The following conclusions were drawn from the results of the study:

i) Based on the statistical analyses, regression analysis, accumulated REF-ET values (2000 to 2010); monthly REF-ET estimates (summed daily values) for the farming season (Dec to April). Hargreaves-Samani method was in best agreement with daily and monthly Epan data. Furthermore, Hargreaves-Samani method was in best agreement with Epan data during the farming season (December - April) producing a slight over estimation of 11.87 mm and percent relative error 0.17% in 11 years.
ii) The comparison of REF-EF estimates with Epan data and FAO 56-PM as benchmarks showed that Hargreaves-Samani method was in best agreement with Epan data while Priestley-Taylor ranked best against FAO 56 PM, seconded by Makkink2 (1984) and thirdly Hargreaves-Samani method. Thus, Hargreaves-Samani performed reasonably well with FAO56-PM.
iii) The mean monthly data correlates better with Epan data and FAO 56-PM than the daily data. The three best REF-ET models are in this order: Hargreaves–Samani, Priestley-Taylor and Makkink (1984) and may be

Table 4. Estimated monthly correction factor for adjusting ET_o empirical models against ET_o-PM.

Month \ ETos	Harg	P – T	MKK1	MKK2	Epan
Jan.	0.9693	1.046	1.237	1.044	0.9402
Feb.	0.9004	1.061	1.314	1.107	0.8974
Mar.	0.8637	0.9715	1.236	1.042	0.8840
April	0.8986	0.9050	1.142	0.9650	0.9428
May	0.8608	0.8949	1.1363	0.9563	0.9253
Jun	0.8712	0.8331	1.048	0.8807	0.9253
July	0.8309	0.8370	1.073	0.8970	0.9412
Aug.	0.8632	0.8162	1.044	0.8747	0.9031
Sept.	0.7741	0.8330	1.086	0.9077	0.7923
Oct.	0.8031	0.8652	1.110	0.9300	0.8003
Nov.	0.8475	0.8771	1.095	0.9213	0.8245
Dec.	0.8475	0.9554	1.156	0.9741	0.8607
Average	0.8645	0.9080	1.340	0.9584	0.8834

recalibrated using the approach stated above.

iv) The FAO – 56 PM is universally accepted the "standard" method for estimating daily or monthly ETo. A major disadvantage to the application of the standardized FAO-56 PM procedure is the relatively high data demand requiring measurements of Temperature, Rel. hum., Rs, wind speed(u) and a plethora of intermediate parameters. Another problem is linked with data quality. Lastly, another serious problem is related to the cost of instrumentation for collecting the required meteorological in automated weather stations (Valiantzas, 2013; Jensen et al., 1997; Allen, 1996). The outcome of this study corroborates with Allen et al. (1998) which recommends Hargreaves-Samani as an alternative model for ETo. Hargreaves-Samani is a temperature–based model which requires only a few input parameters such as mean temperature, minimum temperature, maximum temperature and extraterrestrial radiation (Ra). Consequently, it is an economic alternative.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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APPENDIX A

Table A1. Summary statistics of ET_o estimation methods against Epan (daily and monthly values).

Indices	FAO 56-PM R R*	Hargreaves-Samani R R*	Makkink-1 R R*	Makkink-2 R R*	Priestley-Taylor R R*
$\bar{P}$ (mm/day)	3.80(3.37) 4 (4)	4.37(3.88) 2 (2)	3.31(2.94) 5 (5)	3.93 (3.5) 3 (3)	4.2 (3.70) 1 (1)
MBE(mm/day)	0.491(-0.381) 4 (4)	0.088(0.136) 1 (2)	-0.973 (-0.81) 5 (5)	-0.348 (-0.25) 3 (3)	-0.13 (-0.054) 2 (1)
MAE(mm/day)	0.686(0.414) 4 (4)	0.230(0.18) 1 (1)	1.05 (0.81) 5 (5)	0.615 (0.349) 3 (3)	0.56 (0.310) 2 (2)
S_d^2	0.448(0.0962) 3 (2)	0.116(0.031) 1 (1)	0.463 (0.31) 5 (5)	0.448 (0.126) 2 (3)	0.49 (0.159) 4 (4)
RMSE(mm/day)	0.830(0.491) 4 (4)	0.351(0.223) 1 (2)	1.19 (0.89) 5 (5)	0.754 (0.134) 3 (1)	0.71 (0.389) 2 (3)
RMSEu(mm/day)	0.597(0.307) 5 (4)	0.321(0.18) 4 (1)	0.27(0.23) 1 (2)	0.305 (0.28) 2 (3)	0.32 (0.315) 3 (5)
RMSEs(mm/day)	0.577(0.384) 2 (4)	0.142(0.14) 1 (1)	1.16(0.85) 5 (5)	0.690 (0.33) 4 (3)	0.63 (0.228) 3 (2)
EF	0.014(0.371) 5 (5)	0.824(0.87) 2 (2)	-1.02(-1.1) 1 (1)	0.187 (0.51) 4 (4)	0.27 (0.605) 3 (3)
D	0.750(0.862) 2 (3)	0.952(0.97) 1 (1)	0.543(0.61) 5 (5)	0.631 (0.84) 3 (4)	0.63 (0.870) 4 (2)
R^2	0.443(0.7846) 2 (2)	0.836(0.922) 1 (1)	0.38(0.678) 4 (3)	0.40 (0.674) 3 (4)	0.30 (0.614) 5 (5)
b(lope)	0.636(0.8273) 2 (4)	0.867(0.945) 1 (3)	0.251(1.234) 5 (5)	0.30 (1.050) 3 (1)	0.26 (0.956) 4 (2)
C(intercept)	1.066(0.9625) 2 (5)	0.658(0.078) 1 (2)	2.234(0.119) 3 (3)	2.70 (0.075) 4 (1)	3.05 (0.216) 5 (4)
Cumulative R & R* values	39 (45)	17 (19)	49 (49)	37 (33)	38 (34)

( ) = Estimates Based on mean Monthly values, N=3575, R =Ranking Based on Daily values; R*=Ranking Based on mean monthly values.

Table A2. Summary statistics of ET_o estimation methods against ETo_{PM} (daily and monthly values).

Indices	Epan R R*	Hargreaves-Samani R R*	Makkink1 equation R R*	Makkink2 R R*	Priestley-Taylor R R*
$\bar{P}$ (mm/day)	4.28 (3.75) 3(3)	4.37 (3.88) 5(5)	3.31 (2.94) 4(4)	3.93 (3.5) 1(1)	4.2 (3.7) 2(2)
MBE(mm/day)	0.491(0.381) 4 (3)	0.579 (0.517) 5 (5)	-0.482 (-0.43) 3(4)	0.144 (0.13) 1 (1)	0.364(0.328) 2 (2)
MAE(mm/day)	0.686(0.414) 4 (2)	0.749 (0.545) 5 (5)	0.542 (0.430) 2 (3)	0.451 (0.289) 1 (1)	0.618(0.461) 3 (4)
S_d^2	0.448(0.096) 3 (2)	0.458 (0.086) 4 (1)	0.364 (0.128) 2 (4)	0.343 (0.111) 1 (3)	0.461(0.161) 5 (5)
RMSE(mm/day)	0.830(0.491) 4 (2)	0.890 (0.594) 5 (5)	0.772 (0.555) 3 (4)	0.603 (0.356) 1 (1)	0.770(0.517) 2 (3)
RMSEu(mm/day)	0.624(0.287) 5 (4)	0.610 (0.276) 4 (3)	0.234 (0.194) 1 (1)	0.269 (0.231) 2 (2)	0.334(0.306) 3 (5)
RMSEs(mm/day)	0.545(0.398) 2 (3)	0.652 (0.530) 3 (5)	0.736 (0.520) 5 (4)	0.540 (0.271) 1 (1)	0.70(0.417) 4 (2)
EF	-0.079 (0.45)3 (2)	-0.241 (0.195) 2 (5)	0.067 (0.297) 5 (4)	0.432 (0.711) 1 (1)	0.071(0.391) 4 (2)
D	0.747(0.864) 1 (2)	0.710 (0.822) 3 (3)	0.627 (0.773) 4 (5)	0.722 (0.901) 2 (1)	0.582(0.814) 4 (5)
R^2	0.442(0.785) 3 (2)	0.410 (0.808) 4 (1)	0.519 (0.778) 2 (3)	0.519 (0.771) 3 (4)	0.28(0.636) 5 (5)
b(lope)	0.696(0.948) 1 (2)	0.634 (0.947) 2 (3)	0.305 (1.416) 4 (5)	0.350 (1.203) 3 (4)	0.261(1.042) 5 (1)
C(intercept)	1.64(-0.188) 1 (1)	1.97 (-0.312) 5 (2)	2.15 (-0.798) 3 (4)	2.61 (-0.84) 4 (5)	3.17(-0.484) 5 (3)
Cumulative R & R* Values	34 (27)	44 (43)	38 (45)	21 (22)	44 (40)

( ) = Estimates based on mean monthly values, N=132, R =Ranking based on daily values; R*=Ranking based on mean monthly values.

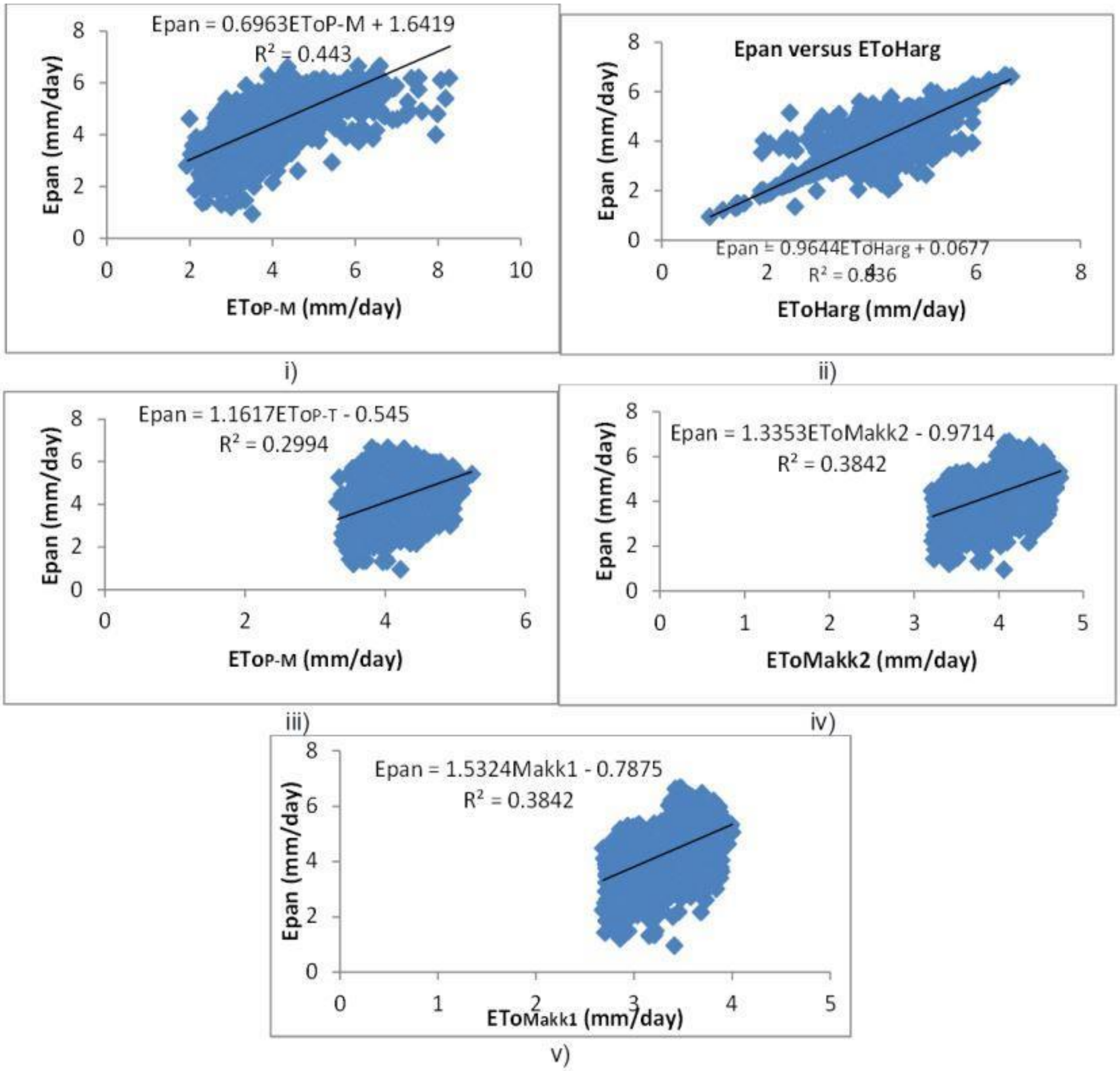

Figure 1a. Regression of Mean Monthly Epan Data against Mean Monthly ET_o models i) Epan versus ET_o PT(Priestley-Taylor) ii) Hargreaves-Samani iii) Epan versus ET_o -PM iv) Epan versus Makkink 2 and v) Epan versus Makkink 1.

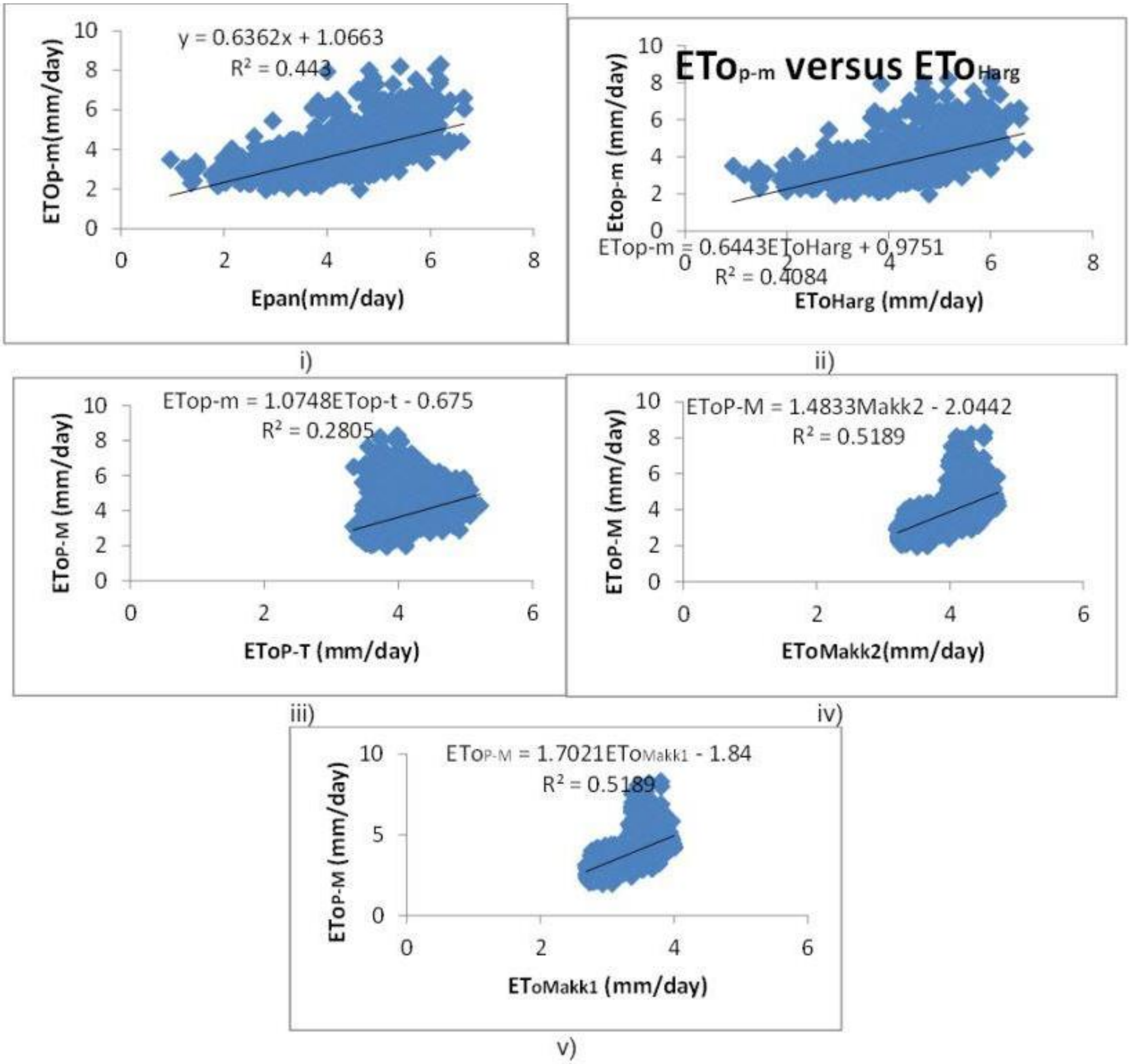

Figure 1b. Regression of Mean Monthly ET_O - PM against Mean Monthly ET_o models i) ET_o - PM versus Epan ii) ET_o - PM versus Hargreaves-Samani iii) ET_o - PM versus PT (Priestley-Taylor) iv) ET_o - PM versus Makkink 2 and v) ET_o - PM versus Makkink 1.