Development and comparative evaluation of radiation-based reference evapotranspiration equations for sub-humid Hazaribagh region of Jharkhand

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Abstract: In this study, two site-specific solar radiation (Rs) and net radiation (Rn) based equations for estimating reference evapotranspiration (ET−0) were developed and their performance were statistically analysed in comparison to widely accepted FAO Penman-Monteith method (PMF-56) and four other standard radiation methods for sub-humid Hazaribagh region of Jharkhand, India. These two equations were developed with daily values of Rs and Rn in conjunction with maximum and minimum air temperature by taking daily PMF-56 ET0 values as index with weather dataset of 15 years (1990-2004). The performance of these equations validated with carefully screened daily weather dataset of eight years (2005-2012) with other considered standard methods revealed that they estimated ET0 better. The eight year average ratio of ET0 values calculated with developed Rs- and Rn- based equations and PMF-56 on daily basis were obtained as 1.07 and 1.10 respectively. These two derived equations resulted in better average values of SEE on daily (0.57 and 0.61) and monthly (1.24 and 1.21) basis. The higher value of Agreement index (D) on monthly ET0 values on daily and monthly basis during validation period confirms efficacy of derived equations. Considering the limitations associated with reliability and availability of weather data especially in developing countries, derived equations presented in this study are recommended to estimate ET0 in sub-humid Hazaribagh region if standard PMF-56 equation cannot be used due to non-availability of required weather parameters.

Keywords: Radiation, reference evapotranspiration, site-specific, statistical performance, India

Citation: Tomar, A. S. 2015. Development and comparative evaluation of radiation-based reference evapotranspiration equations for sub-humid Hazaribagh region of Jharkhand. Agric Eng Int: CIGR Journal, 17(3): 10-20.

1 Introduction

The ET rate is a function of factors such as temperature, solar radiation, humidity, wind, and characteristics of specific vegetation that is transpiring, and varies significantly based on vegetation types (Allen et al., 1998). If environmental demand for water (ET) exceeds the water available to plant through precipitation or stored in the soil, then transpiration may cease resulting in crop loss and, therefore, reliable estimates of ET along with knowledge of total precipitation and soil moisture storage capacity, can provide estimates of water need through irrigation. Evapotranspiration can be estimated directly. For instance, a lysimeter is employed to measure ET by considering change in soil moisture of known volume of soil that is covered with vegetation (Watson and Burnett, 1995), but ET estimation using lysimeter can be expensive both economically and in time investments to install, check, and maintain them (Dingman, 1994; Allen et al., 1998).

To simplify the process of determining ET, several methods have been proposed at places where its direct measurement is lacking such as: Thornthwaite, Hargreaves, Priestly-Taylor, Turc, Makkink, Penman and etc. Many of these methods have been derived empirically based on field experiments, whereas, others have been derived through theoretical approaches. The FAO-56 Penman-Monteith (PMF-56) method was

Received date: 2014-11-12 **Accepted date:** 2015-06-11

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recommended and most widely used for estimating reference evapotranspiration. The standardization of this method is based on the fact that it takes care of almost all factors that may affect evapotranspiration. But in most weather stations, all required meteorological data are not easily available which restricts application of this more accurate method and necessitates use of methods that require less meteorological data. The superior performance of PMF-56 method in various climates has been confirmed by various researchers (Jensen et al., 1990; Smith et al., 1991; Allen et al., 1994; Allen et al., 1998;
Allen et al., 2000; Walter et al., 2001).

After the availability of Penman's combination-based ET_0 equation in the year 1948, researchers came up with a large number of combination-, pan evaporation-, radiation- and temperature- based equations to estimate ET_0. The International Commission for Irrigation and Drainage and the Food and Agriculture Organization of the United Nations Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements (Smith et al., 1991) recommended FAO56-Penman-Monteith (PMF-56) method as a standard method to estimate ET_0 which requires solar radiation, wind speed, air temperature, and humidity data, however, all these input variables for a given location especially in developing countries may not be available where data quality and difficulties in gathering all necessary weather parameters can present serious limitations. When climate data required for estimating ET_0 with PMF-56 method are not available or are not reliable for a place, then empirical or simplified temperature- or radiation- based equations requiring fewer parameters can be used. According to Hargreaves and Samani (1985), any procedure to estimate ET_0 with commonly available data should incorporate minimum computation to provide consistent and reliable estimates.

The concept of using one equation to calibrate or validate other equations is not new. Hargreaves and Samani (1985) reported that equations requiring solar radiation and mean air temperature produce reasonable ET_0 estimates. Allen et al. (1994) stressed that PMF-56 equation should be considered superior to most lysimeter-measured ET_0 data for calibrating other ET_0 equations. Gunston and Batchelor (1983) used FAO-Penman equation (Doorenbos and Pruitt, 1977) to calibrate and modify coefficients of Priestley-Taylor (Priestley and Taylor, 1972) equation for a tropical region. Allen and Brockway (1983) used 1972 Kimberley-Penman equation (Wright and Jensen, 1972) to develop adjustment coefficients of FAO-Blaney-Criddle equation (Doorenbos and Pruitt, 1977). Allen (1992) used PMF-56 equation (Allen et al., 1998) to develop calibration factors for temperature-based Hargreaves (Hargreaves and Samani, 1985) equation. The FAO Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements (Smith et al., 1991) recommended that empirical methods should be calibrated or validated for new regions by using standard PMF-56 method and it should be done at locations having sufficient and carefully screened weather measurements are available to apply PMF-56 equation (Allen et al., 1994).

Keeping in view the relevance of various radiation-based ET_0 methods, present study was taken up on daily, weekly and monthly basis for sub-humid Hazaribagh region of Jharkhand with objectives: (i) to develop site-specific radiation-based ET_0 equations by using multi-linear regression technique; (ii) to validate derived ET_0 equations using PMF-56 ET_0 method as an index; and (iii) to conduct performance analysis of derived ET_0 equations in comparison with different considered radiation-based methods.

2 Materials and methods

2.1 Study area and weather dataset

Daily measured weather dataset for a period of 23 years (1 January 1990 to 31 December 2012) obtained for sub-humid Hazaribagh (23.89°N latitude, 85.5°E longitude and at an altitude of 604.00 m above mean sea level) were used in this study. The study area experiences three distinct seasons, i.e., summer (March-May), rainy season (June-December), and a cold winter (January-February) with an average annual rainfall of about 783 mm.

2.2 Estimation of reference evapotranspiration by different available methods

2.2.1 FAO Penman Monteith method

On the basis of results of an Expert Consultation held in May 1990, the FAO Penman-Monteith (PMF-56) method has been recommended as a standard method for ET_0 computation as ET_0 estimated by this method gave values which are in close proximity with actual evapotranspiration measured in a wide range of location and climatic conditions. In addition, this method has provision for application in situations where limited data are available. Keeping in view the above mentioned advantages, the PMF-56 method was chosen in present study for computing reference evapotranspiration for Hazaribagh station using meteorological data on daily basis, expressed mathematically (Smith et al., 1992) as Equation 1:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

Where ET_0 is reference evapotranspiration, mm/d; R_n is net radiation at crop surface, MJ/m^2/d; G is soil heat influx density, MJ/m^2/d; T is mean daily air temperature, °C; U_2 is wind speed at 2 m height, m/s; e_s is saturation vapour pressure, kPa; e_a is actual vapour pressure, kPa; e_s-e_a is saturation vapour pressure deficit, kPa; Δ is slope of vapour pressure curve, kPa/°C, and γ is psychometric constant, kPa °/C.

The computation of daily ET_0 using Equation 1 requires meteorological parameters consisting of air temperature (maximum and minimum), mean daily actual vapour pressure (e_a) derived from either dew point temperature or relative humidity (maximum and minimum), daily average of 24 h wind speed measured at two meter height (U_2), and net radiation (R_n) measured or computed from solar and long wave radiation or from actual duration of sunshine hours (n). Since soil heat flux (G) has a relatively small value, therefore, it may be ignored when computation of ET_0 is done on daily basis.

2.2.2 Radiation-based ET_0 methods

Four commonly used radiation-based equations, namely, FAO24-Radiation (Doorenbos and Pruitt, 1977), Jensen-Haise (1963), McGuinness-Bordne (1972) and Priestley-Taylor (1972) were evaluated and compared in this study. In the following Equation 2, Equation 3, Equation 4 and Equation 5, all weather parameters have the same meaning as defined in PMF-56 model unless specifically mentioned.

(i) FAO24-Radiation: $ET_0 = a\left(\frac{\Delta}{\Delta+\gamma}R_s\right) + b$ (2)

Where R_s is solar radiation in mm/d and *"a", "b"* are adjustment factors. The adjustment factor "a" varies with mean relative humidity and daytime wind speed and value of "b" is to be taken as -0.3 mm/d. The value of "a" can be calculated with the following expression:

$$a = 1.066 - 0.13 \times 10^{-2}RH + 0.045U_d - 0.20 \times 10^{-3}RH \times U_d - 0.315 \times 10^{-4}RH^2 - 0.11 \times 10^{-2}{U_d}^2$$

Where RH is mean relative humidity in percent and U_d is mean daytime wind speed in m/s.

(ii) Jensen and Haise: $ET_0 = \frac{C_T\,(T_{av} - T_x) \times R_s}{\lambda}$ (3)

Where ET_0 is in mm/d, R_s is in mm/d, C_T (a temperature constant) = 0.025, and T_x = -3 when T_{av} is in ℃. These coefficients were considered to be constant for a given area (Xu and Singh, 2000). Considering the formulation presented by Adeboye et al. (2009) and observations of Xu and Singh (2000), daily values of C_T and T_x were calculated by using following equations to get ET_0 values:

$$C_T = \frac{1}{\left[\left(45 - \frac{h}{137}\right) + \left(\frac{365}{e^o(T_{max}) - e^o(T_{min})}\right)\right]}$$; and

$$T_x = -2.5 - 0.14 \times [e^o(T_{max}) - e^o(T_{min})] - \frac{h}{500}$$

Where h is altitude of location (m), and $e°(T_{max})$, $e°(T_{min})$ are saturation vapour pressure (kPa) at daily maximum and minimum air temperature respectively.

(iii) McGuinness and Bordne:

$$ET_0 = \left\{(0.0082 \times T_{av} - 0.19)\left(\frac{R_s}{1500}\right)\right\} \times 2.54 \quad (4)$$

Where ET_0 is in cm/d for a monthly period, T_{av} is in °F and R_s is in cal/cm^2/d.

(iv) Priestley and Taylor:

$$ET_0 = 1.26\left(\frac{\Delta}{\Delta+\gamma}\frac{R_n - G}{\lambda}\right) \quad (5)$$

Where ET_0 is in mm/d, Δ is slope of saturation vapour pressure-temperature curve, kPa °C, R_n is net radiation, MJ/m^{-2}/d and G is soil heat flux density, MJ/m^2/d which has been considered as zero for daily values in accordance with Allen et al. (1998).

2.3 Assumptions and tools used for statistical analysis

To ensure rigorous comparison of different selected methods and evaluate the performance of different radiation- based ET_0 methods in comparison with PMF-56 method, an extended analysis in terms of statistical indices, namely, Agreement Index (D), Root Mean Square Error (RMSE), Mean Bias Error (MBE), Percentage Error of Estimate (PE), coefficient of determination (R^2), correlation coefficient (r) and Standard Error of Estimates (SEE) was undertaken with the help of Microsoft™ Excel® as computing tool to analyse results and draw fruitful inferences from them. The D, RMSE, MBE, R^2, r and SEE are defined as:

2.3.1 Agreement index (D)

The value of D is both relative and bounded measure which can widely be used to make cross comparison between different methods or models (Willmott, 1982). The value of D can be obtained mathematically by Equation 6:

$$D = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (6)$$

2.3.2 Root Mean Square Error (RMSE)

RMSE gives a relatively high weight to large errors which means that RMSE is negatively-oriented score and is most useful when large errors are particularly undesirable. It is expressed mathematically as Equation 7:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (7)$$

2.3.3 Mean Bias Error (MBE)

The MBE may take positive or negative values and is calculated by mathematical expression Equation 8:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \quad (8)$$

2.3.4 Coefficient of determination (R^2)

In statistics, coefficient of determination (R^2) indicates how well the data points fit a statistical model. The value of R^2 ranges from 0 to 1.

2.3.5 Correlation coefficient (r)

It measures the degree to which two things vary together and it may be positive or negative co-variation in nature. Mostly its value varies from -1 to +1. If there will be complete independence between two variables, there is a chance that value of "r" becomes zero.

2.3.6 Standard Error of Estimates (SEE)

It is expressed mathematically as Equation 9:

$$SEE = \sqrt{\left[\frac{1}{n(n-2)}\right]\left[n\sum P_i^2 - (\sum P_i)^2 - \frac{[n\sum O_iP_i] - (\sum O_i)(\sum P_i)}{n\sum O_i^2 - (\sum O_i)^2}\right]^2} \quad (9)$$

In Equation 6, Equation 7, Equation 8 and Equation 9, O_i is observed PMF-56 ET_0, mm/d; P_i is predicted ET_0 value estimated by using considered equations, mm/d; $\bar{O}$ is mean of observed values, and n is total number of observations.

2.4 Development and calibration of equations

In this study, a multi-linear regression approach was being used as linear form presumes that each parameter impacts ET_0 independent of value of other parameters. This regression technique was used to derive four equations in-order to simplify PMF-56 method by reducing requirement of input parameters and computation. The form of multi-linear equation that relates a dependent variable to a set of quantitative independent variables is a direct extension of a polynomial regression model with one independent variable.

The PMF-56 ET_0 values were taken as dependent variables and values of R_s, T_{max} and T_{min} and R_n, T_{max} and T_{min} were used as independent variables to determine coefficients of R_s- and R_n- based equations respectively with multi-linear regression approach by considering 65% of daily weather dataset (1990-2004) for calibration, whereas, remaining 35% dataset (2005-2012) was used for validation purpose. The same procedure and weather datasets were used to derive both the equations. The following Equation 10 of multi-linear regression model was used in this study:

$$ET_0 = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \cdots + \cdots + \alpha_n X_n \quad + \qquad (10)$$

Where ET_0 is grass reference ET from PMF-56 PM equation (dependent variable), α_0 is intercept; α_1 to α_n represents slopes of regression line; and X_1 to X_n are independent variables.

The first-order multi-linear regression equation to estimate daily values of PMF-56 ET_0 , mm/d as a function of incoming solar radiation (R_s, MJ/m^2/d) and net radiation (R_n, MJ/m^2/d) with daily maximum (T_{max}, ℃) and minimum air temperature (T_{min}, ℃) were obtained as Equation 11 and Equation 12:

$$ET_0 = -5.754749 + 0.166396\ R_s + 0.234816\ T_{max} - 0.001487\ T_{min} \qquad (11)$$

$$ET_0 = -5.406513 + 0.269159\ R_n + 0.280857\ T_{max} - 0.081073\ T_{min} \qquad (12)$$

3 Results and discussion

The performance of site-specific developed two radiation-based ET_0 equations were evaluated by comparing their daily, weekly and monthly estimates with those obtained from PMF-56 and four commonly used radiation-based ET_0 equations, namely, FAO24-Radiation (Doorenbos and Pruitt, 1977), Jensen-Haise (1963), McGuinness-Bordne (1972) and Priestley-Taylor (1972). The performance of these standard ET_0 methods was analysed in terms of Standard Error of Estimates (SEE) and their lower values indicated better performance. For weekly and monthly comparisons, daily ET_0 values averaged over one week and month period were plotted against values obtained by PMF-56 method. The long-term daily, weekly and monthly average ratios of ET_0 method/ET_0 PMF-56 were also computed to quantify over- and under-estimation of derived equations relative to PMF-56 ET_0 values individually for all eight validation years.

The calibration of ET_0 estimates using Equations 11 and Equation 12 are presented in Figure 1 and Figure 2 respectively. For calibrating Equation 11, intercept and slope for regression line for each independent variable (R_s, T_{max} and T_{min}) were found significant (p = 0.001, n = 5,479) with SEE of daily values averaging 0.61 mm/d over 15 year period (R^2 = 0.864). Similarly, R^2 values for calibrating Equation 12was obtained as 0.832, whereas, for validation (2005-2012) with 2,922 observations, the value of R^2 was increased to 0.885 and 0.866 with values of average daily SEE as 0.57 and 0.61 for these developed equations respectively.

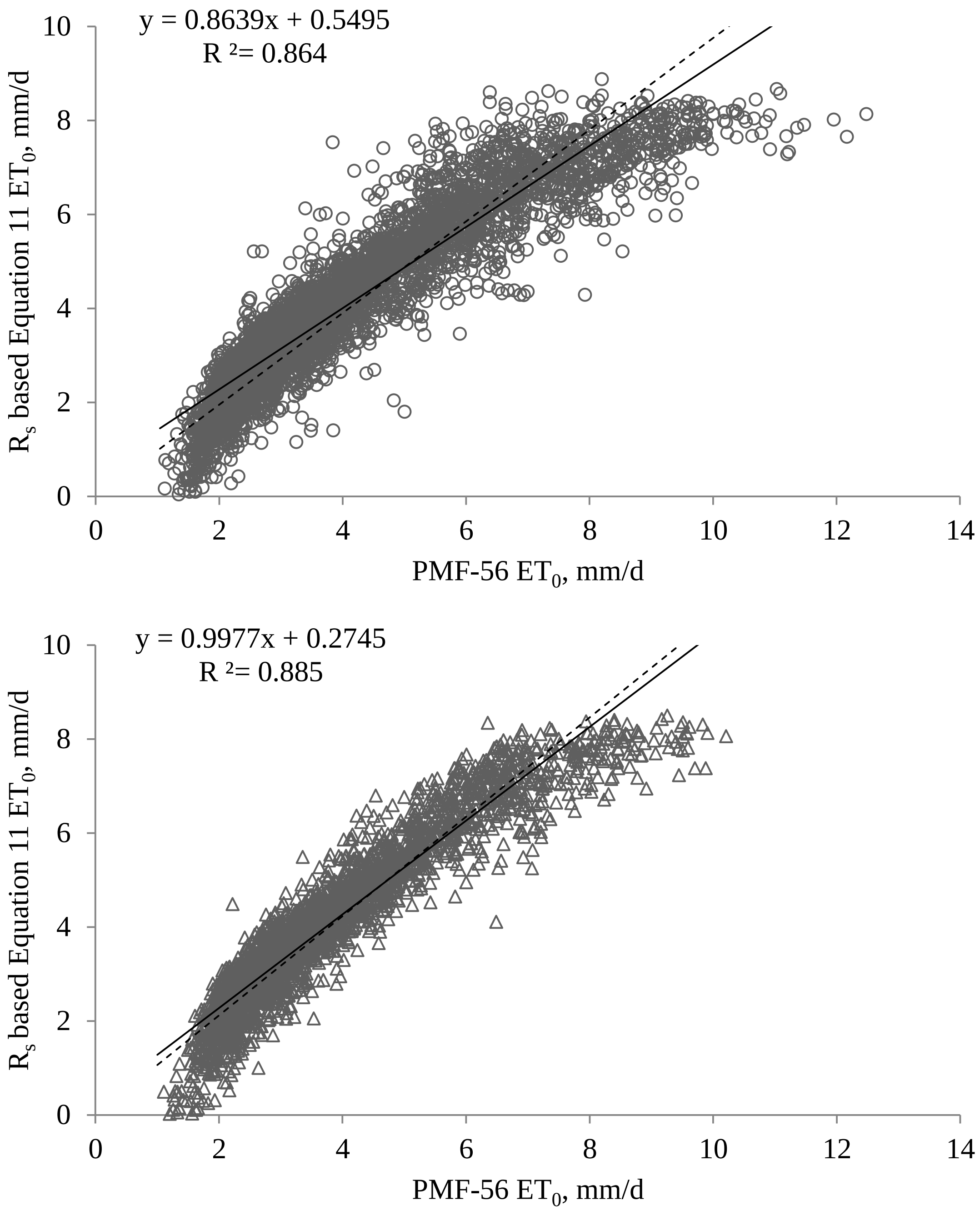
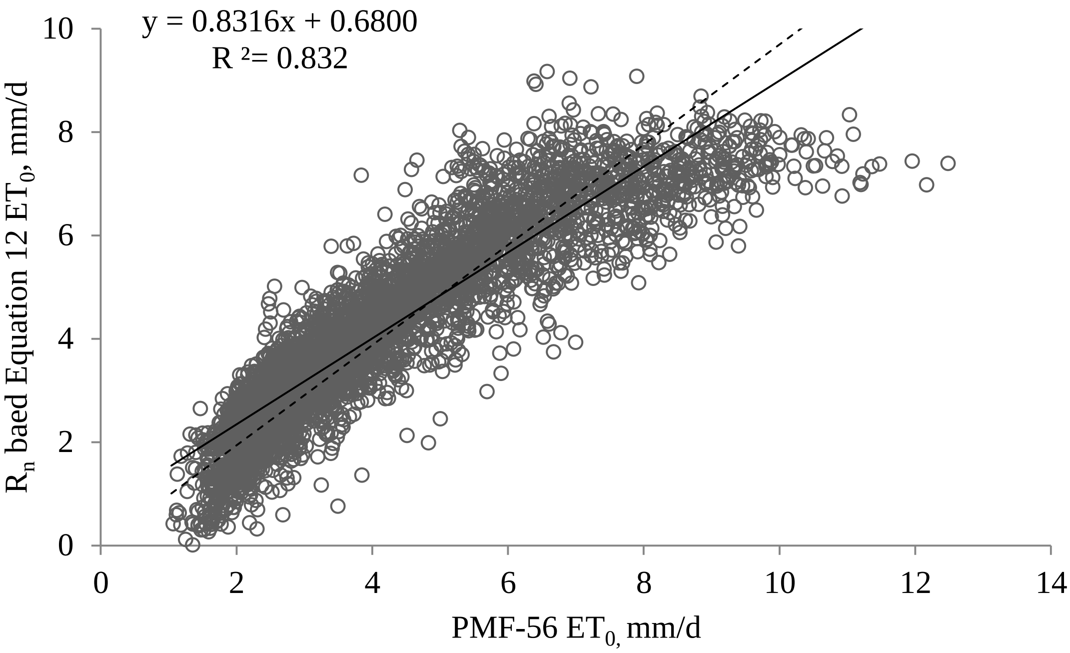


Figure 1 Regression analyses for calibration and validation of developed R_s-based Equation 11



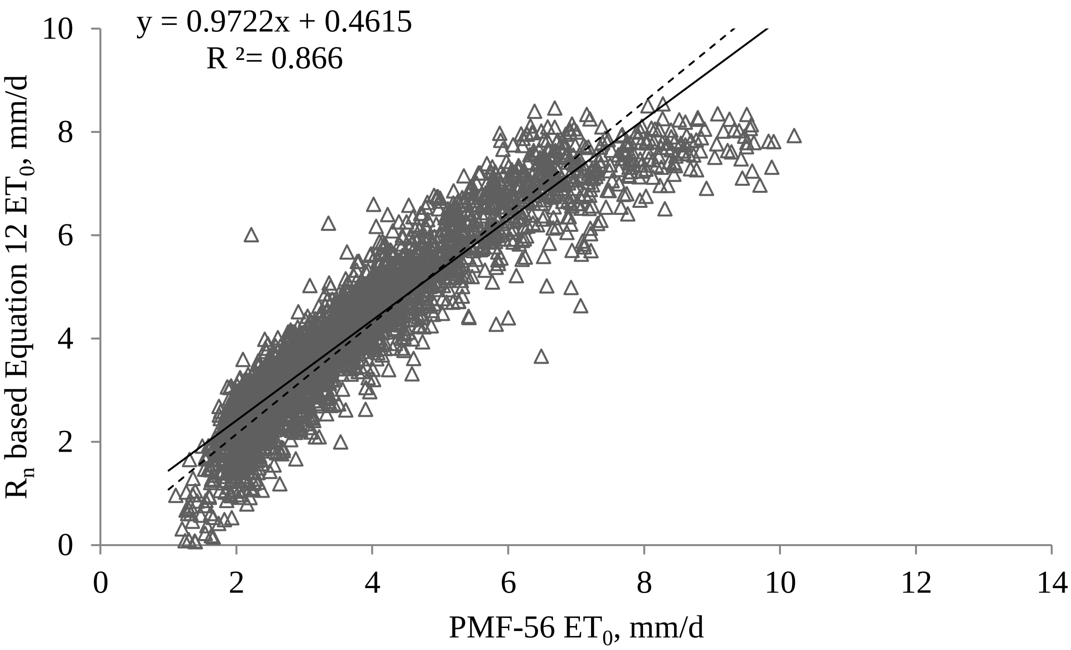


Figure 2 Regression analyses for calibration and validation of developed R_n-based Equation 12

The relative performance of developed equations in terms of statistical indices and average ratios of ET_0 method/ET_0 PMF-56 for study period (1990-2012) at different timescales (Table 1) reveals that on daily basis, highest value of D (0.96), lowest values of RMSE (0.68) and SEE (0.60) were found with R_s-based Equation 11 which may be due to the fact that this equation is less dependent of PMF-56 equation. For Equation 12, the value of RMSE was found 11.76% higher than that of Equation 11. Similarly, in terms of daily average ratio of ET_0 method/ET_0 PMF-56, the lower value (1.02) obtained with Equation 11 extends its superiority over Equation 12 as it over-estimates ET_0.

Table 1 Statistical performance of radiation-based methods versus PMF-56 model for estimating ET_0 during study period (1990-2012)

Methods	D	RMSE	MBE	PE	R^2	r	SEE	Ratio
(a) Daily basis								
FAO24-Radiation	0.92	0.99	0.60	15.08	0.83	0.91	0.76	1.18
Jansen-Haise	0.82	1.64	-1.45	36.43	0.83	0.91	0.73	0.59
Priestley-Taylor	0.87	1.05	-0.22	7.06	0.71	0.84	0.68	1.00
Equation 11	0.96	0.68	0.09	4.79	0.88	0.94	0.60	1.02
Equation 12	0.95	0.76	0.12	5.67	0.86	0.93	0.65	1.04
(b) Weekly basis								
FAO24-Radiation	0.93	0.86	0.59	15.02	0.87	0.93	0.59	1.19
Jansen-Haise	0.81	1.57	-1.45	36.46	0.88	0.94	0.57	0.59
Priestley-Taylor	0.88	0.93	-0.22	7.06	0.77	0.87	0.55	0.99
Equation 11	0.98	0.51	0.09	4.79	0.94	0.97	0.41	1.03
Equation 12	0.97	0.57	0.12	5.66	0.92	0.96	0.44	1.04
(c) Monthly basis								
FAO24-Radiation	0.94	3.42	2.57	15.02	0.91	0.95	2.21	1.19
Jansen-Haise	0.81	6.63	-6.27	36.41	0.92	0.96	2.06	0.60
McGuinness-Bordne	0.71	9.44	7.63	44.69	0.63	0.79	5.85	1.49
Priestley-Taylor	0.90	3.72	-0.97	7.06	0.81	0.90	2.26	0.99
Equation 11	0.99	1.77	0.40	4.79	0.97	0.98	1.32	1.03
Equation 12	0.99	2.00	0.54	5.66	0.96	0.98	1.40	1.04

Note: D = Agreement index, RMSE = Root Mean Square Error, mm/d; MBE = Mean Bias Error, mm/d; PE = Percentage Error of Estimate, %; R^2 = Coefficient of determination; r = Correlation coefficient, SEE = Standard Error of Estimates, mm/d, Ratio = Ratio of ET_0 method/ET_0 PMF-56, Equation 11 = Developed R_s-based equation, Equation 12 = Developed R_n-based equation.

Results in Table 1 shows that ET_0 calculated from both developed equations were strongly correlated with PMF-56 ET_0 values with higher D for daily, weekly and monthly estimates as 0.96 and 0.95; 0.98 and 0.97; 0.99 and 0.99 respectively for all validation years and SEE of ET_0 estimates on daily, weekly and monthly basis were found lower than that obtained with other radiation equations considered in this study.

3.1 Validation and comparison of performance of derived equations with other methods

Eight year of measured daily weather data was used to validate performance of both the developed equations. The comparison of daily ET_0 values estimated using Equation 11 and Equation 12 with PMF-56 ET_0 values for validation years (Table 2) showed that ET_0 values calculated by developed equations were well correlated with PMF-56 values.

Table 2 Standard Error of Estimates of evapotranspiration at different timescales and average daily ratio of ET_0 method/ET_0 PMF-56 of considered radiation methods and developed equations for validation years (2005-2012)

Validation year	Performance indicator	FAO24-Rad	J-H	M-B	P-T	Equation 11	Equation 12
2005	Daily SEE	0.65	0.63	1.28	0.63	0.60	0.64
	Weekly SEE	0.49	0.46	1.22	0.51	0.41	0.41
	Monthly SEE	1.76	1.72	5.63	2.17	1.39	1.33
	Average ratio	1.14	0.55	1.59	1.03	0.97	1.00
2006	Daily SEE	0.64	0.66	1.29	0.53	0.50	0.56
	Weekly SEE	0.54	0.51	1.22	0.40	0.32	0.34
	Monthly SEE	2.29	1.90	5.45	1.59	0.93	0.93
	Average ratio	1.20	0.59	1.66	1.11	1.08	1.13
2007	Daily SEE	0.61	0.56	1.36	0.54	0.45	0.53
	Weekly SEE	0.50	0.43	1.30	0.42	0.30	0.35
	Monthly SEE	2.03	1.66	5.78	1.49	0.78	0.82
	Average ratio	1.16	0.56	1.65	1.09	1.04	1.10
2008	Daily SEE	0.69	0.89	1.25	0.48	0.60	0.59
	Weekly SEE	0.57	0.60	1.16	0.36	0.46	0.39
	Monthly SEE	2.19	2.43	5.23	1.39	1.57	1.38
	Average ratio	1.21	0.64	1.64	1.08	1.08	1.14
2009	Daily SEE	0.83	0.84	1.24	0.67	0.59	0.63
	Weekly SEE	0.67	0.70	1.14	0.54	0.40	0.41
	Monthly SEE	2.56	2.73	5.01	2.23	1.36	1.31
	Average ratio	1.25	0.68	1.51	0.97	1.13	1.13
2010	Daily SEE	0.77	0.81	1.29	0.73	0.66	0.67
	Weekly SEE	0.57	0.61	1.13	0.61	0.42	0.41
	Monthly SEE	1.89	2.25	4.96	2.70	1.45	1.41
	Average ratio	1.20	0.67	1.51	0.96	1.07	1.09
2011	Daily SEE	0.77	0.65	1.37	0.53	0.52	0.56
	Weekly SEE	0.63	0.52	1.26	0.41	0.34	0.34
	Monthly SEE	2.61	2.27	5.42	1.73	1.05	0.97
	Average ratio	1.24	0.64	1.60	1.02	1.10	1.12
2012	Daily SEE	0.86	0.77	1.35	0.62	0.67	0.69
	Weekly SEE	0.66	0.52	1.24	0.48	0.38	0.40
	Monthly SEE	2.64	2.07	5.52	2.22	1.42	1.52
	Average ratio	1.21	0.65	1.51	0.97	1.05	1.07
Average	Daily SEE	0.73	0.73	1.30	0.59	0.57	0.61
	Weekly SEE	0.58	0.54	1.21	0.47	0.38	0.38
	Monthly SEE	2.25	2.13	5.38	1.94	1.24	1.21
	Average ratio	1.20	0.62	1.58	1.03	1.07	1.10

Note: SEE = Standard Error of Estimates, mm/d; FAO24-Rad = FAO24-Radiation (Doorenbos and Pruitt, 1977); J-H = Jensen-Haise (1963); M-B = McGuinness-Bordne (1972); P-T = Priestley-Taylor (1972); Equation 11 = Developed R_s-based equation; Equation 12 = Developed R_n-based equation.

The average ratio of ET_0 obtained from Equation 11to PMF-56 ET_0 was observed as 1.07 (Table 2). In general, Equation 11 gave best estimates of daily SEE values among all methods, 0.57 mm/d followed by Priestley-Taylor (0.59 mm/d) and Equation 12 as 0.61 mm/d. The SEE of daily ET_0 estimates varied significantly among different methods and during validation years, average daily SEE for FAO24-Radiation, Jensen-Haise and McGuinness-Bordne methods were obtained as 0.73, 0.73, and 1.30 mm/d respectively.

On weekly basis, both developed equations performed best with lowest SEE values (0.38 mm/d) in comparison with all other methods. Similarly, on monthly basis, developed equations produced better daily SEE results

(1.24 and 1.21 mm/d) in comparison with other considered methods. In general, these equations produced closest peak month ET_0 estimate to PMF-56 method. Eight years average SEE values for months with Priestley-Taylor, Jensen-Haise and FAO24-Radiation methods were found relatively lower (1.94, 2.13, 2.25 mm/d respectively) in comparison with McGuinness-Bordne method. The ratio of ET_0 method/ET_0 PMF-56 by Equations 11 and Equation 12 was averaged as 1.07 and 1.10 respectively. The Jensen-Haise method produced lowest ratio (0.62) and McGuinness-Bordne method gave highest value (1.58) among all methods, whereas, ratio for FAO24-Radiation and Priestley-Taylor methods were obtained as 1.20 and 1.03 respectively.

The comparison of annual total estimates using developed equations with PMF-56 (Table 3) for validation years (2005-2012) shows that with PMF-56, they were obtained as 1452.62, 1282.96, 1286.81, 1312.56, 1517.47, 1519.42, 1378.32 and 1507.54 mm respectively. Both developed equation estimates for annual total ET_0 were found close to those obtained with PMF-56. The estimates from Equation 11 were 1421.55, 1397.25, 1347.62, 1450.65, 1672.72, 1637.46, 1514.57 and 1591.86 mm, whereas, with Equation 12, respective annual ET_0 values were found as 1455.22, 1452.45, 1421.99, 1511.73, 1661.20, 1644.89, 1546.28 and 1599.13 mm. The average percent deviation of PMF56-ET_0 values during validation years with Equation 11 and Equation 12 were observed as 6.94% and 9.38% respectively.

Table 3 Comparison of annual PMF-56 ET_0 estimates with considered methods and developed equations for validation years (2005-2012)

Validation year	PMF-56	FAO24-Rad	J-H	M-B	P-T	Equation 11	Equation 12
2005	1452.62	1594.02	906.02	2094.05	1385.08	1421.55	1455.22
2006	1282.96	1509.62	807.04	2042.55	1393.62	1397.25	1452.45
2007	1286.81	1465.84	790.83	2009.44	1361.58	1347.62	1421.99
2008	1312.56	1575.26	904.95	2059.61	1389.28	1450.65	1511.73
2009	1517.47	1854.70	1100.00	2168.85	1413.35	1672.72	1661.20
2010	1519.42	1789.60	1117.25	2166.74	1396.27	1637.46	1644.89
2011	1378.32	1662.92	949.49	2091.09	1374.82	1514.57	1546.28
2012	1507.54	1804.03	1092.57	2117.26	1378.01	1591.86	1599.13
Deviation from PMF-56 (%)		17.71	-32.12	49.27	-1.02	6.94	9.38

Note: PMF-56 = FAO-56 Penman-Monteith; FAO24-Rad = FAO24-Radiation; J-H = Jensen-Haise; M-B = McGuinness-Bordne; P-T = Priestley-Taylor (1972); Equation 11 = Developed R_s-based equation; Equation 12= Developed R_n-based equation.

4 Conclusions

Two site-specific equations for estimating reference evapotranspiration (ET_0) developed in this study are suggested as practical methods over other considered radiation-based methods evaluated in this study for estimating ET_0 at sub-humid Hazaribagh region if standard PMF-56 equation cannot be used because of limitations associated with availability and reliability of climatological data. Furthermore, evaluation of these developed equations is recommended in other sub-humid locations.

References

Adeboye, O. B., J. A. Osunbitan, K. O. Adekalu, and D. A. Okunade. 2009. Evaluation of FAO-56 Penman Monteith and temperature based models in estimating reference evapotranspiration. *Agricultural Engineering International:*

the CIGR E-Journal: Manuscript No. 1291, Volume XI. October, 2009.

Allen, R. G., I. A. Walter, R. Elliot, B. Mecham, M.E. Jensen, D. Itenfisu, T. A. Howell,
R. Snyder, P. Brown, S. Echings, M. Hattendorf, R. H. Cuenca, J. L. Wright, and D. Martin D. 2000. Issues, requirements and challenges in selecting and specifying a standardized ET equation. In: Proc. 4th National Irrigation Symposium, American Society of Agricultural Engineers, Phoenix.

Allen, R. G., M. Smith, A. Perrier, and L. S. Pereira. 1994. An update for the definition of reference evapotranspiration. *International Commission on Irrigation and Drainage Bulletin*, 43(2): 1-34.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration - guidelines for computing crop water requirements. FAO Irrigation and Drainage paper No. 56. Food and Agriculture Organization of United Nations. Rome, Italy.

Allen, R. G., and C. E. Brockway. 1983. Estimating consumptive irrigation requirements for crops in Idaho. Idaho Department of Water Resources.

Dingman, S. L. 1994. Physical Hydrology. Upper Saddle River, NJ: Prentice Hall.

Doorenbos, J., and W. O. Pruitt. 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage paper No. 24, 2nd ed., FAO, Rome, Italy.

Gunston, H., and C. H. Batchelor. 1983. A comparison of the Priestley-Taylor and Penman methods for estimating reference crop evapotranspiration in tropical countries. *Agricultural Water Management*, 6(1): 65-77.

Hargreaves, G. H., and Z. A. Samani. 1985. Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture*, 1(2): 96-99.

Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. Evapotranspiration and Irrigation water requirements. ASCE Manual and Report on Engineering Practices No. 70. ASCE, New York

McGuinness, J. L., and E. F. Bordne. 1972. A comparison of lysimeter-derived potential evapotranspiration with computed values. Technical Bulletin 1452, Agricultural Research Service, US Department of Agriculture, Washington, DC.

Priestley, C. H. B., and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100: 81-92.

Smith, M., R. G. Allen, J. L. Monteith, A. Perrier, L. Pereira and A. Segeren. 1992. Report of the expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements. UN-FAO, Rome, Italy, 54p.

Walter, I., R., R. Allen, M. Elliott, D. Jensen, B. Itenfisu, Mecham, T. Howell, R. Snyder, P. Brown, S. Echings, T. Spofford, M. Hattendorf, R. Cuenca, J. Wright, and D. Martin. 2001. ASCE's Standardized Reference Evapotranspiration Equation. *Watershed Management and Operations Management*: DOI: http://dx.doi.org/10.1061/40499(2000)126

Watson, I., and A. D. Burnett. 1995. Hydrology: an environmental approach. Boca Raton, FL: CRC Press.

Willmott, C. J. 1982. Some comments on the evaluation of model performance. *American Meteorological Society*, 63(11): 1309-1312.

Xu, C. Y., and V. P. Singh. 2000. Evaluation and generalization of radiation-based methods for calculating evaporation. *Hydrological Processes*, 14(2): 339-349.