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Performance of radiation-based reference evapotranspiration equation developed for Indian sub-humid conditions

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ABSTRACT

In this study, asite-specific radiation based equation for estimating reference evapotranspiration (ET_{-0}) was developed and its performance was statistically analysed in comparison to widely accepted FAO Penman-Monteith (FAO-56 PM) model and four radiation-based ET_{-0} methods for sub-humid Hazaribagh region of Jharkhand state. The equation was developed with daily values of incoming solar radiation in conjunction with air temperature (minimum and maximum) by considering daily FAO-56 PM ET_0 values as index with weather dataset of 15 years (1990-2004). The performance of developed equation validated with eight years (2005-2012) daily weather dataset revealed that it estimated ET_0values better than other radiation-based methods. The respective higher and lower values of agreement index and root mean square error with FAO-56 PM ET_0 values during validation period confirms efficacy of developed equation whose performance tested at another Indian sub-humid location (Pantnagar) confirmed its suitability as well. Considering the limitations associated with reliability and availability of weather data especially in developing countries, developed equation is recommended as practical one to estimate ET_0 in sub-humid climatic conditions if FAO-56 PM model cannot be used due to non-availability of required weather parameters at a location.

Keywords: Radiation-based equation, reference evapotranspiration, sub-humid, Hazaribagh, Pantnagar

Under diminishing water resources, increasing consumption and pollution, water available for irrigation is shrinking. In Indian conditions, distribution of precipitation (main source of water for crop production)is very uneven and uncertain. For effective water management under water scarce situation, farmers have to opt proper irrigation scheduling for which it is essential to know environmental demand for surface water whose loss occurs primarily through evapotranspiration (ET). Accordingto Hansen *et al.* (1980), ET is the amount of water returned to the atmosphere through evaporation (moisture loss from soil, standing water etc.) and transpiration (biological use and release of water by vegetation). 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 is essentially required (Watson and Burnett, 1995).

Reference evapotranspiration (ET_0) is a modification of ET concept that provides a standard crop (a short, clipped grass) with an unlimited water supply so that a user can calculate maximum evaporative demand from that surface for a given day. This value, adjusted for a particular crop is its consumptive use (or demand) and its deficit represent that component of consumptive use that goes unfilled, either by precipitation or by soil moisture during the given time period (Allen *et al.*, 1998).The information about ET_0 is required for crop production, environment assessment, irrigation scheduling, water resources management etc. Since its direct measurement using lysimeter is cumbersome, challenging, time consumingthe most common procedure to estimate ET_0 is from observed meteorological variables (Dingman, 1994; Allen *et al.*, 1998; Barnett *et al.*, 1998).

The International Commission for Irrigation and Drainage and the Food andAgriculture Organization (FAO) of the United Nations Expert Consultation onRevision of Methodologies for Crop Water Requirements (Smith *et al.*, 1991) recommended FAO Penman–Monteith (FAO-56 PM) model as standard 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,like India,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 FAO-56 PM model are not available or reliable for a location, empirical or simplified ET_0equations requiring fewer parameters can be used.

Keeping in view the above, the present study was taken up with objectives: (i) to develop a radiation-based ET_0 equation considering FAO-56 PM ET_0 model as index; (ii) to evaluate the performance of developed equation in comparison to radiation-based ET_0 methods; and (iii) to validate developed equation at another sub-humid location.

MATERIALS AND METHODS

Study area and weather dataset

Daily 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, 604.00 m above m.s.l.) region of Jharkhand state was used in this study. The study area experiences three distinct seasons i.e., summer (February-May), monsoon (June-September) and winter (October-January) with an average annual rainfall of about 783 mm.

Reference evapotranspiration estimation

In this study, FAO-56 PMmodel was chosen as index to computedaily ET_0 values, expressed mathematically (Smith *et al.*, 1992) as:

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

where ET_0 is reference evapotranspiration (mm day^{-1}); R_n is net radiation at crop surface (MJm^{-2}day^{-1}); G is soil heat flux density (MJm^{-2}day^{-1}); T_{av} is mean daily air temperature (˚C); U_2 is wind speed at 2 m height (msec^{-1}); e_s is saturation vapour pressure (kPa); e_a is actual vapour pressure (kPa); e_s-e_a is saturation vapour pressure deficit (kPa); y is slope of vapour pressure curve (kPa˚C^{-1}); and ã is psychrometric constant (kPa˚C^{-1}).Since soil heat flux density (G) has relatively a small value, it was considered zero for daily calculations in accordance with Allen *et al.* (1998).

In addition to FAO-56PM model, four radiation-based ET_0 methods namely, FAO24-Radiation (Doorenbos and Pruitt, 1977), Jensen–Haise (1963), McGuinness-Bordne (1972) and Priestley-Taylor (1972) were considered to evaluate the performance of developed equation.

Development of radiation-based ET_0 equation

A radiation-based ET_0equation for sub-humid Hazaribagh region of Jharkhand state was developed with Multiple Linear Regression (MLR) approach by considering 65% of daily weather dataset (1990-2004) for calibration, whereas, remaining 35% dataset (2005-2012) was used for validating it. The MLR approach was used as linear form presumes that each parameter impacts ET_0 independent of other parameters and it reduces the requirement of input parameters.For determining coefficients of developed equation, daily FAO-56 PM ET_0 values were taken as dependent variable, whereas, daily values of R_s, T_{max} and T_{min} were used as independent variables.

Statistical analysis

To ensure rigorous comparison of developed equation and considered methods to evaluate their performance in comparison to FAO-56 PM model, an extended analysis in terms of statistical indices namely, Agreement index (D), Root Mean Square Error (RMSE), Coefficient of determination (R^2) and Standard Error of Estimates (SEE) was undertaken with the help of Microsoft™ Excel® as computing tool.On the basis of literature reviewed, higher values of D and R^2 (near to 1.00) and values near to 0.00 for RMSE and SEE were considered "good".The quantification of under- and over-estimation of developed equation and radiation-based methods as compared to FAO-56 PM model was done in terms of their ratio (ET_0 method/ET_0FAO-56 PM)and its value near to 1.00 was considered "good".

RESULTS AND DISCUSSION

Radiation-based ET_0 equation

The first-order MLR equation to estimate values of FAO-56 PM ET_0 (mm day^{-1}) as a function of R_s (MJ m^{-2} day^{-1}), maximum air temperature (T_{max}, °C) and minimum air temperature (T_{min}, °C) was determined as:

$$ET_0 = -5.7547 + 0.1664\,R_s + 0.2348\,T_{max} - 0.0015\,T_{min} \quad \ldots (2)$$

For calibrating this equationwith 5479 number of daily observationsover 15 years period (1990-2004), the curvilinear regression (Fig. 1) was found significant (R^2 = 0.903).

Performance of equation during calibration period

The performance of developed equation was evaluated by comparing its daily and monthly estimates with those obtained with FAO-56 PMmodel and considered methods in terms of statistical indices and average ratio of ET_0 method/ET_0FAO-56 PM.For monthly comparisons, daily ET_0 values averaged over one month period were plotted

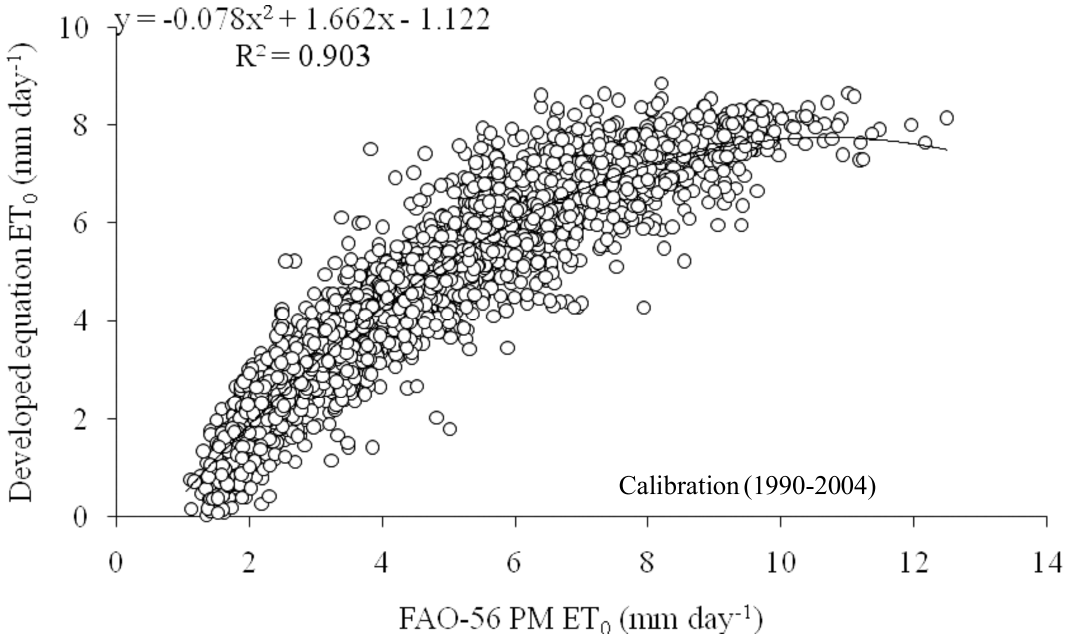

Fig. 1: Regression analysis for calibrating developed ET_0equation

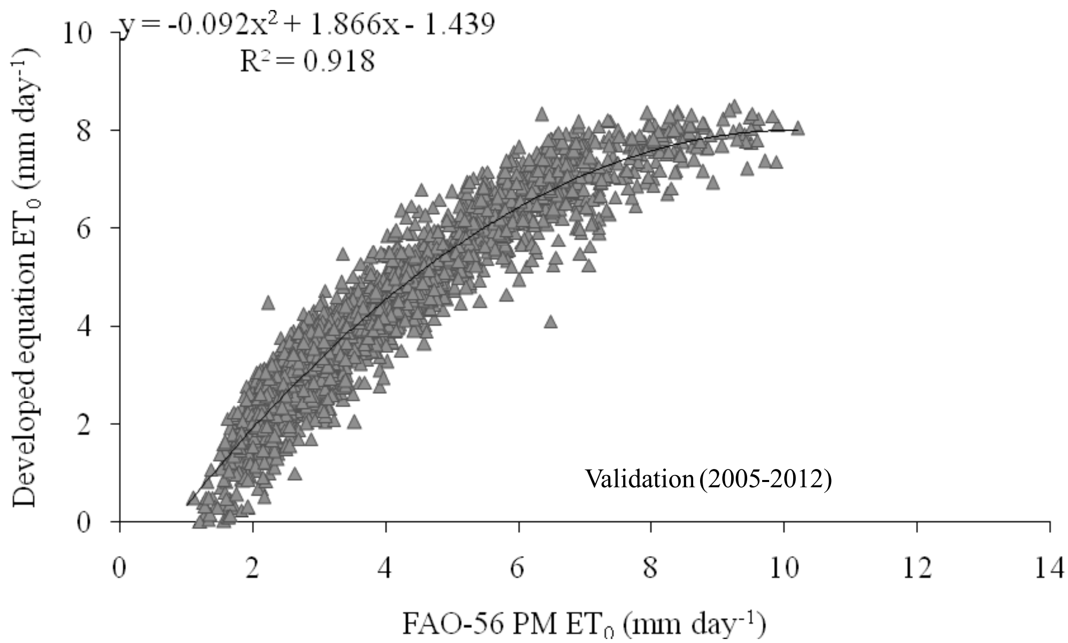

Fig. 2 : Regression analysis for validating developed ET_0equation

against calculated FAO-56 PM values.

The relative performance of developed equation for calibration period (1990-2004) on daily and monthly basis (Table 1) reveals that on daily basis, highest values of D (0.96) and R^2 (0.88); lowest values of RMSE (0.69 mm day^{-1}) and SEE (0.61 mm day^{-1}) were obtained with developed equation. Similarly, the value of ratio as 1.01 obtained with developed equation extends its superiority over other methods.FromTable 1, it is clear that the developed equation performed best on both daily and monthly basis.

Validation of the equation

Eight years of daily weather dataset, consisting of 2922 observations was used to validate the developed equation. The comparison of daily ET_0 values estimated using developed equation with that of radiation-based methods on daily and monthly basis for validation period (2005-2012) is presented in Table 2.

From Table 2, it is clear that ET_0values calculated with developed equation followed FAO-56 PM values closely

Table 1: Comparative performance of developed equation and radiation-based methods versus FAO-56 PM model during calibration period (1990-2004) at Hazaribagh

Equation / Methods	D	RMSE	R^2	SEE	Ratio
		Daily basis			
Developed equation	0.96	0.69	0.88	0.61	1.01
FAO24-Radiation	0.93	0.98	0.83	0.78	1.17
Jensen-Haise	0.81	1.76	0.83	0.74	0.56
McGuiness-Bordne	0.71	2.29	0.49	1.44	1.54
Priestley-Taylor	0.87	4.20	0.78	2.43	0.97
		Monthly basis			
Developed equation	0.99	1.76	0.96	1.36	1.01
FAO24-Radiation	0.94	3.29	0.91	2.20	1.18
Jensen-Haise	0.80	7.12	0.92	2.03	0.58
McGuiness-Bordne	0.73	9.36	0.60	6.11	1.47
Priestley-Taylor	0.87	4.20	0.78	2.43	0.97

D = Agreement index, RMSE = Root Mean Square Error (mmday^{-1}), R^2 = Coefficient of determination,
SEE = Standard Error of Estimates (mm day^{-1}), Ratio = Ratio of ET_0 method/ET_0FAO-56 PM.

Table 2: Comparative performance of developed equation and radiation-based methods versus FAO-56 PM model during validation period (2005-2012) at Hazaribagh

Equation / Methods	D	RMSE	R^2	SEE	Ratio
		Daily basis			
Developed equation	0.96	0.66	0.90	0.57	1.06
FAO24-Radiation	0.92	1.01	0.84	0.73	1.20
Jensen-Haise	0.85	1.43	0.84	0.73	0.62
McGuiness-Bordne	0.69	2.30	0.56	1.30	1.58
Priestley-Taylor	0.93	2.83	0.87	0.59	1.02
		Monthly basis			
Developed equation	0.99	1.80	0.97	1.24	1.07
FAO24-Radiation	0.92	3.66	0.90	2.25	1.21
Jensen-Haise	0.83	5.72	0.91	2.13	0.64
McGuiness-Bordne	0.69	9.58	0.68	5.37	1.52
Priestley-Taylor	0.93	2.83	0.87	1.94	1.02

D = Agreement index, RMSE = Root Mean Square Error (mm day^{-1}), R^2 = Coefficient of determination,
SEE = Standard Error of Estimates (mm day^{-1}), Ratio = Ratio of ET_0 method/ET_0FAO-56 PM.

demonstrating that it can be used to estimate ET_0 with reasonable accuracy. On daily basis, developed equation performed best with highest values of D (0.96) and R^2 (0.90); lowest values of RMSE (0.66 mm day^{-1}) and SEE (0.57mm day^{-1}) in comparison to radiation-based methods, whereas, on monthly basis, lowest average value of SEE (1.24mm day^{-1}) in comparison to McGuinness-Bordne (5.37mm day^{-1}), FAO24-Radiation (2.25mm day^{-1}), Jensen-Haise (2.13mm day^{-1}) and Priestley-Taylor (1.94mm day^{-1}) methods confirms its better performance. On daily basis, the average ratio of ET_0 method/ET_0FAO-56 PM with developed equation was obtained as 1.06, whereas, its highest value (1.58) was obtained with McGuinness-Bordne method. From Fig. 2, it is evident that ET_0 values calculated by developed equation

Table 3: Standard error of estimates on daily & monthly basic of reference evapotranspiration and average ratio (ET_0 method/ ET_0FAO-56 PM) of developed equation and radiation-based methods mean over me validation period (2005-2012) at Hazaribagh.

Performance indicator	Developed equation	FAO24-Radiation	Jensen-Haise	McGuiness-Bordne	Priestley-Taylor
Daily SEE	0.57	0.73	0.73	1.30	0.59
Monthly SEE	1.24	2.25	2.13	5.37	1.94
Average ratio	1.06	1.20	0.62	1.58	1.02

SEE = Standard Error of Estimates (mm day^{-1})

Table 4: Comparative performance of developed equation and radiation-based methods versus FAO-56 PM model during study period (1990-2012) at Hazaribagh

Equation / Methods	D	RMSE	R^2	SEE	Ratio
		Daily basis			
Developed equation	0.96	0.68	0.88	0.60	1.02
FAO24-Radiation	0.92	0.99	0.83	0.76	1.18
Jensen-Haise	0.82	1.64	0.83	0.73	0.59
McGuiness-Bordne	0.71	2.29	0.52	1.39	1.56
Priestley-Taylor	0.87	1.05	0.71	0.68	1.00
		Monthly basis			
Developed equation	0.99	1.77	0.97	1.32	1.03
FAO24-Radiation	0.94	3.42	0.91	2.21	1.19
Jensen-Haise	0.81	6.63	0.92	2.06	0.60
McGuiness-Bordne	0.71	9.44	0.63	5.85	1.49
Priestley-Taylor	0.90	3.72	0.81	2.26	0.99

D = Agreement index, RMSE = Root Mean Square Error (mm day^{-1}), R^2 = Coefficient of determination,
SEE = Standard Error of Estimates (mm day^{-1}), Ratio = Ratio of ET_0 method/ET_0FAO-56 PM.

were strongly correlated (R^2= 0.918) with that of the FAO-56 PM model.

The values of SEE and ratio for developed equation and radiation-based methods on daily and monthly basis for individual years during validation period (2005-2012) are presented in Table 3. From Table 3, it is clear that developed equation resulted in lowest average SEE of daily estimate (0.57 mm day^{-1}), whereas, its value for radiation-based methods was found much higher ranging from 0.73 to 1.30 mm day^{-1}. Ingeneral, the performance of developed equation was found better at both the timescales.

Performance during study period (1990-2012)

The statistical performance of developed equationin comparison to radiation-based methods during study period (Table 4) reveals that on both daily and monthly basis, ET_0values calculated with developed equation were strongly correlated with that of FAO-56 PM model with highest values of R^2(0.99 and 0.97) andD (0.96 and 0.88) and lowest daily and monthly SEE values as 0.60 mm day^{-1} and 1.32 mm day^{-1} respectively.

From Table 4, it is clear that the ratio of ET_0 method/ ET_0FAO-56 PM with developed equation at both the time scales was obtained near to 1.00. It was also observed that McGuinness-Bordneand Jensen-Haise methods respectively gave almost 50 percent higher and 40 percent lower valueson both daily and monthly basis in comparison to its "good" value of 1.00.

Performance at another sub-humid location

The performance of developed equation was further evaluated at another sub-humid location, Pantnagar (29°N latitude, 79.3°E longitude, 243.80 m above m.s.l.), located in the foothills of the great Himalayas in Uttarakhand and is presented in Table 5. The continuous daily full weather dataset for 24 year duration (1990-2013) obtained from meteorological observatory situated in the premises of Crop Research Centre of the Govind Ballabh Pant University of

Table 5: Comparative performance of developed equation and radiation-based methods versus FAO-56 PM model at Pantnagar (1990-2013)

Equation / Methods	D	RMSE	R^2	SEE	Ratio
		Daily basis			
Developed equation	0.98	0.84	0.91	0.64	1.00
FAO24-Radiation	0.95	0.86	0.89	0.68	1.17
Jensen-Haise	0.89	1.48	0.82	0.80	0.62
McGuiness-Bordne	0.75	2.33	0.66	1.38	1.60
Priestley-Taylor	0.94	0.88	0.81	0.73	1.01
		Monthly basis			
Developed equation	0.99	2.78	0.97	1.68	1.00
FAO24-Radiation	0.96	2.83	0.95	1.77	1.18
Jensen-Haise	0.86	5.74	0.89	2.34	0.64
McGuiness-Bordne	0.75	9.44	0.80	5.05	1.53
Priestley-Taylor	0.96	2.80	0.88	2.44	1.00

D = Agreement index, RMSE = Root Mean Square Error (mm day^{-1}), R^2 = Coefficient of determination,
SEE = Standard Error of Estimates (mm day^{-1}), Ratio = Ratio of ET_0 method/ET_0 FAO-56 PM.

Agriculture & Technology, Pantnagar (Uttarakhand) was used in this study.

From Table 5, it is clear that in comparison to radiation-based methods, developed equation performed better as it produced highest values of D (0.98 and 0.91)and R^2 (0.99 and 0.97); lowest values of RMSE (0.84 and 0.64 mm day^{-1})and SEE (2.78 and 1.68 mm day^{-1}) and ratio (1.00 and 1.00) on daily and monthly basis respectively which confirms that developed equation can be used successfully to estimate ET_0 at other sub-humid locations.

CONCLUSIONS

A site-specific radiation-based ET_0 equation was developed with multiple linear regression approach for sub-humid Hazaribagh region of Jharkhand statewith daily weather dataset of 15 years duration (1990-2004), whereas, eight years (2005-2012) of daily weather datasetwas used to validate it. The estimates of daily and monthly ET_0values obtained with developed equation were foundvery close to that of the FAO-56 PM model in comparison to radiation-based methods.

The performance of developed equation evaluated at another Indian sub-humid location (Pantnagar, Uttarakhand) with daily weather dataset of 24 years (1990-2013) confirmed that it can be utilized as a practical method to estimate ET_0 successfully in Indian sub-humid regions if standard FAO-56 PM model cannot be used due to limitations associated with availability and reliability of required meteorological dataset.The evaluation of developed equation is recommended at other sub-humid locations as well.

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