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Comparative Performance of Reference Evapotranspiration Equations at Sub-Humid Tarai Region of Uttarakhand, India

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ABSTRACT

In order to estimate reference evapotranspiration (ET_0) with the widely accepted FAO-56 PM model especially, in developing countries like India, quality of data and difficulties in gathering all necessary, weather parameters can present serious limitations. Keeping in view, the relevance of precise ET_0 estimation, an attempt has been made to evaluate, decide and select alternative radiation-based methods to get almost at par ET_0 values (from observed climatic data) on the basis of their performance with widely acclaimed FAO-56 PM method as an index for sub-humid *Tarai* region of Uttarakhand, India. The higher value of Agreement index of ET_0 values obtained with FAO24-Radiation method confirms its appropriateness, whereas, value of ET_0 method/ET_0 FAO-56 PM ratio as 1.00 by Castaneda-Rao method validates its suitability in place of FAO-56 PM at the study area located in the Indian sub-humid region.

Key words: Evaluation, FAO-56 penman-monteith, reference ET, radiation-based, statistical analysis, sub-humid climate

INTRODUCTION

World Bank and the UN through a study indicated that the irrigated agriculture will need to provide 70% of the world's increased food requirements in 2025 (Anonymous, 2003). Postel (1999) indicated that food production levels needed in 2025 could require up to 2,000 cubic kilometers of additional irrigation water for cultivating crops. Water management and crop yields can be improved with the help of increased use of reliable methods for estimating crop evapotranspiration. Many methods have been proposed and used over the last 50 years and various international agencies are attempting to develop an accord with respect to the best and most appropriate methods to use for ET_0 calculations (Smith *et al*., 1991; Allen *et al*., 1994a, b; IWMI., 1997).

In India, about 70% population is dependent on agriculture and allied activities (Tripathi and Prasad, 2009). Due to inadequate and uneven distribution of rainfall during crop growth period, it becomes necessary to apply additional water to the soil in the form of irrigation for plant use (Hansen *et al*., 1980). In order to improve crop water use efficiency, accurate estimation of evapotranspiration (ET), the sum of amount of water returned to atmosphere through combined process of evaporation and transpiration, is essentially required for efficient water management (Watson and Burnett, 1995; Tomar and Ranade, 2001).

Lysimeter are normally used for measuring ET directly by considering change in soil moisture from known volume of soil covered with vegetation (Watson and Burnett, 1995), but its use is very expensive, takes more time to install and requires more maintenance due to which ET is estimated with the help of a large number of empirical or semi-empirical formulae. A modification of ET concept is reference evapotranspiration (ET_0) 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 the consumptive use (or demand) and its deficit represents that component of consumptive use that goes unfilled during the given time period. This deficit value is the amount of water that must be supplied through irrigation to meet the water demand of crops (Dingman, 1994; Allen *et al*., 1998).

The FAO Penman-Monteith (FAO-56 PM) method is recommended as the standard method for determining ET_0, as it is physically based and explicitly incorporates both physiological and aerodynamic parameters. The superior performance of this method in various climates has been evaluated and confirmed by various researchers (Allen *et al*., 1998; Jensen *et al*., 1990; Smith *et al*., 1991; Allen *et al*., 1994a; Chiew *et al*., 1995; Allen *et al*., 2000; Walter *et al*., 2000). The method requires solar radiation, wind speed, air temperature and humidity data but all these input variables may not be available for a given location due to non-availability of well-established weather stations and thus, some parameters are not recorded. Especially, in developing countries like India, quality of data and difficulties in gathering all necessary weather parameters can present serious limitations. The FAO Expert Consultation on Methodologies for Crop Water Requirements recommended that empirical methods be validated for new regions using standard FAO-56 PM method (Smith *et al*., 1991; Allen *et al*., 1994b). Keeping in view the relevance of precise ET_0 estimation and unavailability of all the required meteorological dataset, an attempt has been made in the present study to evaluate, decide and select alternative radiation-based methods to get almost at par ET_0 values from observed climatic data on the basis of their performance with widely acclaimed FAO-56 PM method as an index for *Tarai* region, situated in the foothills of the great Himalayas in Uttarakhand, India.

MATERIALS AND METHODS

Study area and weather dataset: The present study was conducted to perform comparative analysis of various radiation-based ET_0 methods for Pantnagar (79.49°E, 29.03°N, 243.80 m msl), located in Udham Singh Nagar district on the basis of 24 years of daily meteorological dataset consisting of temperature (maximum and minimum); relative humidity (maximum and minimum) and duration of actual sunshine hours collected from Govind Ballabh Pant University of Agriculture and Technology, Pantnagar in Uttarakhand (Fig. 1).

FAO-56 penman monteith model and radiation-based ET_0 methods: The original Penman-Monteith combination equation, combined with equations of aerodynamic and surface resistance called as “FAO-56 Penman Monteith model” (Allen *et al*., 1998; Smith *et al*., 1991) is given below:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2\,(e_3 - e_B)}{\Delta + \gamma(1 + 0.34u_2)}$$

where, ET_0 is reference evapotranspiration (mm day^{-1}), R_n is net radiation at crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature (°C), u_2 is wind speed at 2 m height (m sec^{-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), Δ is slope of vapour pressure curve (kPa $°C^{-1}$) and γ is psychometric constant (kPa $°C^{-1}$). Being the FAO-56 PM method gives

Fig. 1: Index map of the study area

proximate close values with actual values measured in a wide range of location and climatic conditions and, therefore, in the present study, it was chosen as index method for ET_0 computation. The commonly used 20 radiation-based ET_0 equations considered in this study are summarized in Table 1.

Assumptions and statistical analysis: The analysis of results to draw fruitful inferences from them in terms of statistical indices was being done as it has been pointed out by Fox (1981) and Willmott (1982) that commonly used correlation measures e.g., correlation coefficient, coefficient of determination and tests of statistical significance in general are often inappropriate or misleading. Different statistical indices considered to evaluate performance of different methods

Table 1: Details of radiation-based ET_0 methods considered in the study

Methods	Equation	References
Abtew (Abt)	$ET_0 = 0.408 \times 0.01786 \times R_s T_{max}$	Abtew (1996)
Berengena-Gavilan (BG)	$ET_0 = 0.408 \times 1.65 \left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G)$	Berengena and Gavilan (2005)
Caprio (Cap)	$ET_0 = (0.01092708\ T_{av} + 0.0060706) R_s$	Caprio (1974)
Castaneda-Rao (CR)	$ET_0 = 0.408 \times 0.70 \left(\frac{\Delta}{\Delta+\gamma}\right) R_s - 0.12$	Castaneda and Rao (2005)
Christiansen (Chr)	$ET_0 = 0.408 \times 0.0385 \times R_s$	Christiansen (1968)
de Bruin (dBr)	$ET_0 = 0.408 \times 0.65 \left(\frac{\Delta}{\Delta+\gamma}\right) R_s$	De Bruin and Stricker (2000)
FAO24-Radiation (FRad)	$ET_0 = 0.408 \times a \left(\frac{\Delta}{\Delta+\gamma}\right) R_s - 0.30$	Doorenbos and Pruitt (1977)
Hansen (Han)	$ET_0 = 0.408 \times 0.70 \left(\frac{\Delta}{\Delta+\gamma}\right) R_s$	Hansen (1984)
Irmak R_n (IrR_n)	$ET_0 = 0.289 \times R_n + 0.023 \times T_{av} + 0.489$	Irmak *et al.* (2003)
Irmak R_s (IrR_s)	$ET_0 = 0.149 \times R_s + 0.079 \times T_{av} - 0.611$	Irmak *et al.* (2003)
Jensen-Haise (JH)	$ET_0 = 0.408 \times C_T (T_{av} - T_x) R_s$	Jensen and Haise (1963)
Jones-Ritchie (JR)	$ET_0 = 0.00387 \times (0.6 T_{max} + 0.4 T_{min} + 29) R_s \times \alpha$	Jones and Ritchie (1990)
Makkink (Mak)	$ET_0 = 0.408 \times 0.61 \left(\frac{\Delta}{\Delta+\gamma}\right) R_s - 0.12$	Makkink (1957)
McGuinness-Bordne (MB)	$ET_0 = \left\{(0.0082 \times T_{av} - 0.19)\left(\frac{R_s}{1500}\right)\right\} \times 2.54$	McGuinness and Bordne (1972)
Modified Priestley-Taylor (MPT)	$ET_0 = 0.408 \times 1.18 \left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G)$	Abtew (1996)
Priestley-Taylor (PT)	$ET_0 = 0.408 \times 1.26 \left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G)$	Priestley and Taylor (1972)
Stephens (Ste)	$ET_0 = 0.408 \times (0.0158\ T_{av} + 0.09) \times R_s$	Stephens (1965) and Jensen (1966)
Stephens-Stewart (SS)	$ET_0 = 0.408 \times (0.0148\ T_{av} + 0.07) \times R_s$	Jensen (1966)
Turc (Tur)	$ET_0 = (0.3107 \times R_s + 0.65) \times \left(\frac{T_1}{T_{av} 15}\right)$	Turc (1961)
Xu-Singh (XS)	$ET_0 = 0.408 \times 0.98 \left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G) - 0.94$	Xu and Singh (2000)

ET_0: Reference crop evapotranspiration (mm day^{-1}), G: Soil heat flux density (MJ m^{-2} day^{-1}), R_n: Net radiation (MJ m^{-2} day^{-1}), R_s: Solar radiation (MJ m^{-2} day^{-1}), T_{av}: Average daily air temperature (°C), T_{max}: Maximum air temperature (°C), T_{min}: Minimum air temperature (°C), u_2: Mean daily wind speed at 2 m height (m sec^{-1}), Δ: Slope of saturation vapor pressure-temperature curve (kPa $°C^{-1}$), γ: Psychometric constant (kPa $°C^{-1}$), λ: Latent heat of vaporization (MJ kg^{-1}) and a, C_T, T_1, T_x, α: Experimental coefficients

includes; Agreement index (D), Root Mean Square Error (RMSE), Mean Bias Error (MBE), Maximum Absolute Error (MaxE), Percentage Error (%), Coefficient of determination (R^2) and Standard Error of Estimate (SEE). The "Agreement Index" (D) is being proposed, as a descriptive measure (Willmott, 1981, 1982; Willmott and Wicks, 1980). The computational forms of considered statistical indices are presented in Table 2. On the basis of literature, reviewed on different statistical indices, higher values of D and R^2 (near to "1.00"), values near to "0.00" for RMSE, MBE, MAXE, PE and SEE were considered "good" for deciding the performance of considered methods. The quantification of under and over-estimation of ET_0 method as compared to that obtained with FAO-56 PM model was being done in terms of their ratio and its value near to "1.00" was considered "good".

Table 2: Computational forms of considered statistical indices

Statistical index	Notation	Computational form
Agreement index	D	$1-\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(\|P_i-\bar{O}\|+\|O_i-\bar{O}\|)^2}$
Root mean square error	RMSE	$\sqrt{\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{n}}$
Mean bias error	MBE	$\frac{1}{n}\sum_{i=1}^{n}(P_i-O_i)$
Maximum absolute error	MAXE	$MAX[\|O_i-P_i\|]_{i=1}^{n}$
Percentage error of estimate	PE	$\left\|\frac{\bar{P}-\bar{O}}{\bar{O}}\right\|\times100\%$
Coefficient of determination	R^2	$1-\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O}\|)^2}$
Standard error of estimates	SEE	$\sqrt{\left[\frac{1}{n(n-2)}\right]\left[n\sum P_i^2-\left(\sum P_i\right)^2\frac{\left[n\sum O_iP_i\right]-\left(\sum O_i\right)\left(\sum P_i\right)}{n\sum O_i^2-\left(\sum O_i\right)^2}\right]^2}$

$\bar{O}$: Mean of FAO-56 PM ET_0 (mm day^{-1}), O_i: FAO-56 PM ET_0 (mm day^{-1}), $\bar{P}$: Mean of FAO-56 PM ET_0 (mm day^{-1}), P_i: Predicted value of ET_0 (mm day^{-1}) estimated by using other equations, n: Total number of observations

RESULTS AND DISCUSSION

Cross comparison of radiation-based ET_0 equations: The performance of considered radiation-based ET_0 equations was evaluated by comparing their monthly ET_0 estimates with those obtained with FAO-56 PM model by plotting daily ET_0 values averaged over month period plotted against corresponding values obtained by FAO-56 PM model. The long-term average ratio of ET_0 method/ET_0 FAO-56 PM were also computed to quantify over-and under-estimation of considered equations relative to the FAO-56 PM ET_0 values.

The statistical analysis of radiation-based ET_0 equations for study area (Table 3) indicated that the FAO24-Radiation method performed best as it gave optimal value of D as 0.96 among 10 best methods obtained for study area. The lowest value of MBE was obtained with Irmak R_s method (0.27) and the lowest value of SEE was obtained with Turc method as 0.11. Considering calculated values of RMSE among 10 best methods, Stephens method was observed best, as it gave lowest RMSE value (2.80 mm day^{-1}) among all other considered methods, whereas, the best value for ratio of ET_0 method/ET_0 FAO-56 PM was obtained with Castaneda-Rao method as 1.00.

Among 16 evaluated ET_0 models, Sahoo *et al.* (2012) found the performance of FAO24-Radiation method best in the sub-humid valley rangeland in the eastern Himalayas. Similarly, Razzaghi and Sepaskhah (2010) found this model the most-appropriate among considered nine ET_0 methods. Kashyap and Panda (2001) mentioned that FAO24-Radiation method shouldn't be recommended for estimating ET_0 in sub-humid climatic regions, however, Irmak *et al.* (2008) favoured its use in concurrence with the findings of Giridhar and Viswanadh (2007) and the present study. In Tabari (2010) found that the Makkink model performed well in cold humid climates in contradiction to the findings of this study. Similarly, the conclusion made by Zhai *et al.* (2010) that the Abtew method should be used only at the high plateau regions is in good agreement with the results obtained in this study. Xystrakis and Matzarakis (2011) found equation proposed by Turc (1961) useful on the basis of evaluation of 13 empirical ET_0 equations for Southern Greece,

Table 3: Statistical performance of radiation-based methods versus FAO-56 PM model for estimating ET_0 values

Methods	D	RMSE	MBE	MAXE	PE	R^2	SEE	Ratio
Abt	0.43	16.19	-14.52	-5.18	90.25	0.87	0.51	0.09
BG	0.89	5.40	4.15	9.82	26.44	0.87	3.15	1.29
Cap	0.90	5.21	4.36	8.50	27.13	0.93	2.57	1.28
CR	0.94	3.09	-0.99	2.24	6.56	0.93	1.46	1.00
Chr	0.44	15.59	-13.93	-4.84	86.58	0.87	0.55	0.14
dBr	0.92	3.51	-1.54	1.91	9.58	0.93	1.39	0.97
FRad	0.96	2.84	2.27	5.54	14.09	0.95	1.77	1.18
Han	0.94	2.99	-0.50	2.76	4.32	0.93	1.49	1.04
IrR_n	0.92	3.47	0.29	3.30	5.15	0.87	1.94	1.11
IrR_s	0.92	3.32	0.27	3.77	4.08	0.89	1.74	1.11
JH	0.86	5.74	-5.21	-1.49	32.32	0.90	2.34	0.64
JR	0.59	9.97	-8.79	-2.62	54.26	0.96	0.56	0.48
Mak	0.87	4.42	-2.86	0.86	17.71	0.93	1.31	0.88
MB	0.76	9.44	7.98	18.96	49.84	0.80	5.05	1.53
MPT	0.94	3.08	-1.31	1.65	8.14	0.88	2.30	0.94
PT	0.96	2.81	-0.38	2.93	4.49	0.88	2.44	1.00
Ste	0.95	2.80	-1.55	1.15	9.51	0.93	1.68	0.93
SS	0.91	3.83	-2.81	-0.05	17.33	0.93	1.58	0.84
Tur	0.41	16.49	-14.92	-5.52	92.15	0.93	0.11	0.09
XS	0.71	8.23	-7.47	-4.40	46.35	0.87	2.08	0.48

Abt: Abtew, BG: Berengena-gavilan, Cap: Caprio, CR: Castaneda-rao, Chr: Christiansen, dBr: de Bruin, FRad: FAO24-Radiation, Han: Hansen, IR_s: Irmak R_s, IR_n: Irmak R_n, JH: Jensen-Haise, JR: Jones-Ritchie, Mak: Makkink, MB: McGuinness-bordne, MPT: Modified priestley-taylor, PT: Priestley-taylor, Ste: Stephens, SS: Stephens-stewart, Tur: Turc, XS: Xu-singh, D: Agreement index, RMSE: Root mean square error (mm day^{-1}), MBE: Mean bias error (mm day^{-1}), MAXE: Maximum absolute error (mm day^{-1}), PE: Percentage error of estimate (%), R^2: Coefficient of determination, SEE: Standard error of estimate (mm day^{-1}), Ratio: Ratio of ET_0 method/ET_0 FAO-56 PM

as it gave less monthly absolute error and in a recent research work, Djaman *et al.* (2015) concluded that Turc equation underestimated ET_0 values in accordance with results obtained in the present study.

CONCLUSION

Considering the limitations associated with reliability and availability of good quality weather data especially in developing countries, the widely acclaimed and well-proven FAO-56 PM model cannot be used to estimate ET_0 due to which identification of simpler ET_0 equations is required. In this study, the performance of 20 radiation-based ET_0 equations as compared to standard, widely accepted and well-proven FAO-56 PM model was evaluated. The following conclusions were drawn from the findings of the present study:

- In terms of highest D and lowest RMSE values, FAO24-Radiation ET_0 method was adjudged best, whereas, Abtew method performed worst
- Castaneda-Rao method gave best estimate of FAO-56 PM model
- ET_0 equations given by McGuinness-Bordne, Berengena-Gavilan, Caprio, FAO24-Radiation, Irmak R_s, Irmak R_n and Hansen over-estimated FAO-56 PM model values
- The de Bruin, modified Priestley-Taylor, Stephens, Makkink, Stephens-Stewart, Jensen-Haise, Xu-Singh, Jones-Ritchie, Turc, Christiansen and Abtew methods under-estimated values calculated with FAO-56 PM model
- Similar kind of site-specific evaluation of available global ET_0 equations (which requires less number of meteorological parameters) in different climatic regions is required to be undertaken to identify, decide and use them in place of standard FAO-56 PM method which requires more number of meteorological parameters for estimating ET_0 values

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