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Performance evaluation of calibrated radiation-based ET_0 equations against standard FAO56-PM model in humid climatic condition

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सार – **उत्तराखंड (भारत) के आर्द्र देहरादून जिले के लिए मानक** FAO56-PM **मॉडल की तुलना में विभिन्न विकिरण-आधारित** ET_0 **समीकरणों के मूल और कैलिब्रेटेड संस्करणों के प्रदर्शन का मूल्यांकन करने के लिए विशिष्ट उद्देश्य से किए गए इस अध्ययन में पाया गया कि सभी कैलिब्रेटेड** ET_0 **समीकरणों ने उनके मूल संस्करणों की तुलना मेंबहुत बेहतर प्रदर्शन किया।**

अंशांकन गुणांकों में 5.37% (Val1) **से** 42.62% (M-B) **तक की कमी पाई गई , जबकि इसमें** 4.83% **(एस-एस) और** 82.57% **(एफ** 24-**रेड) के बीच में वृद्धि हुई। अंशांकन के बाद सभी समीकरणों** (Val1, Han, C-R **और** dB-S **को छोड़कर) ने सहमति सूचकांक** (D) **के मान में** 0.58% (MP-T) **और** 64.43% (M-B) **के बीच महत्वपूर्ण वृद्धि हुई।** Val1, Han, C-R **और** dB-S **समीकरणों के कैलिब्रेटेड संस्करणों के साथ,** D **का मान क्रमशः** 0.95%, 2.76%, 3.40% **और** 3.48% **तक कम हो गया और** RMSE **मान** 26.72% (Val1) 20.60% (Han), 42.22% (C-R), **और** 40.13% (dB-S) **के रूप में वृद्धि हुई। जबकि शेष** 16 **समीकरणों के अंशांकित संस्करणों ने** RMSE **मूल्यों में** 26.39% (MP-T) **और** 85.79% (B-G) **के बीच महत्वपूर्ण कमी पाई गई। अंशांकित समीकरणों के लिए** MAXE, MBE, PE **और** SEE **के मान में** 15.05% (Val1) **से** 593.77% (F24-R) **की सीमा में क्रमश:** 41.28% (X-S) **से** 429.47% (dB-S); 13.52% (Han) **से** 97.02% (B-G), **और** 5.25% (Val1) **से** 42.63% (M-B) **ह्रास हुआ, जबकि अंशांकन के बाद, इन सांख्यिकीय सूचकांकों का मान** 75.00% (Val1) **से** 373.33%(Tan) **की सीमा में बढ़ गया।;** 299.17(Val1); 59.27% (Han) **से** 299.17% (Val1), **और** 4.73% (S-S) **से** 82.83% (F24-Rad) **तक बढ़ गया ।**

अंशांकित B-G, MP-T, P-T, **और** Val2 **समीकरणों ने क्रमशः** 34.24%, 8.05%, 13.90% **और** 17.52% **के मूल गुणांक में गिरावट के साथ** R **का सबसे अच्छा मान** 0.99 **प्राप्त किया गया, जबकि** R **के अधिकतम मान के संदर्भ में सबसे खराब परिणाम अंशांकित बर्ट** (1.13) **और** X-S (0.60) **समीकरणों के साथ पाए गए।**

ABSTRACT. In this study conducted with specific objective to evaluate performance of original and calibrated versions of different radiation-based ET_0 equations in comparison to standard FAO56-PM model for humid Dehradun district of Uttarakhand (India), it was found that all calibrated ET_0 equations performed much better in comparison to their original versions.

The calibration coefficients were found to decrease in the range of 5.37% (Val 1) to 42.62% (M-B) while it was increased in between 4.83% (S-S) and 82.57% (F24-Rad). All equations (except Val1, Han, C-R and dB-S) after calibration showed significant increment in value of agreement index (D) in between 0.58% (MP-T) and 64.43% (M-B). With calibrated versions of Val1, Han, C-R and dB-S equations, value of D was decreased to the tune of 0.95%, 2.76%, 3.40% and 3.48%, respectively and yielded increased RMSE values as 26.72% (Val 1), 20.60% (Han), 42.22% (C-R), and 40.13% (dB-S), while calibrated versions of remaining 16 equations showed significant decrement in RMSE values in between 26.39% (MP-T) and 85.79% (B-G). The values of MAXE, MBE, PE and SEE for calibrated equations decreased in the range from 15.05% (Val1) to 593.77% (F24-R); 41.28% (X-S) to 429.47% (dB-S); 13.52% (Han) to 97.02% (B-G) and 5.25% (Val1) to 42.63% (M-B), respectively, whereas after calibration, values of these statistical indices increased in the range of 75.00% (Val 1) to 373.33% (Tan); 299.17% (Val 1); 59.27% (Han) to 299.17% (Val 1), and 4.73% (S-S) to 82.83% (F24-Rad).

The calibrated B-G, MP-T, P-T, and Val2 equations yielded best *R* values as 0.99 with decrement in their original coefficients of 34.24%, 8.05%, 13.90% and 17.52%, respectively, while worst results in terms of higher *R* value were found with calibrated Bert (1.13) and X-S (0.60) equations.

Key words – Radiation-based equations, Calibration, Reference evapotranspiration, Humid, Dehradun.

1. Introduction

Water security is very important as water is becoming a scarce commodity with growing human population, severe neglect, and over-exploitation. It is estimated that due to increasing population, national per capita annual availability of water in country has reduced from 1816 m^3 in 2001 to 1544 m^3 in 2011 (CWC, 2015) which will drop down to 1341 m^3 in 2025 and to 1140 m^3 in 2050 (Lal and Stewart, 2012). Similarly, depletion of groundwater and intensive irrigation in India has posed serious problems for groundwater managers in the form of saltwater intrusion, water tables depletion, drying of aquifers, groundwater pollution, water logging, salinity, etc. It is also reported that in many parts of the country, water table is declining at the rate of 1-2 m/year (Singh and Singh, 2002). Due to all these issues of extremely serious nature, it is expected that availability of fresh water for irrigation, domestic and industrial uses will reduce drastically and the country will face major water crisis in near future. Due to variation in crop canopy and climatic conditions, it is important to utilize available irrigation water resources in such a way that it will match substantial water need of crops required at different growth stages (Doorenbos and Pruitt, 1977).

Evapotranspiration (ET), also called as consumptive use, is the sum of amount of water returned to the atmosphere through combined process of evaporation and transpiration (Hansen *et al*., 1980; Watson and Burnett, 1995). It is one of the basic elements of hydrological cycle and is a very important, and essential parameter for scientific studies related to crop water requirement, water budget, irrigation scheduling, optimal crop production, environmental assessment, management of irrigated areas, development of best management practices for minimizing degradation of groundwater & surface water, and watershed (Irmak *et al*., 2003; Temesgen *et al*., 2005; Aytek, 2009; Chattopadhyay *et al*., 2009; Sabziparvar and Tabari, 2010; Sabziparvar *et al*., 2011).

The calculated values of ET help in determining reference evapotranspiration (ET_0), which is the rate of loss of available soil water from specific crop and can be estimated either with lysimeters or meteorological data (Lopez-Urrea *et al*., 2006, Xing *et al*., 2008) as it considers only evaporative power of atmosphere at a specific location and the time of the year without paying much emphasis upon crop characteristics and soil factors. The ET_0 values can directly be measured by lysimeter if change in soil moisture from known volume of soil is considered with vegetation (Watson and Burnett, 1995), but this method has certain limitations such as its use is very expensive, takes more time to install, and requires more maintenance. Therefore, several methods were developed by researchers to indirectly estimate ET_0 from observed meteorological parameters using large number of empirical or semi-empirical equations causing confusion to select any method as "standard" or "index". Therefore, the Food and Agricultural Organization (FAO) of the United Nations proposed Penman-Monteith model in its Irrigation and Drainage Paper No. 56 (referred to as FAO56-PM model) as standard method for determining ET0 from complete meteorological dataset.

Across the globe, researchers have confirmed superior performance of FAO56-PM model in comparison to other ET_0 methods in different climatic conditions (Allen *et al*., 1998; Walter *et al*., 2000; Fontenot, 2004; Garcia *et al*., 2004; Gavin and Agnew, 2004; Donatelli *et al*., 2006; Popova *et al*., 2006; Cai *et al*., 2007; Ali and Shui, 2009; Xu *et al*., 2013). However, serious limitation of FAO56-PM model is data requirement for a large number of climatic parameters which are not always available for most of the locations, especially in developing countries (Wang *et al*., 2007; Aytek, 2009).

A number of researchers necessitated to opt local calibration of existing empirical methods before employing them to calculate ET_0 values due to their widely non-consistent performances as some of these methods optimally work only under specific climatic conditions as they were being developed for specific climatic conditions. So, for using them at other climatic conditions, their calibration is essentially required. Various scientists and researchers revealed a widely varying performance of available ET_0 equations under diverse climatic conditions mentioning that these equations require local calibration (Allen *et al*., 1998; Pereira *et al*., 2006; Wang *et al*., 2009). The standard FAO56-PM model can be used to calibrate and validate empirical methods for new regions as per the recommendation of FAO Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements (Smith *et al*., 1991) and therefore, calibration of existing ET_0 equations against a more reliable reference in the form of FAO56-PM model may

TABLE 1

Details of radiation-based ET_0 methods considered in the study

Method (s)	Mathematical form
Abt	$ET_0 = 0.408 \times 0.01786 \times R_s \times T_{max}$
B-G	$ET_0 = 0.408 \times 1.65\left(\frac{\Delta}{\Delta+\gamma}\right) \times (R_n - G)$
Bert	$ET_0 = 0.408 \times 0.0193 \times R_a \times (T_{mean} + 17.8) \times (T_{max} - T_{min})^{0.517}$
Cap	$ET_0 = 6.1 \times 10^{-6} \times R_s \times (1.8 \times T_{mean} + 1.0)$
C-R	$ET_0 = 0.408 \times 0.70\left(\frac{\Delta}{\Delta+\gamma}\right) R_s - 0.12$
dB-S	$ET_0 = 0.408 \times 0.65\left(\frac{\Delta}{\Delta+\gamma}\right) R_s$
F24-Rad	$ET_0 = 0.408 \times a\left(\frac{\Delta}{\Delta+\gamma}\right) R_s - 0.30$
Han	$ET_0 = 0.408 \times 0.70\left(\frac{\Delta}{\Delta+\gamma}\right) R_s$
Ir-R_n	$ET_0 = 0.289 \times R_n + 0.023 \times T_{mean} + 0.489$
Ir-R_s	$ET_0 = 0.149 \times R_s + 0.079 \times T_{mean} - 0.611$
J-H	$ET_0 = 0.0102 \times R_s \times T_{mean} + 3.2$
M-B	$ET_0 = \left\{[0.0082 \times T_{mean} - 0.19]\left(\frac{R_s}{1500}\right)\right\} \times 2.54$
MP-T	$ET_0 = 0.408 \times 1.18\left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G)$
P-T	$ET_0 = 0.408 \times 1.26\left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G)$
S-S	$ET_0 = 0.408 \times (0.0148\ T_{mean} + 0.07) \times R_s$
Tan	$ET_0 = 0.408 \times 10^{-4} \times (0.002Z + 7) \times R_a \times (T_{mean} + 36.6) \times (T_{max} - T_{min})^{0.5}$
Traj	$ET_0 = 0.408 \times 0.0023 \times R_a \times (T_{mean} + 17.8) \times (T_{max} - T_{min})^{0.424}$
Val 1	$ET_0 = 0.0393\left\{R_s \times \sqrt{T_{mean} + 9.5} - 4.83461 \times R_s^{0.6} \times \varphi^{0.15} + 1.22137 \times (T_{mean} + 20) \times \left[1 - \left(\frac{RH}{100}\right)\right] \times U_2^{0.7}\right\}$
Val 2	$ET_0 = 0.051\left[(1-\alpha) \times R_s \times \sqrt{T_{mean} + 9.5} - 2.4 \times \left(\frac{R_s}{R_a}\right)^2 \times \varphi^{0.15}\right] + (T_{mean} + 20) \times \left[1 - \left(\frac{RH}{100}\right)\right] \times (0.5 + 0.536U_2) + 0.00012Z$
X-S	$ET_0 = 0.408 \times 0.98\left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G) - 0.94$

ET_0 : reference crop evapotranspiration (mm day^{-1}), G : soil heat flux density (MJ m^{-2} day^{-1}), RH : mean relative humidity (%), R_n : net radiation (MJ m^{-2} day^{-1}), R_s : solar radiation (MJ m^{-2} day^{-1}), T_{mean} : mean 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 s^{-1}), Z : height above mean sea level (m), Δ : slope of saturation vapour pressure–temperature curve (kPa °C^{-1}), γ : psychrometric constant (kPa °C^{-1}), φ : latitude (radian), Abt : Abtew, B-G : Berengena-Gavilan, Bert : Berti, Cap : Caprio, C-R : Castaneda-Rao, dB-S : de Bruin-Stricker, F24-Rad : FAO24-radiation, Han : Hansen, Ir-R_n : Irmak-R_n, Ir-R_s : Irmak-R_s, J-H : Jensen-Haise, M-B : McGuinness-Bordne, MP-T : Modified Priestley-Taylor, P-T : Priestley-Taylor, S-S : Stephens-Stewart, Tan : Tang, Traj : Trajkovic, Val 1 : Valiantzas 1, Val 2 : Valiantzas 2, X-S : Xu-Singh

TABLE 2

Computational forms of considered statistical indices

Statistical index	Notation	Computational form
Agreement index	D	$1-\dfrac{\sum_{i=1}^{n}\left(O_i-P_i\right)^2}{\sum_{i=1}^{n}\left(\left\|P_i-\overline{O}\right\|+\left\|O_i-\overline{O}\right\|\right)^2}$
Root mean square error	RMSE	$\sqrt{\dfrac{\sum_{i=1}^{n}\left(P_i-O_i\right)^2}{n}}$
Maximum absolute error	MAXE	$\mathrm{MAX}\left[\left\|O_i-P_i\right\|\right]_{i=1}^{n}$
Mean bias error	MBE	$\dfrac{1}{\mathrm{n}}\sum_{i=1}^{n}\left(P_i-O_i\right)$
Percentage error of estimate	PE	$\left\|\dfrac{\overline{P}-\overline{O}}{\overline{O}}\right\|\times 100\%$
Standard error of estimate	SEE	$\sqrt{\left[\dfrac{1}{n(n-2)}\right]\left\{n\sum P_i^2-\left(\sum P_i\right)^2-\dfrac{\left[n\sum O_iP_i\right]-\left[\sum O_i\right]\left[\sum P_i\right]}{n\sum O_i^2-\left(\sum O_i\right)^2}\right\}^2}$

$\overline{O}$: mean of FAO-56 PM ET_0 (mm day^{-1}), O_i : FAO-56 PM ET_0 (mm day^{-1}), $\overline{P}$: mean of FAO-56 PM ET_0 (mm day^{-1}), P_i: predicted value of ET_0 (mm day^{-1}) estimated by using other methods, n : total number of observations

provide a useful powerful tool for estimating ET_0 values for agricultural and environmental related studies (Fontenot, 2004).

A number of available ET_0 equations were calibrated by various researchers (Xu and Singh, 2000; Xu and Singh, 2002; Irmak *et al*., 2003; Berengena and Gavilan, 2005; Trajkovic, 2005; Fooladmand and Haghighat, 2007; Trajkovic, 2007; Ahmadi and Fooladmand, 2008; Landeras *et al*., 2008; Lee, 2010; Sepaskhah and Razzaghi, 2009; Zhai *et al*., 2009; Tabari and Talaee, 2011; Ravazzani *et al*., 2012; Thepadia and Martinez, 2012; Criestia *et al*., 2013; Lima *et al*., 2013; Mendicino and Senatore, 2013; Tabari *et al*., 2013; Xu *et al*., 2013; Heydari and Heydari, 2014; Heydari *et al*., 2014; Kra, 2014; Valipour, 2015; Almorox and Grieser, 2016; Ahooghalandari *et al*., 2017; Cadro *et al*., 2017; Cobaner *et al*., 2016; Feng *et al*., 2017; Issaka *et al*., 2017; Valipour, 2017) throughout the world for different climatic conditions considering FAO56-PM model as an index.

From the above, it is evident that various studies were conducted to calibrate ET_0 equations, however, very little information is available for Indian conditions and especially, no such study has been conducted for Indian humid locations. Therefore, in the present study, an attempt has been made to evaluate performance of original and calibrated versions of some radiation-based ET_0 equations namely, Abtew (1996), Berengena-Gavilan (2005), Berti *et al*. (2014), Caprio (1974), Castaneda and Rao (2005), de Bruin and Stricker (2000), FAO24-Radiation (Doorenbos, 1977), Hansen (1984), Irmak *et al*. (2003), Jensen and Haise (1963), McGuinness-Bordne (1972), Modified Priestley-Taylor (1996), Priestley-Taylor (1972), Tang *et al*. (2019), Trajkovic (2007), Valiantzas (2013), and Xu and Singh (2000)considering standard FAO56-PM model as an index.

2. Data and methodology

The study on evaluation and calibration of different radiation-based ET_0 equations was carried out for the

TABLE 3

Original and calibrated coefficients of different ET_0 methods

S. No.	Method (s)	Coefficient	
		Original	Calibrated
1.	Abt	0.01786	0.01404 (-21.39%)
2.	B-G	1.65	1.08490 (-34.25%)
3.	Bert	0.00193	0.00145 (-24.87%)
4.	Cap	6.1	4.23329 (-30.60%)
5.	C-R	0.7	0.59543 (-14.94%)
6.	dB-S	0.65	0.57339 (-11.79%)
7.	F24-Rad	0.408	0.74488 (+ 82.57%)
8.	Han	0.7	0.57334 (-18.09%)
9.	Ir-R_n	0.489	0.37812 (-22.67%)
10.	Ir-R_s	0.149	0.12627 (-15.26%)
11.	J-H	0.0102	0.00674 (-33.92%)
12.	M-B	0.01471	0.00844 (-42.62%)
13.	MP-T	1.18	1.08502 (-8.05%)
14.	P-T	1.26	1.08483 (-13.90%)
15.	S-S	0.07	0.07338 (+ 4.83%)
16.	Tan	0.0001	0.00014 (+ 40.00%)
17.	Traj	0.0023	0.00184 (-20.00%)
18.	Val 1	0.0393	0.03719 (-5.37%)
19.	Val 2	0.051	0.04267 (-16.33%)
20.	X-S	0.98	1.31372 (+ 34.05%)

Abt : Abtew, B-G : Berengena-Gavilan, Bert : Berti, Cap : Caprio, C-R : Castaneda-Rao, dB-S : de Bruin-Stricker, F24-Rad : FAO24-radiation, Han : Hansen, Ir-R_n : Irmak-R_n, Ir-R_s : Irmak-R_s, J-H : Jensen-Haise, M-B : McGuinness-Bordne, MP-T : Modified Priestley-Taylor, P-T : Priestley-Taylor, S-S : Stephens-Stewart, Tan : Tang, Traj : Trajkovic, Val 1 : Valiantzas 1, Val 2 : Valiantzas 2, X-S : Xu-Singh

Figures in parenthesis show percent deviation in comparison to original coefficient, (+) represents increment, and (-) shows decrement w.r.t. original coefficient.

humid Dehradun district (78°04' E longitude, 32°19' N latitude and 516.5 m above mean sea level) of Uttarakhand state using 31 years (1989-2019) of daily meteorological dataset consisting of air temperature (maximum and minimum), relative humidity (maximum and minimum), wind speed and actual sunshine hours. Prior to analysis, quality control of meteorological dataset was ensured by removing days with missing data and detecting outliers. For calibration purpose, 65% meteorological dataset (20 years, 1989-2008) was utilized while remaining 35% dataset of 11 years (2009-2019) was considered for validation purpose.

2.1. *Reference evapotranspiration estimation*

2.1.1. *FAO56-PM model*

This model is considered as standard to estimate daily ET_0 as recommended by the American Society of Civil Engineers Task Committee on standardization, the International Irrigation and Drainage Committee, and the Food and Agriculture Organization (FAO) of the United Nations for different climatic conditions as it provided values in close proximity with actual evapotranspiration measured in a wide range of locations and climatic conditions. According to Allen *et al*. (1998), recommended form of FAO56-PM model consisting of aerodynamic and surface resistance terms is:

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T_{\mathrm{mean}} + 273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

where ET_0 is reference evapotranspiration (mm day^{-1}), Δ is slope of saturated vapour pressure curve (kPa °C^{-1}), R_n is net radiation at crop surface (MJm^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), γ is psychrometric constant (kPa °C $^{-1}$), T_{mean} is mean daily air temperature (°C), U_2 is wind speed at 2 m height (msec^{-1}), e_s is saturated vapour pressure (kPa), e_a is actual vapour pressure (kPa), and e_s-e_a is vapour pressure deficit (kPa).

The nature of climate system allows soil heat flux (G) on daily timescale to be ignored as on daily basis, its value is nearly zero (Allen *et al*., 1998).

2.1.2. *Radiation-based ET_0 methods*

The energy required for phase change of water is provided by solar radiation but it limits evapotranspiration process where water is readily available. The pertinent details of different radiation-based ET_0 methods considered in this study are presented in Table 1.

2.2. *Calibration coefficient determination*

In order to get calibration coefficient of all ET_0 methods considering FAO56-PM model as an index, following steps were taken:

(*i*) calculating ratio of ET_0 method to $\mathrm{ET}_{0\ \mathrm{FAO56\text{-}PM}}$ (R).

$$R = \frac{\mathrm{ET}_{0\,\mathrm{method}}}{\mathrm{ET}_{0\,\mathrm{FAO56-PM}}}$$

(*ii*) multiplying inverse of this ratio (1/R) with original coefficient to get calibrated coefficient.

(*iii*) calibrated ET_0 values were determined as:

$$\text{Calibrated}\ \mathrm{ET}_0 = \frac{\text{Calibrated coefficient} \times \text{Original value}\ \mathrm{ET}_{0\,\mathrm{method}}}{\text{Original coefficient}}$$

2.3. *Statistical analysis*

Various statistical indices could be used to compare ET0 values calculated by different methods and those obtained by FAO56-PM model and to evaluate obtained results. Details of various statistical indices used in this study are presented in Table 2 and Microsoft TM Excel® was used as computing tool to analyse obtained results in order to draw fruitful interferences from them.

3. Results and discussion

3.1. *Calibration coefficient*

The values of original coefficient, calibration coefficient and percent deviation of calibration coefficient from original coefficient for different radiation-based ET_0 methods (Table 3) shows that calibration coefficients were found to decrease in the range of 5.37% (Val 1) to 42.62% (M-B) while increment in their values was obtained in between 4.83% (S-S) and 82.57% (F24-Rad).

For Abt equation, calibration coefficient was obtained as 0.01404 which was lower to the tune of 21.39% in comparison to its original coefficient (0.01786), whereas for B-G equation, in comparison to its original coefficient (1.65), about 34.25% lower calibration coefficient as 1.08490 was obtained. The calibration coefficient of Bert equation was found decreased to the tune of about 24.87% in comparison to its original coefficient of 0.00193.

Likewise, calibration coefficient for Cap equation was found 30.60% lesser (4.23329) in comparison to its original coefficient of 6.1. At humid Dehradun district, calibration coefficient of C-R equation was found 14.94% lesser in comparison to its original coefficient (0.70) with value of calibration coefficient as 0.59543. For dB-S equation, in comparison to its original coefficient (0.65), obtained calibration coefficient (0.57339) was about 11.79% lower, whereas for F24-Rad equation, the calibration coefficient was found increased to the tune of about 82.57% in comparison to its original coefficient of 0.408.

The calibration coefficient of Han equation obtained as 0.57334 was found lower to the tune of about 18.09% in comparison to its original equation coefficient (0.70). The calibration coefficients for Ir-R_n and Ir-R_n equations as 0.37812 and 0.12627 were found lower to the tune of 22.67% and 15.26% in comparison to their respective original coefficients of 0.489 and 0.149.

For J-H equation, calibration coefficient as 0.00674 showed decrement of about 33.92% to its original coefficient (0.0102). In case of M-B, MP-T and P-T equations, in comparison to their respective original coefficients of 0.01471, 1.18 and 1.26, their lower values as 0.00844, 1.08502 and 1.08483 to the tune of 42.62%,

TABLE 4

Comparative performance of original and calibrated ET_0 methods *vs* FAO56-PM model during validation period (2009-2019)

S. No.	Method (s)	Features	Statistical indices						R
			D	RMSE	MAXE	MBE	PE	SEE	
1.	Abt	Original	0.9389	0.6574	1.3800	0.5630	20.4772	0.3120	1.2404
		Calibrated	0.9803	0.3235	0.4200	-0.1453	5.2853	0.2452	0.9751
		% variation	4.41	-50.79	-69.57	-125.81	-74.19	-21.42	-21.39
2.	B-G	Original	0.7933	1.4986	2.4900	1.3698	49.8256	0.3068	1.4981
		Calibrated	0.9916	0.2174	0.2700	-0.0408	1.4838	0.2017	0.9851
		% variation	25.00	-85.49	-89.16	-102.98	-97.02	-34.24	-34.24
3.	Bert	Original	0.8226	1.2672	2.4200	1.1877	43.2036	0.3404	1.5040
		Calibrated	0.9790	0.3432	0.7200	0.2089	7.5970	0.2555	1.1301
		% variation	19.01	-72.92	-70.25	-82.42	-82.42	-24.93	-24.86
4.	Cap	Original	0.8537	1.2013	2.4900	1.0695	38.9032	0.2403	1.3813
		Calibrated	0.9934	0.1961	0.3200	-0.0992	3.6077	0.1668	0.9585
		% variation	16.36	-83.67	-87.15	-109.27	-90.73	-30.60	-30.61
5.	C-R	Original	0.9741	0.3557	0.9600	0.1754	6.3805	0.1876	1.1366
		Calibrated	0.9409	0.5059	0.6300	-0.2794	10.1621	0.1620	0.9584
		% variation	-3.40	42.22	-34.38	-259.27	59.27	-13.65	-15.68
6.	dB-S	Original	0.9702	0.3682	0.9200	0.0775	2.8195	0.1733	1.1072
		Calibrated	0.9364	0.5160	0.6800	-0.2554	9.2895	0.1564	0.9768
		% variation	-3.48	40.13	-26.09	-429.47	229.47	-9.78	-11.78
7.	F24-Rad	Original	0.6234	1.5351	-0.1392	-1.3616	49.5285	0.1961	0.5303
		Calibrated	0.9549	0.4809	0.6872	-0.2159	7.8549	0.3585	0.9682
		% variation	53.17	-68.67	-593.77	-84.14	-84.14	82.83	82.58
8.	Han	Original	0.9630	0.4279	1.0793	0.2954	10.7459	0.1866	1.1927
		Calibrated	0.9364	0.5161	0.6778	-0.2555	9.2928	0.1560	0.9769
		% variation	-2.76	20.60	-37.21	-186.48	-13.52	-16.37	-18.09
9.	Ir-R_n	Original	0.9055	0.7161	0.9000	0.6563	23.8712	0.1761	1.3431
		Calibrated	0.9414	0.4833	0.4400	-0.1161	4.2248	0.1420	1.0385
		% variation	3.97	-32.51	-51.11	-117.70	-82.30	-19.35	-22.68
10.	Ir-R_s	Original	0.9183	0.6489	1.1300	0.5686	20.6820	0.1680	1.3133
		Calibrated	0.9541	0.4364	0.7900	0.0625	2.2749	0.1480	1.1129
		% variation	3.90	-32.76	-30.09	-89.00	-89.00	-11.92	-15.26
11.	J-H	Original	0.8340	1.2924	2.5300	1.1857	42.9705	0.2269	1.4406
		Calibrated	0.9895	0.2403	0.2800	-0.1527	5.5323	0.1497	0.9519
		% variation	18.66	-81.40	-88.93	-112.87	-87.13	-34.02	-33.92
12.		Original	0.5705	2.8577	5.2300	2.5076	91.2124	0.9990	1.9176
	M-B	Calibrated	0.9381	0.6312	1.8400	0.2670	9.7139	0.5731	1.1004
		% variation	64.43	-77.91	-64.82	-89.35	-89.35	-42.63	-42.62

TABLE 4 (*Contd.*)

S. No.	Method (s)	Features	Statistical indices						R
			D	RMSE	MAXE	MBE	PE	SEE	
13.	MP-T	Original	0.9858	0.2954	0.6000	0.1966	7.1497	0.2192	1.0714
		Calibrated	0.9916	0.2174	0.2800	-0.0406	1.4769	0.2018	0.9851
		% variation	0.58	-26.39	-53.33	-120.66	-79.34	-7.91	-8.05
14.	P-T	Original	0.9666	0.4738	0.8800	0.3962	14.4128	0.2343	1.1440
		Calibrated	0.9916	0.2175	0.2700	-0.0410	1.4918	0.2017	0.9850
		% variation	2.59	-54.10	-69.32	-110.35	-89.65	-13.90	-13.90
15.	S-S	Original	0.9750	0.3596	0.1600	-0.2776	10.0965	0.1338	0.9116
		Calibrated	0.9882	0.2510	0.2800	-0.1582	5.7554	0.1402	0.9556
		% variation	1.36	-30.20	75.00	-43.00	-43.00	4.73	4.83
16.	Tan	Original	0.8131	0.9153	0.1500	-0.7275	26.4622	0.1759	0.7902
		Calibrated	0.9731	0.3618	0.7100	0.0812	2.9527	0.2461	1.1064
		% variation	19.67	-60.47	373.33	-111.16	-88.84	39.93	40.02
7	Traj	Original	0.8816	0.9534	1.7689	0.9067	32.9825	0.2474	1.3944
		Calibrated	0.9845	0.2904	0.6597	0.1756	6.3860	0.1980	1.1155
		% variation	11.68	-69.54	-62.71	-80.64	-80.64	-20.00	-20.00
18.	Val 1	Original	0.9860	0.2764	0.6321	-0.0485	1.7630	0.2454	1.0139
		Calibrated	0.9766	0.3502	0.5370	-0.1935	7.0373	0.2325	0.9595
		% variation	-0.95	26.72	-15.05	299.17	299.17	-5.25	-5.37
19.	Val 2	Original	0.9677	0.4491	0.7786	0.4226	15.3715	0.1497	1.1983
		Calibrated	0.9899	0.2300	0.2237	-0.1145	4.1651	0.1299	0.9883
		% variation	2.29	-48.78	-71.28	-127.10	-72.90	-13.22	-17.52
20.	X-S	Original	0.7722	1.2691	-1.0000	-1.2427	45.2042	0.1753	0.4509
		Calibrated	0.9163	0.7879	-0.1835	-0.7298	26.5446	0.2443	0.6044
		% variation	18.65	-37.92	-81.65	-41.28	-41.28	39.38	34.04

D : Agreement index, RMSE: Root mean square error (mm day^{-1}), MAXE : Maximum absolute error (mm day^{-1}), MBE : Mean bias error (mm day^{-1}), PE : Percentage error of estimate (%), SEE : Standard error of estimate, R : Ratio of $ET_{0method}/ET_{0FAO56\text{-}PM}$, Abt : Abtew, B-G : Berengena-Gavilan, Bert : Berti, Cap : Caprio, C-R : Castaneda-Rao, dB-S : de Bruin-Stricker, F24-Rad : FAO24-radiation, Han : Hansen, Ir-R_n : Irmak-R_n, Ir-R_s : Irmak-R_s, J-H : Jensen-Haise, M-B : McGuinness-Bordne, MP-T : Modified Priestley-Taylor, P-T : Priestley-Taylor, S-S : Stephens-Stewart, Tan : Tang, Traj : Trajkovic, Val 1 : Valiantzas 1, Val 2 : Valiantzas 2, X-S : Xu-Singh (-) sign shows decrement w.r.t. original values

8.05% and 13.90%, respectively were obtained. The calibration coefficient for Rav equation showed 29.57% downward fluctuation with calibration coefficient as 0.00162 in comparison to its original coefficient (0.0023).

The S-S and Tan equations showed higher calibration coefficients as 0.07338 and 0.00014, respectively, which is about 4.83% and 40.00% higher in comparison to their respective original values of 0.07 and 0.0001. The calibration coefficient of Traj equation (0.00184) was found 20.00% lower in comparison to its original coefficient (0.0023).

The Val 1 and Val 2 equations in general, showed 5.37% and 16.33% lower calibration coefficients in comparison to their respective original coefficients of 0.0393 and 0.051. The calibration coefficient for X-S equation was found 34.05% higher (1.31372) than its original coefficient of 0.98.

3.2. *Evaluation of original and calibrated ET0 equations vs FAO56-PM model*

The value of statistical indices and ratio of ET_0 method to ET_0 FAO56-PM (R) obtained for different original and calibrated (or adjusted) ET_0 equations (Table 4) reveal that in maximum cases, calibrated ET_0 equations resulted in significant increment in value of D and decrement in errors (RMSE, MAXE, MBE, PE, and SEE) while value of R near to 1.00 indicated closer estimates of calibrated ET_0 equations with standard FAO56-PM model. The calibration of radiation-based ET_0 equations revealed significant improvement in their performance as except Val1, Han, C-R and dB-S methods, increment in D value was observed with all methods in the range from 0.58% (MP-T) to 64.43% (M-B). With Val1, Han, C-R and dB-S methods, the value of D was found to decrease to the tune of 0.95%, 2.76%, 3.40% and 3.48%, respectively. Similarly, with calibrated equations, RMSE was decreased in the range of 26.39% (MP-T) and 85.79% (B-G), while calibrated versions of Han, Val 1, dB-S and C-R equations yielded increased RMSE value to the tune of 20.60%, 26.72%, 40.13%, and 42.22%, respectively.

After calibration, values of MAXE, MBE, PE and SEE were found decreased in the range from 15.05% (Val 1) to 593.77% (F24-Rad); 41.28% (X-S) to 429.47% (dB-S); 13.52% (Han) to 97.02% (B-G), and 5.25% (Val1) to 42.63% (M-B), respectively, whereas values of MAXE, MBE, PE and MSE with calibrated ET_0 equations were increased in the range of 75.00% (Val 1) to 373.33% (Tan); 299.17% (Val 1); 59.27% (Han) to 299.17% (Val 1), and 4.73% (S-S) to 82.83% (F24-Rad). In 16 calibrated methods, value of ratio (R) gets lowered in the range from 5.37% (X-S) to 42.62% (M-B) while increment in its value was observed in only four methods, *viz.*, S-S (4.83%), 34.05% (X-S), 40.00% (Tan) and 82.58% (F24-Rad).

The calibrated versions of B-G, MP-T, P-T, and Val 2 equations yielded best results in terms of ratio (R) as 0.99 in comparison to those obtained with their original versions as 1.50, 1.07, 1.14 and 1.20 with decrement of 34.24%, 8.05%, 13.90% and 17.52%, respectively, whereas worst results were found with calibrated Bert and X-S methods with value of ratio (R) as 1.13 and 0.60, respectively in comparison to their original ratio of 1.50 and 0.45, respectively.

4. Conclusions

The performance of original and calibrated versions of 20 radiation-based ET_0 equations for humid Dehradun district of Uttarakhand evaluated in comparison to standard FAO-56 PM model in terms of statistical indices (D, RMSE, MAXE, MBE, PE, and SEE) and ratio of $ET_{0method}/ET_{0FAO56\text{-}PM}$ (R) revealed that:

(*i*) The decrement and increment in calibration coefficients were observed in the range of 5.37% (Val 1) to 42.62% (M-B) and 4.83% (S-S) and 82.57% (F24-Rad), respectively.

(*ii*) Except calibrated versions of Val1, Han, C-R and dB-S methods, all other methods resulted in significant increment in value of D in between 0.58% (MP-T) and 64.43% (M-B). The value of D with calibrated versions of Val1, Han, C-R and dB-S methods decreased to the tune of 0.95%, 2.76%, 3.40% and 3.48%, respectively.

(*iii*) Calibrated versions of Han, Val1, dB-S and C-R equations yielded increased RMSE value to the tune of 20.60%, 26.72%, 40.13%, and 42.22%, respectively while calibrated versions of remaining 16 methods showed significant decrement in RMSE values in between 26.39% (MP-T) and 85.79% (B-G).

(*iv*) The values of MAXE, MBE, PE and SEE for calibrated methods decreased in the range from 15.05% (Val1) to 593.77% (F24-R); 41.28% (X-S) to 429.47% (dB-S); 13.52% (Han) to 97.02% (B-G), and 5.25% (Val1) to 42.63% (M-B), respectively, whereas after calibration, values of these statistical indices increased in the range of 75.00% (Val 1) to 373.33% (Tan), 299.17% (Val 1), 59.27% (Han) to 299.17% (Val 1) and 4.73% (S-S) to 82.83% (F24-Rad), respectively.

(*v*) In 16 calibrated methods, value of R gets lowered from 5.37% (X-S) to 42.62% (M-B) while in only four methods increment in its value was observed as 4.83% (S-S), 34.05% (X-S), 40.00% (Tan), and 82.58% (F24-Rad).

(*vi*) Calibrated B-G, MP-T, P-T, and Val 2 equations yielded best R values as 0.99 with decrement of 34.24%, 8.05%, 13.90% and 17.52%, respectively and worst results were found with calibrated Bert and X-S methods with value of R as 1.13 and 0.60 respectively.

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