Performance evaluation of calibrated radiation-based ET₀ equations against standard FAO56-PM model in humid climatic condition

ARVIND SINGH TOMAR
Department of Irrigation & Drainage Engineering, College of Technology, G. B. Pant University of Agriculture & Technology, Pantnagar – 263 145, India
(Received 11 May 2021, Accepted 14 March, 2022)
e mail : arvindstomar@gmail.com

ABSTRACT. In this study conducted with specific objective to evaluate performance of original and calibrated versions of different radiation-based ET₀ equations in comparison to standard FAO56-PM model for humid Dehradun district of Uttarakhand (India), it was found that all calibrated ET₀ equations performed much better in comparison to their original versions.

The calibration coefficients were found to decrease in the range of 5.37% (Val1) 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% (Val1); 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 17.52% (Val1) 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 after calibration, values of these statistical indices increased in the range of 75.00% (Val1) 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).
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
| Method(s)       | Mathematical form                                                                 |
|----------------|-----------------------------------------------------------------------------------|
| Abt            | \( ET_0 = 0.408 \times 0.01786 \times R_s \times T_{\text{mean}} \)               |
| B-G            | \( ET_0 = 0.408 \times 1.65 \left( \frac{\Delta}{\Delta + \gamma} \right) \times (R_n - G) \) |
| Bert           | \( ET_0 = 0.408 \times 0.0193 \times R_s \times (T_{\text{mean}} + 17.8) \times (T_{\text{max}} - T_{\text{min}})^{0.517} \) |
| Cap            | \( ET_0 = 6.1 \times 10^4 \times R_s \times (1.8 \times T_{\text{mean}} + 1) \)      |
| 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-Ra          | \( ET_0 = 0.289 \times R_s + 0.023 \times T_{\text{mean}} + 0.489 \)               |
| Ir-Rs          | \( ET_0 = 0.149 \times R_s + 0.079 \times T_{\text{mean}} - 0.611 \)               |
| J-H            | \( ET_0 = 0.0102 \times R_s \times T_{\text{mean}} + 3.2 \)                       |
| M-B            | \( ET_0 = \left( 0.0082 \times T_{\text{mean}} - 0.19 \right) \left( \frac{R_s}{1500} \right) \times 2.54 \) |
| 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            | \( ET_0 = 0.408 \times \left( 0.0148 \times T_{\text{mean}} + 0.07 \right) \times R_s \)  |
| Tan            | \( ET_0 = 0.408 \times 10^{-4} \times (0.002Z + 7) \times R_s \times (T_{\text{mean}} + 36.6) \times (T_{\text{max}} - T_{\text{min}})^{0.5} \) |
| Traj           | \( ET_0 = 0.408 \times 0.0023 \times R_s \times (T_{\text{mean}} + 17.8) \times (T_{\text{max}} - T_{\text{min}})^{0.424} \) |
| Val 1          | \( ET_0 = 0.0393 \left( R_s \times \sqrt{T_{\text{mean}} + 9.5 - 4.83461 \times R_s^{0.6} \times \phi^{0.15} + 1.22137 \times (T_{\text{mean}} + 20) \times \left[ 1 - \left( \frac{R_H}{100} \right) \right] \times \phi^{0.7} \right) \) |
| Val 2          | \( ET_0 = 0.051 \left( (1 - \alpha) \times R_s \times \sqrt{T_{\text{mean}} + 9.5 - 2.4 \times \left( \frac{R_s}{R_g} \right)^2 \times \phi^{0.15} \right) + (T_{\text{mean}} + 20) \times \left[ 1 - \left( \frac{R_H}{100} \right) \right] \times (0.5 + 0.536U_2) + 0.00012Z \) |
| 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 (%), \( R_s \): net radiation (MJ m\(^{-2}\) day\(^{-1}\)), \( R_n \): solar radiation (MJ m\(^{-2}\) day\(^{-1}\)), \( T_{\text{mean}} \): mean daily air temperature (°C), \( T_{\text{max}} \): maximum air temperature (°C), \( T_{\text{min}} \): minimum air temperature (°C), \( U_2 \): mean daily wind speed at 2 m height (m s\(^{-1}\)), Z: height above mean sea level (m), \( \Delta \): slope of saturation vapour pressure-temperature curve (kPa °C\(^{-1}\)), \( \gamma \): psychrometric constant (kPa °C\(^{-1}\)), \( \phi \): 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-Ra: Irmak-Ra, Ir-Rs: Irmak-Rs, J-H: Jensen-Haise, M-B: McGuinness-Bordine, 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
provide a useful powerful tool for estimating ET₀ values for agricultural and environmental related studies (Fontenot, 2004).

A number of available ET₀ 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 Talaei, 2011; Ravazzeni 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 ET₀ 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 ET₀ 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 ET₀ equations was carried out for the
TABLE 3

Original and calibrated coefficients of different ET₀ methods

| S. No. | Method (s) | Original | Calibrated | Coefficient |
|--------|------------|----------|------------|-------------|
| 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-Rn      | 0.489    | 0.37812    | (-22.67%)   |
| 10.    | Ir-Rs      | 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-Rn : Irmak-Rn, Ir-Rs : Irmak-Rs, 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.

2.1. Reference evapotranspiration estimation

2.1.1. FAO56-PM model

This model is considered as standard to estimate daily ET₀ 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:

\[
ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T_{\text{mean}} + 273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}
\]

where \( ET_0 \) is reference evapotranspiration (mm day\(^{-1}\)), \( \Delta \) is slope of saturated vapour pressure curve (kPa °C\(^{-1}\)), \( R_n \) is net radiation at crop surface (MJ m\(^{-2}\) day\(^{-1}\)), \( G \) is soil heat flux density (MJ m\(^{-2}\) day\(^{-1}\)), \( T_{\text{mean}} \) is mean daily air temperature (°C), \( U_2 \) is wind speed at 2 m height (m/sec\(^{-1}\)), \( e_s \) 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 ET\(_0\) FAO56-PM (R).

\[
R = \frac{ET_0 \text{ method}}{ET_0 \text{ FAO56-PM}}
\]

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

(iii) calibrated ET\(_0\) values were determined as:

\[
\text{Calibrated } ET_0 = \frac{\text{Calibrated coefficient } \times \text{Original value } ET_0 \text{ method}}{\text{Original coefficient}}
\]

### 2.3. Statistical analysis

Various statistical indices could be used to compare ET\(_0\) 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\textsuperscript{®} 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 |
|--------|-----------|----------|---------------------|---|
| 1.     | Abt       | Original | 0.9389 0.6574 1.3800 0.5630 20.4772 0.3120 1.2404 | 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 -97.02 -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 0.9765 |
|        |           | % 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 -25.27 0.27 -9.73 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 -84.14 1.1872 1.1178 |
| 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 -84.14 0.1876 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 -84.14 18.09 |
| 9.     | Ir-R$_b$  | 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 22.68 |
| 10.    | Ir-R$_c$  | 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 -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 5.3233 0.1497 0.9519 |
|        |           | % variation | 18.66 -81.40 -112.87 -78.13 -33.92 |
| 12.    | M-B       | Original | 0.5705 2.8577 5.2300 2.5076 91.2124 0.9990 1.9176 |
|        |           | Calibrated | 0.9381 0.6312 1.8400 0.2670 9.7139 0.5731 1.1004 |
|        |           | % variation | 64.43 -77.91 -64.82 -89.35 42.63 -42.62 |
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 ET0 method to ET0 FAO56-PM (R) obtained for different

| 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 | 0.3692 | 14.1428 | 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 | -0.0410 | 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 | 0.9534 | 1.7689 | 0.9067 | 32.9825 | 0.2474 | 1.3944 |
|       |            | 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 | 0.9677 | 0.3502 | 0.5370 | -0.1935 | 7.0373 | 0.2325 | 0.9595 |
|       |            | Calibrated | 0.9766 | 0.3520 | 0.5370 | -0.1935 | 7.0373 | 0.2325 | 0.9595 |
|       |            | % variation | 0.95 | 26.72 | 75.00 | -43.00 | -43.00 | 5.25 | 5.37 |
| 19.   | Val 2      | 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 ET0method/ET0FAO56-PM.
original and calibrated (or adjusted) ET₀ equations (Table 4) reveal that in maximum cases, calibrated ET₀ 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 ET₀ equations with standard FAO56-PM model. The calibration of radiation-based ET₀ 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 SEE with calibrated ET₀ 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 ET₀ equations for humid Dehradun district of Uttarakhand evaluated in comparison to standard FAO56-PM model in terms of statistical indices (D, RMSE, MAXE, MBE, PE, and SEE) and ratio of ET₀method/ET₀FAO56-PM (R) revealed that:

(i) The decrement in 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-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 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.

Disclaimer: The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Abtew, W., 1996, “Evapotranspiration measurements and modelling for three wetland systems in South Florida”, J. Amer. Water Resour. Assoc., 32, 465-473. https://doi.org/10.1111/j.1752-1688.1996.tb04044.x.

Ahmadi, S. H. and Fooladmand, H. R., 2008, “Spatially distributed monthly reference evapotranspiration derived from the calibration of Thornthwaite equation: A case study, South of Iran”, Irrig. Sci., 26, 303-312. https://doi.org/10.1007/s00271-007-0094-8.

Ahooghalandari, M., Khidani, M. and Jahromi, M. E., 2017, “Calibration of Valiantzas’ reference evapotranspiration equations for the Pilbara region, Western Australia”, Theory
Landeras, G., Ortiz-Barredo, A. and Lopez, J. J., 2008, “Comparison of artificial neural network models and empirical and semi-empirical equations for daily reference evapotranspiration estimation in the Basque Country (Northern Spain)”, *Agril. Water Manage.*, 95, 553-565. https://doi.org/10.1016/j.agwat.2007.12.011.

Lee, K. H., 2010, “Relative comparison of the local recalibration of the temperature-based evapotranspiration equation for the Korea Peninsula”, *J. Irrig. Drain. Engg.*, 136, 585-594. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000221.

Lima, J, Antonio, A, Souza, E, Hammecker, C, Montenegro, S. and Lira, C, 2013, “Calibration of Hargreaves-Samani equation for estimating reference evapotranspiration in sub-humid region of Brazil”, *J. Water Resour. Protec.*, 5, 1-5. https://doi.org/10.4236/jwarp.2013.512A001.

Lopez-Urrea, R., Martin de Santa Olalla, F., Fabeiro, C. and Moratalla, A., 2008, “Comparison of some reference evapotranspiration equations for semiarid conditions”, *Agril. Water Manage.*, 86, 277-282. http://www.sciencedirect.com/science/article/pii/S0378-3774(07)00153-3.

McGuinness, J. L. and Bordine, E. F., 1972, “A comparison of lysimeter-derived potential evapotranspiration with computed values”, Tech. Bull. No. 1452, Agricultural Research Service, US Department of Agriculture, Washington, DC, USA.

Mendicino, G. and Senatore, A., 2013, “Regionalization of the Hargreaves coefficient for the assessment of distributed reference evapotranspiration in southern Italy”, *J. Irrig. Drain. Engg.*, 139, 349-362. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000547.

Pereira, A. R., Green, S. and Villa Nova, N. A., 2006, “Penman-Monteith reference evapotranspiration adapted to estimate irrigated tree transpiration”, *Agric. Water Manage.*, 83, 153-161. http://www.sciencedirect.com/science/article/pii/S0378-3774(05)00361-6.

Popova, Z., Kercheva, M. and Pereira, L. S., 2006, “Validation of the FAO methodology for computing ET0 with limited data: Application to south Bulgaria”, *Irrig. Drain.*, 55, 201-215. https://doi.org/10.1061/IRD.229.

Priestley, C. H. B. and Taylor, R. J., 1972, “On the assessment of surface heat flux and evaporation using large-scale parameters”, *Mon. Wea. Rev.*, 100, 81-92.

Ravazzani, G., Corbari, C., Morella, S., Gianoli, P. and Mancini, M., 2012, “Modified Hargreaves-Samani equation for the assessment of reference evapotranspiration in Alpine River Basins”, *J. Irrig. Drain. Engg.*, 138, 592-599. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000453.

Sabziparvar, A. A. and Tabari, H., 2010, “Regional estimation of reference evapotranspiration in arid and semi-arid regions”, *J. Irrig. and Drain. Engg.*, 136, 724-731. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000242.

Sabziparvar, A. A., Mirmasoudi, S. H., Tabari, H., Nazemosadat, M. J. and Maryanaji, Z., 2011, “ENSO teleconnection impacts on reference evapotranspiration variability in some warm climates of Iran”, *Inter. J. Climatol.*, 31, 1710-1723. https://doi.org/10.1002/joc.2187.

Sepaskhah, A. and Razzaghi, F., 2009, “Evaluation of the adjusted Thronthwaite and Hargreaves-Samani methods for estimation of daily evapotranspiration in a semi-arid region of Iran”, *Arch. Agro. Soil Sci.*, 55, 51-66. https://doi.org/10.1080/03650340802383148.

Singh, D. K. and Singh, A. K., 2002, “Groundwater situation in India: Problems and perspective”, *Inter. J. Water Resour. Manage.*, 18, 563-580. https://doi.org/10.1080/0790062022000017400.

Smith M., Allen, R. G., Monteith, J. L., Pereira, L. and Segeren, A. 1991, “Report of the expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements”, UN-FAO, Rome.

Tabari, H. and Taleaee, P. H., 2011, “Local calibration of the Hargreaves and Priestley-Taylor equations for estimating reference evapotranspiration in arid and cold climates of Iran based on the Penman-Monteith model”, *J. Hydrol. Engg.*, 16, 837-845. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000366.

Tabari, H., Taleaee, P. and Some, B., 2013, “Spatial modeling of reference evapotranspiration using adjusted Blaney-Criddle equation in an arid environment”, *J. Hydrol. Sci.*, 58, 408-419. https://doi.org/10.1080/02626667.2012.755265.

Tang, P., Xu, B., Gao, Z., Li, H., Gao, X. and Wang, C., 2019, “Estimating reference evapotranspiration based on an improved HS model”, *Hydrol. Res.*, 50, 187-199. https://doi.org/10.2166/NH.2018.022.

Temesgen, B., Eching, S., Davidoff, B. and Frame, K., 2005, “Comparison of some reference evapotranspiration equations for California”, *J. Irrig. Drain. Engg.*, 131, 73-84. https://doi.org/10.1061/(ASCE)0733-9437(2005)131:1(73).

Thepadia, M. and Martinez, C. J., 2012, “Regional calibration of solar radiation and reference evapotranspiration estimates with minimal data in Florida”, *J. Irrig. Drain. Engg.*, 138, 111-119. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000394.

Trajkovic, S., 2005, “Temperature-based approaches for estimating reference evapotranspiration”, *J. Irrig. Drain. Engg.*, 131, 316-323. https://doi.org/10.1061/(ASCE)0733-9437(2005)131:4(316).

Trajkovic, S., 2007, “Hargreaves versus Penman-Monteith under humid conditions”, *J. Irrig. Drain. Engg.*, 133, 38-42. https://doi.org/10.1061/(ASCE)0733-9437(2007)133:1(38).

Valiantzas, J. D., 2013, “Simplified forms for the standardized FAO-56 Penman-Monteith reference evapotranspiration using limited weather data”, *J. Hydrol.*, 505, 13-23. https://doi.org/10.1016/j.jhydrol.2013.09.005.

Valipour, M., 2015, “Investigation of Valiantzas’ evapotranspiration equation in Iran”, *Theor. Appl. Climatol.*, 121, 267-278. https://doi.org/10.1007/s00704-014-1240-x

Valipour, M., 2017, “Calibration of mass transfer-based models to predict reference crop evapotranspiration”, *Appl. Water Sci.*, 7, 625-635. https://doi.org/10.1007/s13201-015-0274-2.

Walter, I. A., Allen, R. G., Elliott, R., Jensen, M. E., Ibenfisu, D., Mecham, B., Howell, T. A., Snyder, R., Brown, P., Eching, S., Spofford, T., Hattendorf, M., Cuenca, R. H., Wright, J. L. and Martin, D., 2000, “ASCE’s Standardized Reference Evapotranspiration Equation”, *Adv. Water Res.*, 23(5), 563-580. https://doi.org/10.1080/02626667.2002.10865744.

Wang, Y. M., Namaona, W., Traore, S. and Zhang, Z. C., 2009, “Seasonal temperature-based models for reference evapotranspiration estimation under semi-arid condition of Malawi”, *African J. Agric. Res.*, 4, 878-886.

Wang, Y. M., Traore, S. and Kerh, T., 2007, “Determination of a reference model for estimating evapotranspiration in Burkina Faso”, *Adv. Water Res.*, 30(1), 155-163. https://doi.org/10.1016/j.ecol.2009.01.005.

Worboys, D., 1979, “An empirical model for estimating transpiration in the semi-arid region of Iran”, *Hydrol. Sci.*, 23(4), 717-726. https://doi.org/10.1080/02626667.1979.10467316.
Watson, I. and Burnett, A. D., 1995, “Hydrology: An Environmental Approach”, Boca Raton, CRC Press.

Xing, Z., Chow, L., Meng, F. R., Rees, H. W., Monteith, J. and Lionel, S, 2008, “Testing reference evapotranspiration estimation methods using evaporation pan and modeling in maritime region of Canada”, J. Irrig. Drain. Engg., 134, 417-424. https://doi.org/10.1061/(ASCE)0733-9437(2008)134:4(417).

Xu, C. Y. and Singh, V. P., 2000, “Evaluation and generalization of radiation-based methods for calculating evaporation”, Hydrol. Process., 14, 339-349. https://doi.org/10.1002/(SICI)1099-1085(20000215)14:2<339::AID-HYP928>3.0.CO;2-O.

Xu, C. Y. and Singh, V. P., 2002, “Cross comparison of empirical equations for calculating potential evapotranspiration with data from Switzerland”, Water Resour. Manage., 16, 197-219. https://doi.org/10.1023/A:1020282515975.

Xu, J., Peng, S., Ding, J., Wei, Q. and Yu, Y., 2013, “Evaluation and calibration of simple methods for daily reference evapotranspiration estimation in humid East China”, Arch. Agro. Soil Sci., 59, 845-858. https://doi.org/10.1080/03650340.2012.683425.

Zhai, L., Feng, Q., Li, Q. and Xu, C., 2009, “Comparison and modification of equations for calculating evapotranspiration (ET) with data from Gansu province, northwest China”, Irrig. Drain. https://doi.org/10.1002/ird.502.