Effect of local calibration on the performance of the Hargreaves reference crop evapotranspiration equation

S. Niranjan and Lakshman Nandagiri

ABSTRACT

Obtaining accurate estimates of reference crop evapotranspiration (ET_0) using limited climatic inputs is essential in data-short situations where the preferred FAO-56 Penman–Monteith (PM) equation cannot be implemented. Among several available for ET_0 estimation, the empirical temperature-based Hargreaves–Samani (HG) equation remains a popular alternative. However, accurate HG estimates can be obtained by local calibration and replacing the mean daily temperature with the effective daily temperature. Therefore, the present study was taken up to evaluate the effects of site-specific calibration of model parameters and the use of effective air temperature on the accuracy of ET_0 estimates by the HG model. For this purpose, climate records for the historical period 2006–2016 of 67 stations located across 10 agro-climatic zones of Karnataka State, India, were used and the analysis was carried out using a monthly time step. Calibration and statistical performance evaluation was performed using FAO-56 PM ET_0 estimates as a reference. Overall results showed significant improvement in HG estimates across all zones with the use of locally calibrated parameters, whereas the use of effective air temperature did not lead to any significant gain in prediction accuracies. The derived information on the spatial distribution of calibrated parameters will help obtain accurate ET_0 estimates with only air temperature inputs.

Key words | Hargreaves–Samani equation, local calibration, Penman–Monteith equation, reference crop evapotranspiration

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HIGHLIGHTS

- Local calibration of the Hargreaves–Samani (HG) ET_0 method with reference to Penman–Monteith ET_0 estimates.
- Significant improvement in accuracy of ET_0 estimates with the local calibration of three parameters in the HG equation across agro-climatic zones.
- Replacing the mean temperature variable in the HG equation with effective temperature yielded minor improvement.
- Spatial maps of optimized HG model parameters were derived.

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INTRODUCTION

Increasing anthropogenic activities are significantly altering climatic regimes and the spatiotemporal dynamics of the hydrological cycle. These changes are affecting freshwater availability, thereby decreasing the per-capita water availability in water-stressed countries such as India. Therefore, there is a need to efficiently use available water resources in all sectors and more so in the agricultural sector which is the largest consumer of freshwater in India. In this situation, improving water management practices through more efficient irrigation scheduling aimed at delivering water to satisfy crop needs for maximum yield is essential. A key variable in procedures for estimation of crop water requirement (CWR) and irrigation water requirement (IWR) is 'reference crop evapotranspiration' (ET_0). Since direct measurement of ET_0 is difficult, several methods for its estimation using regularly recorded climate data have been proposed by previous researchers. The United Nations (UN) Food and Agriculture Organization (FAO) has proposed standardized procedures for the calculation of ET_0 using ground-based climatological measurements (Doorenbos & Pruitt 1977; Allen *et al.* 1998). In particular, the FAO-56 report (Allen *et al.* 1998) recommends the sole use of the physically based Penman–Monteith (PM) equation for computation of ET_0 and provides detailed procedures/equations for converting observed climatological measurements into variables necessary for the application of the PM equation. However, since the PM equation requires data pertaining to 5–6 climate variables that may not be available at all locations, several other empirical to semi-empirical ET_0 equations that require fewer climate variables continue to remain popular among researchers and practitioners (Mohan 1991; McKenney & Rosenberg 1993; Xu & Singh 2002; Urrea *et al.* 2006; Jabloun & Sahli 2008). Over the past few decades, a large number of studies have been taken up to evaluate the accuracies of these simpler ET_0 equations relative to the PM equation in various climatic regions of the world (Jensen *et al.* 1997; Itenfisu *et al.* 2003; Garcia *et al.* 2004; Temesgen *et al.* 2005; Nandagiri & Kovoor 2006; Espadafor *et al.* 2011; Jhajharia *et al.* 2012; Almorox *et al.* 2015). The results of comparative studies have indicated the need for local calibration of parameters present in the simpler empirical to semi-empirical equations to attain acceptable levels of accuracies (e.g., Valero *et al.* 2013; Valiantzas 2013, 2015). One such simpler equation is the Hargreaves (HG) equation proposed by Hargreaves & Samani (1985). This temperature-based equation has been subject to comparisons with the PM equation in several parts of the world and found to provide reasonably accurate estimates of ET_0 in certain climatic conditions (e.g., Sentelhas *et al.* 2010; Valiantzas 2015). Allen *et al.* (1998) recommend the use of the HG equation as an alternative to the PM equation in data-scarce situations.

However, a few studies have shown that the HG equation may require local calibration to provide ET_0 estimates comparable to the PM equation (Trajkovic 2007; Tabari & Talaee 2011; Shahidian *et al.* 2013; Pandey *et al.* 2014). For example, Gavilán *et al.* (2006) evaluated the HG equation in semi-arid conditions in Southern Spain using data from 86 meteorological stations. Accuracies of daily ET_0 estimates were evaluated relative to the FAO-56 PM equation and it was found that the performance of the HG equation varied with location with deviations being larger in coastal and inland areas. They reported significantly better performance of the HG equation when the regional calibration of parameters was carried out using two methods by calibrating climate variables and kriging spatial interpolation. Martinez-Cob & Tejero-Juste (2004) evaluated the performance of the HG equation in windy and non-windy conditions in semi-arid north-east Spain and recommended local calibration at non-windy locations. Trajkovic (2007) calibrated the HG equation in the humid western Balkan region of south-east Europe and found that ET_0 estimates were in close agreement with the PM method. Tabari & Talaee (2011) studied the effect of local calibration on the performances of the HG and Priestley–Taylor (PT) methods relative to the PM method in arid and cold climates of Iran using historical climate records of 12 stations. They obtained parameter values that were significantly different from the standardized values which yielded smaller errors in ET_0 estimates. Pandey *et al.* (2014) evaluated the effect of local calibration of the HG equation in the east Sikkim, India, using daily, weekly, and monthly time steps and noted a significant reduction in error for all three time steps. Subburayan *et al.* (2011) calibrated the HG equation for a hot and humid location in India. The study found that the average underestimation of HG against PM was 28%. The exponent in the Hargreaves was found to be 0.653 which deviated from the standard HG exponent of 0.5. Though the results of original HG ET_0 estimates indicated a deviation from the FAO56 PM method, a significant decrease in standard error estimates was observed in modified HG estimates. Patel *et al.* (2015) calibrated the HG equation using the fuzzy logic method at eight locations across four climatic regions in India. The study used CLIMWAT datasets for input climatic variables and the results showed significant improvements of ET_0 estimates by the modified HG method across all climatic zones in India. Berti *et al.* (2014) calibrated the HG equation in north-eastern Italy using climate records of 35 agro-meteorological stations for the period 1994–2006. They found that the local calibration of one parameter in the HG equation reduced the overestimation in ET_0 estimates relative to the PM equation to 2.6%. Mendicino & Senatore (2013) calibrated the HG equation in southern Italy and found that the adjusted HG equation provided better estimates of daily ET_0. They developed a quadratic regression relationship between one of the HG parameters and the mean temperature. Vanderlinden *et al.* (2004) applied the HG equation at 16 meteorological stations in southern Spain during 1961–1998 and reported a gain in unbiasedness and precision due to local calibration. From the review of previous studies, it is evident that the optimal parameters involved in the HG equation exhibit significant deviations from the standard values suggested by Hargreaves & Samani (1985) and Allen *et al.* (1998) in different climatic regimes of the world. Therefore, the application of the HG equation in data-scarce situations requires local calibration if accurate estimates of ET_0 are to be obtained. However, since either the measured value of ET_0 or those estimated by the data-intensive PM equation is required for local calibration, there is a need to develop procedures for regionalizing the parameters, so that they may be estimated at locations where calibration data is unavailable. Such regionalization efforts can be successful only when a large number of climate stations covering a wide variety of climatic conditions are considered.

In addition to calibration of parameters, efforts have been made to redefine the mean daily temperature which forms the most important input in temperature-based ET_0 estimation methods such as the Thornthwaite and Blaney–Criddle equation. Instead of using mean temperature calculated as an average of the maximum and minimum temperatures, alternate forms of an 'effective' temperature have been used with the Thornthwaite equation by Pereira & Pruitt (2004) and Dinpashoh (2006) resulting in more accurate estimates of ET_0. Similar efforts involving the use of effective temperature in the Blaney–Criddle ET_0 equation have been made (e.g., Fooladmand & Ahmadi 2009; Fooladmand 2011) and reductions in estimation errors have been reported. However, no such efforts involving the use of effective temperature with the HG equation seem to have been made.

The present study was taken up to evaluate the performance of the HG ET_0 equation with and without local calibration of parameters. Additionally, the effect of replacing the mean temperature with an effective temperature on the performance of the HG equation was also assessed. Since measured ET_0 is rarely available, it was proposed to determine optimal HG model parameters and so also parameters of the effective temperature variable using ET_0 estimates obtained with the PM equation. In addition to temporal variabilities, the intention was to assess the spatial variabilities in ET_0 estimates and parameters at a regional scale with significant heterogeneity in climatic conditions. It is for this reason that the selected study area was Karnataka State located in south India.

METHODOLOGY

Study area, climate dataset, and agro-climatic zones

The study area under consideration is Karnataka State, India. The geographical area of the State is 19.1 Mha and is situated between 11°40′ and 18°27′ North latitudes and 74°5′ and 78°33′ East longitudes and accounts for 5.8% of India's total geographical area. There exists a large diversity in geographic and physiographic conditions in the State which is responsible for the climatic differentiation from arid to semi-arid in the plateau region, sub-humid to humid tropical in the Western Ghats mountains, and humid tropical monsoon type in the west coast plains (Initiative – Karnataka B. C. C. (2011)).

The study area has been divided into 10 agro-climatic zones (Ramachandra *et al.* 2004; KSDA, Government of Karnataka 2018). The zone-wise classification helps in better evaluation and understanding of climatic variability at a regional scale and was, therefore, adopted in the present study. The map of the study area with the agro-climatic zones is shown in Figure 1.

The climatic dataset was obtained from hydro-meteorological stations (HM) observatories operated and maintained by the Water Resources Development Organization (WRDO), Government of Karnataka State, India. From a network of over 89 HM stations, 67 stations' data for the period 2006–2016 was chosen for the present study. The dataset consisted of daily values of six climatic variables, namely maximum air temperature ($T_{\max}$), minimum air temperature ($T_{\min}$), maximum relative humidity ($RH_{\max}$), minimum relative humidity ($RH_{\min}$), actual hours of sunshine (n), and wind speed (u). Despite quality checks by WRDO, data gaps existed which were filled-in from the nearest neighbour for short periods (1–5 days). For longer periods of missing data, the corresponding values from the nearest grid point (Figure 1) of the Climate Forecast System Reanalysis (CFSR) (Globalweather 2018) were used. Finally, for each of the selected 67 stations, a dataset comprising six climatic variables for 11 years (2006–2016) was prepared for use in the analysis. Table 1 shows the list of selected climate stations, their location details, and the agro-climatic zones in which they are located. Daily values of the climate variables were converted into monthly mean daily values and a total of 132 months were considered in the analysis.

Hargreaves (HG) ET_0 equations

The Hargreaves (HG) equation (Hargreaves & Samani 1985; Allen *et al.* 1998) for daily ET_0 estimation is given by:

$$ET_{0,HGO} = 0.0023 \times (T_{\mathrm{mean}} + 17.8) \times (T_{\max} - T_{\min})^{0.5} \times R_a \tag{1}$$

where $ET_{0,HGO}$ is the daily reference evapotranspiration estimated by the 'original' HG equation (mm/day), $T_{\max}$ is the maximum air temperature (°C), $T_{\min}$ is the minimum air temperature (°C), T_{mean} is the mean air temperature $(^{\circ}C) = (T_{\max} + T_{\min})/2$, and R_a is the extra-terrestrial radiation (mm/day).

In this study, Equation (1) is rewritten in a general form as:

$$ET_{0,HGM} = A\,(T_{\mathrm{mean}} + B)(T_{\max} - T_{\min})^{C}\,R_a \tag{2}$$

where $ET_{0,HGM}$ is the daily reference evapotranspiration estimated by the 'modified' HG equation (mm/day) and the other variables retain the same definitions as above. A, B, and C are model parameters that need to be determined by calibration.

Three more versions of the HG equation were obtained by replacing the mean air temperature (T_{mean}) in Equation (2) with effective air temperature (T_{eff}). That is,

$$ET_{0,HG} = A\,(T_{\mathrm{eff}} + B)(T_{\max} - T_{\min})^{C}\,R_a \tag{3}$$

Effective air temperature (T_{eff}) may be defined by any one of the following expressions:

$$T_{\mathrm{eff},K} = 0.5\,K\,(3T_{\max} - T_{\min}) \tag{3a}$$

$$T_{\mathrm{eff},f} = f\,T_{\min} + (1 - f)T_{\max} \tag{3b}$$

$$T_{\mathrm{eff},gh} = g\,T_{\min} + h\,T_{\max} \tag{3c}$$

where K, f, g, and h are model parameters that need to be determined by calibration. While Equation (3a) was suggested by Fooladmand & Ahmadi (2009), Equations (3b) and (3c) were proposed by Ma & Guttorp (2013).

The following notations are used for ET_0 values calculated using T_{eff} values instead of T_{mean} in Equation (2): $ET_{0,HGK}$, $ET_{0,HGf,}$ and $ET_{0,HGgh}$ when Equations (3a)–(3c), respectively, are used. In effect, the present study uses five different versions of the HG equation for estimating daily ET_0 using monthly mean climate inputs for the period of record.

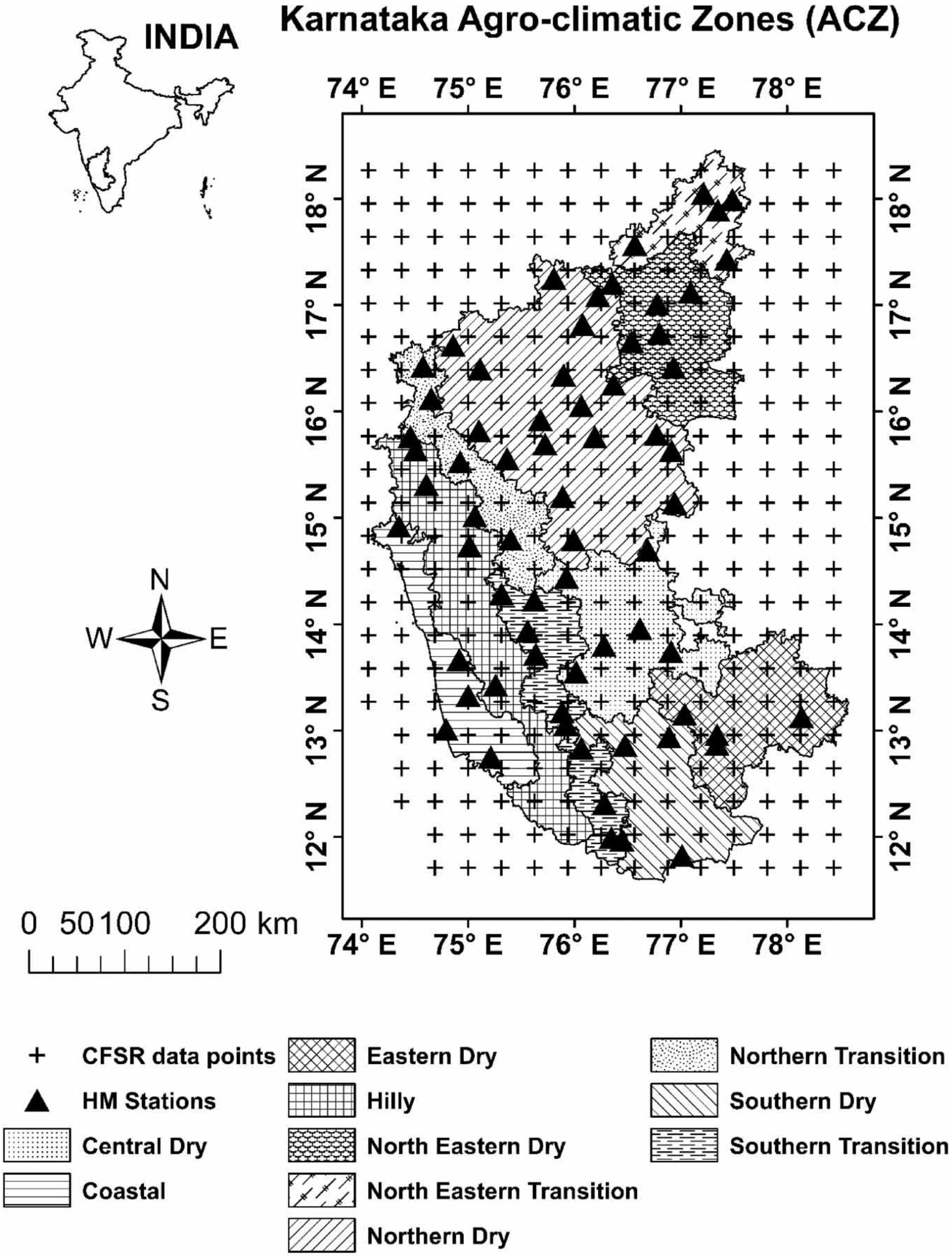

Figure 1 | Map of the study area showing agro-climatic zones, location of climate stations, and CFSR grid points.

Table 1 | Details of selected climate stations

Zone	Zone ID	Station	Station ID	Altitude (m)	Latitude (N)	Longitude (E)
Central Dry	CD	Davangere	CD1	606	14°26′	75°55′
		Hiriyur	CD2	616	13°57′	76°36′
		Hosadurga	CD3	735	13°47′	76°16′
		Kadur	CD4	775	13°33′	76°00′
		Rayapura	CD5	590	14°41′	76°41′
		Sira	CD6	654	13°44′	76°54′
Coastal	CO	Ajekar	CO1	66	13°19′	74°59′
		Hosangadi	CO2	69	13°40′	74°54′
		Kadra	CO3	24	14°55′	74°20′
		Puttur	CO4	118	12°45′	75°12′
		Surathkal	CO5	26	13°00′	74°47′
Eastern Dry	ED	Hebbur	ED1	811	13°09′	77°02′
		Kolar	ED2	839	13°07′	78°07′
		Manchanbele	ED3	726	12°52′	77°20′
		Thippagondanahalli	ED4	762	12°57′	77°20′
Hilly	HL	Bachanaki	HL1	573	15°01′	75°03′
		Barchi	HL2	477	15°18′	74°36′
		Dharma	HL3	596	14°44′	75°00′
		Khanapur	HL4	680	15°38′	74°30′
		Sringeri	HL5	672	13°25′	75°15′
North Eastern Dry	NED	Afzalpur	NED1	423	17°12′	76°21′
		Bheemarayanagudi	NED2	451	16°44′	76°47′
		Chittapur	NED3	425	17°07′	77°05′
		Deodurga	NED4	398	16°24′	76°55′
		Jewargi	NED5	413	17°00′	76°46′
		Kembhavi	NED6	496	16°39′	76°32′
		Narayanpur	NED7	477	16°15′	76°21′
North Eastern Transition	NET	Aland	NET1	514	17°34′	76°33′
		Bhalki	NET2	593	18°02′	77°12′
		Chincholi	NET3	454	17°25′	77°25′
		Halhalli	NET4	633	17°53′	77°20′
		Janwada	NET5	557	17°59′	77°28′
Northern Dry	ND	Almatti	ND1	548	16°20′	75°53′
		Almel	ND2	449	17°05′	76°13′
		Badami	ND3	566	15°55′	75°40′
		Bellary	ND4	453	15°08′	76°56′
		Devara Hipparagi	ND5	539	16°49′	76°04′
		Harapanahalli	ND6	632	14°47′	75°59′
		Hungund	ND7	535	16°03′	76°03′
		Kudachi	ND8	553	16°37′	74°51′
		Kushtagi	ND9	639	15°45′	76°11′
		Mahalingpur	ND10	584	16°24′	75°06′
		Mundargi	ND11	530	15°12′	75°53′
		Navalgund	ND12	581	15°33′	75°21′
		Navilutheerta	ND13	657	15°49′	75°05′
		Ron	ND14	579	15°41′	75°43′
		Sindhanur	ND15	397	15°47′	76°46′
		Siruguppa	ND16	381	15°37′	76°54′
		Zalki	ND17	479	17°15′	75°48′

(*continued*)

Table 1 | continued

Zone	Zone ID	Station	Station ID	Altitude (m)	Latitude (N)	Longitude (E)
Northern Transition	NT	Chikkodi	NT1	644	16°25′	74°34′
		Haveri	NT2	583	14°47′	75°23′
		Hidkal Dam	NT3	676	16°07′	74°39′
		Santibastwad	NT4	764	15°45′	74°27′
		Walmi	NT5	699	15°31′	74°55′
Southern Dry	SD	Gorur	SD1	901	12°50′	76°03′
		Marconahalli	SD2	737	12°56′	76°53′
		Shravanabelgola	SD3	871	12°51′	76°28′
		Suvarnavathi	SD4	764	11°49′	77°00′
Southern Transition	ST	BR Project	ST1	639	13°43′	75°38′
		Belur	ST2	994	13°10′	75°52′
		Channahally	ST3	985	13°03′	75°55′
		Honnali	ST4	585	14°13′	75°37′
		Hunsur	ST5	801	12°18′	76°16′
		Kabini	ST6	710	11°59′	76°20′
		Kutrahalli	ST7	603	14°17′	75°18′
		Nugu	ST8	736	11°58′	76°26′
		Shimoga	ST9	606	13°56′	75°33′

Penman–Monteith (PM) ET_0 equation

Since measured ET_0 values were unavailable for the study area under consideration, the HG equations were calibrated using ET_0 values estimated using the PM equation. Accordingly, as recommended by Allen *et al.* (1998), the following form of the PM equation is used.

$$ET_{0,PM} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_{mean} + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.37u_2)} \quad (4)$$

where $ET_{0,PM}$ is the daily reference evapotranspiration estimated by the PM equation (mm/day), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T_{mean} is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $(e_s - e_a)$ is the vapour pressure deficit (kPa), Δ is the slope of saturation vapour pressure versus temperature curve, and γ is the psychrometric constant (kPa °C^{-1}).

Allen *et al.* (1998) provided a detailed procedure for the application of Equation (4) using the observed daily data of maximum and minimum air temperatures (T_{max}, T_{min}), maximum and minimum relative humidities (RH_{max}, RH_{min}), actual sunshine hours (n), and wind speed (u_2). Latitude, longitude, and altitude details of the station (Table 1) are also needed in the computations.

Computation of ET_0 and calibration procedure

A computer program was developed in MATLAB® to calculate daily ET_0 values (mm/day) by the PM model (Equation (4)), the HG model (Equations (1) and (2)), and the HG models using T_{eff} defined by Equations (3), (3a)–(3c) at each station (Table 1) for each month in the period of record (2006–2016). The accuracy of the developed program was verified using numerical examples given in Allen *et al.* (1998).

Since the record length of 11 years was too short to carry out a month-wise analysis, the HG equations (Equations (1)–(3)) were locally calibrated at each station using the annual period. Accordingly, the available month-wise data was divided into a calibration set and a validation set. The period January 2006–December 2012 (84 months) was used for calibrating the HG equations and was validated for the period January 2013–December 2016 (48 months). At each station, calibration was performed in two steps: (1) $ET_{0,HGM}$ values (Equation (2)) were first used with corresponding values of $ET_{0,PM}$ (Equation (4)) to determine optimal values of parameters A, B, and C. (2) Retaining these optimal values of A, B, and C, the other three versions of the HG equation with T_{mean} replaced by alternate definitions of T_{eff} (Equations (3), (3a)–(3c)) were calibrated separately with corresponding values of $ET_{0,PM}$ to obtain optimal model parameters K, f, and g and h for each station.

In all cases of local calibration, optimal model parameters were obtained by minimizing the sum of squared errors (SSE) between PM ET_0 estimates and those obtained from the HG equation. That is:

$$SSE = \sum_{i=1}^{N} (Y_i - X_i)^2 \tag{5}$$

where Y_i is the $ET_{0,PM}$ and X_i is the $ET_{0,HGM}$ or $ET_{0,HGK}$ or $ET_{0,HGf}$ or $ET_{0,HGgh}$ depending on the particular HG equation being calibrated, and N is the total number of months. In this study, optimal model parameters were obtained using the SOLVER Add-in in Microsoft® Excel® (2013) by minimizing SSE (Equation (5)) adopting the generalized reduced gradient (GRG) nonlinear method.

Accuracy assessment of the HG equations (Equations (1)–(3)) relative to the PM equation was accomplished in both calibration and validation phases using the coefficient of determination (R^2), root-mean-square error (RMSE), and mean bias error (MBE) statistics computed as:

$$R^2 = \left[\frac{N\sum Y_i X_i - \sum Y_i \sum X_i}{\sqrt{\left[N\sum Y_i^2 - \left(\sum Y_i\right)^2\right]\left[N\sum X_i^2 - \left(\sum X_i\right)^2\right]}} \right]^2 \tag{6}$$

$$RMSE = \sqrt{\frac{\sum (Y_i - X_i)^2}{N}} \tag{7}$$

$$MBE = \frac{\sum_{i=1}^{n} (Y_i - X_i)}{N} \tag{8}$$

where Y is the $ET_{0,PM}$ and X is the $ET_{0,HGO}$ or $ET_{0,HGM}$ or $ET_{0,HGK}$ or $ET_{0,HGf,}$ or $ET_{0,HGgh}$ depending on which of the HG equations is being evaluated. For a perfect estimation, $R^2 = 1$, $RMSE = 0$, and $MBE = 0$. A convenient method for interpreting the overall performance of a given HG equation using the above three statistics across the 67 stations was devised in which a 'score' was computed using the following steps: (1) Considering a particular HG equation, one of the statistics, say R^2 is selected and the number of stations at which this HG equation yielded the highest value of R^2 relative to the other equations is noted. (2) A similar count is made for the number of stations at which the HG equation yielded the lowest RMSE and lowest MBE. (3) Next, the ratio of the number of stations at which the particular HG equation yielded the best values of statistics to the total number of stations is calculated. (4) The same steps are applied to all the HG equations whose performance was evaluated to identify the equation which performed best at the largest number of stations in each zone and also in the study area as a whole.

RESULTS AND DISCUSSION

Mean monthly $ET_{0,PM}$ values obtained using the PM method (Equation (4)) are shown in Figure 2 to provide an overview of the magnitudes and intra-annual variability. It can be seen that ET_0 values are in the range of 3.0 mm/day in January and increase monotonically over the summer season to reach peak values of 5.0 mm/day in May. With the onset of the south-west monsoon rainfall in June, ET_0 values reduce and remain constant at about 3.5 mm/day during the monsoon season which lasts up to October.

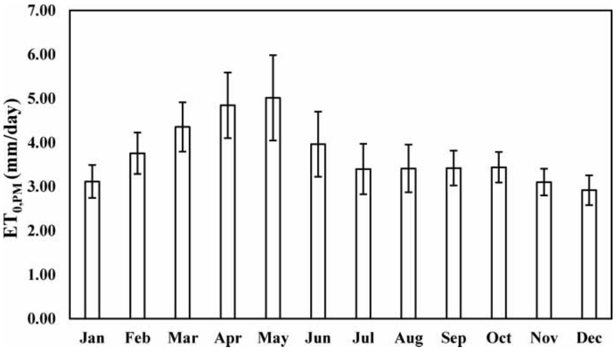

Figure 2 | Mean and standard deviations of monthly $ET_{0,PM}$ (mm/day) over 67 stations for the period 2006–2016.

Subsequently, during the winter season, ET_0 values reduce to 3.0 mm/day. However, the standard deviation bars shown in Figure 2 are indicative of significant variations in monthly ET_0 values across the 67 stations located in different agro-climatic zones. The spatial variability as indicated by larger values of standard deviation appears to be more during April, May, and June and reduces during peak monsoon months of July–August and the winter season (November–February).

Original versus modified HG equations

The effect of local calibration on the performance of the HG equation relative to the PM equation was analysed through the implementation of Equations (1), (2), and (4) at each of the stations using the procedure described in the previous section. As an example, a comparison of ET_0 estimates during the validation phase is presented for the Davangere station (CD1) located in the Central Dry (CD) agro-climatic zone. The scatter plot showing ET_0 estimates by the PM equation ($ET_{0,PM}$) versus estimates by the original HG equation ($ET_{0,HGO}$) for 48 months (2013–2016) in the validation phase at the Davangere station is shown in Figure 3(a). The original HG equation with standard values of parameters (Equation (1)) overestimates ET_0 values in comparison to the PM equation (Equation (4)) with the overestimation being slightly larger for higher values of ET_0. Although a reasonably high value of $R^2 =$ 0.8072 (Equation (6)) was obtained, the values of RMSE (Equation (7)) and MBE (Equation (8)) of 1.006 and 0.9493 mm/day are indicative of somewhat large errors and bias in the $ET_{0,HGO}$ estimates. The calibration of the modified HG equation (Equation (2)) using PM ET_0 estimates for 84 months during 2006–2012 at the Davangere station yielded the following optimal values for the parameters: $A = 0.00424$, $B = -1.0024$, and $C = 0.4054$. While the difference between the optimal value of parameters C is not very different from the standard values of 0.5 (Equation (1)), parameters A and B are significantly different from the standard value of 0.0023 and 17.8, respectively. With these values of optimal parameters, the application of the modified HG equation (Equation (2)) for the validation period yielded $ET_{0,HGM}$ values which are compared with the corresponding values of $ET_{0,PM}$ in Figure 3(b) for the Davangere station. The effect of local calibration is evident from the significant reduction in bias (MBE = 0.171 mm/day) even though there is not much improvement in the value of R^2 (0.8294). RMSE was also reduced to 0.3473 mm/day for the modified HG equation (Figure 3(b)). Therefore, it may be concluded that for the Davangere station, the local calibration of the HG equation resulted in a significant reduction in error and also a bias in ET_0 estimates.

Results of a similar performance analysis during the validation phase for the original and modified HG equations relative to the PM equation for all 67 stations are presented

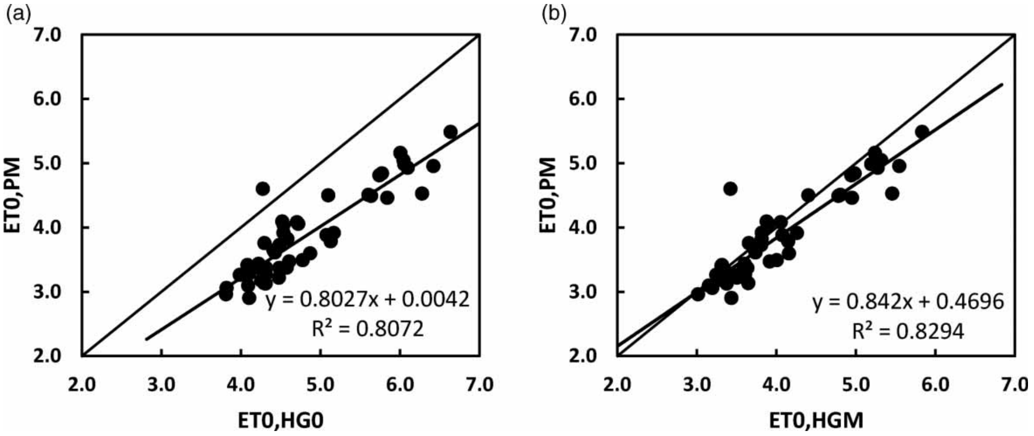

Figure 3 | Comparison of estimates by PM equation ($ET_{0,PM}$) with estimates by the (a) original HG equation ($ET_{0,HGO}$) and (b) modified HG equation ($ET_{0,HGM}$) for validation phase at Davangere station (CD1).

in Table 2. For brevity minimum and maximum values of R^2, RMSE, and MBE obtained for stations pooled in each agro-climatic zone in the State are shown therein separately for $ET_{0,HGO}$ and $ET_{0,HGM}$ estimates in comparison to $ET_{0,PM}$ estimates.

The examination of the minimum and maximum values of R^2 indicates that the modified HG equation (Equation (2)) yields $ET_{0,HGM}$ estimates which are better than $ET_{0,HGO}$ estimates provided by the original HG equation (Equation (1)) in six out of the 10 agro-climatic zones, and for the State as a whole (Table 2). In terms of R^2, it appears that local calibration does not provide any benefit in the Coastal (CO), Hilly (HL), Northern Transition (NT), and Southern Transition (ST) zones. However, the examination of RMSE values (Table 2) for the $ET_{0,HGO}$, and $ET_{0,HGM}$ estimates indicate that for the State and in all zones, local calibration results in a significant reduction in error with the reduction in some cases being more than 50%. The only exception is the NT zone where RMSE values are in favour of the original HG $ET_{0,HGO}$ estimates. From Table 2, it can also be seen that $ET_{0,HGM}$ estimates by the modified HG equation (Equation (2)) with the local calibration of parameters yields significantly lower values of MBE in all cases in comparison to the $ET_{0,HGO}$ estimates by the original HG equation (Equation (1)). Therefore, it appears from the results shown in Table 2 that the local calibration of the HG equation results in a significant reduction in both error and bias at stations located across the 10 agro-climatic zones of the study area. Considering the State as a whole, the modified HG equation appears to be superior to the original HG equation based on all three performance statistics (Table 2).

Table 2 | Minimum and maximum values of validation phase performance statistics of the original (Equation (1)) and modified (Equation (2)) HG equations and HG equation using effective temperature (Equations (3), (3a) and (3c)) relative to the PM equation (Equation (4)) for stations pooled in each agro-climatic zone

Zone	No. of stations	Statistic equation	R^2				RMSE (mm/day)				MBE (mm/day)			
			$ET_{0,HGO}$	$ET_{0,HGM}$	$ET_{0,HGK}$	$ET_{0,HGgh}$	$ET_{0,HGO}$	$ET_{0,HGM}$	$ET_{0,HGK}$	$ET_{0,HGgh}$	$ET_{0,HGO}$	$ET_{0,HGM}$	$ET_{0,HGK}$	$ET_{0,HGgh}$
CD	6	Min	0.38	0.41	0.37	0.41	0.69	0.25	0.39	0.25	0.61	0.004	0.005	0.01
		Max	0.88	0.92	0.83	0.92	2.07	1.32	1.28	1.29	1.86	−1.24	−1.2	−1.21
CO	5	Min	0.26	0.30	0.17	0.30	0.69	0.54	0.57	0.54	0.17	0.38	0.35	0.37
		Max	0.40	0.36	0.45	0.30	0.98	0.75	0.69	0.78	1.9	0.57	0.61	0.57
ED	4	Min	0.14	0.14	0.03	0.13	1.00	0.71	0.91	0.68	−0.19	0.34	0.41	0.36
		Max	0.35	0.69	0.46	0.71	2.09	1.23	1.63	1.34	1.88	0.69	0.93	0.73
HL	5	Min	0.52	0.52	0.48	0.46	0.67	0.30	0.34	0.30	0.34	0.03	0.002	0.03
		Max	0.91	0.86	0.87	0.86	1.66	0.96	0.99	0.96	1.59	−0.75	−0.83	−0.72
NED	7	Min	0.48	0.43	0.47	0.42	0.98	0.38	0.50	0.38	0.88	0.19	0.16	0.12
		Max	0.92	0.93	0.88	0.93	1.88	1.20	1.04	1.23	1.74	0.93	0.7	0.95
NET	5	Min	0.51	0.53	0.44	0.53	0.91	0.36	0.48	0.36	0.002	−0.05	0.03	−0.05
		Max	0.83	0.90	0.76	0.90	1.58	0.94	1.00	0.94	1.17	−0.35	−0.83	−0.35
ND	17	Min	0.11	0.15	0.17	0.15	0.85	0.21	0.24	0.21	0.37	−0.02	0.03	−0.02
		Max	0.91	0.92	0.91	0.92	2.09	2.01	2.08	2.01	2.02	−1.11	1.05	−1.1
NT	5	Min	0.52	0.30	0.35	0.35	0.36	0.80	0.39	0.39	0.33	0.00	−0.03	0.002
		Max	0.81	0.78	0.87	0.87	0.88	1.64	1.14	1.15	1.33	−0.7	−0.71	−0.68
SD	4	Min	0.28	0.50	0.43	0.50	0.77	0.25	0.32	0.25	−0.17	−0.1	−0.16	−0.09
		Max	0.84	0.85	0.79	0.86	2.07	1.02	1.17	1.02	1.91	−0.79	−0.9	−0.79
ST	9	Min	0.21	0.20	0.20	0.17	0.41	0.39	0.39	0.39	−0.04	−0.01	−0.03	−0.01
		Max	0.89	0.87	0.89	0.87	1.78	1.03	1.00	1.03	1.6	−0.83	−0.84	−0.83
State	67	Min	0.11	0.14	0.03	0.13	0.41	0.21	0.24	0.21	0.02	0.00	0.002	0.002
		Max	0.92	0.93	0.91	0.93	2.09	2.01	2.08	2.01	2.02	−1.24	−1.2	−1.21

Table 3 | Mean and standard deviations of optimal HG equation parameters (Equation (2)) for stations pooled in each agro-climatic zone

		A		**B**		**C**	
Zone	**No. of stations**	**Mean**	**Std. Dev**	**Mean**	**Std. Dev**	**Mean**	**Std. Dev**
CD	6	0.0042	0.0018	11.61	22.64	0.30	0.09
CO	5	0.0065	0.0045	−0.74	11.53	0.30	0.22
ED	4	0.0025	0.0017	34.95	26.09	0.39	0.25
HL	5	0.0035	0.0020	25.07	17.89	0.20	0.13
NED	7	0.0063	0.0030	6.83	30.44	0.26	0.04
NET	5	0.0048	0.0023	3.14	5.68	0.30	0.17
ND	17	0.0067	0.0038	3.75	14.20	0.27	0.26
NT	5	0.0032	0.0016	26.73	17.86	0.26	0.10
SD	4	0.0033	0.0019	32.53	27.48	0.21	0.17
ST	9	0.0034	0.0014	18.76	20.24	0.27	0.15
State	67	0.0049	0.0029	13.30	20.83	0.27	0.17

Table 3 shows the optimal parameters for the modified HG equation (Equation (2)) whose performance assessment is shown in Table 2. The calibration of the modified HG equation to obtain optimal model parameters A, B, and C in Equation (2) was performed as described in the ‘Computation of ET_0 and calibration procedure’ section. Again for brevity, rather than showing parameter values for individual stations, mean values and standard deviations for stations pooled under each agro-climatic zone are shown therein. The last row in Table 3 shows mean parameter values and associated standard deviations for all 67 stations considered in the analysis.

It can be seen that although the mean value of parameter A of 0.0049 for the State as a whole (Table 3) deviates significantly from the standard value of $A = 0.0023$ in the original HG equation (Equation (1)), not only is the standard deviation quite high, but also significant departures from the standard value can be seen when stations are pooled under different zones. The mean values of A range from as low as 0.0032 in the Northern Transition Zone (NT) to as high as 0.0067 in the Northern Dry (ND) zone. This implies that the original HG equation is not applicable without the local calibration of this parameter in the study area. A similar conclusion can be drawn by examining the values of parameter B (Table 2) which show variations from as low as −0.74 in the Coastal zone (CO) to as high as 34.95 in the Eastern Dry zone (ED) which are quite different from the standard value of 17.8 proposed by the original HG equation (Equation (1)). Parameter C (Table 2) while showing relatively lower variability across the zones still deviates from the standard value of 0.5 (Equation (1)) with a mean value of 0.27 for the study area as a whole. The lowest value of $C = 0.20$ was recorded in the Hilly zone (HL) with a moderate SD of 0.13 among the five stations, whereas the Eastern Dry (ED) zone with four stations yielded the highest mean value of $C = 0.39$ with a higher SD of 0.25.

Figure 4 shows maps depicting the spatial variabilities of the optimized HG model parameters A, B, and C over the study area. These maps were derived by interpolating station-wise values of parameters using the inverse distance method. While Figure 4(a) and 4(b) indicates significant variations in parameters A and B with some clustering in certain areas, the variability of parameter C appears to be more uniform across the study area (Figure 4(c)). An effort was made to explore the possibility of a correlation between station-wise values of A and B with station elevations but no significant relationships could be extracted. However, when the mean values of parameters for the agro-climatic zones (Table 3) were regressed against mean elevations for the zones, it was found that parameter A was negatively

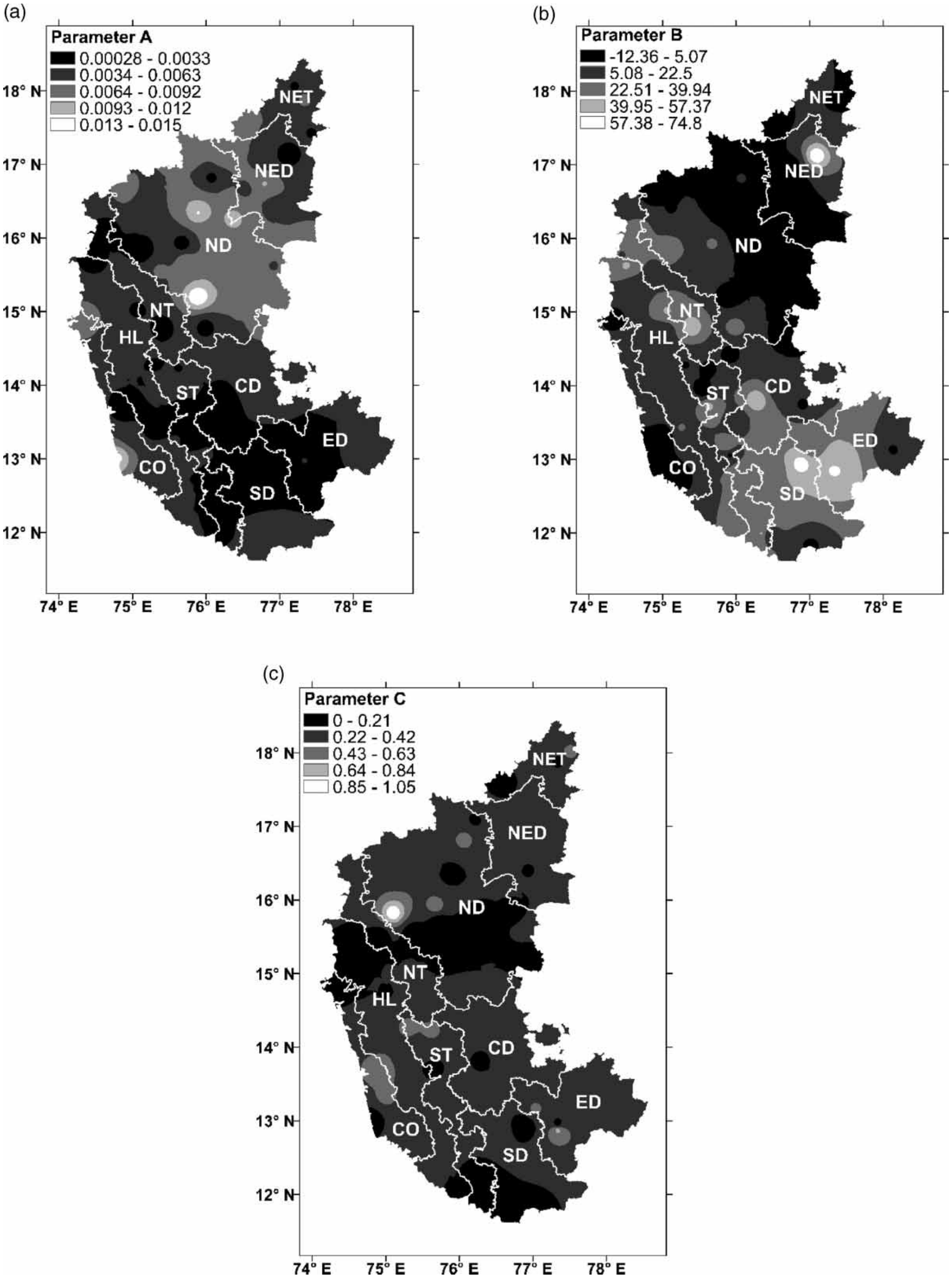

Figure 4 | Maps depicting spatial variations of optimized HG model parameters A, B, and C (Equation (1)) over the study area.

correlated with elevation with $R^2 = 0.6305$ and parameter B was positively correlated with $R^2 = 0.5944$. These results indicate that elevation explains about 60% of the observed variability in these two parameters. Whether other terrain factors have an additional influence needs to be investigated in future studies aimed at regionalization of parameters.

Performance of HG equations with effective temperature

The performances of the HG equations with mean temperature (T_{mean}) being replaced with effective temperature (T_{eff}) (Equation (3)) defined by three alternative methods (Equations (3a)–(3c)) were evaluated using the procedure described in the 'Computation of ET_0 and calibration procedure' section. While retaining the optimal values of parameters A, B, and C obtained through calibration of HG ET_0 estimates by Equation (2) with those from the PM method (Equation (4)), the HG equation with T_{eff} (Equation (3)) was again calibrated with the PM method. The optimal values of parameters K (Equation (3a)), f (Equation (3b)), and g and h (Equation (3c)) were obtained by calibration with ET_0 estimates by the PM method (Equation (4)) using the monthly values for the period January 2006–December 2012 (84 months) and were validated for the period January 2013–December 2016 (48 months).

As an example, Figure 5 shows the results of the comparative evaluation of ET_0 estimates by these methods during the validation phase for the Davangere station (CD1) located in the Central Dry (CD) agro-climatic zone. The scatter plot (Figure 5(a)) showing ET_0 estimates by the PM equation ($\mathrm{ET}_{0,\mathrm{PM}}$) versus estimates by the HG equation with T_{eff} defined by Equation (3a) ($\mathrm{ET}_{0,\mathrm{HGK}}$). The optimal value of parameter $K = 0.6947$ yielded these results with optimal values of parameters $\mathrm{A} = 0.00424$, $\mathrm{B} = -1.0024$, and $\mathrm{C} = 0.4054$ obtained in the earlier step. From the scatter plot (Figure 5(a)), it is evident that $\mathrm{ET}_{0,\mathrm{HGK}}$ estimates

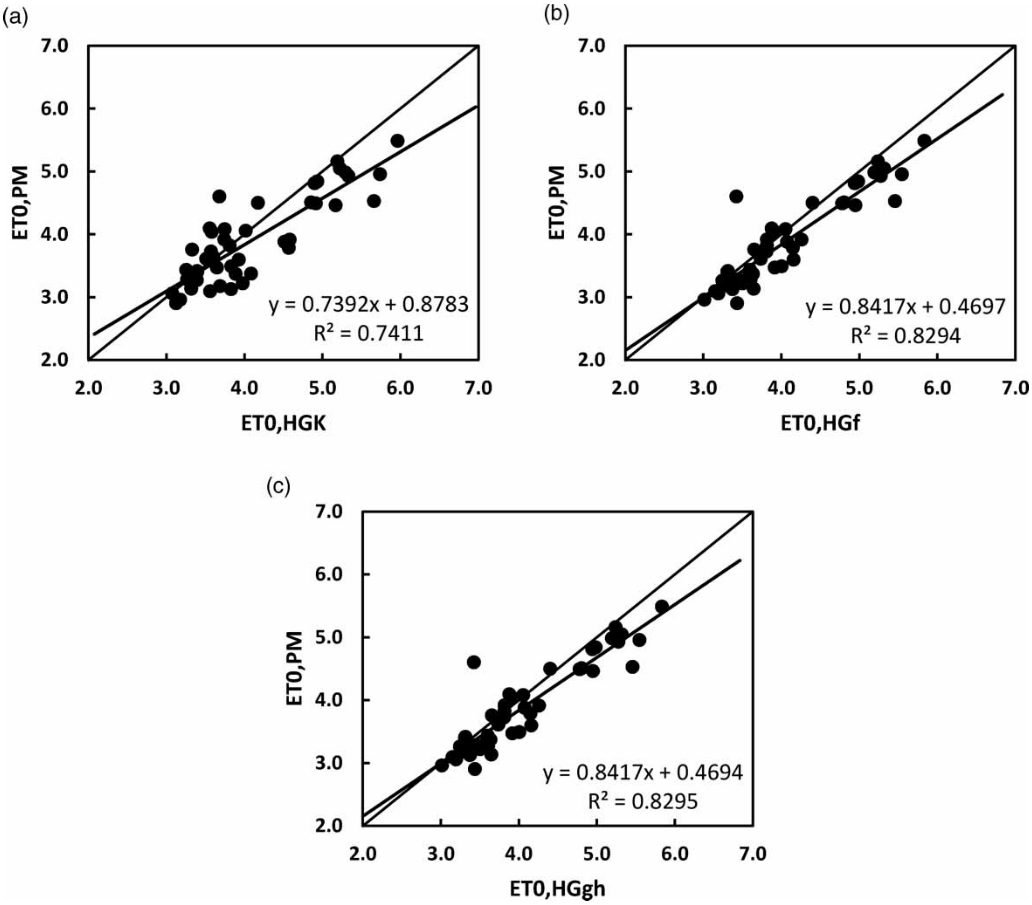

Figure 5 | Comparison of estimates by PM equation ($\mathrm{ET}_{0,\mathrm{PM}}$) with estimates by the (a) HG Equation (3a) ($\mathrm{ET}_{0,\mathrm{HGK}}$), (b) HG Equation (3b) ($\mathrm{ET}_{0,\mathrm{HGf}}$), and (c) HG Equation (3c) ($\mathrm{ET}_{0,\mathrm{HGgh}}$) for the validation phase at Davangere station (CD1).

deviate from the $ET_{0,PM}$ estimates with a large scatter for medium-range values and overestimation for higher values of ET_0. Performance evaluation yielded values of $R^2 = 0.7411$, RMSE = 0.4403 mm/day, and MBE = 0.182 mm/day for this case. On the other hand, Figure 5(b) indicates a better comparison between estimates $ET_{0,HGf}$ and $ET_{0,PM}$ with an optimized parameter value of $f = 0.4992$. Although a slight overestimation for higher values still exists, the use of Equation (3b) to define T_{eff} significantly improves the performance of the HG model (Equation (3)). While R^2 increases to 0.8294, RMSE and MBE reduce to 0.3481 and 0.172 mm/day, respectively, when Equations (3) and (3b) are implemented for the Davangere station (Figure 5(b)). However, since the value of $f = 0.4992$, the results shown in Figure 5(b) are almost the same as those shown for $ET_{0,HGM}$ in Figure 3(b) which uses T_{mean} with a weightage of 0.5 for T_{min}. Therefore, for the Davangere station, the use of Equation (3) with T_{eff} defined by Equation (3b) does not yield any additional benefit. While the same inference is true for the comparison between estimates of $ET_{0,PM}$ and $ET_{0,HGgh}$ shown in Figure 5(c) with the optimal parameter values of $g = 0.5021$ and $h = 0.4990$, later analysis showed that for other stations values of g and h deviated significantly from 0.5.

Using a similar procedure, $ET_{0,HGf}$ estimates by the HG equation (Equation (3)) with T_{eff} defined by Equation (3b) were used to calibrate the parameter f at the remaining 66 stations using $ET_{0,PM}$ estimates. Station-wise optimal values of f (not shown for brevity) indicated that they varied between 0.49 and 0.54. For the study area as a whole, the mean value of $f = 0.50$ with a standard deviation of 0.01 was obtained from which it may be concluded that Equation (3b) does not offer any significant improvement in accuracy over the use of T_{mean} in the HG equation (Equation (2)). Since $ET_{0,HGgh}$ values were almost identical to $ET_{0,HGM}$ estimates, the former approach was discarded from all further analysis of this study.

Table 4 | Mean and standard deviations of optimal parameters of HG equations using effective temperature (Equations (3), (3a) and (3c)) for stations pooled in each agro-climatic zone

		K		*g*		*h*	
Zone	**No. of stations**	**Mean**	**Std. Dev**	**Mean**	**Std. Dev**	**Mean**	**Std. Dev**
CD	6	0.67	0.06	0.42	0.25	0.55	0.17
CO	5	0.74	0.05	0.60	0.14	0.43	0.10
ED	4	0.69	0.05	0.41	0.40	0.56	0.27
HL	5	0.66	0.04	0.63	0.14	0.43	0.08
NED	7	0.70	0.01	0.79	0.67	0.32	0.43
NET	5	0.64	0.04	0.51	0.03	0.49	0.02
ND	17	0.68	0.02	0.51	0.04	0.49	0.03
NT	5	0.67	0.03	0.68	0.21	0.39	0.13
SD	4	0.67	0.04	0.62	0.13	0.42	0.08
ST	9	0.67	0.02	0.53	0.08	0.48	0.05
State	67	0.68	0.04	0.56	0.27	0.46	0.17

Table 4 shows the optimal values of parameters K (Equation (3a)) and g and h (Equation (3c)) which were obtained by calibration with ET_0 estimates by the PM method (Equation (4)) using the monthly values for the period January 2006–December 2012 (84 months). For brevity, mean and standard deviation values for the parameters for stations pooled under different agro-climatic zones and for the State are shown therein. It can be seen that the mean value of parameter K was 0.68 with a reasonably low value of the standard deviation of 0.04 for the State as a whole. The range of values of K for most of the zones was between 0.64 and 0.68 except for the CO zone where the highest mean value of 0.74 was recorded. The parameter g shows high variability ranging from 0.41 in the ED zone to 0.79 in the NED zone. The overall mean value of g is 0.56 with a high SD of 0.27 which indicates that local calibration is required for this parameter. The parameter h also showed high variability with the lowest value of 0.32 in NED and the highest value of 0.56 in the ED zone. The parameter h was also accompanied by high values of standard deviation (Table 4) indicating high variability within any given agro-climatic zone. Also, it is interesting to note from Table 4 that except for Central Dry (CD) and Eastern Dry (ED) zones where optimized mean g values are lower than the optimized mean values of h, in all other zones and for the State as a whole, the opposite is true. This implies that the weightage assigned to T_{min} (parameter g) is larger than that assigned to T_{max} (parameter h) while computing T_{eff} by Equation (3c) in a large part of the study area. Figure 6 depicts the spatial variabilities of the optimized HG model parameters K, g, and h over the study area obtained by interpolating between station-wise parameter values. Significant clusters with low values and high values of parameter K in certain areas were visible. Variability of parameters g and h across the state was more or less uniform.

Performance statistics of the HG equations using effective temperature (Equations (3), (3a) and (3c)) relative to the PM equation (Equation (4)) during the validation phase of 48 months (2013–2016) are shown in Table 2. Again, for brevity, the minimum and maximum values of statistics R^2, RMSE, and MBE for stations pooled under different agro-climatic zones and also for the State as a whole are listed therein. The comparison of $ET_{0,HGK}$ values relative to $ET_{0,PM}$ estimates indicates that the local calibration of parameter K in Equation (3a) does not yield many benefits in terms of performance statistics R^2, RMSE, and MBE values. Except in very few cases such as the CO and NT zones (Table 2), the maximum values of R^2 for this method indicate that it fails to match the performance of the modified HG equation. Surprisingly, despite local calibration, the accuracy of $ET_{0,HGK}$ estimates does not match even the original HG equation estimates ($ET_{0,HGO}$). The same conclusion regarding the accuracy of $ET_{0,HGK}$ estimates being poorer than $ET_{0,HGM}$ and $ET_{0,HGO}$ values in most of the zones and for the State as a whole may be drawn upon examination of results in Table 2. On the other hand, the performance of the HG equation (Equation (3)) with T_{eff} defined by Equation (3c) (i.e., $ET_{0,HGgh}$) is significantly superior. In terms of R^2 values, this approach involving local calibration of parameters g and h is better than the original HG equation (Equation (1)) in all zones and better than or on a par with the modified HG equation (Equation (2)) in many zones. The values of RMSE and MBE for $ET_{0,HGgh}$ estimates (Table 2) also indicate that this approach provides the lowest errors and bias in several zones, and for the State as a whole, it performs on a par with the modified HG equation (Equation (2)).

Since the results of the performance evaluation of the four HG models tested in the present study during the validation phase are presented in Table 2 by pooling stations in each zone and for the study area as a whole, a simple favourable statistic-based approach was implemented to provide information on station-wise performances. Accordingly, as described in the 'Computation of ET_0 and calibration procedure' section, a score of 1 was assigned to the method which yielded the best value of a particular performance statistic (highest value of R^2, lowest values of RMSE, and MBE) at each station. Subsequently, scores were summed for each method under each statistic for all stations pooled in agro-climatic zones and for the State as a whole. For example, at the Davangere station located in the CD zone, R^2 values obtained during the validation phase are 0.81, 0.83, 0.74, and 0.83 for $ET_{0,HGO}$, $ET_{0,HGm}$, $ET_{0,HGK}$, and $ET_{0,HGgh}$ estimates, respectively. Accordingly, the modified HG equation (Equation (2)) with the highest R^2 value of 0.83 was assigned a score of 1. However, since $ET_{0,HGgh}$ estimates also yielded the same value of R^2, Equation (3) with T_{eff} computed using Equation (3c) was also assigned a score of 1. Next, considering the values of RMSE and MBE at the Davangere station, scores were assigned to the HG equations. Using this procedure, scores were assigned to all four HG equations at all 67 stations considered in the present analysis. Results of this analysis shown in Table 5 are presented in terms of the number of stations with favourable performance yielded by each method during the validation phase in different zones.

The last row in Table 5 indicates that the performance of the original HG equation (Equation (1)) with standard values of parameters was the poorest among all methods considered at the 67 stations located in the State. Although the method yielded the highest R^2 and lowest MBE values between $ET_{0,HGO}$ and $ET_{0,PM}$ estimates at 15 and 12 stations, respectively, RMSE values were lowest at only four stations. In terms of R^2 and MBE values, the best performance of the original HG equation was recorded in the Southern Transition (ST) zone. With the local calibration of parameters, the performance of the modified HG equation (Equation (2)) showed remarkable improvement in performance in terms of all three statistics. $ET_{0,HGM}$ estimates yield the highest value of R^2 at 34 stations (Table 5) and the lowest RMSE values at 45 of the 67 stations in the State. MBE values were lowest at 24 stations. It is not only the number of stations at which the modified HG equation performed better but as was pointed out earlier, results shown in Table 2 indicate that the magnitude of reduction in error and bias was quite substantial for $ET_{0,HGM}$ estimates in comparison to $ET_{0,HGO}$ estimates. The performance of Equation (2) with optimized parameters was best in the Northern Dry (ND) zone and also consistently good across all the agro-climatic zones recording the best statistics

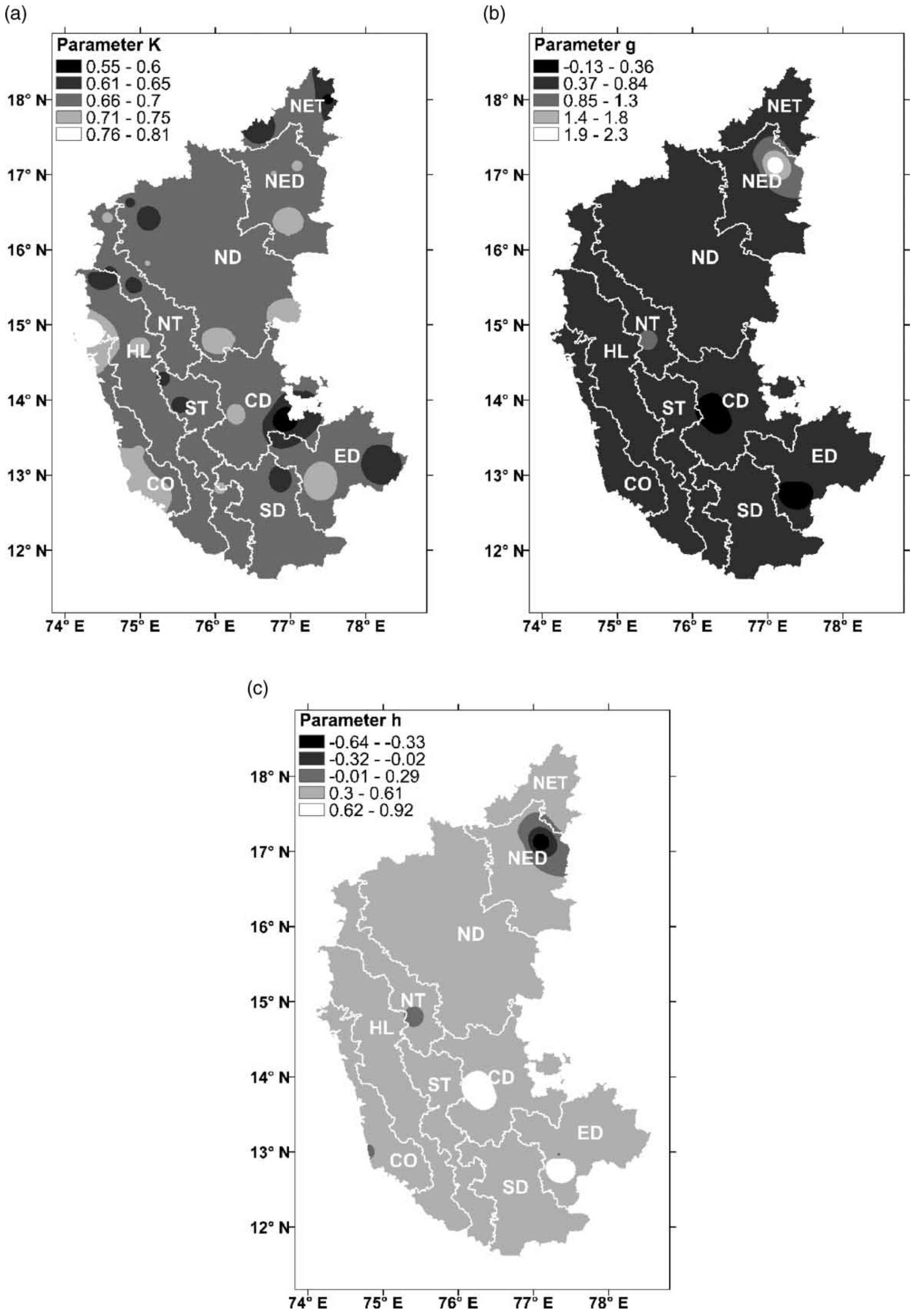

Figure 6 | Maps depicting spatial variations of optimized HG model parameters *K*, *g*, and *h* (Equations (3a) and (3c)) over the study area.

Table 5 | Results of favourable statistic-based performance analysis of the four HG equations for stations pooled in each agro-climatic zone

		R^2				RMSE (mm/day)				MBE (mm/day)			
Zone	**No. of stations**	$\mathrm{ET}_{0,\mathrm{HGO}}$	$\mathrm{ET}_{0,\mathrm{HGM}}$	$\mathrm{ET}_{0,\mathrm{HGK}}$	$\mathrm{ET}_{0,\mathrm{HGgh}}$	$\mathrm{ET}_{0,\mathrm{HGO}}$	$\mathrm{ET}_{0,\mathrm{HGM}}$	$\mathrm{ET}_{0,\mathrm{HGK}}$	$\mathrm{ET}_{0,\mathrm{HGgh}}$	$\mathrm{ET}_{0,\mathrm{HGO}}$	$\mathrm{ET}_{0,\mathrm{HGM}}$	$\mathrm{ET}_{0,\mathrm{HGK}}$	$\mathrm{ET}_{0,\mathrm{HGgh}}$
CD	6	2[a]	4	1	4	0[a]	3	3	3	1[a]	2	3	1
CO	5	1	3	3	3	0	4	1	4	1	1	3	2
ED	4	2	2	0	1	0	3	0	1	1	2	0	1
HL	5	2	1	1	2	0	2	2	3	0	0	2	3
NED	7	1	4	1	5	0	4	3	3	0	3	4	2
NET	5	1	4	0	3	1	4	0	3	1	2	2	1
ND	17	1	11	4	12	1	13	3	11	1	10	6	10
NT	5	1	1	0	4	1	2	0	4	1	2	1	2
SD	4	0	2	0	4	0	3	0	4	2	0	0	2
ST	9	4	2	4	4	1	7	2	5	4	2	3	2
State	67	15	34	14	42	4	45	14	41	12	24	24	26

[a] Numbers indicate the number of stations where the HG equation yielded the highest value of R^2 and lowest values of RMSE and MBE in comparison to the other equations.

at more than 50% of the stations in many zones. The performance of the HG equation using T_{eff} in place of T_{mean} (Equation (3)) with T_{eff} being computed by Equation (3a) ($\mathrm{ET}_{0,\mathrm{HGK}}$ estimates) was superior to the original HG equation ($\mathrm{ET}_{0,\mathrm{HGO}}$ estimates) in terms of RMSE and MBE but slightly poorer in terms of R^2 (Table 2). Given the fact that this approach involved the optimization of an additional parameter (K), its performance was not significantly better across any of the zones either. On the contrary, the other HG equation using T_{eff} in place of T_{mean} (Equation (3)) with T_{eff} being computed by Equation (3c) ($\mathrm{ET}_{0,\mathrm{HGgh}}$ estimates) provided the best comparisons to $\mathrm{ET}_{0,\mathrm{PM}}$ estimates among all the methods tested in terms of the highest R^2 (42 stations) and lowest MBE (26 stations) across 67 stations located in the State (Table 2). However, in terms of the number of stations with minimum RMSE, this method was slightly poorer than the modified HG equation ($\mathrm{ET}_{0,\mathrm{HGM}}$ estimates). Results shown in Table 2 indicate that $\mathrm{ET}_{0,\mathrm{HGgh}}$ estimates compare favourably with $\mathrm{ET}_{0,\mathrm{PM}}$ estimates across all agro-climatic zones. But it must be noted that despite having the advantage of error minimization with an additional two parameters $\mathrm{ET}_{0,\mathrm{HGgh}}$ estimates did not yield substantially lower errors nor bias in comparison to $\mathrm{ET}_{0,\mathrm{HGM}}$ estimates (Table 2).

Therefore, from the overall results of performance analysis of the four HG equations considered in the present study, it appears that the modified HG equation (Equation (2)) with the local calibration of three parameters is the most preferred approach to obtain estimates of ET_0 with limited data which are closest to those obtained by the more data-intensive PM method (Equation (4)) in Karnataka State, India. Although replacing the mean temperature (T_{mean}) with the effective mean temperature (T_{eff}) defined by Equation (3c) provides slightly more accurate results (Tables 2 and 5), this benefit is offset by the need to optimize two additional parameters.

The novel 'favourable statistic-based' evaluation approach developed and implemented in this study appears to be extremely useful in extracting precise information on the relative performances of multiple models when they are evaluated using diverse statistical measures using large datasets.

DISCUSSION

The main focus of the present study was to evaluate the effect of simultaneous local calibration of all three parameters in the Hargreaves–Samani (HG) ET_0 equation on its accuracy in a region subject to significant spatial heterogeneity in climatic conditions. Also, the study considered the effect of replacing the mean air temperature (T_{mean}) variable in the HG equation with an effective air temperature

(T_{eff}) which uses variable weightages for the maximum and minimum air temperature variables. The analysis was carried out using climate records for the 11-year historical period (2006–2016) for 67 stations located in 10 different agro-climatic zones of Karnataka State, India. A comprehensive performance evaluation of the original HG equation with the standard parameters modified HG equation with the local calibration of three parameters, and local calibration of three alternative versions of the modified HG equation with the use of T_{eff} (Equations (3), (3a)–(3c)) was carried out. Accuracy of monthly mean daily ET_0 estimates by all five methods was assessed using ET_0 estimates by the FAO-56 PM equation as a reference considering stations pooled under different agro-climatic zones and also the entire study area.

Results indicated that the performance of the original HG equation during the validation phase was quite poor as reflected in low values of coefficient of determination (R^2) and high values of RMSE and MBE values across all zones. Among all the methods evaluated, this approach yielded the best values of performance statistics at the smallest number of stations in the study area. Therefore, it may be deduced that the standard values of the three parameters in Equation (1) do not apply to a large number of stations in Karnataka State if ET_0 estimates comparable to those by the PM method ($\mathrm{ET}_{0,\mathrm{PM}}$) are desired. On the other hand, results shown in Table 2 indicate that when the parameters of the HG equation (A, B, and C) were treated as unknowns (Equation (2)) and their optimal values were determined at each station by minimizing the sum of squared errors with reference to $\mathrm{ET}_{0,\mathrm{PM}}$ estimates, the accuracy of $\mathrm{ET}_{0,\mathrm{HG}}$ values improved significantly. It was noted that when Equation (2) with optimal values of A, B, and C was independently validated, RMSE values at most stations located across different agro-climatic zones were reduced by more than 50% in comparison to the original HG equation. Although R^2 values were quite low at a few stations, MBE values also improved indicating a reduction in bias in $\mathrm{ET}_{0,\mathrm{HGM}}$ estimates in comparison to $\mathrm{ET}_{0,\mathrm{PM}}$ estimates. This improvement in the performance of the modified HG equation was on account of the fact that the optimal parameter values were quite different from the standard values. For example, the mean value of parameter A varied over the range 0.0032–0.0067 for stations pooled under the 10 agro-climatic zones with a mean value of 0.0049 for the 67 stations in the study area indicating a significant departure from the standard value of 0.0023. Parameter B indicated much higher variability across the zones ranging from −0.74 to 34.95 with a mean value of 13.3 for the study area as against the standard value of 17.8. Although exhibiting comparatively lower variability, the mean value of parameter C was 0.27 for the study area with a range of 0.20–0.39 across the zones indicating a departure from the standard value of 0.5. Using station-wise values of optimized parameters, maps depicting spatial variabilities of A, B, and C were generated which will prove useful to researchers/practitioners to select location-specific values in the study area. Although preliminary analysis revealed that parameters A and B were correlated with station elevations, further studies are needed to explore the effect of other influencing variables before methods for regional parameter estimation can be developed. Results indicated that replacing T_{mean} with T_{eff} defined by Equation (3c) does offer a small increase in accuracy of ET_0 estimates, but this is offset by the need to optimize two additional parameters (g and h) in Equations (3) and (3c).

CONCLUSIONS

Overall results of this study lead to three important conclusions: (1) use of the original HG equation with standard values of parameters may yield ET_0 estimates which are quite different from those obtained by the FAO-56 recommended PM equation, and therefore, the local calibration of the HG equation is strongly recommended for the sake of accuracy. (2) The optimized parameters of the modified HG equations considered in this study showed significant variations between the 67 climate stations. Elevation seemed to explain about 60% of this variability for two of the parameters. The mean values of HG model parameters for different agro-climatic zones in the study area and also maps showing spatial variability of the parameters were developed for the benefit of practitioners who wished to obtain estimates of ET_0 comparable to the PM method using only air temperature data. (3) The original HG equation appears to adequately represent the most important variables, since replacing the T_{mean} term (with equal weightage for $T_{\max}$ and $T_{\min}$) with an alternative T_{eff} with variable weightages for these variables did not lead to any substantial improvement in accuracy of ET_0 estimates.

The limitation in the study was the equations that were calibrated with respect to PM ET_0 estimates and not with measured values. Also, relationships between optimal parameters and other terrain variables could not be established due to the limited spatial extent of the study area. However, the overall methodology developed in this study may be extended to other hydro-climatic regions to derive accurate estimates of ET_0 using minimal data inputs.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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