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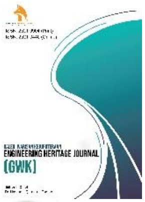

RESEARCH ARTICLE

CALIBRATION OF TWO MODELS FOR ESTIMATING REFERENCE EVAPOTRANSPIRATION BY USING FAO-56 PENMAN-MONTEITH MODEL UNDER ARID CONDITIONS

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ABSTRACT

The Penman-Monteith method (P-M) to estimate the reference evapotranspiration (ET$_o$) is the most reliable method and recommended by the FAO as the standard to verify other empi- rical methods. However, the Thornthwaite (Th) and Hargreaves-Samani (H-S) models are widely used because they are based on measurements of air temperature, frequently recorded in any meteorological stations. In this study, the daily meteorological parameters of air temperature, relative humidity, wind velocity, were available at six stations (Riyadh), (Ha'il), (Tabuk), (Turayf), (Makkah) and (Jazan). The net radiation was computed using a mathematical model based on a serie of related equations. Therefore, the application of Penman-Monteith became possible to calibrate the Thornthwaite and Hargreaves-Samani models. The local calibration of the both models (Th and H-S) in arid conditions is based on modifying the original coefficients of the named models using the ratio for estimated ET (Th and H-S mpdels) and the reference ET$_o$ of (P-M model). In the comparison, the indices of concordance (D), confidence (C), correlation coefficient (r) were analyzed, together with the root mean square error (RMSE) and Nash-Stucliff Efficiency (NSE). So, the ET of H-S model without adjustment were greater than the ET$_o$ of P-M during all the months at the total of the studied stations. Contrary, the use of non-adjusted Th ET show a smaller values of the monthly average in a total of the selected stations. After adjustment of the original coefficients of (0.0023) for H-S model and (1.6) for the Th model, we can obtain the new equations of estimating the monthly average of ET fitting better with the P-M Et$_o$ model.

KEYWORDS

Calibration, evapotranspiration, Hargreaves-Samani model, Thornthwaite model, Penman-Monteith model, Saudi Arabia.

1. INTRODUCTION

In the countries located in arid zones, the information about evapotranspiration (ET) is significant for water resources planning and human uses (Slabbers, 1977; Stefano and Ferro, 1997; Wu, 1997; Qiu et al., 2013; Benli et al., 2006). Also, ET is very important for understanding the spatial distribution of the natural plant communities (Monteith, 1964, 1965; DeVries et al., 2010). The knowledge and measurement of the changes in ET are necessary to understand any modification in the energy balance and the eco-hydrological changes (Kabenge et al., 2013; Kosugi and Katsuyama, 2007; Schume et al., 2005; Djaman and Irmak, 2013a; Djaman et al., 2013b; Irmak et al., 2013; Rijsberman and Frank, 2006). Potential ET is a related to the atmospheric forcing and surface types. In general, techniques for estimating ETo are based on one or more atmospheric variables, or on some measurements related to these variables, like pan evaporation (Bautista and Bautista, 2009).

The Penman-Monteith method (PM) is considered to be the most physical model and recommended by the FAO as the sole standard to verify other empirical methods (Allen et al., 1998). The FAO Penman-Monteith method is based on a strong theoretical basis, using the energy balances to model ETo. However, it needs four meteorological parameters: Air temperature, Relative humidity, Wind, and Net radiation, which may not be everywhere available (Smith et al., 1991; Camargo and Camargo, 2000).

Other methods as for example, Thornthwaite and Hargreaves require few meteorological data (Thornthwaite, 1948). So, these methods were developed for use in climate studies and are most applied to various climates similar to that where they were developed (Wilson et al., 2001; Berti et al., 2014; Bogawski and Bednorz, 2014; Manoj and Dholakia, 2013). In fact, these methods need recalibrating the constants involved in their formulae in order to be extrapolated to other climatic areas (Valiantzas, 2013; Ravanazzi et al., 2012; Rojas and Schiffield, 2013). Thornthwaite's model (TM) was developed the in east-central USA, based on mean air temperature, a widely available variable, and two tabular indexes: number of sunny hours, and monthly heat index (Jensen, 1973). So, the TM is not recommended for use in areas that are not climatically similar to the east-central USA.

In the hand, Hargreaves' model (HM) is a simple model based only on two meteorological parameters, temperature (mean, maximum and minimum) and incident radiation (Hargreaves and Samani, 1985). Although the incident radiation uses the extraterrestrial radiation (Ra) to estimate the ETo, for a given latitude and day. Ra can be obtained from tables or it can be calculated by means of a set of equations using temperature. In many and various regions, the meteorological stations do not have enough data to use PM. Therefore, many studies aim to develop statistical procedures for estimating regional and temporal adjustments to HM and TM in order to obtain the best estimations of ETo in arid regions (El-Nesr et al., 2010; Jabloun and Sahli, 2008; Mohawesh, 2011; Sabzipavar and Tabari, 2010).

In this study, Saudi Arabia area contains 25 meteorological stations have

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historical data for calibrating the TM and HM using the Penman-Monteith ETo. The objectives of this study were to evaluate the efficiency of the (TM and HM) equations using the PM model in arid climate. So, the kind of this study can be justified by the fact that temperature-based evaporation calculation methods, although widely criticized, are still widely used in climate studies in Saudi Arabia.

2. MATERIALS AND METHODS

2.1 Study Area

The daily data of the year 2017 were the recent available in 25 meteorological stations located in contrasting environmental conditions of various regions in Saudi Arabia. The selected meteorological stations are supervised by the General Authority of Meteorology and Environmental Protection (GAMEP) (Table 1). The geographic locations of the meteorological stations over Saudi Arabia are shown in Figure 1.

2.2 Materials and Dataset

In this study, the daily meteorological data recorded during 2017 at six Meteorological stations supervised by the General Authority of Meteorology and Environmental Protection (GAMEP) have been used (Table 3). The selected stations represent the diversity of Saudia Arabia relief.

Table 1: Meteorology Stations Distributed by Administrative Regions.

Region	Station Code	Station name	Longitude (E)	Latitude (N)	Elevation (m)
1- Ar Riyad	40437	Riyadh KK Airport	46°43'19"	24°55'31"	613.6
2- Makkah Al Mukarramah	41030	Makkah	39°46'08"	21°26'16"	240.4
3- Ha'il	40394	Ha'il	41°41'28"	27°26'04"	1001.5
4- Tabuk	40375	Tabuk	36°36'25"	28°22'35"	768.1
5- Northern Boundries	40356	Turayf	38°44'22"	31°41'16"	852.4
6- Jazan	41140	Jazan	42°35'05"	16°53'49"	7.2

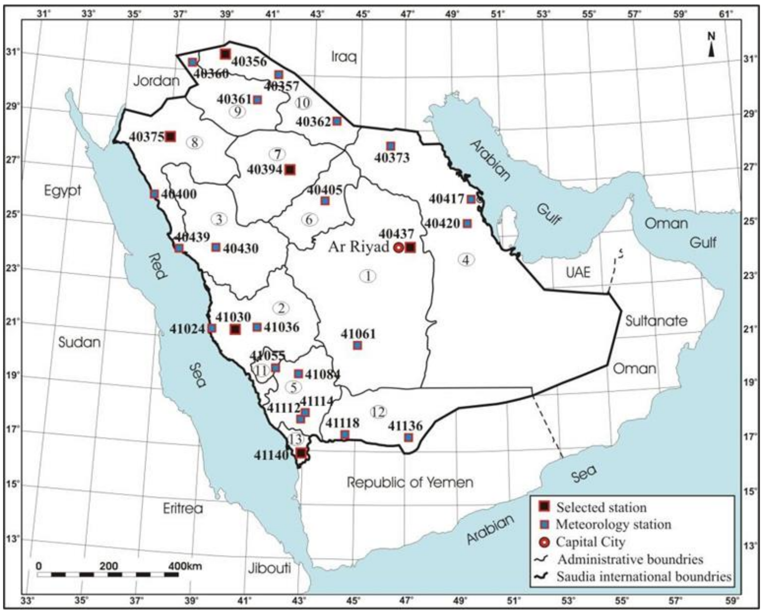

Figure 1: The spatial distribution of the meteorology stations.

Table 3: Climatic Variables Recorded at The Selected Stations.

Month	Riyadh				Turayf				Tabuk			
	T'	Tx	Tm	Ra	T'	Tx	Tm	Ra	T'	Tx	Tm	Ra
Jan	21.9	9.4	37.5	24.2	6.6	12.3	0.8	20.3	11.9	18.8	4.9	22.2
Feb	26.0	11.4	29.6	28.3	6.5	14.5	(-1.6)	30.6	12.0	19.4	4.6	26.6
Mar	31.1	16.9	23.5	33.3	13.1	19.7	6.4	30.9	18.0	25.2	10.7	32.1
Apr	32.3	19.8	33.9	37.5	16.9	25.7	8.1	40.0	23.6	31.1	16.0	37.1
May	38.0	24.9	16.4	39.8	21.0	31.5	10.4	41.3	28.1	35.7	20.5	40.0
Jun	42.8	28.6	10.5	40.5	24.2	36.0	12.4	40.6	31.7	39.4	23.9	41.0
Jul	45.0	30.1	8.8	40.0	28.2	41.0	15.3	40.6	34.7	41.5	27.9	40.4
Aug	44.5	29.0	11.3	38.2	27.4	39.5	15.3	37.7	34.4	42.0	26.8	38.0
Sep	40.8	24.7	10.6	34.6	25.4	37.1	13.7	32.7	30.9	38.4	23.4	33.7
Oct	36.0	20.5	17.4	29.6	18.9	28.3	9.5	26.5	24.0	31.4	16.6	28.1
Nov	27.2	14.8	36.2	25.0	14.0	21.2	6.8	21.2	18.2	24.7	11.7	23.1
Dec	22.4	7.5	31.7	22.9	10.6	18.8	2.4	18.8	15.2	22.8	7.5	20.8
Month	Ha'il				Makkah				Jazan			
	T'	Tx	Tm	Ra	T'	Tx	Tm	Ra	T'	Tx	Tm	Ra
Jan	11.9	18.7	5.1	23.7	26.7	33.0	20.3	26.2	26.8	31.1	22.5	29.6
Feb	12.7	20.4	4.9	23.7	25.6	31.3	19.9	29.9	27.6	32.0	23.2	32.4
Mar	18.1	24.7	11.5	23.8	28.9	35.0	22.8	34.3	28.9	33.2	24.5	35.4
Apr	24.1	31.5	16.6	24.0	33.5	40.2	26.7	37.8	31.6	36.4	26.8	37.2
May	27.3	34.6	19.9	24.1	36.5	42.8	30.1	39.5	33.3	37.7	28.8	37.5
Jun	30.5	38.0	22.9	24.1	37.7	44.8	30.5	39.9	34.5	38.4	30.6	37.2
Jul	31.6	38.9	24.2	24.1	37.9	44.7	31.1	39.6	35.3	39.0	31.5	37.4
Aug	32.8	40.6	25.0	24.1	37.6	44.0	31.2	38.2	34.6	38.5	30.6	37.4
Sep	30.2	38.3	22.1	24.0	37.1	44.2	30.0	35.3	33.9	38.2	29.5	36.3
Oct	25.9	33.3	18.4	23.8	34.5	41.9	27.0	31.0	31.9	36.7	27.0	33.5
Nov	16.2	23.5	8.8	23.7	30.6	36.7	24.4	26.7	30.1	34.7	25.5	30.3
Dec	14.5	21.7	7.3	23.7	28.7	35.6	21.8	24.9	27.8	32.1	23.4	28.7

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2.3 Description of the Models for the Estimation of ET And Eto

2.3.1 Penman-Monteith Model (P-M)

The estimation of ETo with Penman-Monteith model uses the following equation:

$$\mathrm{Etp}\ (\mathrm{mm.day^{-1}}) = \frac{0.408\Delta R_n - G + \gamma\left(\frac{900}{T+273.16}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

Where Δ is the slope of the saturation vapor pressure versus air temperature curve (kPa °C^{-1}); Rn is the daily net radiation (MJm^{-2}d^{-1}); G is the soil heat flux (MJm^{-2}d^{-1}); γ is the psychrometric constant (kPa°C^{-1}); T is the daily mean temperature of the air at 2 m of height (°C); U_2 is the daily mean of wind speed at 2 m of height (m s^{-1}); e_s is the saturation vapour pressure (kPa); e_a is the actual vapour pressure (kPa) (Allen et al., 1998).

The parameters of Eq. (1) can be estimated from the observed climatic variables. But, the missing climatic data of **Net Solar radiation** can be estimated empirically. The Net radiation (R_n) is computed as the algebraic sum of the net short and long wave radiation (R_{ns} and R_{nl}, respectively).

$$R_n = R_{ns} - R_{nl} \quad (2)$$

Where, R_{ns} results from the balance between incoming and reflected solar radiation (R_s) adopting an albedo of 0.23 as follows:

$$R_{ns} = (1 - \alpha)\ R_s \quad (3)$$

R_s is not measured, it can be estimated from the observed duration of sunshine hours with the Angstrôm equation (Angstrôm, 1924):

$$R_s = \left(0.25 + 0.5\frac{n}{N}\right)R_a \quad (4)$$

where R_s is solar or shortwave radiation (MJ m^{-2} day^{-1}), n is actual sunshine duration (h). It can be computed by the following equation:

$$n = \frac{2}{15}\omega_s \quad (5)$$

where ω_s is the sunset hour angle, given by:

$$\omega_s = \mathrm{Cos}^{-1}\ (-\tan\text{Ø}\ \tan\delta) \quad (6)$$

where Ø is the latitude angle in [rad] and δ is the solar decimation in [rad], computed by:

$$\delta = 0.409\mathrm{Sin}\left[\frac{2\pi}{365}J - 1.39\right] \quad (7)$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December).

N is the maximum possible sunshine duration (h). It can be computed by the following equation:

$$N = \frac{24}{\pi}\omega_s \quad (8)$$

n/N is relative sunshine duration, R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}), computed for any given day as a function of the latitude of the site as follows:

$$R_a = \frac{24(60)}{\pi}G_{sc}d_r[\omega_s \mathrm{Sin}\text{Ø}\mathrm{Sin}\delta + \mathrm{Cos}\text{Ø}\mathrm{Cos}\delta\mathrm{Sin}\omega \quad (9)$$

where G_{sc} is the solar constant equals 0.0820 MJ m^{-2} min^{-1} and d_r is the inverse relative distance Earth-Sun given by:

$$d_r = 1 + 0.033\ \mathrm{Cos}\left[\frac{2\pi}{365}J\right] \quad (10)$$

R_{nl} results from the balance between the down-coming and the outgoing long wave radiation emitted by the vegetation and the soil. Computations were performed as proposed by (Allen et al., 1998).

where:

$$R_{nl} = \sigma\left[\frac{T_{max}{}^4(\,^oK) - T_{min}{}^4(\,^oK)}{2}\right][0.34 - 0.14\sqrt{e_a}]\left[1.35\frac{R_s}{R_{so}} - 0.35\right] \quad (11)$$

R_{nl} , net outgoing long wave radiation [MJ m^{-2} day^{-1}],

σ , Stefan-Boltzmann constant [4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}],

T_{max} (°K), maximum absolute temperature during the 24-hour period [°K = °C + 273.16], $T_{min,}$ (°K), minimum absolute temperature during the 24-hour period [°K = °C + 273.16], ea , actual vapour pressure [kPa],

Rs/Rso relative shortwave radiation (limited to ≤ 1.0), Rs , shortwave radiation by equation (4) [MJ m-2 day-1],

Rso , calculated clear-sky radiation [MJ m-2 day-1] by the follows equation :

$$\mathrm{Rso} = (0.75 + 2 * 10\text{-}5\ z)\ \mathrm{Ra} \quad (12)$$

Where z station elevation above sea level [m] and Ra is extraterrestrial radiation (MJ m−2 day−1) computed by the equation (9).

2.3.1 Reference Evapotranspiration Estimation Models

Table 2 summarized the selected ET models and the required climatic variables for every model.

Table 2: Required Climatic Variables of Calibrated ET Models

ET_o Model	Data base	Scale	Reference
Thornthwaite	Tj’	Monthly	Thornthwaite, 1948
Hargreaves-Samani	Tx, Tm, T’, Ra, Rs	Daily	Hargreaves-Samani, 1985

Tj’: monthly average of temperature (°C), T’: daily average of temperature (°C), Tx: daily average of maximum temperature (°C), Tm: daily average of minimum temperature (°C), Ra: extraterrestrial radiation (MJm^{-2}day^{-1}), Rs: solar radiation (MJm^{-2}day^{-1}).

2.3.1.1 Hargreaves-Samani Model (H-S)

The estimation of ET with Hargeaves-Samani model uses the following equation:

The HS method requires only observed T_{min} and T_{max} for the estimation of ETo (mm day^{-1}), which is given as (Hargreaves and Samani, 1985):

$$\mathrm{ET}\ (\mathrm{mm\ day^{-1}}) = C_i\ [T'(^oC) + 17.8]\ [T_{max}\ (^oC) - T_{min}\ (^oC)]^{0.5}\ R_a \quad (13)$$

where:

ETo, daily evapotranspiration (mm day^{-1}),

T_{max}, T_{min}, T’ are the daily maximum, minimum and mean air temperature (°C), respectively, C_i = 0.002 is the original empirical constant proposed by Hargreaves and Samani, Ra, the water equivalent of the extraterrestrial radiation (mm day^{-1}) (Hargreaves and Samani, 1985).

2.3.1.1 Thornthwaite model (Th)

Thornthwaite analyzed this effect of air temperature on transports water from the earth to atmosphere with data of evapotranspiration (Thornthwaite, 1948). He found that a general form of the relation can be: $e = Ct^a$; where e, is the monthly evapotranspiration in centimeters and (t) is the mean air temperature in °C. The coefficients (C) and (a) vary from place and season. Thornthwaite proposed a general equation with a value of C = 16. Since the calculation of the evapotranspiration is not appropriate in areas with a monthly average temperature less than 0, an equation was developed to integrate this parameter, which corresponds to the monthly (i) and annual (I) heat index (Bautista et al., 2009). Based on these, he proposed calculating the exponent (a). An adjustment factor relating to the specific number of days per month and hours of sunlight, depending on the season and latitude is integrated to the equation. Finally, Thornthwaite proposed the following equation of the monthly evapotranspiration (Thornthwaite, 1948):

$$\mathrm{ETP\ (cm)} = 1.6\ (b)\left[\frac{10\ .\ T_j}{I_j}\right]^{\alpha} \quad (14)$$

Where:

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ETP: monthly evapotranspiration (cm).

I : sum of the monthly thermal Index, $i_j = (T'/5)^{1.514}$ T' : monthly mean temperature (°C),

$\alpha = 0.49239 + (1792 \times 10^{-5}\, i_j) - (771 \times 10^{-7}\, i^{2}) + (675 \times 10^{-9}\, i^{3})$

j j

b : reduction factor, given by the following equation :

$$b = y_o + (X - X_o)\frac{(y_1 - y_o)}{(X_1 - X_o)} \tag{15}$$

where :

X: station latitude.

y_o: tabulated value of reduction factor corresponds to the month and the latitude N preceding the station latitude.

y_1: tabulated value of reduction factor corresponds to the month and the latitude S next station latitude

X_o: latitude N preceding the station site. X_1 : latitude S next the station site.

2.4 Adjustment of Models

The test estimations of ET_o with Hargreaves-Samani H-SM, Thornthwaite (TM), Schendel, Ivanov and Blaney-Criddle models were adjusted to the result of the reference equation, that is Penman-Monteith (P-MM). Adjustments were made by changing the value of the corresponding constant, (C_i) in the case of Hargreaves-Samani, (C) in the case of Thornthwaite, (k) in the case of Blaney-Criddle and (a) in the cases of Ivanov and Schendel, with the original values of 0.0023, 16, 0.85 and 0.45, 0.0018 and 16 respectively (Borges and Mendiondo, 2007).

The adjusted values of the ET coefficients can be computed as follows: (a)-Hargreaves-Samani model

$$\mathbf{C_i adj = (0.0023) / ET(H\text{-}S) / ET_o\,(PM)} \tag{16}$$

(b)- Thornthwaite model:

$$\mathbf{C_i adj = (1.6) / ETP(Thornthwaite) / ET_o\,(PM)} \tag{17}$$

2.5 Model Performance Evaluation

The performance models was evaluated using five statistical indicators, which are : (Table 3).

Table 3: Statistical Indicators Used for The Performance Evaluation of Eto Models.

Statistical Indicator	Formula	Decision Rule	Reference
Concordance index (D)	$D = 1 - \frac{\sum_{i:1}^{n}(P_i - O_i)^2}{\sum_{i:1}^{n}(\lvert P_i - O'\rvert + \lvert O_i - O'\rvert)^2}$	Higher values are preferred	Bautista et al., 2009
Correlation coefficient	$r = \frac{\sum_{i=1}^{n}(O_i - O')(P_i - P')}{\sqrt{\sum_{i=1}^{n}(O_i - O')^2 \sum_{i=1}^{n}(P_i - P')^2}}$	0.80 ≤ r < 1.00 , Excellent 0.60 ≤ r < 0.60 , Very good 0.40 ≤ r < 0.70 , Good 0.20 ≤ r < 0.70 , Acceptable r < 0.20 , Unsatisfactory	Mohamed et al., 2018
RMSE-observations standard deviation ratio model	$RSR = \frac{\sqrt{\sum_{i:1}^{n}(O_i - P_i)^2}}{\sqrt{\sum_{i:1}^{n}(O_i - O')^2}}$	0.00 ≤ RSR < 0.50 , Excellent 0.50 ≤ RSR < 0.60 , Satisfactory 0.60 ≤ RSR < 0.70 , Acceptable RSR > 0.70 , Unsatisfactory	Moriasi et al., 2007
Nash-Stucliff Efficiency	$NSE = 1 - \frac{\sum_{i:1}^{n}(P_i - O_i)^2}{\sum_{i:1}^{n}(O_i - O')^2}$	0.8 ≤ NSE < 1 , Excellent 0.65 ≤ NSE < 0.8 , Satisfactory 0.5 ≤ NSE < 0.65 , Acceptable NSE > 0.5 , Unsatisfactory	Tajeda et al., 2022

n : number of observations, O_i : the value of Penman-Montetith model (PM), O' : the mean of Penman- Monteith model (PM), P_i : the value of the tested models Hargreaves-Samani (H-S).and Thornthwaite (Th).

3. RESULTS AND DISCUSSIONS

3.1 Comparison of P-M ET_o with Two Models Without Adjustment

From table 4 and the figure 2, the Penman-Monteith ET_o exceed those estimated by the Tornthwaite model during the different months, with a difference between 0.7% and 155.9% in the Riyadh and between 55.1% and 165.1% in the Jazan. The P-M ET_o also exceed their estimated counterparts during the various months of the year at Hail and Turayf, except for the winter months (December-January-February). During these months, the difference between the estimated and reference values ranged between 4.7% and 17.7% at Hail and between 5.1% and 49.4% at Turayf. During the various months of the year the P-M ET_o values exceed their estimated counterparts at Tabuk, except for the month of January, which is characterized by a monthly average greater with 6.8%. At the Makkah station, it also exceeds All P-M ET_o exceed the estimated during the various months of the year, except for December, which is characterized by a monthly average greater with 9.7% than the P-M model. Contrary to the Tornthwaite estimates, all the estimated values of the HS model are greater than the P-M ET_o during the different months of the year for all stations with a difference ranging between 53.5% (January) and 59.8% (July) in Riyadh, 70.3% (July) and 70.4% (December) in Hail, 47.0% (January) and 71.9% (June) in Tabuk, 46.5% (January) and 63.9% (July) in Turaif, 52.2% (January) and 50.0% (April) in Jizan, and between 59.7% (February) and 72.6% % (June) in Makkah.

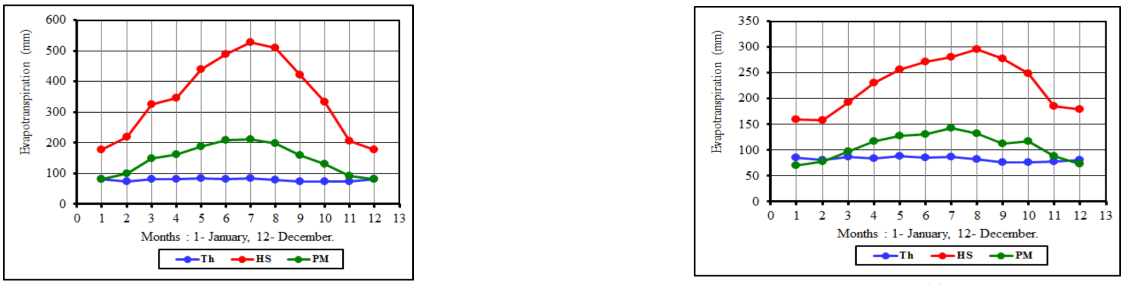
The evapotranspiration estimates from both models (PM vs. HM and PM vs. TM) were compared using simple error analysis. The models were compared before and after adjustment. For each location, the following parameters were calculated: Nash-Stucliff Efficiency (NSE), Concordance index (D). Correlation coefficient and RMSE-observations standard deviation ratio model (RSR). Table 5 summarizes the performance results.

The linear regression models between PM and Thornthwaite without adjustment present a negative correlation at Tabuk and the lower correlation values of (r), ranged from 0.20 to 0.47 for the stations of Ha'il, Riyadh and Makkah. But the correlation for Turayf and Jazan are excellent with (0.86 < r < 0.89) respectively. The low values of (r) can be explained by the slope and the value of origin in the y-axis of Thornthwaite ET (Figure 3). For this reason, the confidence index (C) values are also low and ranged from 0.07 to 0.14 , for Ha'il and Turayf, respectively. In the same context, the (1.1 < RSR < 1.7), (-0.1 < NSE < -0.7) and (0.16 < D < 0.66), the (RSR), (NSE) and (D) parameters are unsatisfactory for the named stations.

With HS model, we obtained over-estimations of ET during all the months in total of selected stations. The linear regression models of the monthly relationship between PM and Hargreaves-Samani without adjustment are higher and better than obtained between PM and Thornthwaite models (Table 5 and Figure 4).

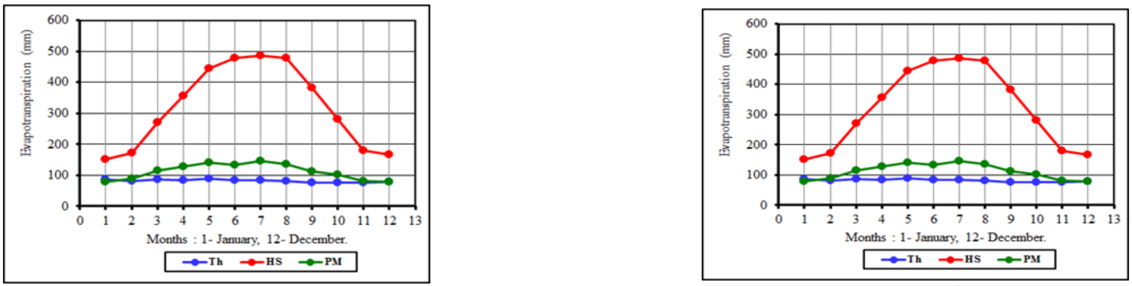
Table 4: Monthly Average of Estimated ET and Reference Et_o at The Selected Stations.

Month	Riyadh			Turayf			Tabuk		
	ET Thorn.	**ET H-S**	**ET_o P-M**	**ET Thorn.**	**ET H-S**	**ET_o P-M**	**ET Thorn.**	**ET H-S**	**ET_o P-M**
Jan	81.2	176.8	82.3	109.5	103.5	55.4	85.5	152.2	79.7
Feb	74.0	217.8	99.2	122.5	166.8	80.4	82.2	171.1	90.0
Mar	80.7	325.0	149.3	104.7	216.7	117.1	87.1	269.9	115.2
Apr	81.6	347.1	162.3	104.1	347.8	151.2	84.6	356.9	129.0
May	84.3	439.0	188.3	108.9	454.9	192.2	88.1	444.4	140.9
Jun	80.4	489.6	207.4	104.3	495.5	192.9	84.5	477.8	134.1
Jul	82.9	528.2	212.1	101.9	586.5	211.6	84.6	485.2	146.8
Aug	78.8	508.8	198.8	97.2	518.9	195.1	80.9	479.0	136.2
Sep	74.0	420.0	160.2	89.0	410.7	166.5	75.4	381.9	112.5
Oct	74.3	332.1	130.4	90.2	261.2	126.0	77.0	280.0	102.4
Nov	73.8	205.5	92.6	86.7	154.6	82.3	75.5	180.3	82.4
Dec	80.8	177.7	81.4	97.1	133.4	68.0	78.7	165.9	79.1
Month	**Ha'il**			**Makkah**			**Jazan**		
	ET Thorn.	**ET H-S**	**ET_o P-M**	**ET Thorn.**	**ET H-S**	**ET_o P-M**	**ET Thorn.**	**ET H-S**	**ET_o P-M**
Jan	86.0	159.8	70.8	71.8	255.7	83.8	73.5	240.3	114.8
Feb	81.4	158.7	77.6	70.5	243.4	98.1	68.2	243.4	120.2
Mar	86.9	192.1	98.1	78.1	346.5	134.3	76.9	301.2	162.5
Apr	83.9	230.5	116.9	77.1	426.8	144.8	76.1	339.4	169.7
May	88.5	255.8	127.2	82.2	472.7	150.3	80.1	351.6	191.9
Jun	84.9	270.7	130.7	79.7	500.5	137.0	77.9	325.2	179.2
Jul	86.4	280.8	143.3	79.8	502.7	143.5	79.4	336.0	210.5
Aug	81.7	296.2	132.4	80.3	468.0	147.9	78.1	339.6	193.9
Sep	75.8	277.7	112.2	73.8	437.4	124.9	73.0	331.1	163.3
Oct	75.6	248.6	117.0	73.3	388.0	105.0	73.1	319.6	152.4
Nov	78.2	185.4	88.9	71.0	272.8	87.3	69.8	263.9	131.6
Dec	80.1	179.4	73.2	72.0	266.7	65.3	72.0	238.6	111.7



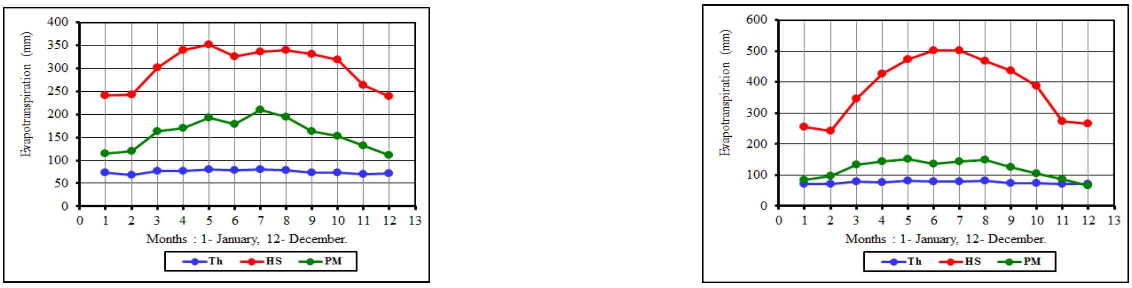
A : Riyadh

B : Ha'il



C: Tabuk

D: Turayf



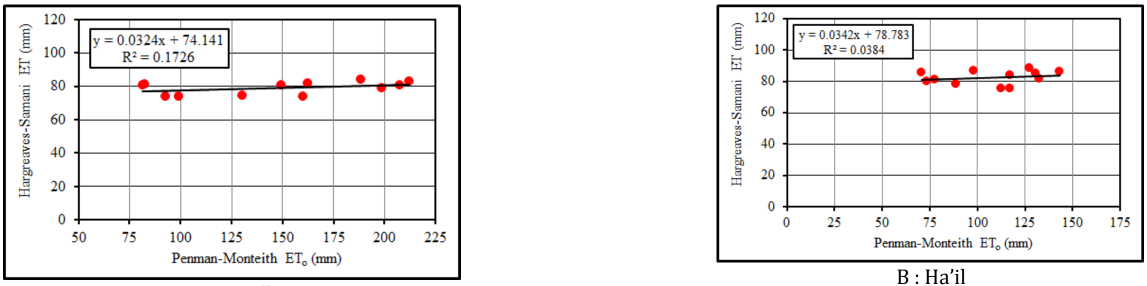
E : Jazan

F: Makkah

Figure 2: Monthly ETo Estimated by Hargreaves-Samani, Thornthwaite and Penman-Monteith Methods.

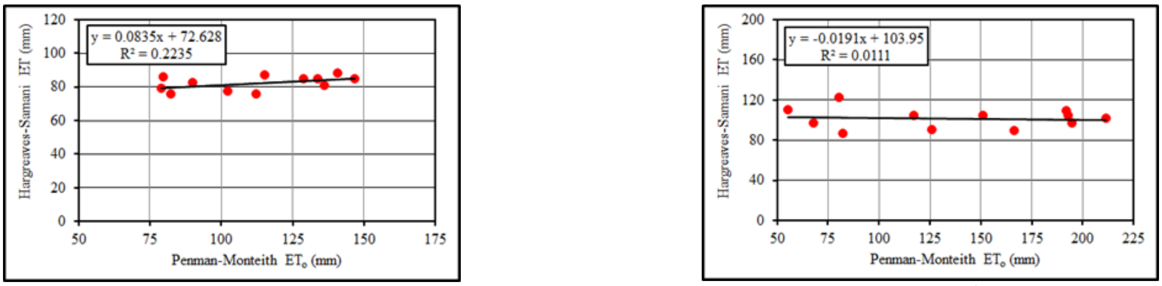
Table 5: Performance Tests of Non-Adjusted ET Estimations

Model Performance	PM-Thornthwaite					PM-H-S				
	RSR	NSE	r	D	C	RSR	NSE	r	D	C
Riyadh	1.32	-0.32	0.42	0.27	0.11	2.14	-1.14	0.98	0.93	0.91
Ha;il	1.20	-0.20	0.20	0.33	0.07	2.27	-1.27	0.33	0.94	0.31
Makkah	1.33	-0.33	0.47	0.29	0.14	3.12	-2.12	0.96	0.91	0.87
Tabuk	1.25	-0.25	(-0.11)	0.39	(-0.04)	3.11	-2.11	0.99	0.91	0.90
Turayf	1.11	-0.11	0.86	0.16	0.14	2.00	-1.00	0.92	0.94	0.86
Jazan	1.67	-0.67	0.89	0.66	0.59	1.27	-0.27	0.87	0.93	0.81



A : Riyadh

B : Ha'il



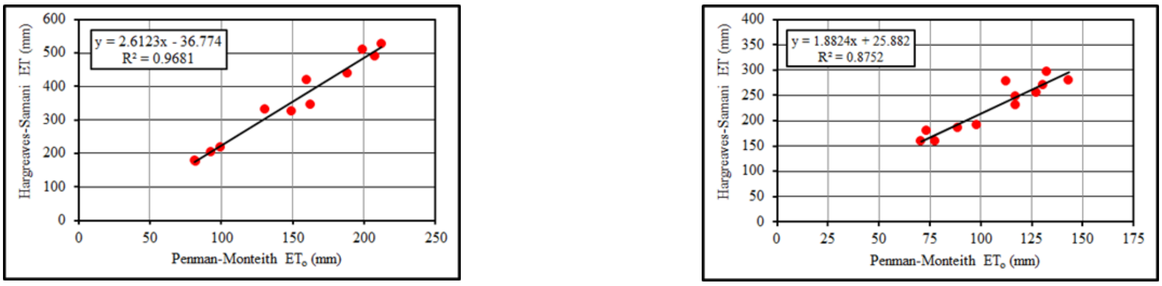
C : Tabuk

D : Turayf

E : Jazan

F: Makkah

Figure 3: Regression Models for Penman (Et_o) and Thornthwaite (ET) Without Adjustment.

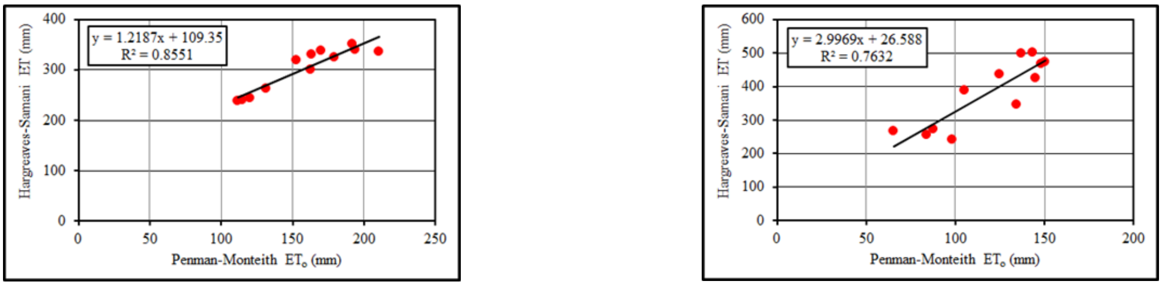


A : Riyadh

B : Ha'il

C : Tabuk

D : Turayf



E: Jazan

F: Makkah

Figure 4: Regression models for Penman (ET_o) and Hargeaves-Samani (ET) without adjustment.

However, in meteorological stations tested, the Thornthwaite model had a lower “D” and “C” index than that of H-S and P-M models. So, the equation of Thornthwaite has been one of the most misused empirical equations generating inacurrate estimates of evapotranspiration for arid and semi-arid areas (Bautista and Bautista, 2009). In dry climatic conditions, many authors concluded that the Thornthwaite model gives the unreliable results of the ET estimations (Chen et al., 2005; Hashimi and Habiban, 1979). So, many researchers propose the modified Thornthwaite equation to improve the performance model in different climatic conditions (Pereira and Pruitt, 2004). Consequently, the ET over- estimations of H-S model and the ET underestimations of Thornthwaite model are modified with changing the values of the original constants of model equations.

3.2 Determination of The Adjusted Constants for HM And TM

The test estimations of ET_o with Hargreaves-Samani and Thornthwaite were adjusted to the result of the reference equation, that is Penman-Monteith. The determination of the new values of the constants (C_i) of Hargreaves-Samani (eq. 16) and Thornthwaite (eq. 17) were calculated for each month respectively. Table 6 summarized the mean of the adjusted constants in every meteorological station.

The adjusted constant is obtained by the ratio of the estimated ET of Thornthwaite and Hagreaves-Samani models and the ETo of Penman-Monteith model using the equations (eq.16 & eq. 17). For the Thornthwaite model all the adjusted constant values is smaller than the original constant (1.6) from February to November at Riyadh and Tabuk, March to November at Ha’il, March to October at Turayf, January to November at Makkah and during the year at Jazan. The value of the constant of adjusted HM is greater than the value of the original constant (0.0023) in the total of the months and in the total of studied stations. So, the proposed values of the adjusted constant are ranged from 0.0049 to 0.006 fo Riyadh, 0.0045 to 0.0094 for Ha’il, 0.004 to 0.0082 for Tabuk, 0.0046 to 0.0064 for Turayf, 0.0057 to 0.0094 for Makkah and from 0.0037 to 0.0093 for Jazan.

3.3 Comparison of PM Eto with Adjusted Models

After adjusting the original constants of both models Thornthwaite and Hargeaves- Samani, the adjusted estimations of ET were summarized in the table 7. Many statistical methods are used to compare the predicted and observed estimations (Efhimiou et al., 2013). In this study, four types of measures are applied to assess the performance of the adjusted ET estimations of Thornthwaite and Hargreaves models using Penman-Monteith ET_o: Nash-Stucliff Efficiency (NSE), Concordance index (D). Correlation coefficient and RMSE-observations standard deviation ratio model (RSR). Table 8 summarizes the performance results.

From table 7, the new monthly adjusted constants exceed the original value (1.6) for the Yhornthwaite model, during all the months, except December and January in Turayf station. While, the adjusted values of the H-S model are smaller than the original value (0.0023) for all the months in the total studied stations. After adjusting the value of the original constants, the performance efficiency of both models Thornthwaite and Hargreaves-Samani was significantly improved (Table 8).

Consequently, we propose the new models equations using the adjusted constant deriving from the average of the monthly constant (Table 10).

Table 6: Adjusted Constants of Original Equations of The Thornthwaite (Th) and Hargreaves-Samani (HS) Models.

Month	Riyadh		Ha'il		Tabuk	
	Th	**HS**	**Th**	**HS**	**Th**	**HS**
Jan	1.62	0.0011	1.32	0.0010	1.49	0.0012
Feb	2.14	0.0010	1.52	0.0011	1.75	0.0012
Mar	2.96	0.0011	1.81	0.0012	2.11	0.0010
Apr	3.18	0.0011	2.23	0.0012	2.44	0.0008
May	3.57	0.0010	2.30	0.0011	2.56	0.0007
Jun	4.13	0.0010	2.46	0.0011	2.54	0.0006
Jul	4.09	0.0009	2.66	0.0012	2.78	0.0007
Aug	4.04	0.0009	2.59	0.0010	2.69	0.0007
Sep	3.46	0.0009	2.37	0.0009	2.39	0.0007
Oct	2.81	0.0009	2.48	0.0011	2.13	0.0008
Nov	2.01	0.0010	1.82	0.0011	1.75	0.0011
Dec	1.61	0.0011	1.46	0.0009	1.61	0.0011
Month	**Turayf**		**Makkah**		**Jazan**	
	Th	**HS**	**Th**	**HS**	**Th**	**HS**
Jan	0.81	0.0012	1.87	0.0008	2.50	0.0011
Feb	1.05	0.0011	2.23	0.0009	2.82	0.0006
Mar	1.79	0.0012	2.75	0.0009	3.38	0.0012
Apr	2.32	0.0010	3.01	0.0008	3.57	0.0011
May	2.82	0.0010	2.93	0.0007	3.83	0.0013
Jun	2.96	0.0009	2.75	0.0006	3.68	0.0013
Jul	3.32	0.0008	2.88	0.0007	4.24	0.0014
Aug	3.21	0.0009	2.94	0.0007	3.97	0.0013
Sep	2.99	0.0009	2.71	0.0007	3.58	0.0011
Oct	2.23	0.0011	2.29	0.0006	3.34	0.0011
Nov	1.52	0.0012	1.97	0.0007	3.02	0.0011
Dec	1.12	0.0012	1.45	0.0006	2.48	0.0011

Table 7: Adjusted ET Estimations of the Thornthwaite (Th) and Hargreaves-Samani (HS) Models.

Month	Riyadh		Ha'il		Tabuk	
	Th	**HS**	**Th**	**HS**	**Th**	**HS**
Jan	82.2	84.6	70.9	69.5	79.7	79.4
Feb	99.0	94.7	77.4	75.9	89.9	89.3
Mar	149.0	155.4	98.3	100.2	114.9	117.3
Apr	162.1	166.0	116.9	120.3	129.0	124.1
May	188.0	190.9	127.2	122.3	140.9	135.3
Jun	207.6	212.9	130.6	129.5	134.2	124.6
Jul	211.9	206.7	143.6	146.5	147.0	147.7
Aug	199.0	199.1	132.2	128.8	136.0	145.8
Sep	160.0	164.3	112.2	108.7	112.6	116.2
Oct	130.6	130.0	117.2	118.9	102.5	97.4
Nov	92.8	89.3	88.9	88.7	82.6	86.2
Dec	81.3	85.0	73.1	70.2	79.2	79.3
Month	**Turayf**		**Makkah**		**Jazan**	
	Th	**HS**	**Th**	**HS**	**Th**	**HS**
Jan	55.4	54.0	83.9	88.9	114.8	114.9
Feb	80.4	79.8	98.2	95.2	120.2	127.0
Mar	117.1	113.1	134.3	135.6	162.5	157.1
Apr	150.9	151.2	145.0	148.5	169.7	162.3
May	191.9	197.8	150.5	143.9	191.7	198.7
Jun	193.0	193.9	137.0	130.6	179.2	183.8
Jul	211.5	204.0	143.6	153.0	210.3	204.5
Aug	194.9	203.0	147.6	142.4	193.8	191.9
Sep	166.4	160.7	124.9	133.1	163.2	158.4
Oct	125.8	124.9	105.0	101.2	152.7	152.9
Nov	82.4	80.7	87.5	83.0	131.7	126.2
Dec	67.9	69.6	65.3	69.6	111.6	**114.1**

Table 8: Performance Tests of the Adjusted ET Estimations

Model Performance	PM-Thornthwaite					PM-H-S				
	RSR	NSE	r	D	C	RSR	NSE	r	D	C
Riyadh	0.07	0.93	0.57	1.00	0.57	0.29	0.71	0.23	1.00	0.23
Ha;il	0.08	0.92	0.69	1.00	0.69	0.34	0.64	0.10	1.00	0.10
Makkah	0.07	0.93	0.55	1.00	0.55	0.45	0.55	0.10	1.00	0.10
Tabuk	0.08	0.92	0.62	1.00	0.62	0.45	0.55	0.11	1.00	0.11
Turayf	0.05	0.95	0.83	1.00	0.83	0.28	0.72	0.28	0.95	0.27
Jazan	0.06	0.94	0.35	1.00	0.35	0.24	0.60	0.21	1.00	0.21

Table 10: The Adjusted Models of Thornthwaite and Hargreaves-Samani.

Station	Thornthwaite	Hargreaves-Samani
Riyadh	$\mathrm{ETP\ (cm)} = 2.97\ (b) \left[\frac{10\ .\ T_j}{I_j}\right]^{\alpha}$	$\mathrm{ET(mm.day^{-1})} = 0.0010\ [T'(^{o}C) + 17.8]\ [T_x(^{o}C) - T_m(^{o}C)]^{0.5} R_a$
Ha’il	$\mathrm{ETP\ (cm)} = 2.09\ (b) \left[\frac{10\ .\ T_j}{I_j}\right]^{\alpha}$	$\mathrm{ET(mm.day^{-1})} = 0.0011\ [T'(^{o}C) + 17.8]\ [T_x(^{o}C) - T_m(^{o}C)]^{0.5} R_a$
Tabuk	$\mathrm{ETP\ (cm)} = 2.19\ (b) \left[\frac{10\ .\ T_j}{I_j}\right]^{\alpha}$	$\mathrm{ET(mm.day^{-1})} = 0.0009\ [T'(^{o}C) + 17.8]\ [T_x(^{o}C) - T_m(^{o}C)]^{0.5} R_a$
Turaf	$\mathrm{ETP\ (cm)} = 2.18\ (b) \left[\frac{10\ .\ T_j}{I_j}\right]^{\alpha}$	$\mathrm{ET(mm.day^{-1})} = 0.0010\ [T'(^{o}C) + 17.8]\ [T_x(^{o}C) - T_m(^{o}C)]^{0.5} R_a$
Makkah	$\mathrm{ETP\ (cm)} = 2.48\ (b) \left[\frac{10\ .\ T_j}{I_j}\right]^{\alpha}$	$\mathrm{ET(mm.day^{-1})} = 0.0007\ [T'(^{o}C) + 17.8]\ [T_x(^{o}C) - T_m(^{o}C)]^{0.5} R_a$
Jazan	$\mathrm{ETP\ (cm)} = 3.37\ (b) \left[\frac{10\ .\ T_j}{I_j}\right]^{\alpha}$	$\mathrm{ET(mm.day^{-1})} = 0.0011\ [T'(^{o}C) + 17.8]\ [T_x(^{o}C) - T_m(^{o}C)]^{0.5} R_a$

4. CONCLUSIONS

The ET estimations using Thornthwaite and H-S non adjusted equations showed that the two models are not suitable for arid study area. Consequently, the ET estimates of H-S model are greater than the ET_o P-M model over the study area. The difference between the estimates of the two models varying from 53 to 62% at Riyadh, 66 to 72% at Ha’il, 48 to 72% at Tabuk, 46 to 64% at Turayf, 60 to 76% at Makkah and from 43 to 53% at Jazan. In the other hand, the ET estimations using Thornthwaite are smaller than the ET_o P-M model with a difference ranged from 1 to 61% at Riyadh, 11 to 40% at Ha’il, 1 to 42% at Tabuk, 11 to 52% at Turayf, 14 to 46% at Makkah and from 36 to 62 at Jazan. During the winter season, the ET estimates of Thornthwaite model exceed than the ET_o reference of P-M model at Turayf and Ha’il; during December at Makkah and during January at Tabuk. The local calibration of ET estimates showed the possibility of modifying the original coefficients of Thornthwaite and H-S models. The two adjusted models can be suitable alternative to P-M model, which requires some climatic measurements that are not readily available in any meteorological station. So, this study conclude with six alternative equations for estimating the ET using the adjusted models of Thornwaite and H-S.

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