



Research article

Reformulating and testing Temesgen-Melesse's temperature-based evapotranspiration estimation method

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ARTICLE INFO

Keywords:

Atmospheric science
 Environmental analysis
 Environmental assessment
 Natural resource management
 Geophysics
 Calibrated TM equation
 ET estimation methods
 Modified TM equation
 PM equation

ABSTRACT

The use of FAO-56 Penman–Monteith (PM) equation is the recommended equation to estimate potential evapotranspiration. However, when data that satisfy the PM equation is not available or incomplete, the use of PM equation is not an option. In this study, one such method known as Temesgen-Melesse's (TM) method was assessed in relation to the PM equation using data of eight class-I meteorological stations in Ethiopia. In the study, first the problems with this method were identified and the TM equation was modified. The modifications made were replacement of the average maximum temperature at the denominator of the equation varying with time with the average of Tmax for each location (which is a constant for a given location). The Second consideration was calibrating the power of the maximum temperature at the numerator using PM data instead of taking it as a constant 2.5 suggested by the authors in their original equation. Then the three (the original TM, the modified TM with constant power of 2.5 and the modified TM with the power calibrated) methods were fitted against PM equation. Thereafter tests using statistical parameters, model tendency parameters and model performances were carried out. The results indicate the modified TM equation to be better than the original TM equation in terms of percent slope (0.8–12.3 against 1.3–15.1) and the correlation coefficient (R^2) and the slope (100% good or satisfactory against 25%). The modified and calibrated equation gave best results in terms of percent error by slope (0.5–2.3), by coefficient of efficiency (100% good or satisfactory), by R^2 and slope (100% good or satisfactory) and by mean percent error (5.7–13.6%). Therefore, whenever data that satisfy PM equation are available (even if for limited years), it is better to calibrate the power of the maximum temperature and to consider more decimal places rather than taking 2.5 as suggested by the authors. When data is not available it is better to use the modified TM equation rather than using the original TM equation. The study would benefit those who want to study long-term climate changes and drought patterns, which involve the use of evapotranspiration with limited data that satisfy the PM equation, but have long-term data of temperature.

1. Introduction

The use of FAO-Penman-Monteith (PM) evapotranspiration (ET) equation is not always a viable option for some locations of the world (Allen et al., 1998). The first reason is the availability of data that satisfy the PM equation (Xu and Singh, 2002). PM equation requires many variables for which hourly or at least daily data must be available (Aguilar and Polo, 2011). But many meteorological stations may not have all the measured data for all the variables required for ET estimation using the combination or the Penman-Monteith (PM) equation or there may be missing data (data-gap) for some of the variables used in PM equation. The quality and integrity of meteorological data may also be another problem (Jensen et al., 1997; Temesgen et al., 1999). The other challenge may be

data errors that can be due to instrument or human error (Semu Ayalew, 2010). The method requires independent calculations of latent heat of vaporization, λ , atmospheric pressure, P , saturation vapor pressure, e_s , actual vapor pressure, e_a , slope of vapor pressure curve, Δ , psychrometric constant, γ , short wave radiation on a clear sky day, R_{so} , extraterrestrial radiation for daily periods, R_a , net solar (shortwave) radiation, R_{ns} , long wave radiation, R_{nl} , net radiation, R_n and soil heat flux, G (Xu and Singh, 2002). On the one hand, there is a challenge of accurately estimating all these parameters (Semu Ayalew, 2010), for places where radiation is not measured but calculated some amount of error may be introduced in the final ET estimation (Xystrakis and Matzarakis, 2011).

In order to overcome these challenges, ET calculation methods (empirical equations) that involve fewer variables are preferred. The

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simpler empirical equations require less input variables (Xystrakis and Matzarakis, 2011). From among these methods there are those that involve radiation (e.g. Priestley and Taylor, 1972; Abtey, 1996) and temperature-based methods (e.g. Thornthwaite, 1948; Blaney and Cridle, 1950; Hargreaves and Samani, 1985; Pereira et al., 2015; Temesgen and Melesse, 2013) and (Valiantzas, 2013). Some of these methods are developed for specific climatic regions (Allen et al., 1998) and therefore regional evaluation and calibration may be necessary before their use (Xu and Singh, 2002; Aguilar and Polo, 2011). Radiation-based methods either use directly measured data or they are estimated from meteorological data such as maximum and minimum temperatures, sunshine hours, cloud, precipitation, latitude, elevation, etc. (Neto et al., 2015) and therefore are not simple in terms of calculation though they are quite simpler than the PM method. From all the three methods the ones involving temperature alone are considered to be the simplest. These are for three reasons. First, temperature is very easy to measure and the possibility of committing errors is very slim with this variable (Semu Ayalew, 2010). Second, it is measured by all meteorological stations despite the age or quality of the meteorological stations, and they are usually available for a longer period (Semu Ayalew, 2010). Temperature can also be reasonably interpolated in areas where measurements are scarce (Aguilar and Polo, 2011).

From among the temperature based methods Temesgen-Melesse's (TM) method (Temesgen and Melesse, 2013) is one of the simplest. The benefit of this method is that it uses only one meteorological variable, maximum temperature, T_{mx} , of the location. This makes the method very appealing since the data of T_{mx} is readily available at almost all meteorological stations. However, there are two challenges with this method. The first problem with this method is its inconsistency at high and low temperatures or ET values. Because of this inconsistency, whenever ET estimated by this method is plotted against the one obtained by the PM method, the fitted line crosses the 1:1 slope line (the line of ET-PM versus itself). Due to the crossing, this method overestimates ET below a certain critical ET and underestimates above the same critical ET. The over and underestimations are with respect to the ET calculated with the PM equation.

Its other challenge is the inadequacy of the maximum temperature power parameter (n) given by the authors. In their method, Temesgen and Melesse, 2013 used an 'n' value of 2.5 for all the stations they studied. They also did not go beyond a single digit after the decimal point. The use of only one figure after the decimal point has the potential to introduce bias that magnifies the disagreement between ET-PM and theirs. The developers of the method must have considered the averaged values of the powers obtained using data of different meteorological stations. However, since T_{mx} has a relatively high value, a slight change in the value of the power after the first decimal place results in a significant change of ET. Thus limiting the power to one decimal place is not an appropriate option. In other words, the power has to be location dependent and needs calibration. However, the calibration requires availability of data that satisfies PM equation, which may not be obtained for some stations.

This study attempts were made to address the two challenges of the TM equation and to come up with viable options. The challenges were addressed individually, first by replacing the T_{mx} at the denominator with a constant term and by obtaining the power of T_{mx} of the numerator by calibration for stations that have complete data to use PM equation.

The meteorological stations selected to test this method with the PM method are of different geographical locations especially in terms of altitude. Such altitude differences show differences among average maximum temperature that range between 19.8 °C (for Debre Birhan located on the highland of Ethiopia, 2750 m above sea level) to 27.8 °C (for stations located within the great African Rift valley, less than 1000 m above sea level). Such variability in temperature is advantageous to test applicability of any ET estimation method under different conditions.

2. Materials and methods

2.1. Stations used in this study

In this study, eight Class I Meteorological Stations that represent different climatic and geographical locations over Ethiopia were used. These stations are Addis Ababa, Addet, Bahir Dar, Dangla, Debre Birhan, Desse, Mekele and Metehara. The data period of each one of these stations is shown at the last column of Table 1. The locations of the study sites in the country are shown in Figure 1.

The geographical locations, some of the averaged-meteorological parameters and data periods of the stations are given in Table 1.

2.2. Data analysis

In this study, a temperature-based ET estimation method developed by Temesgen and Melesse (abbreviated as ET_{TM} or as ET-TM in figures), its two other versions (ET-TM_{mod} and ET-TM_{modopt}), were compared with the standard FAO-56 Penman-Monteith (ET_{PM} or ET-PM in figures) equation. In order to measure the performances of the three methods against ET-PM, different techniques were used. Method tendencies (overestimation/underestimation) were checked using the slope of the regression line (Ablewi, 2012), by Coefficient of Residual Mean (CRM) as recommended by Ablewi (2012) and by comparing with the 1:1 slope line. Thereafter, performances of the three methods against ET-PM equation were checked using Coefficient of Efficiency (CE) as recommended by TegosEstratiadis and Koutsoyiannis, 2013, Ablewi (2012) and Maule et al. (2006); by simultaneously considering the slope and correlation coefficient (R^2) of the regression line and the cross correlation between ET obtained by the three methods and ET-PM as suggested by Allen et al. (1998), Ablewi (2012), Xu and Singh (2001) and Wang et al. (2009); by coefficient of variation (CV) and using 95% prediction bounds. Besides, root mean square errors (RMSE) were used to check precision in time series analysis and mean percentage errors, MPE, as suggested by Ablewi (2012), Medeiros et al. (2011), Ilesanmi, 2014 and Xu and Singh (2001). Performance parameters were calculated using Microsoft office Excel while plots were drawn and statistical parameters and data statistics were obtained using Matlab R2018a software.

2.3. ET estimation by the TM method

For ET function to be related to ET-PM, the value should show similar linear pattern as that of ET-PM. However, as seen in Eq. 1, ET-TM method has T_{mx} (a variable) at the denominator (Temesgen and Melesse, 2013).

$$ET_{TM} = \frac{T_{mx}^{2.5}}{48 T_{mx} - 330} \quad (1)$$

The TM method variation from PM method is primarily due to this variable, T_{mx} , at the denominator. This created the plot of ET-TM cross the 1:1 slope line at different locations for different meteorological stations. Several trials were made to eliminate the crossing of the two lines and finally, it was realized that ET-TM must not contain variable at the denominator in order to have a good linear correlation with ET-PM. The corrections made on the TM method were done in two stages. The first was by replacing the variable T_{mx} with a constant term and this was given as ET-TM_{mod}. The second was replacing the value of 2.5 with a value 'n' that can be calibrated. The calibration was done on the ET-TM_{mod} and the results were given as ET-TM_{modopt}. The statistical parameters, model tendencies and model performances of the three ET estimation methods (ET-TM, ET-TM_{mod} and ET-TM_{modopt}) were evaluated from the plots of the three methods against ET-PM (Eq. 2) and by using the mathematical methods shown in Section 2.4. The PM-ET used for comparison is the formula given by Allen et al. (2006).

Table 1. Information about the stations.

Station	Location		Altitude (m)	Temperature (°C)			RH	SS (hr)	WS (m/s)	Data period (months)
	Latitude (N)	Longitude (E)		T _{mean}	T _{mx}	T _{mn}				
Addis Ababa	8.59°	38.48°	2386	17.1	23.8	10.3	59	6.7	0.6	132
Addet	11.27°	37.49°	2179	17.6	25.6	9.7	80.5	7.8	0.7	110
Bahir Dar	11.36°	37.24°	1800	18.2	25.6	10.8	72.1	7.8	0.1	127
Dangla	11.25°	36.83°	2116	17.7	25.7	9.7	85.4	7	0.7	36
Debre Birhan	9.38°	39.3°	2750	13.6	19.8	7.3	54	4.8	1.6	132
Desse	11.07°	39.38°	2553	15.6	22.8	8.3	58	7.7	0.9	132
Mekele	13.31°	39.28°	2000	20.1	26.8	13.3	64	7.2	1.8	132
Methara	8.51°	39.55°	944	22.6	27.8	17.3	74	8.7	1.2	132

T_{mean} = mean temperature; T_{mx} = maximum temperature; T_{mn} = minimum temperature; RH = relative humidity; SS = sunshine hours; WS = wind speed. (Source: Mengistu and Amente, 2017)

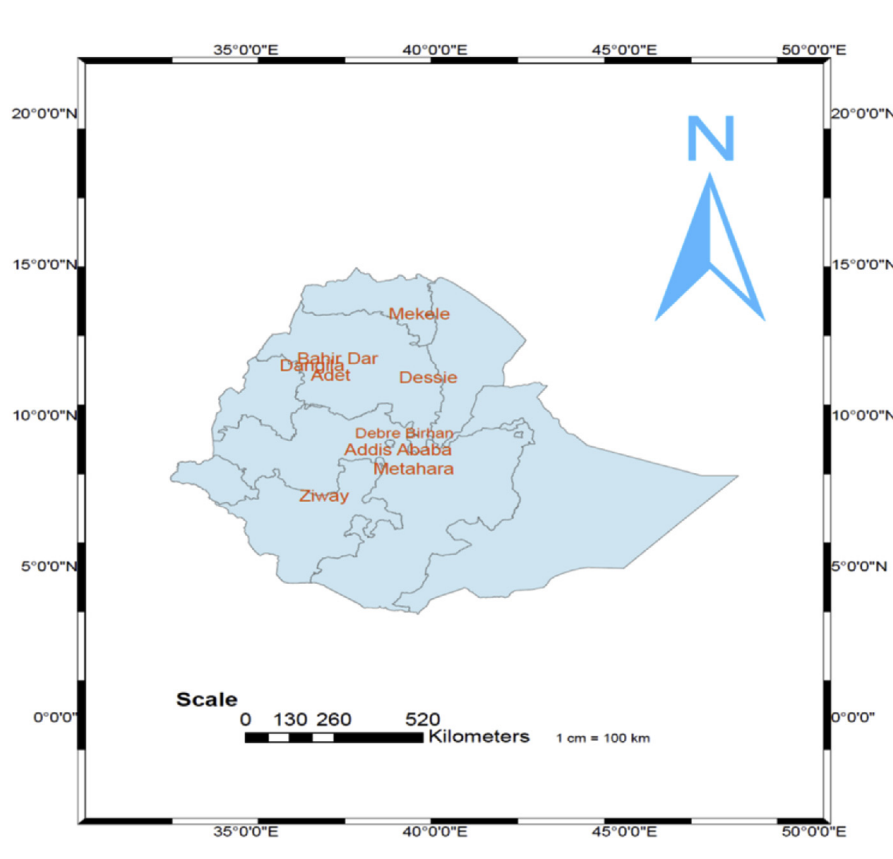


Figure 1. Location map of the study areas (Mengistu and Amente, 2017).

$$ET_{PM} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

ET_{PM} is reference evapotranspiration (mm d^{-1}); R_n is the net radiation at the crop surface ($\text{MJm}^{-2}\text{d}^{-1}$); G is soil heat flux density ($\text{MJm}^{-2}\text{d}^{-1}$), assumed to be zero on daily basis; T ($^{\circ}\text{C}$) is mean daily air temperature at 2 m height; u_2 is wind speed at 2 m height (m s^{-1}); e_s is saturation vapor pressure (kPa); e_a is actual vapor pressure (kPa); $e_s - e_a$ is saturation vapor pressure deficit (kPa); Δ is slope of vapor pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$); and γ is psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

2.4. Mathematical methods to find statistical parameters, model tendencies and performance tests

The model tendencies, statistical parameters and performance tests are essential to check how the models operate. The first ones are the statistical parameters obtained while correlating any two methods. In this study, the ET obtained using the PM method was always used as a predictor. The linear relation between the predictor and the predicted (the original ET-TM, the modified and the modified and optimized methods) were tested by plotting them against ET-PM and linearly fitting them with (Eq. 3a) and without intercepts (Eq. 4b).

$$y = bx + a, \tag{3}$$

$$y^* = b^*x \tag{4}$$

The slopes (b or b^*) are used as test parameters. Eq. 3 is used to show how the linear fit behaves compared to the 1:1 slope line. For y and x to be closely correlated, b must be close to one and a must be close to zero. Deviation of the slope from one and intercept from zero indicates bias (Xu and Singh, 2001). But since the intercept is interfering with the slope, Eq. 3 does not clearly indicate how far the fitted line gets closer to the 1:1 slope line. Therefore, in order to know the model tendencies, it is necessary to use the slope of Eq. 4 (b^*) with the fitted line and to use b^* with R^2 to test the performance of the model. The R^2 is the cross-correlation between y' and x during regression and it is given (Wang et al., 2009; Alblewi, 2012) by,

$$R^2 = \frac{\sum_1^m (y_i - \bar{y})(y'_i - \bar{y}')}{\left(\sum_1^m (y_i - \bar{y})^2 \sum_1^m (y'_i - \bar{y}')^2\right)^{0.5}} \tag{5}$$

The ‘ m ’ in this case is the number of data considered, y_i represents ET-PM value of the i^{th} data, y'_i is regression estimated value of ET for the i^{th} value and \bar{y} and \bar{y}' are the average values of y and y' , respectively. A measure of $R^2 \geq 0.7$ is required for the cross-correlation to be considered good (Alblewi, 2012). When R^2 is considered together with the slope (b^*), $R^2 \geq 0.7$ and $0.7 \leq b \leq 1.3$ are required to assure good condition and homogeneity of the correlation (Allen et al., 2006). The three parameters (R^2 , b or b^* and a) are regression parameters. In this study, the R^2 , b and b^* and the constant ‘ a ’ were evaluated for each station, but the tendencies were evaluated using Eq. 4 and Eq. 5.

A one to one (1:1) slope line is the plot done between ET-PM and itself. This line is important to see if there are crossing between two quantities that are to be correlated. The linear plot between the two quantities must be as close as possible to the 1:1 line without crossing it. If the 1:1 slope line is parallel to the linearly fitted line and is below the 1:1 slope line it indicates underestimation (UE) of ET, Data crossing 1:1 line, when using variables with same units, may point to bias in the variable that is being tested and if above, overestimation (OE) provided the variables have the same unit.

Root Mean Square Error (RMSE) is a measure of relative error, which is the error of the estimated method compared with the PM method. RMSE is given (Adeboye et al., 2009; Medeiros et al., 2011; Alblewi, 2012; Ilesanmi, 2014) as:

$$RMSE = \left(\frac{\sum_1^n (ET_i - ET_{PMi})^2}{n}\right)^{0.5} \tag{6}$$

ET_i is the ET estimated by one of the three methods, whereas ET_{PMi} is the PM ET. Both values are at the i^{th} observation. RMSE is indicator of the deviation and accuracy in estimation (Aguilar and Polo, 2011). It ranges from zero to infinity but its value is considered good when it is closer to zero. The corresponding relative RMSE (rRMSE) is the ratio of RMSE

divided by the mean value of ET-PM, which when multiplied by 100% gives the relative error (Fernandes et al., 2012). These values are given in parenthesis next to RMSE values in Tables 2 and 3. Neto et al. (2015) considers RMSE to be inappropriate parameter for evaluating model performance because of its change with variability of the error squares in the data. On the other hand, Ilesanmi. 2014 consider it more appropriate for large data compared to mean absolute error (MAE). In this study, the RMSE values (mm/d) and the relative errors (%) were evaluated for the curve fits with and without intercepts.

Coefficient of Efficiency (CE) is generally used as performance measure (Maule et al., 2006; TegosEstratiadis and Koutsoyiannis, 2013; Alblewi, 2012). A measure of CE is given as:

$$CE = 1 - \frac{\sum_1^n (ET_{PM}(i) - ET(i))^2}{\sum_1^n (ET_{PM}(i) - < ET_{PM} >)^2} \tag{7}$$

$EP_{PM}(i)$ and $ET(i)$ is the PM and the parametric model values for the i^{th} month and $(\bar{ET})_{PM}$ are the PM evapotranspiration averaged over all the n months. The actual range of CE lies between minus infinity and one. According to Alblewi (2012), if $0.75 \leq CE \leq 1$ the performance of the method is considered good, $0.36 < CE < 0.75$, satisfactory while CE below 0.36 is considered poor. According to Maule et al. (2006), when CE is below zero, the method to be estimated is assumed to be a better predictor than the method that is supposed to predict it.

Coefficient of Residual Mean (CRM) is the way to compute residuals to check whether the method over or underestimates a given value. It is expressed (Alblewi, 2012) as:

$$CRM = \frac{\sum_1^n ET_{PMi} - \sum_1^n ET_i}{\sum_1^n ET_{PMi}} \tag{8}$$

The variables are as explained for Eqs. 7 and 8. Even though CRM values range between minus infinity to plus infinity, what is actually considered is whether the value is above or below zero. Positive value indicates underestimation while negative value indicates overestimation. A value close to zero implies close agreement between ET-PM and the estimated ET.

Mean Percentage Error (MPE) is used to measure the error between the predictor (ET-PM) and the predicted (the estimated methods). It is given as (Edebeatu, 2015):

$$MPE = \frac{\sum_1^n \left[\frac{x-y}{x}\right]}{n} (100\%) \tag{9}$$

The variable x represents either one of the estimated ET methods and y represents ET-PM, both observed during observation i , while n is the total number of observations. Low MPE is preferred to show agreement between two models.

Coefficient of Variation (CV) is defined as the ratio of the standard deviation (s) over the mean (\bar{x}). CV in percent form is given as:

$$CV(\%) = \frac{s}{\bar{x}} (100\%) \tag{10}$$

Table 2. Summaries of \bar{T}_{mx} , the calibrated ‘ n ’ values (n_{opt}), ET-TM and ET-TM $_{n_{opt}}$ of the eight stations.

Station	$\bar{T}_{mx}(^{\circ}\text{C})$	n_{opt}	Original n	$(T_{mx})^{n_{opt}}(^{\circ}\text{C})$	$(T_{mx})^{2.5} (^{\circ}\text{C})^2$	Denominator of TM mthd.	ET-TM $_{n_{opt}}^{\text{(mm/day)}}$	ET-TM(mm/day)	Diff.	% error
Addis Ababa	23.74	2.494	2.5	2694.32	2746.01	809.52	3.33	3.39	-0.06	-1.92
Addet	25.57	2.475	2.5	3048.83	3306.18	897.36	3.40	3.68	-0.29	-8.44
Bahir Dar	26.82	2.482	2.5	3511.03	3725.18	957.36	3.67	3.89	-0.22	-6.10
Dangla	25.72	2.490	2.5	3247.69	3354.88	904.56	3.59	3.71	-0.12	-3.30
Debre Birhan	19.86	2.540	2.5	1980.92	1757.71	623.28	3.18	2.82	0.36	11.27
Desse	22.86	2.524	2.5	2693.45	2498.56	767.28	3.51	3.26	0.25	7.24
Mekele	26.86	2.511	2.5	3876.91	3739.08	959.28	4.04	3.90	0.14	3.55
Methara	27.86	2.513	2.5	4277.97	4096.88	1007.28	4.25	4.07	0.18	4.23

diff = the difference between ET-TM and the ET-TM $_{n_{opt}}$. The T_{mx} used in the evaluation of ET-TM $_{n_{opt}}$ is \bar{T}_{mx} .

Table 3. Statistical parameters, model tendencies and performance tests of the four methods shown for the eight stations.

Station	Method	Statistical parameters			RMSE	CE	CRM	Model tendency			Model performance				
		R ²	Slope (b)	Int. (a)				By CRM	By slope	By 1:1 line	CE	R ² & slope	PB	CV	MPE
Addis Ababa	ET _{TM}	0.787	0.460	1.843	0.306 (8.9%)	0.65	0.001	Agreement	UE (54%)	Mixed	S	G & G	All in	7.9	7.4
	ET _{TMm}	0.783	1.057	-0.170	0.292 (8.5%)	0.68	-0.007	Agreement	OE (5.7%)	Slight OE	S	G & G	All in	18.1	7.0
	ET _{TMmo}	0.783	1.038	-0.160	0.286 (8.4%)	0.70	0.009	Agreement	OE (3.8%)	Slight UE	S	G & G	All in	18.0	7.0
Addet	ET _{TM}	0.823	0.695	1.214	0.277 (7.8%)	0.753	-0.035	Slight OE	UE (30.5%)	Mixed	G	G & G	All in	11.61	6.45
	ET _{TMm}	0.830	1.571	-1.856	0.541 (15.2%)	0.058	-0.052	Slight OE	OE (57.1%)	Mixed	BP	G & P	Most in	25.71	11.17
	ET _{TMmo}	0.830	1.434	-1.658	0.449 (12.6%)	0.352	0.029	Slight UE	OE (43.4%)	Mixed	S	G & P	Most in	25.45	12.18
Bahir Dar	ET _{TM}	0.799	0.613	1.630	0.371 (10.1%)	0.653	-0.055	Slight OE	UE (38.7%)	Mixed	S	G & G	Most in	11.13	7.61
	ET _{TMm}	0.805	1.346	-1.032	0.530 (14.4%)	0.292	-0.066	Slight OE	UE (34.6%)	Mixed	P	G & P	Most in	24.10	10.53
	ET _{TMmo}	0.805	1.259	-0.939	0.423 (11.5%)	0.548	-0.004	Agreement	UE (25.9%)	Mixed	S	G & G	All in	23.93	9.52
Dangla	ET _{TM}	0.628	0.497	2.012	0.510 (14.8%)	0.421	-0.0083	Slight OE	UE (50.3%)	Mixed	S	G & G	All in	11.47	10.43
	ET _{TMm}	0.639	1.110	-0.037	0.660 (19.2%)	0.032	-0.099	Slight OE	OE (11%)	OE	BP	G & G	One out	25.01	13.43
	ET _{TMmo}	0.638	0.973	0.016	0.498 (14.5%)	0.449	0.021	Slight UE	OE (2.7%)	Slight OE	S	G & G	All in	24.66	13.63
Debre Birhan	ET _{TM}	0.821	0.350	1.686	0.598 (18.3%)	0.049	0.133	OE	UE (65%)	Mixed	S	G & P	Most in	8.40	17.10
	ET _{TMm}	0.813	0.909	-0.107	0.487 (14.9%)	0.368	0.124	OE	UE (9.1%)	UE	S	G & G	All in	21.69	15.55
	ET _{TMmo}	0.813	1.041	-0.173	0.310 (9.5%)	0.744	0.013	Slight OE	OE (4.1%)	Overlap	S	G & G	All in	22.04	7.47
Desse	ET _{TM}	0.790	0.437	1.693	0.460 (12.8%)	0.256	0.091	Slight UE	UE (56.3%)	Mixed	P	G & P	Most in	8.07	10.75
	ET _{TMm}	0.788	1.029	-0.406	0.413 (11.5%)	0.399	0.083	Slight UE	OE (2.9%)	UE	S	G & G	Most in	18.86	11.36
	ET _{TMmo}	0.788	1.121	-0.475	0.315 (8.8%)	0.642	0.013	Slight UE	OE (12.1%)	Slight OE	S	G & G	All in	19.05	7.57
Mekele	ET _{TM}	0.818	0.377	2.368	0.482 (11.8%)	0.517	0.043	Slight UE	UE (62.3%)	Mixed	S	G & P	All in	7.43	9.96
	ET _{TMm}	0.815	0.818	0.592	0.334 (8.2%)	0.768	0.037	Slight UE	OE (18.2%)	UE	G	G & G	All in	16.07	6.69
	ET _{TMmo}	0.814	0.852	0.599	0.300 (7.4%)	0.813	0.001	Agreement	OE (14.8%)	Slight UE	G	G & G	All in	16.14	5.73
Metehara	ET _{TM}	0.794	0.407	2.322	0.463 (10.8%)	0.483	0.052	Slight UE	UE (59.3%)	Mixed	S	G & P	All in	7.26	9.14
	ET _{TMm}	0.788	0.871	0.353	0.364 (8.5%)	0.681	0.047	Slight UE	OE (12.9%)	UE	S	G & G	All in	15.49	7.19
	ET _{TMmo}	0.788	0.914	0.350	0.311 (7.2%)	0.767	0.005	Agreement	OE (8.6%)	Slight UE	G	G & G	All in	15.58	5.83

Both *s* and \bar{x} are obtained from the data statistics. CV of less than 10% is preferred to make the data reliable. The CVs indicate the seasonal variations of the ETs of a given location. The CV may not mean much in this case other than showing the variations of the ET values.

Prediction bound (PB) at 95% was included in the performance test to check whether the data points are totally or partially included within the PB. The assumption is based on the fact that when most of the data points are within the PB, the two methods are within 5% error from each other.

3. Results and discussion

3.1. Corrections made to the TM method

The first correction made to the TM method was to replace the T_{mx} at the denominator with the average of all the monthly-averaged maximum temperatures considered for the study period, \bar{T}_{mx} . Based on this correction, Eq. (1) is modified to

$$ET_{TM_{mod}} = \frac{T_{mx}^{2.5}}{48 \bar{T}_{mx} - 330} \tag{11}$$

Using T_{xm} (mean of t_{mx} values) instead of T_{mx} did not improve ET estimated with the ET-TM equation and results suggest that further adjustments to the original equation were required. Thus, a version of the equation was tested in which the power in the numerator was considered a variable that could be calibrated, depending upon the climate and characteristics of the time-series.

$$ET_{TM_{mod}} = \frac{T_{mx}^n}{48 \bar{T}_{mx} - 330} \tag{12}$$

For stations that don't require 15–30 years of meteorological data to evaluate ET-PM, the ET values were evaluated and plotted against T_{mx} data of the same location and the 'n' values were calibrated (n_{opt}) using Eq. (12). The equation obtained after 'n' was optimized has the form of

$$ET_{TM_{modopt}} = \frac{T_{mx}^{n_{opt}}}{48 \bar{T}_{mx} - 330} \tag{13}$$

In order to modify ET-TM it was necessary to find the average temperatures of all the monthly-averaged (\bar{T}_{mx}) for a given station. The 'n' values were obtained using Eq. (13) instead of Eq. (1). Table 2 shows how the modified equation with calibrated 'n' (ET-TM_{nopt}) differed from the original ET-TM.

The ET calculation in both ET-TM and ET-TM_{nopt} were done using only one maximum temperature, \bar{T}_{mx} for the sake of illustration. As seen from the table, the percent difference ranges from the low end of 1.9% to the high end of 11.3%. The errors may even be higher when the monthly-averaged maximum temperatures, T_{mx} , are taken instead of the average of the monthly averages, \bar{T}_{mx} . This indicates variability of the performance of ET-TM among the different stations, which means, the choice of 2.5 may be acceptable for some stations but not for all.

3.2. Plots of the three methods against ET-PM and curve fitting with intercepts

In order to compare the performances of the original and the modified TM ET evaluation methods, plots of the original, the modified and the modified with 'n' optimized (calibrated) were made. The plots and the linear fits with intercepts are shown in Figure 2.

As observed in all the plots, the linear fit with intercept done for the original ET-TM produced lines that always crossed the 1:1 slope line. The ET estimated by the original TM method exhibited overestimation at low ET-PM and underestimation at high ET-PM. The others methods changed the slopes of the fitted lines and managed to make the fitted lines nearly parallel to the 1:1 slope line except for Addet and Bahir Dar stations.

The fitted lines with intercepts generally showed relatively higher R² values, but this is intriguing since in most cases the intercepts were not close to zero. This means that the consideration of the slope of this fit is not a good indicator of agreement among the different methods since the intercept is masking the effect of the slope. However, the use of curve

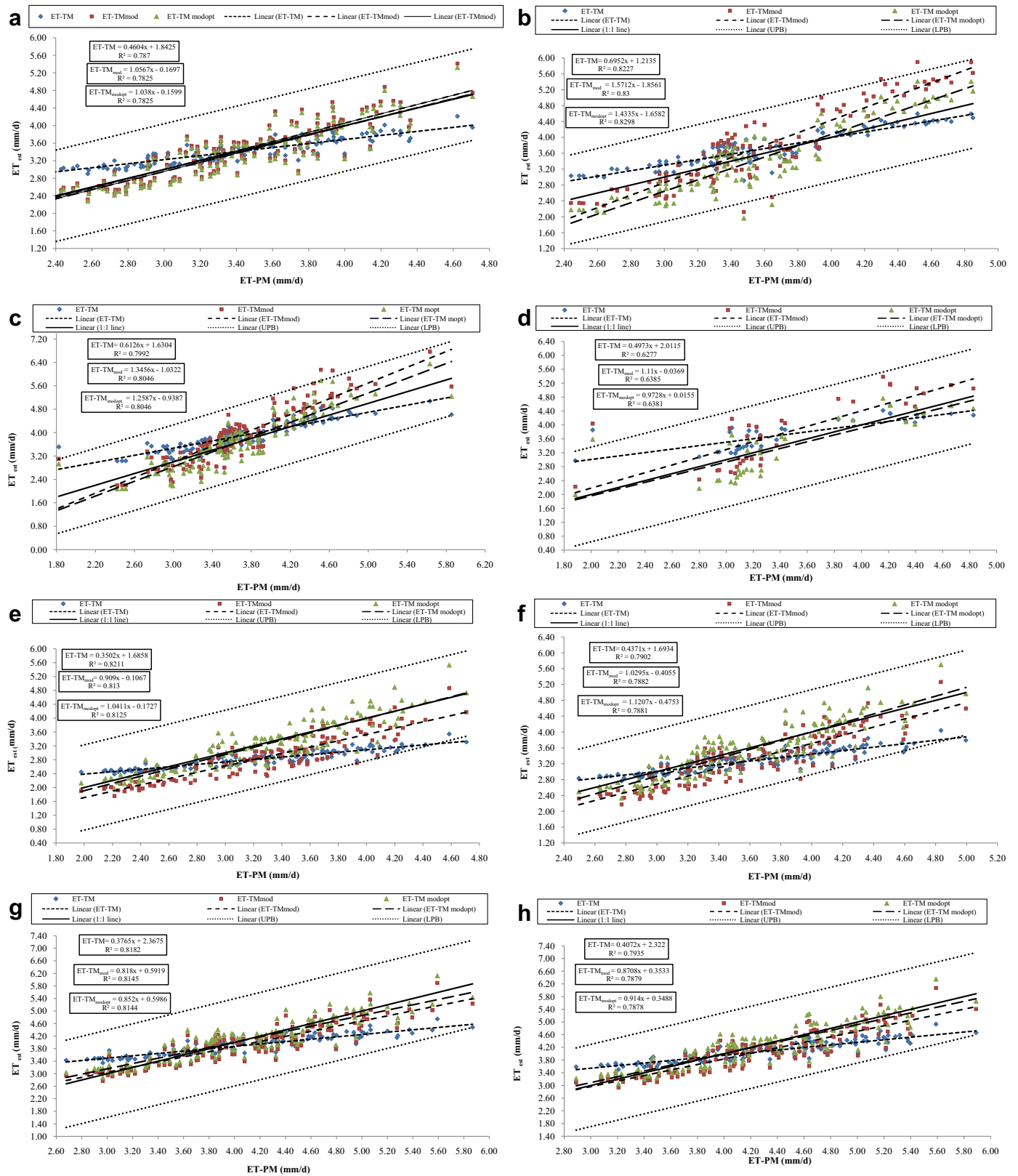


Figure 2. Plots and linear curve fits with intercepts of the original and modified ET-TM versus ET-PM done for the eight stations. The stations are represented as: a) Addis Ababa, b) Addet, c) Bahir Dar, d) Dangla, e) Debre Birhan, f) Desse, g) Mekele and h) Metehara.

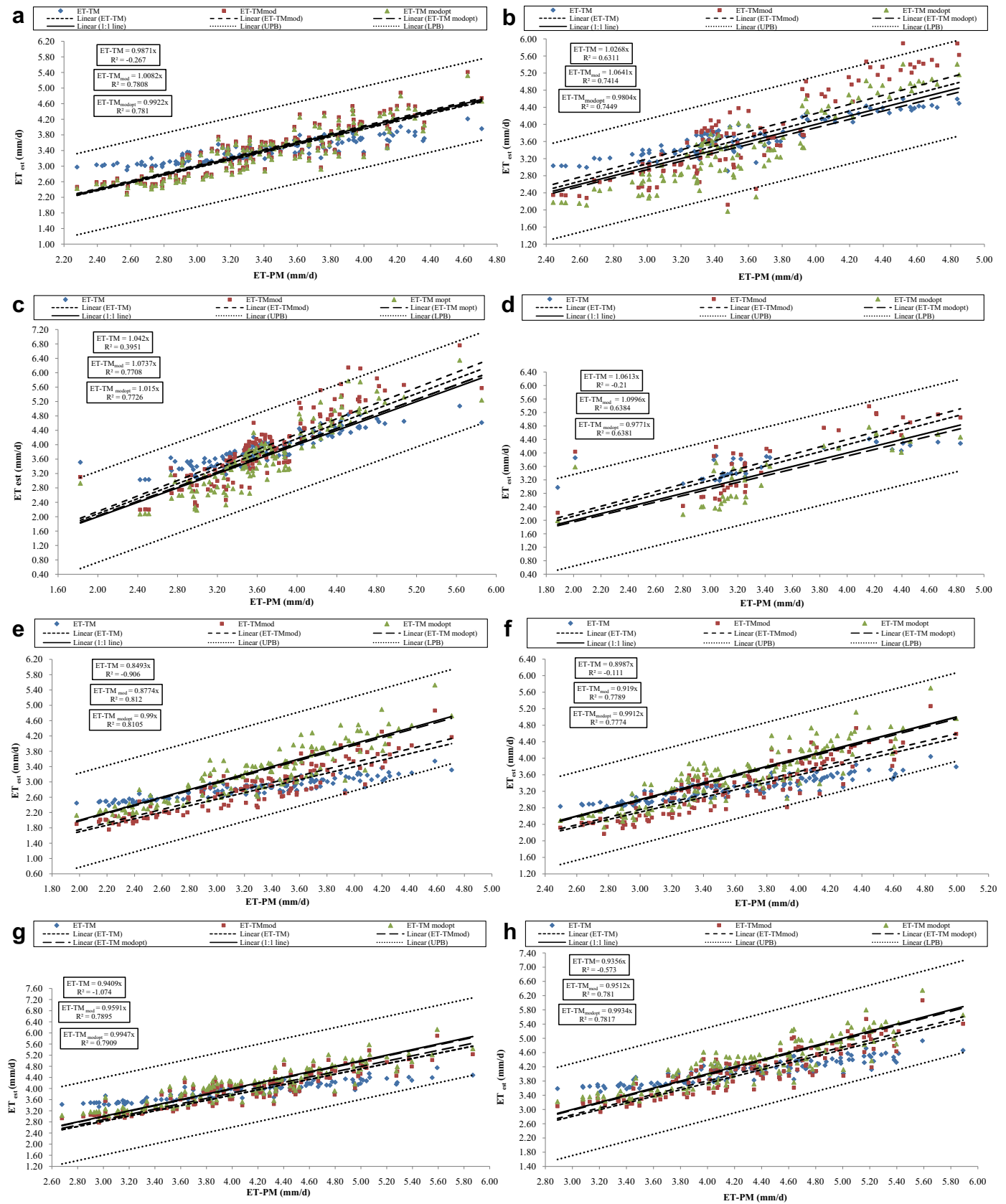


Figure 3. Plots and linear curve fits without intercepts of the original and modified ET-TM versus ET-PM done for the eight stations. The stations are represented as: a) Addis Ababa, b) Addet, c) Bahir Dar, d) Danglaj, e) Debre Birhan, f) Desse, g) Mekele and h) Metehara.

fitting with intercept is advantageous in order to see how the slope varies when the fits are done without intercepts. Better understanding of the correlations between the estimated ETs and the ET-PM are obtained by using the different types of model tests. Summaries of statistical parameters, model tendencies and performance tests that are explained under section 2.4 are shown in Table 3.

As observed in Table 3, model testing by the slope method shows slight disagreement with the other methods such as the CRM. Agreement between CRM and the evaluation of model tendency by the slope is necessary to check whether the curve fitting done is the right one or not. For instance, model tendency test by slope for the original TM-ET estimation method showed underestimations in excess of 30% for all the stations which is not good. In the curve fitting method with intercept, agreement was not observed as expected because of the influence of the intercept on the slope.

The use of RMSE indicates ET error between the lowest of 0.300 mm/d (7.4%) to the highest of 0.66 mm/d (19.2%). The RMSE of the modified ET is better than those of the original ET in all except the three stations (Addet, Bahir Dar and Dangla). The modified ET with the parameter ‘n’ calibrated showed the least values ranging from 0.300 mm/d – 0.498 mm/d.

Stations like Addis Ababa, Debre Birhan, Desse, Mekele and Metehara exhibited acceptable results in terms of CRM, model tendency by slope, by CE, by RMSE, by R² & slope and MPE for the modified (ET_{TMm}) and the modified with calibrated ‘n’ (ET_{TMmo}) methods. Addet and Bahir Dar showed good performance for the modified with calibrated ‘n’ method only.

Whenever the fitted line crosses the 1:1 slope line, it is not possible to tell whether the model overestimates or underestimates and therefore the condition is mentioned as mixed. The prediction bound (PB) in most

cases is acceptable except in few cases where few points were observed outside the prediction bounds.

3.3. Curve fits without intercepts

An alternative way to look at the different methods is by doing curve fitting without intercepts. This method eliminates the crossings between the fitted lines and the 1:1 slope lines. Besides, since the intercept is not present, testing model tendency by slope gives a more reliable result when curve fit is done by this method provided that the R² is good or satisfactory. In addition, the R² also clearly shows how each method agrees with the ET-PM result (Figure 3).

Plots and curve fittings without intercepts eliminate the crossing between the fitted line and the 1:1 slope line. In this case the R² slightly reduces from the ones shown in Figure 1, but for the methods that perform well the changes are not much. For the methods that are totally in disagreement, the R² is very poor and noted as ‘P’. The slopes in this case are good indicators of tendencies since they are not influenced by the intercepts.

The fit without intercepts is superior to the one with intercept since it clearly shows when a certain method performs well or not. For instance, in the case of Addis Ababa station, the two methods (ET_{TMm} and ET_{TMmo}) showed almost perfect fit with the 1:1 slope line. The ET-TM on the other hand, exhibited poor R² despite its closeness to the 1:1 line. Hence in the case of curve fit without intercept, it is essential to observe and consider the value of R² since the closeness to the 1:1 slope line disguises if not looked at with R².

The other benefit of curve fit without intercept is its capability to show overestimation or underestimation of the method clearly. It has the ability to even show differences between ET_{TMm} and ET_{TMmo} as well. For

Table 4. Statistical parameters, model tendencies and performance tests of the four methods shown for the eight stations. (Curve fitting without intercept).

Station	Method	Statistical parameters		RMSE	CE	CRM	Model tendency			Model performance				
		R ²	Slope (b)				By CRM	By slope	By 1:1 line	By CE	By R ² & slope	PB	CV	MPE
Addis Ababa	ET _{TM}	0.267	0.987	0.306 (8.9%)	0.65	0.001	Agreement	UE (1.3%)	Overlap	S	P & G	All in	7.9	7.4
	ET _{TMm}	0.781	1.008	0.292 (8.5%)	0.68	-0.007	Agreement	OE (0.8%)	Overlap	S	G & G	All in	18.1	7.0
	ET _{TMmo}	0.781	0.993	0.286 (8.4%)	0.70	0.009	Agreement	UE (0.7%)	Overlap	S	G & G	All in	18.0	7.0
Addet	ET _{TM}	0.631	1.027	0.277 (7.8%)	0.753	-0.035	Slight OE	OE (2.7%)	Slight OE	G	S & G	All in	11.61	6.45
	ET _{TMm}	0.741	1.064	0.541 (15.2%)	0.058	-0.052	Slight OE	OE (6.4%)	Slight OE	BP	S & G	Most in	25.71	11.17
	ET _{TMmo}	0.745	0.980	0.449 (12.6%)	0.352	0.029	Slight UE	OE (2.0%)	Slight UE	S	S & G	Most in	25.45	12.18
Bahir Dar	ET _{TM}	0.395	1.042	0.371 (10.1%)	0.653	-0.055	Slight OE	OE (4.2%)	Slight OE	S	P & G	Most in	11.13	7.61
	ET _{TMm}	0.771	1.073	0.530 (14.4%)	0.292	-0.066	Slight OE	OE (7.3%)	Slight OE	P	G & G	Most in	24.10	10.53
	ET _{TMmo}	0.773	1.015	0.423 (11.5%)	0.548	-0.004	Agreement	OE (1.5%)	Slight OE	S	G & G	All in	23.93	9.52
Dangla	ET _{TM}	0.210	1.061	0.510 (14.8%)	0.421	-0.0083	Slight OE	OE (6.1%)	OE	S	P & G	One out	11.47	10.43
	ET _{TMm}	0.638	1.100	0.660 (19.2%)	0.032	-0.099	Slight OE	OE (10%)	OE	BP	S & G	One out	25.01	13.43
	ET _{TMmo}	0.638	0.977	0.498 (14.5%)	0.449	0.021	Slight UE	UE (2.3%)	Slight UE	S	S & G	All in	24.66	13.63
Debre Birhan	ET _{TM}	-0.906	0.849	0.598 (18.3%)	0.049	0.133	OE	UE (15.1%)	UE	S	P & G	Most in	8.40	17.10
	ET _{TMm}	0.812	0.877	0.487 (14.9%)	0.368	0.124	OE	UE (12.3%)	UE	S	G & G	Most in	21.69	15.55
	ET _{TMmo}	0.811	0.990	0.310 (9.5%)	0.744	0.013	Slight OE	UE (1%)	Overlap	S	G & G	All in	22.04	7.47
Desse	ET _{TM}	-0.111	0.899	0.460 (12.8%)	0.256	0.091	Slight UE	UE (10.1%)	UE	P	P & G	Most in	8.07	10.75
	ET _{TMm}	0.779	0.919	0.413 (11.5%)	0.399	0.083	Slight UE	UE (8.1%)	UE	S	G & G	Most in	18.86	11.36
	ET _{TMmo}	0.777	0.991	0.315 (8.8%)	0.642	0.013	Slight UE	UE (0.9%)	Overlap	S	G & G	All in	19.05	7.57
Mekele	ET _{TM}	-1.074	0.941	0.482 (11.8%)	0.517	0.043	Slight UE	UE (5.9%)	UE	S	P & G	All in	7.43	9.96
	ET _{TMm}	0.790	0.959	0.334 (8.2%)	0.768	0.037	Slight UE	OE (4.1%)	UE	G	G & G	All in	16.07	6.69
	ET _{TMmo}	0.791	0.995	0.300 (7.4%)	0.813	0.001	Agreement	OE (0.5%)	Overlap	G	G & G	All in	16.14	5.73
Metehara	ET _{TM}	0.573	0.936	0.463 (10.8%)	0.483	0.052	Slight UE	UE (6.4%)	UE	S	S & G	All in	7.26	9.14
	ET _{TMm}	0.781	0.951	0.364 (8.5%)	0.681	0.047	Slight UE	OE (4.9%)	UE	S	G & G	All in	15.49	7.19
	ET _{TMmo}	0.782	0.993	0.311 (7.2%)	0.767	0.005	Agreement	OE (0.7%)	Overlap	G	G & G	All in	15.58	5.83

Int. = intercept; ET_{TM} = Temesgen and Melesse method; ET_{TMm} = modified ET_{TM} method; ET_{TMmo} = modified and ‘n’ optimized ET_{TM} method; ET_{nclct} = ET_{TM} method with ‘n’ calculated from altitude and latitude; OE = overestimation; UE = underestimation; S = satisfactory; G = good; P = poor, PB = 95% prediction bound and BP = beyond prediction. Numbers in brackets under ‘by slope’ represent percent OE or UE while the ones under RMSE represent percent error of ET.

Table 5. Summary of performance comparisons of the four methods.

Method	Percent error by slope	CE		R ² and slope		MPE
		G & S	P	G & S	P	
ET-TM	1.3–15.1	7	1	2	6	6.5–17.1
ET-TM _{mod}	0.8–12.3	5	3	8	0	6.7–15.6
ET-TM _{modopt}	0.5–2.3	8	0	8	0	5.7–13.6

G & S = good & satisfactory; P = poor. The corresponding numbers indicate the number of stations.

instance, in some cases they both methods overestimate (e.g. Bahir Dar). In other cases, one overestimates while the other underestimates (e.g. Addet and Dangla). In the rest of the cases both slightly underestimated. But to get more information, it is necessary to see the statistical parameters, model tendencies and performance tests for this case as well (Table 4).

Curve fitting without intercept decreases model tendency by slopes to less than 10% in most cases. It also improves agreement between tendency tests by CRM to the 'by slope' method. The CVs are generally less than 25% except for Addet station, which means for most stations it is good or satisfactory. The R² in this case is a good indicator of agreement between the different methods. The performances of the four methods are summarized in Table 5.

The overall result of Table 5 indicates the modified TM method with 'n' optimized ('n' calibrated) (ET-TM_{nopt}) as the best ET estimation method based on the four performance test methods. This is logical the power "n" is calibrated based upon location and considered up to three decimal places unlike the original TM method that considered only up to the first decimal place. Considering more digits after the decimal is essential especially when it is a power of a number such as that of maximum temperature. As far as comparison between ET-TM and ET-TM_{mod} is concerned, the former performed well in terms of CE but is outperformed by the latter in terms of percent error by slope, R² and slope and MPE.

4. Conclusion

In this study, two problems with one of the temperature-based ET estimation method known as Temesgen-Melesse's method (ET-TM) were identified. The problems were the variable nature of the maximum temperature (T_{mx}) used in the denominator of the TM equation and the location independent power of T_{mx} (2.5) in the numerator of the equation, which did not do well for a number of stations. The TM equation was first modified by replacing the monthly-averaged maximum temperature (T_{mx} that acted as a variable) at the denominator of the equation with the overall average of all the monthly-averaged values (T_{mx} that is a constant for a given location). The modified equation (ET-TM_{mod}) managed in improving the slope of the fit between the original ET-TM and ET-PM to get closer to the 1:1 slope line.

For the second problem it was necessary to consider the constant power of 2.5 as a variable and to calibrate the power for each station using limited data that satisfy PM equation. The calibration result gave the best result compared to the original and the modified TM equations. The modified equation with the constant power of 2.5 outperformed the original TM equation in almost all cases, but did not do as well as the one with the calibrated 'n'. Therefore, even when data that satisfies PM equation are not available, it is better to use the modified equation than the original TM equation. However, when there is data that satisfy the PM equation (even if the data is limited) it is better to calibrate the power for a given location, from the limited data, to get a better estimate of ET. The study benefits those who need long-term estimation of ET either for climate study or to study drought patterns of a given location or region, but lack data to use the PM method either because the meteorological stations do not have the complete data or have missing data.

Unlike the studies of *Xystrakis and Matzarakis (2011)* who constantly observed underestimation by 429 temperature-based methods, in this study both overestimation (e.g. Addet, Bahir Dar and Dangla stations) and slight underestimations were observed for the rest of the stations. The overestimation or underestimation seems to be dependent sometimes on the nature of the data and on the values of the parameters used in the equations (e.g. Addis Ababa station). *Xystrakis and Matzarakis (2011)* also propose the need to modify some parameters of the PM equation prior to using in semi-arid environments.

Such changes may involve the use of different parameters (coefficients) during day and night times (*ASCE Environmental and Water Resources Institute (ASCE-EWRI), 2005*). But such modifications require the use of hourly meteorological observations (*Xystrakis and Matzarakis, 2011*). *Hupet and Vanclooster (2001)* mention the possibility of observing high bias in the absence of such hourly data. The integrity of meteorological data (*Jensen et al., 1997; Temesgen et al., 1999*) and the quality of the data (*Semu Ayalew, 2010*) may also have contribution in the deviation of curve fits from the 1:1 slope line even after calibration of the parameter 'n'. Sometimes changes in the location of meteorological stations or changes of instruments may have influence. The lack of trained manpower could also be another factor. The biases observed with three stations (Addet, Bahir Dar and Dangla) could be attributed to anyone of these causes.

Declarations

Author contribution statement

Berhanu Mengistu Chekol: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Gelana Amente: Analyzed and interpreted the data.

Funding statement

The author of this publication receives research funding from Haramaya University which is developing products related to research described in this publication.. The terms of this arrangement have been reviewed and approved by the Haramaya University in accordance with its policy on objectivity in research.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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