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Research Paper

Evaluation of empirical methods for estimating reference evapotranspiration in Central High Lands and Arid Western Lowlands of Eritrea

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ABSTRACT

FAO Penman-Monteith (FAO56-PM) method remains difficult to implement across Eritrea due to severe shortages of standardized meteorological data. This study evaluated the accuracy of five alternative empirical methods by comparing them with the FAO56-PM model using established performance metrics (R^2, RRMSE, NSE, %MBE, and MAPE). Cumulative Performance Index (CPI) was used to determine the overall performances of five alternative ET_o methods. The study identified the modified Hargreaves-Samani (CPI=3.6), Romanenko (CPI=3), and Schendel (CPI=2.6) methods as the most viable simplified alternatives for the data-scarce Central Highlands. However, no method proved optimal for the Arid Western Lowlands. Hargreaves-Samani and Blaney-Criddle methods performed poorly, with combined CPI values of 1.7 and 1.4, respectively. The findings suggest that the modified Hargreaves-Samani and Romanenko methods can effectively replace the FAO56-PM model for estimating crop water requirements in both irrigated and rainfed agricultural systems across all crop types in the Central Highlands. However, the study underscores the critical need for rigorous local calibration and validation of the Hargreaves-Samani, Blaney-Criddle, and Schendel methods to enhance their accuracy.

***Keywords*:** Reference evapotranspiration (ETo), FAO56-PM, Hargreaves-Samani, Blaney-Criddle, Schendel, Cumulative Performance Index (CPI)

The FAO Penman-Monteith (FAO56-PM) model is widely accepted as the standard empirical method for determining reference evapotranspiration (ETo) across diverse regions and climates (Allen *et al.,* 1998; Saxena *et. al.,* 2020; Sarma and Bharadwaj, 2020). However, its applicability depends on the availability of complete meteorological data (Allen *et al.,* 1998). In Eritrea, the scarcity of standard meteorological data is a major constraint, as most weather stations are equipped only with precipitation and temperature measurements (Fessehaye *et al.,* 2022). Despite this limitation, no prior study has evaluated alternative ETo estimation methods against the FAO56-PM model in Eritrea's data-scarce regions. To address this gap, the authors reviewed multiple studies (Abdelraouf *et al.,* 2024; Dong *et al.,* 2024) to identify reliable simplified ETo estimation alternatives for the study area.

The developers of the FAO56-PM method (Allen *et al.,* 1998) recommended the Hargreaves-Samani (H-S) equation (Hargreaves and Samani, 1985) as the sole surrogate for estimating ETo when only air temperature data are available. However, H-S estimates must first be validated against FAO56-PM at stations with complete weather data (Allen *et al.,* 1998), as aerodynamic effects on ETo may outweigh temperature influences (Rao and Wani, 2011; Tabari *et al.,* 2011). While the H-S method demonstrated superior performance in eastern and semi-arid regions of Iran compared to the Makkink and Priestley-Taylor methods (Sabziparvar and Tabari, 2010) and in semi-arid and arid regions of India (Meshram *et al.,* 2010), it overestimated ETo in the Sahelian zones of Senegal's river basins (Djaman *et al.,* 2015). Consequently, several studies have proposed modified Hargreaves-Samani (MH-S) equations to minimize deviations from FAO56-PM (Allen *et al.,* 1998, Ravazzani

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et al., 2012).

The Blaney-Criddle (B-C) method, which requires only mean temperature data, has been suggested as an alternative for arid and semi-arid regions (Abdelraouf *et al.,* 2024). However, its performance remains contentious, with studies reporting poor accuracy in similar climates due to its failure to account for advective effects (Saikia *et al.,* 2005; Tabari *et al.,* 2011; Djaman *et al.,* 2015). In contrast, the Schendel (SC) and Romanenko (RM) methods have proven suitable for less humid regions, such as the Sahelian Senegal river basins (Djaman *et al.,* 2015), which share climatic similarities with Eritrea. Notably, RM has exhibited excellent performance in China's subtropical monsoon region (Dong *et al.,* 2024), moderately humid regions of India (Kalekar and Krishnamurthy, 2018), and humid zones of Iran (Tabari *et al.,* 2011). Given the regional variability in alternative ETo model performance, identifying locally applicable methods for data-limited areas is essential. Thus, based on their simplicity and prior success in arid/semi-arid and moist climates (analogous to the study area), five ETo methods—B-C, H-S, MH-S, SC, and RM—were selected for evaluation.

The densely populated Central Highlands (CHLs) of Eritrea possess reasonably good agricultural potential for intensified agriculture development and has high to moderate annual rainfall (450 mm) with optimal temperature for agricultural production (MoA, 2012). In contrast, the Arid Western Lowlands (AWLLs), covering 37% of Eritrea's land area, feature vast arable plains, fertile riverbanks (Gash, Barka, and Anseba rivers), and a mix of arid and moist ecological zones. These lowlands hold promise for high-value agronomic and horticultural crops. The Eritrean government is investing heavily in modern irrigation systems and efficient water management to reduce reliance on rainfed agriculture (MoA, 2012). Consequently, accurate ETo estimation is critical for determining crop water requirements and optimizing agricultural water management (Kumar *et al.,* 2024; Abdelraouf *et al.,* 2024; Dong *et al.,* 2024).

In light of this background, the study aims to evaluate the performance of the afore mentioned five alternate ETo methods against the standard FAO56-PM model to identify suitable alternatives for reference evapotranspiration estimation in data-limited regions of Eritrea's Central Highlands and Arid Western Lowlands.

MATERIALS AND METHODS

Study area

The study was conducted in the Central Highlands (CHLs; 2000–2500 m above mean sea level [AMSL]) and Arid Western Lowlands (AWLLs; 400–1600 m AMSL) of Eritrea. The CHLs exhibit an average annual temperature range of 10–25°C, while for AWLLs it ranges from 12–29°C. Average annual rainfall ranges between 200-500 mm in the AWLLs and 200-700 mm in the CHLs. Both regions experience: a short rainy season (March–April), which is insufficient for crop cultivation, and a main rainy season (June–September), followed by extended sunny and dry periods. Topographically, AWLLs feature small hills, ridges, valleys, and rolling to flat plains, with mean annual potential evapotranspiration ranging between 1800–2000 mm. The dominant landforms of CHLs are steep escarpments, mountains with dissected rolling hills and plateau with mean annual potential evapotranspiration 1600- 1800 mm.

Data collection and processing

Meteorological data were collected from the records of Asmara (1992-2023) and Kirmud (2004-2023) manual metrological stations. Asmara represents CHLs and has an altitude of 2,325 m above mean sea level, latitude of 15.293^0 north of equator and longitude of 38.916^0 east of Greenwich meridian. Kirmud, representing AWLLs, in sub zone of Forto with a latitude of 15.6979 N, longitude of 36.9804 E and altitude of 729 m above mean sea level. During field study, it was ensured that all meteorological instruments were fixed at the height of 2 m above the ground and in compliance with FAO recommendation for agrometeorological station.

All data collection and processing practices employed Allen *et al.,* (1998) procedures. Mean daily air temperature (Tmean) [^{o}C], maximum daily temperature (Tmax) [^{o}C], minimum daily temperature (Tmin) [^{o}C], mean daily relative humidity (RHmean) [%], daily wind speed (u_2) [ms^{-1}], and sunshine hours (SH) [hours] had been already aggregated to mean monthly values. After conducting quality control for any missing or outliers' data, ET_o of every month of each year was determined. Monthly weather data is indeed very similar to the average of the daily ETo values calculated with daily average weather data for that month (Allen *et al.,* 1998). Finally, mean monthly ET_o of all years were used as an input for evaluating the performance of alternate methods against FAO56-PM model using evaluation metrics

Methods of ET_o estimation

Five alternate methods and FAO56-PM method were depicted in Table 1. Development of all models and evaluation metrics were carried out in Microsoft excel sheets.

Performance evaluation criteria

Performance evaluation metrics such as coefficient of determination (R^2), Relative Root Means Square Error (RRMSE), The Nash-Sutcliffe Efficient (NSE), Mean Absolute Percent Error (MAPE), and Mean Biased Error Percentage (%MBE) were employed to evaluate the alternative ET_o methods against the FAO56-PM model.

$$R^2 = \frac{(\sum_{i=1}^{n}(P_i - P_{av})(R_i - R_{av}))^2}{\sum_{i=1}^{n}(P_i - P_{av})^2 \sum_{i=1}^{n}(R_i - R_{av})^2}$$

$$RRMSE = \frac{1}{R_{av}} \sqrt{\sum_{i=1}^{n} (\frac{P_i - R_i}{n})^2}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(P_i - R_i)^2}{\sum_{i=1}^{n}(R_i - R_{av})^2}$$

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} (/ \frac{R_i - P_i}{R_i} /) * 100\%$$

$$\%MBE = \frac{1}{n} \left(\sum_{i=1}^{n} (\frac{P_i - R_i}{R_i} \right) 100\%$$

Table 1: List of FAO56-PM method and simple alternative ET_o methods

Model	Empirical formula	Reference
FAO56-PM	$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+278} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$	Allen *et al.,* (1998)
B-C	$ET_o = p\,(0.457\,T_{mean} + 8.128)$	Abdelraouf *et al.,* (2024)
H-S	$ET_o = 0.408x\, 0.0023\,(T_{mean} + 17.8)(\sqrt{T_{max} - T_{min}})R_a$	Hargreaves and Samani (1985)
MH-S	$ET_o = (0.817 + 0.00022\,Z)\,0.0023\,(T_{mean} + 17.8)(T_{mx} - T_{min})$	Ravazzani *et al.,* (2012)
Schendel	$ET_o = 16 * \frac{T_{mean}}{RH_{mean}}$	Dong *et al.,* (2024)
Romanenko	$ET_o = 4.5[1 + (\frac{T_{mean}}{25})]^2 \left(1 - \frac{e_a}{e_s}\right)$	Oudin *et al.,* (2005)

Note: ETo is reference evapotranspiration (mm day^{-1}); Rn: net radiation (MJ m^{-2}), G: soil heat flux (MJ.m^{-2}); T_{mean}: mean air temperature (°C);T_{mx} is maximum temperature, T_{min} is minimum temperature, u_2: wind speed at 2 m height (m.s^{-1}); e_s saturation vapor pressure (kPa); e_a: current vapour pressure (kPa); Δ: slope of vapor pressure curve (kPa.°C^{-1}) and γ: psychometric constant (kPa.°C^{-1}), B-C is Blaney-Criddle, H-S is Hargreaves-Samani, M H-S= modified Hargreaves-Samani, p is mean daily percentage of annual daytime hours (dimensionless) and R_a is extraterrestrial radiation (MJ m^{-2}), RH= relative humidity (%)

Table 2: Rating accuracy value (RAV)

Range of accuracy value					RAV
R^2	RRMSE (%)	NSE	MAPE (%)	%MBE	
≥0.9	≤10	≥0.9	≤10	+5≥ MBE≥ -5	4 (excellent)
0.9-0.7	10-20	0.9-0.7	10-20	+10≥MBE≥-10%	3 (good)
0.7-0.5	20-30	0.7-0.5	20-50	+15≥MBE≥-15%	2 (Fair)
<0.5	>30	<0.5	>50	+15<MBE<-15%	1 (poor)

Table 3: Cumulative performance evaluation criteria for alternative ET_o methods against FAO56-PM method

CPI Range	Interpretation
4.0 ≤ CPI ≥ 3.5	Excellent
3.5 < CPI ≤ 2.5	Good
2.5 < CPI ≤ 1.5	Fair
CPI < 1.5	Poor

where n= number of observations, R_i = FAO56-PM ET_o estimates, R_{av} = average FAO56-PM ET_o estimates, P_i= predicted ET_o estimates of alternative ET_o method.

Performance rating scales help to setup a standardized framework of performance evaluation system so that to ensure all methods are evaluated with the same criteria equally. In this study we employed four-point scaling system (Table 2). Finally, Cumulative Performance Index (CPI) was used to determine the overall performances of five alternative ET_o methods (Table 4). CPI is employed to aggregate multiple performance metrics of alternate ET_o models into a single score for the purpose of comprehensive comparison. CPI is developed based on average RAV value of RRMSE, R^2, NSE, MAPE and % MBE, and accordingly, categories are specified in Table 3 systematically.

$$CPI_{AM} = \frac{\sum_{EM}^{n} RAV}{n}$$

where CPI=Cumulative Performance Index, AM= alternate ETo method, RAV= rating accuracy value, EM= evaluation metrics, and n= number of evaluation metrics.

RESULTS AND DISCUSSION

Table 4 presents the annual monthly wind speed, sunshine hours, relative humidity, and air temperature for both stations. In both locations, the lowest monthly mean (Tmean), maximum (Tmax), and minimum (Tmin) temperatures were recorded in January. Lowest maximum (Tmax) temperature of Asmara occurs in July. The highest monthly Tmean in Asmara was observed in June (18.7°C), while in Kirmud, it occurred in May (31.4°C). Similarly, the highest monthly Tmin in Asmara was recorded in July and August (12.6°C), whereas Kirmud's highest Tmin was in May (31.4°C). The highest Tmax values were recorded in March and April (26.2°C) for Asmara and in May (41.1°C) for Kirmud. These temperature fluctuations are primarily linked to seasonal changes. Generally, temperatures decrease during the rainy and winter seasons but rise during spring and autumn.

In both stations, relative humidity was highest during the rainy season, as prolonged rainfall allows the air to absorb more moisture. However, Kirmud experienced elevated relative humidity almost equal to the raining season during cold winter December to February. Highest sunshine hours were recorded between October and May, likely due to reduced cloud cover. Wind speed is strongly influenced by air temperature. Kirmud exhibited stronger wind speeds (4.4 m s^{-1}) compared to Asmara (3.8 m s^{-1}). This difference can be attributed to temperature-induced air pressure variations, where higher temperatures lead to greater pressure differences, ultimately increasing wind speed.

Table 4: Average monthly climatical data for Asmara (1992-2024) and Kirmud (2004-2023)

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
						Asmara							
Tmax (°C)	23.5	25	26.2	26.2	25.9	25.8	22.7	22.3	23.8	22.7	22.8	22.9	24.2
Tmin (°C)	4.4	5.8	7.6	9.6	11.1	11.6	12.6	12.6	10	9	7.3	5.7	8.9
Tmean (°C)	14	15.4	16.9	17.9	18.5	18.7	17.6	17.5	16.9	15.8	15.1	14.3	16.5
u2 (ms^{-1})	3.6	3.7	3.8	4.1	4	4	4.3	4.1	3.6	4.1	3.6	3.8	3.8
SH (hrs)	9.5	9.7	9.4	8.5	8.9	8.3	5.7	5.7	8.3	9	9.3	9.6	8.5
RH (%)	56	48	46	53	50	51	78	82	62	60	65	63	60
Prec.	1.5	1.7	10.7	35.2	38.9	24.2	150.5	150.7	22.2	16.2	9.5	2	470
						Kirmud							
Tmax (°C)	32.0	34.6	37.7	40.1	41.1	38.8	36.2	34.5	37.1	38.4	36.2	33.6	36.7
Tmin (°C)	14.2	15.1	16.5	19.1	21.8	23.2	21.8	20.9	21.1	20.7	17.9	15.8	19.1
Tmean (°C)	23.1	24.8	27.1	29.6	31.4	31.0	29.3	27.7	29.1	29.5	27.0	24.7	27.9
u2 (ms^{-1})	4.7	4.4	4.5	4.3	4.1	5.8	5.6	4.2	3.3	3.2	4.1	5.0	4.4
SH (hrs)	8.4	8.7	9.5	9.4	9.4	8.6	7.3	7.0	8.3	9.2	9.3	8.6	8.6
RH (%)	64	62	55	49	39	42	57	64	57	53	58	63	55.3
Pre.	0.0	0.0	0.0	3.8	8.6	12.1	61.3	90.2	44.0	15.2	0.8	0.1	236.1

Note: u_2 is monthly wind speed measured, SH is monthly sunshine hours, T_{max} is maximum monthly temperature, T_{min} is minimum monthly temperature, T_{mean} is mean monthly temperature, RH is relative humidity, hrs is hours, ms^{-1} is meter per second. Prec. is precipitation

Table 5: Performance evaluation metrics of the five ETo alternate methods

	Methods				
Metrics	B-C (RAV)	H-S(RAV)	SC(RAV)	MH-S(RAV)	MR(RAV)
			Asmara		
R^2	0.14 (1)	0.69 (2)	0.89 (3)	0.7 (3)	0.91 (4)
NSE	-0.11(1)	0.16 (1)	0.56 (2)	0.85 (3)	0.63 (2)
RRMSE (%)	29 (2)	25 (2)	20 (3)	10 (4)	17 (3)
MAPE (%)	25 (2)	22 (2)	18 (3)	9 (4)	10 (4)
MBE (%)	-21(1)	-21 (1)	-18 (1)	4 (4)	-13 (2)
CPI	Poor (1.4)	Fair (1.6)	Good (2.6)	Excellent (3.6)	Good (3.0)
			Kirmud		
R^2	0.02 (1)	0.11 (1)	0.32 (1)	0.11 (1)	0.40 (1)
NSE	-0.2 (1)	0.22 (1)	0.5 (2)	0.04 (1)	0.22 (1)
RRMSE (%)	52 (1)	23 (2)	35 (1)	46 (1)	23 (2)
MAPE (%)	19 (3)	15 (3)	12(3)	16 (3)	15 (3)
MBE (%)	-19 (1)	-15 (2)	1.2 (4)	-16 (1)	6 (3)
CPI	Poor (1.4)	Fair (1.8)	Fair (2.2)	Poor (1.4)	Fair (2.0)

The performance evaluation metrices presented in Table 5 revealed that all methods, except MH-S, SC and MR methods in Asmara, scored R^2 values less than 0.7 in both stations, and this indicates the models' weaknesses to quantify total variations in FAO56-PM ET_o values. Only MH-S and MR in Asmara and SC in both regions scored NSE above 0.5, and accordingly, all the remaining alternative models, which were used in this study, have poor predictive capability. Based on MAPE results, all models, except B-C and H-S showed fair performance in Asmara, recorded good to excellent performance rating ranges across both regions. Thus, the models have good ability to capture the underlying patterns in the data effectively.

Temperature-based methods (B-C, H-S, and MH-S) underestimated FAO56-PM ET_o estimates by 19%, 15%, and 16% respectively in Kirmud as the missing values of wind and relative humidity suppressed the ETo values. In contrast, MR and SC (humidity-based models) performed excellent with %MBE of 6% and 1.2%, respectively in Kirmud. This shows semi humid (RH =55.5%±10%) and dry condition (mean annual precipitation of 236±100) of Kirmud favour these models. In Asmara, all models underestimated FAO56-PM estimates significantly, except MH-S, which showed excellent performance with %MBE (4%). MH-S showed excellent performance with RRMSE of 10%, which confirms to report of its developers (Ravazzani *et al.,* 2012). In contrast, RRMSE of all remaining models, except MR method, were found unsatisfactory, and accordingly, these models (H-S, B-C and SC) are questionable to use them as alternate methods because they showed significant deviations from FAO56-PM estimates. Therefore, depending on one testing evaluation metric can be a misleading if a need arises to use them in determining reference evapotranspiration for high-stakes decisions. Thus, more focus should be given to comprehensive evaluation of MAPE, R^2, NSE, RRMSE and %MBE (Dong *et al.,* 2024).

MH-S showed topmost excellent performance in Asmara with CPI value of 3.6 (Table 5) though Ravazzani *et al.,* (2012) developed it for alpine river basin to reduce error for estimating ETo. Developers of this equation (Ravazzani *et al.,* 2012) noted that MH-S is more applicable than original H-S equation as its (MH-S) application is not limited to growing period only for estimating daily ETo. MR and SC also showed good performance in Asmara with CPI values of 3.0 and 2.6, and in Kirmud with CPI values of 2 and 2.2 (fair performance), respectively. This study confirms to the works of Djaman *et al.,* (2015), Kalekar and Krishnamurthy, (2018), Dong *et al.,* (2024) that reported SC and MR methods are suitable methods in less humid regions. MR could also perform well in highly humid regions of Iran (Tabari *et al.,* 2011). Therefore, for Agrometeorological stations with relative humidity and temperature data, MH-S, SC and RM methods can be taken as alternative ET_o methods in CHLs.

In both arid and semi-arid regions, original H-S and B-C equations performed poorly as both of them failed to account humidity and wind characteristics of the study areas. Our results confirmed to the works of Djaman *et al.,* (2015) who reported the poor performance of H-S method in Sahelian regions. In case of B-C equation, the same results found in the works of Saikia *et al.,* (2005) in the same climate characteristics of Umiam, and Meshram *et al.* (2010) in the hot climate of Solapur (India). However, our results did not agree with report of Abdelraouf *et al.,* (2024) who found best performance of this method in eastern arid and semiarid Egypt. In Kirmud, except SC and MR (with fair performance), other methods performed poorly. Relatively, results of this study show that the models' ability to predict FAO56-PM ET_o accurately is higher in central highlands than arid west land due to the phenomena of higher dominance of the impact of combined meteorological variables on ET_o in arid west land. Even MH-S model, which showed excellent performance in CHLs, did not repeat its performance in dry, less humid and windy arid west land. Therefore, in Kirmud, all alternate ET_o methods (even SC and MR methods) need rigor local calibration and validation cautiously in order to improve their accuracies (Allen *et al.,* 1998; Djaman *et al.,* 2015).

When we look at the mean of the two stations after combining CPI values of both highest best models, MH-S and MR methods found under good category of performance (CPI=2.5). SC method showed fair performance (CPI=2.4) and need intervention/calibration in order to increase its performance.

CONCLUSION

The study compared five ETo estimation methods versus the FAO56-PM method. The results showed that the most suitable methods in Asmara representing Central Highlands (CHL) are MH-S, RM and SC methods. However, the estimated values of SC method were underestimated significantly when compared to the standard FAO56-PM method in Asmara. In Kirmud, representing arid west low land (AWLL) all methods, except SC and MR (showed fair performance), performed poorly. Relatively, results of this study show that the models' ability to predict FAO56-PM ET_o accurately is higher in CHLs than AWLLs. Thus, for Agrometeorological stations with relative humidity and temperature data, MH-S and RM method can be taken as an alternative ET_o methods in data scarce CHLs for estimating ET_o. The study highlights the need for rigorous local calibration and validation of alternate ET_o methods cautiously, and exploring machine learning approaches for better accuracy in Kirmud.

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