



Journal of Agrometeorology

(A publication of Association of Agrometeorologists)

ISSN : 0972-1665 (print), 2583-2980 (online)

Vol. No. 28 (1) : 88 - 91 (March - 2026)

<https://doi.org/10.54386/jam.v28i1.3243>

<https://journal.agrimetassociation.org/index.php/jam>



Short communication

Performance of the FAO-56 Penman-Monteith method with limited meteorological data in Eritrea: A case study of Halhale

T. W. GHEBRETNSAE^{1,2*}, E. S. MOHAMED^{1,3}, A. B. BOKRE⁴, and T. TESFAY^{1,2}

¹Department of Environmental Management, Institute of Environmental Engineering, RUDN University, 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation

²Department of Land Resources and Environment, Hamelmalo Agricultural College, Eritrea

³National Authority for Remote Sensing and Space Sciences, Cairo, Egypt

⁴Ministry of Agriculture, Keren, Asmara, Eritrea

*Corresponding author email: tesfaweld333@gmail.com

The FAO56-Penman-Monteith (FAO56-PM) method is widely used to calculate crop water requirements (Sharma & Changade, 2025). It also serves as a standard benchmark for evaluating alternative ETo methods in data-scarce regions (Ghebretnsae *et al.*, 2025). However, its requirement for comprehensive climate datasets is a significant constraint in countries like Eritrea, where meteorological stations often lack complete records. For such data-limited contexts, researchers are strongly recommended to use the FAO56-PM method with estimated missing variables or the Hargreaves-Samani equation as reliable alternatives (Allen *et al.*, 1998).

Research has shown that the relative importance of climatic variables for ETo estimation is region-specific, influenced by the local climate regime, geographic location, season, and other factors. Wind speed was found to have less impact on the accuracy of ETo estimates particularly in humid climates of China (Gong *et al.*, 2006), semiarid climates of Tunisia (Jabloun & Sahli, 2013), and semi-arid part of Manitoba (Ndulue & Ranjan, 2021). Contrarily, wind speed was a major source of error in less humid climate and windy areas of Côte d'Ivoire (Koudahe *et al.*, 2018). Solar radiation and relative humidity were more important than wind speed for an accurate PM-ET_o calculation (Gong *et al.*, 2006). Ndulue and Ranjan (2021) works showed that the effect of solar radiation on ETo estimates is higher than that of wind speed and relative humidity in tropical sub-humid of Brazil. Solar radiation worked poorly for humid conditions but yielded quite good results for semiarid conditions of Côte d'Ivoire (Koudahe *et al.*, 2018).

Gong *et al.* (2006) concluded that the accuracy rank of these three climate variables in terms of FAO56-PM ETo estimates differ from region to region. Thus, identifying a proper ETo estimation model in climate data-limiting agricultural area is crucial.

The southern Central Highlands (CHLs) of Eritrea have a favorable climate and significant agricultural potential. To support the shift from traditional to commercial farming, the region is prioritizing efficient water use. Accurate estimation of reference evapotranspiration (ETo) is crucial for this, but is hindered by scarce climate data. This study addresses this gap by evaluating the performance of the FAO-56 Penman-Monteith and Hargreaves-Samani ETo methods under Eritrea's data-scarce conditions.

The FAO56-PM method was evaluated using limited data from the Halhale manual meteorological station in Eritrea. The station (15.060 N, 38.50 W, 1917 m AMSL), located in the country's southern CHLs, complies with FAO agrometeorological recommendations. Over 90% of the area's rainfall occurs in summer (June to August), coinciding with the northernmost movement of the Intertropical Convergence Zone. Data collection and processing followed Allen *et al.* (1998). Mean monthly values for maximum and minimum temperature, relative humidity, wind speed at 2m, and sunshine hours were used. After quality control for missing data and outliers, mean monthly reference evapotranspiration (ETo) was determined. According to Allen *et al.* (1998), ETo calculated from mean monthly data is very similar to the average of daily ETo values.

Article info - DOI: <https://doi.org/10.54386/jam.v28i1.3243>

Received: 13 October 2025; Accepted: 26 November 2025; Published online : 1 March 2026

"This work is licensed under Creative Common Attribution-Non Commercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) © Author (s)"

Table 1: Results of analysis of ET_o values for the 7 cases of missing variables and Hargreaves method

Statistical measures	Missing variables							H-S
	RH	SR	WS	RH+WS	SR+WS	SR+RH	SR+RH+WS	
R ²	0.92 (4)	0.87 (3)	0.97 (4)	0.85 (3)	0.88 (3)	0.76 (3)	0.75 (3)	0.81 (3)
%MBE	0.68 (4)	10.7 (2)	2.8 (4)	3.8 (4)	13.4 (2)	11.5 (2)	14.4 (2)	-8.3 (3)
NSE	0.96 (4)	0.74 (3)	0.97 (4)	0.92 (4)	0.65 (2)	0.70 (3)	0.58 (2)	0.78 (3)
RRMSE	5.8 (4)	15 (3)	4.7 (4)	8.6 (4)	17.5 (3)	16.4 (3)	19.3 (3)	14.2 (3)
MAPE	3.6 (4)	11.1 (3)	3.2 (4)	6 (4)	13.7 (3)	12 (3)	14.9 (3)	9.4 (4)
CPI	4.0 (E)	2.8 (G)	4.0 (E)	3.8 (E)	2.6 (G)	2.8 (G)	2.5 (G)	3.2 (G)
RMSE	0.27	0.68	0.22	0.39	0.79	0.74	0.86	0.64

Note: Values in parenthesis are range of accuracy value (RAV), E is excellent, G is good

ET_o was calculated using both the standard FAO Penman-Monteith (1) and the Hargreaves and Samani (2) equations. All calculations were performed in Microsoft Excel using a custom spreadsheet following the FAO-56 guidelines (Allen *et al.*, 1998).

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

$$ET_o = 0.408 \times 0.0023 (T + 17.8) \sqrt{(T_{max} - T_{min})} R_a \quad (2)$$

Missing solar radiation, actual vapour pressure and wind data for ET_o calculation were estimated following Allen *et al.* (1998). Radiation data were derived from air temperature differences using Hargreaves' radiation equation (3). For areas where there is no humidity data or poor quality, actual vapour pressure (*e_a*) was determined using equation 4. A default wind speed value of 2 m s⁻¹ was used for sites with missing data.

$$R_s = k_{R_s} R_a \sqrt{(T_{max} - T_{min})} \quad (3)$$

$$e_a = 0.611 e^{\left[\frac{17.27T_{dew}}{T_{dew} + 237.3} \right]} \quad (4)$$

In the preceding equations (1-4), the parameters are defined as: ET_o, reference evapotranspiration (mm day⁻¹); R_n and R_s net and solar radiation (MJ m⁻² day⁻¹), G, soil heat flux (MJ m⁻² day⁻¹); u₂, wind speed (m s⁻¹) at 2 m; e_s and e_a, saturation and actual vapor pressure (kPa); Δ, the slope of the saturation vapor pressure curve (kPa °C⁻¹); and γ, the psychrometric constant (kPa °C⁻¹). Air temperatures (T_{mean}, T_{max}, T_{min}, T_{dew}) are in °C. T_{min} is used instead of T_{dew}. The adjustment coefficient (k_{rs}) uses a value of 0.16 for interior locations, following Allen *et al.* (1998).

To evaluate the performance of the FAO56-PM method under missing data, we created different combinations of data omitting of climatic variables relative humidity, solar radiation, and wind speed. The single omitted variables are relative humidity (RH), solar radiation (SR), and wind speed (WS). The combination of two variable omitted are solar radiation and wind seed (SR+WS), relative humidity and wind speed (RH+WS), and solar radiation and relative humidity (SR+RH) and finally all three omitted variables are solar radiation, relative humidity and wind speed (SR+RH+WS). This study evaluated the performance of the FAO56-PM model with incomplete weather data by comparing its outputs against the

benchmark model. The assessment used various statistical indicators (R², RMSE, RRMSE, NSE, MAE, MAPE) to gauge accuracy, and MBE% to identify any systematic over- or underestimation of evapotranspiration (ET_o). Furthermore, the range of accuracy value (RAV) and cumulative performance index (CPI) for all test scenarios and H-S were determined using the method similar to the works of Ghebretnsae *et al.* (2025).

This study used the factor perturbation approach to find the most sensitive climate variable affecting ET_o. In this method, single climate variables—wind speed, vapour pressure deficit, solar radiation—were changed by ±5% to ±25%. For temperature, due to its non-linear relationship with saturation vapour pressure in the FAO Penman-Monteith equation, absolute changes of ±0.5°C to ±2.5°C were applied to the daily mean (T_{mean}). Each change's sensitivity was measured as the percentage change in daily ET_o (mm day⁻¹). Finally, the link between the perturbation size (°C for T_{mean}, % for wind speed, solar radiation and vapour pressure) and the resulting change in ET_o was graphed to compare each variable's sensitivity.

The analysis for Halhale showed that missing solar radiation (RMSE=0.68 mm day⁻¹) had a greater impact on ET_o estimates than missing wind speed (RMSE=0.22 mm day⁻¹), relative humidity (RMSE=0.27 mm day⁻¹), or their combination (RMSE=0.39 mm day⁻¹) (Table 1). Our results agree with study of Ndulue and Ranjan (2021), who reported that R_s has highest impact on the accuracy of ET_o estimates as compared to other climate variables. R² ranged from 0.75 (SR+RH+WS) to 0.97 (WS), and accordingly, all test scenarios and H-S method were found within acceptable level of performance. Generally, similar trends of performance like R² were also observed in NSE indicator index. H-S method underestimates FAO56 PM ET_o by 8.3%, while all other methods over estimate FAO56-PM ET_o estimates in between 0.68% (RH) and 14.4% (SR+RH+WS). This study clearly indicates that the H-S model outperforms the SR+RH+WS method.

In data-limited regions such as Eritrea, it is critical to determine the superior method, given that assessing accuracy alone is not enough (Ghebretnsae *et al.*, 2025). Generally, both H-S (CPI=3.0) and SR+RH+WS (CPI=2.5) methods showed good performances in Halhale, and they can be used as surrogate methods for FAO56-PM method in data limited areas of southern part of CHLs if only temperature data are available (Allen *et al.*,

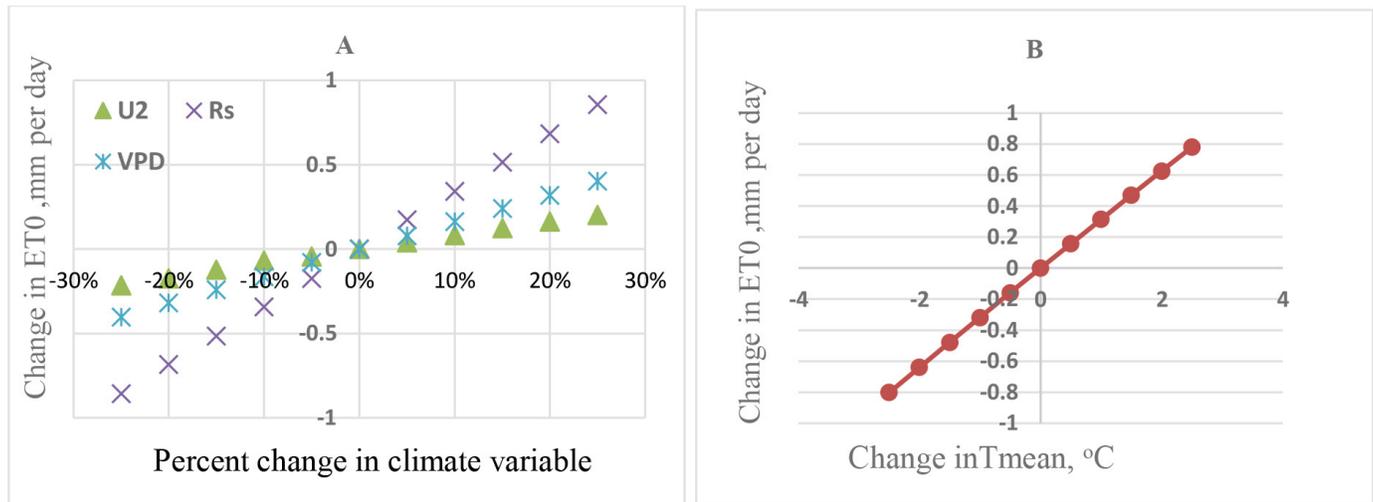


Fig.1: Sensitivity of reference evapotranspiration (ET₀) to (A) relative changes in wind speed (u_2), solar radiation (R_s), vapour pressure deficit (VPD), and (B) absolute changes in mean air temperature change (T_{mean})

1998). According to the report of Ghebretnsae *et al.* (2025), H-S method showed only fair performance in arid Western Lowlands of Eritrea. Our results strongly agree with findings of Tabari (2010), who reported that H-S performed well in warm humid and semi-arid climate but poorly in cold humid and arid climate of Iran. At the Halhale station, the FAO-56 PM method performed well (CPI = 2.75) when solar radiation (R_s) was the only missing data. Thus, installing solar radiation measurements at this location would further improve ET₀ accuracy. ET₀ calculations were excellent (CPI=4) when the only missing data is equal to the global average of wind speed. Many authors recommended the users to use with caution global average wind speed ($u_2 = 2 \text{ m s}^{-1}$) (Allen *et al.*, 1998, Jabloun and Sahli, 2013), which is very close to the average wind speed at Halhale (1.69 m s^{-1}). RH (missing relative humidity) also showed excellent performance (CPI=4.0).

The findings ensured that T_{dew} is equal to T_{min}, and can be used to calculate actual vapour pressure when relative humidity data were missing. Since relative humidity measurements are liable to personal and instrument errors, it is better to utilize a dewpoint temperature that is predicted from daily minimum air temperature, rather than to use unreliable relative humidity measurements (Allen *et al.*, 1998). Therefore, areas which have similar condition with Halhale require no measurement of wind speed and relative humidity to estimate ET₀.

Based on the results of the sensitivity analyses, solar radiation showed the highest influence on ET₀ values, followed by T_{mean}, vapour pressure deficit, and finally wind speed (Fig. 1). This highlights the dominance of solar radiation in this higher-altitude region, which is subject to cooler temperatures and potential cloud cover. We recommended careful measurement of solar radiation and temperature for reliable ET₀ estimates in data scarce regions of southern CHLs.

This research confirms that reliable ET₀ estimation in Eritrea's data-scarce southern Central Highlands is achievable using primarily temperature data. These findings provide a practical pathway for

informed irrigation planning and enhanced climate resilience across the country's agricultural regions.

ACKNOWLEDGEMENT

The Eritrean Ministry of Agriculture deserve the authors' heartfelt acknowledgment for their invaluable support in granting access to the meteorological data for Halhale. We also extend our gratitude to all the staff Halhale Agrometeorological Station for their guidance, technical assistance, and moral support throughout this project.

Conflict of Interests: The authors declare that there is no conflict of interest related to this article.

Data availability: The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Funding: No fund was obtained for this project

Authors contribution: T. W. GHEBRETNSAE: conceptualization, methodology, editing; E. S. MOHAMED: supervising, methodology, editing; A. B. BOKRE: typing, data collection and processing; T. TESFAY: editing

Disclaimer: The contents, opinions, and views expressed in the research article published in the Journal of Agrometeorology are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

Publisher's Note: The periodical remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56.

- Ghebretnsae, T. W., E. S. Mohamed, A. B. Bokre, T. Tesfay, & W. Ogbazghi. (2025). Evaluation of empirical methods for estimating reference evapotranspiration in Central High Lands and Arid Western Lowlands of Eritrea. *Journal of Agrometeorology*, 27(3), 349–354. <https://doi.org/10.54386/jam.v27i3.3073>
- Gong, L., Xu, C.-Y., Chen, D., Halldin, S., & Chen, Y. D. (2006). Sensitivity of the Penman–Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin. *Journal of Hydrology*, 329(3–4), 620–629. <https://doi.org/10.1016/j.jhydrol.2006.03.027>
- Jabloun, M., & Sahli, A. (2013). Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data: Application to Tunisia. *Agriculture Water Management*, 95(6), 707–715. <https://doi.org/10.1016/j.agwat.2008.01.009>
- Koudahe, K., Djaman, K., & Adewumi, J. K. (2018). Evaluation of the Penman–Monteith reference evapotranspiration under limited data and its sensitivity to key climatic variables under humid and semiarid conditions. *Modeling Earth System and Environment*, 4(4), 1239–1257. <https://doi.org/10.1007/s40808-018-0497-y>
- Ndulue, E., & Ranjan, R.S. (2021). Performance of the FAO Penman-Monteith equation under limiting conditions and fourteen reference evapotranspiration models in southern Manitoba. *Theoretical and Applied Climatology*, 143, 1285–1298. <https://doi.org/10.1007/s00704-020-03505-9>
- Sharma, V., and Changade, N. M. (2025). Irrigation water requirement of drip irrigated tomato and capsicum under controlled and open-field environments. *Journal of Agrometeorology*, 27 (1), 77–81. <https://doi.org/10.54386/jam.v27i1.2727>
- Tabari, H. (2010). Evaluation of Reference Crop Evapotranspiration Equations in Various Climates. *Water Resources Management*, 24, 2311–2337. <https://doi.org/10.1007/s11269-009-9553-8>