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EVALUATION OF EMPIRICAL REFERENCE EVAPOTRANSPIRATION ESTIMATION METHODS IN THE ZIWAY AREA, CENTRAL RIFT VALLEY, ETHIOPIA

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ABSTRACT. Reference evapotranspiration (ET_O) is a fundamental component of irrigation scheduling, estimation of crop water requirements, and sustainable water-resource management, particularly in semi-arid regions where water resources are limited. This study evaluated the performance of four empirical ET_O estimation methods (Blaney–Criddle, Hargreaves, Radiation, and Modified Penman) against the FAO-56 Penman–Monteith method in the Ziway area of the Central Rift Valley, Ethiopia. Long-term meteorological data (1990–2023), including air temperature, relative humidity, sunshine duration, wind speed, and rainfall, were obtained from the Ziway Meteorological Station. The FAO-56 Penman–Monteith method implemented in CROPWAT 8.0 served as the benchmark, and model performance was evaluated using root mean square error (RMSE), mean absolute error (MAE), mean bias error (MBE), coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), Willmott's index of agreement (d), mean absolute percentage error (MAPE), and normalised root mean square error (NRMSE). Monthly ET_O estimated by the benchmark method ranged from 2.87 to 5.00 mm day^{-1}. Among the evaluated methods, the Modified Penman method produced the lowest prediction errors, whereas the Hargreaves method exhibited the strongest correlation with the benchmark. Comparison of rainfall and ET_O showed that atmospheric evaporative demand exceeded precipitation during most months of the year, particularly during the dry and pre-rainy seasons, indicating the need for supplementary irrigation. Because independent evapotranspiration measurements, such as lysimeter or eddy-covariance observations, were unavailable, the results should be interpreted as agreement with the FAO-56 Penman–Monteith benchmark rather than as absolute model accuracy. These findings provide useful

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guidance for selecting appropriate ET_O estimation methods under data-limited conditions in the semi-arid regions of Ethiopia.

Keywords: atmospheric water deficit; Ethiopia; FAO-56 Penman–Monteith; Hargreaves; irrigation management; Modified Penman; reference evapotranspiration; Ziway.

INTRODUCTION

Accurate estimation of reference evapotranspiration (ET_O) is essential for irrigation scheduling, determination of crop water requirements, and sustainable water-resource management, particularly in semi-arid environments where water scarcity constrains agricultural productivity (Allen *et al.*, 1998; Trajkovic *et al.*, 2023). ET_O represents the evaporative demand of the atmosphere from a hypothetical reference crop surface and serves as the basis for estimating crop evapotranspiration and irrigation water requirements (Allen *et al.*, 1998). Reliable ET_O estimates are therefore critical for improving irrigation efficiency, enhancing agricultural productivity, and ensuring sustainable use of available water resources.

Agriculture is the backbone of the Ethiopian economy and is highly dependent on climatic conditions. The Central Rift Valley, including the Ziway area, is characterised by recurrent droughts, erratic rainfall distribution, high temperatures, and increasing pressure on water resources due to expanding irrigated agriculture (Awulachew *et al.*, 2007; Mekonnen *et al.*, 2021).

Under these conditions, efficient irrigation water management is necessary to maximise crop production while minimising water losses. Accurate estimation of ET_O is a prerequisite for determining crop water requirements and developing effective irrigation schedules.

The FAO-56 Penman–Monteith (PM) method is widely accepted as the international standard for estimating ET_O because it integrates the effects of net radiation, air temperature, humidity, and wind speed on the evapotranspiration process (Allen *et al.*, 1998). Numerous studies have demonstrated its reliability under diverse climatic conditions (Gao *et al.*, 2007; Xu and Singh, 2002). However, the application of the FAO-56 PM method is often constrained by the requirement for complete meteorological datasets, which are not always available in many developing countries, including Ethiopia.

To overcome these limitations, several empirical methods have been developed that require fewer climatic inputs. Among the most commonly used methods are the Blaney–Criddle method (Blaney and Criddle, 1950), the Hargreaves method (Hargreaves and Samani, 1985), the Radiation method (Doorenbos and Pruitt, 1977), and the Modified Penman method (Smith, 1991). These methods are frequently applied in data-scarce regions because of their simplicity and lower data requirements. However, their performance varies considerably depending on local climatic conditions, making site-specific evaluation essential before their adoption for irrigation planning (Gao *et al.*, 2007; Jensen *et al.*, 1990).

Several studies have compared empirical ET_O estimation methods across different climatic regions and reported significant differences in model performance (Gao *et al.*, 2007; Xu and

Singh, 2002). Their performance varies considerably across climatic zones because evapotranspiration is strongly influenced by local meteorological conditions and data availability. Recent studies have emphasised the importance of evaluating and calibrating empirical ET_O estimation methods under local climatic conditions before their application to irrigation planning and water-resource management (Koç and Can, 2023; Raja *et al.*, 2024). In Ethiopia, alternative ET_O estimation methods have also been evaluated under different agroecological conditions (Gebeyehu, 2021; Tadese *et al.*, 2020).

Nevertheless, comprehensive assessments of these methods for the Ziway area remain limited despite the area's importance for irrigated crop production and the increasing demand for efficient water-resource management.

Therefore, this study aimed to evaluate four commonly used empirical ET_O estimation methods—Blaney–Criddle, Hargreaves, Radiation, and Modified Penman—against the FAO-56 Penman–Monteith benchmark under the semi-arid climatic conditions of the Ziway area.

Specifically, the study aimed to: (1) estimate reference evapotranspiration using the Blaney–Criddle, Hargreaves, Radiation, Modified Penman, and FAO-56 Penman–Monteith methods; (2) evaluate the agreement of the empirical ET_O estimation methods with the FAO-56 Penman–Monteith benchmark; (3) compare monthly rainfall and reference evapotranspiration as indicators of atmospheric water deficit; and (4) identify suitable ET_O estimation methods for irrigation planning under semi-arid conditions.

MATERIALS AND METHODS

Description of the study area

This study was conducted in the Ziway area, located in the Central Rift Valley of Ethiopia within the Oromia Regional State. The area is situated between 7°50′N and 8°10′ N latitude and between 38°40′E and 38°56′ E longitude at an average elevation of approximately 1,640 m above sea level. The climate is classified as semi-arid and is characterised by bimodal rainfall distribution, with a short rainy season occurring from February to April and a main rainy season extending from June to September. The mean annual rainfall is generally insufficient to satisfy crop water requirements throughout the year, making irrigation an essential component of agricultural production (Awulachew *et al.*, 2007; Mekonnen *et al.*, 2021).

Meteorological data used in this study were obtained from the Ziway Meteorological Station operated by the Ethiopian Meteorological Institute (EMI). The station is located within the Lake Ziway Basin, one of Ethiopia's major irrigated agricultural zones with extensive horticultural and cereal crop production. The study area experiences relatively high temperatures, moderate wind speeds, and substantial atmospheric evaporative demand, making accurate estimation of reference evapotranspiration important for irrigation planning and water-resource management (Allen *et al.*, 1998; Mekonnen *et al.*, 2021). Because the Ziway Meteorological Station provides continuous long-term climatic observations and is widely used in regional climatic assessments, it was considered representative of the prevailing agro-climatic conditions of the Ziway irrigated agricultural zone (Awulachew *et al.*, 2007). *Figure 1* presents the geographical location of the Ziway Meteorological Station within the Central Rift Valley of Ethiopia. The map illustrates the location of the study area relative to Lake Ziway and the surrounding irrigated agricultural areas to demonstrate the representativeness of the meteorological station for the study.

Meteorological data collection

As mentioned, meteorological data were obtained from the EMI for the Ziway Meteorological Station, covering the period from 1990 to 2023. The collected climatic variables included maximum air temperature (Tmax, °C), minimum air temperature (Tmin, °C), relative humidity (RH, %), wind speed (U_2, m s^{-1}), sunshine duration (hours), and rainfall (mm). These variables were selected because they are required to estimate ET_O using the FAO-56 Penman–Monteith method and the other selected empirical methods (Allen *et al.*, 1998).

Daily meteorological observations were compiled and subjected to quality control before commencing the analysis. Monthly mean values were subsequently derived from the daily records and used to estimate ET_O and for comparative evaluation of the selected methods. Long-term monthly averages for the period of 1990–2023 were calculated to characterise seasonal variations in climatic conditions and atmospheric evaporative demand in the study area.

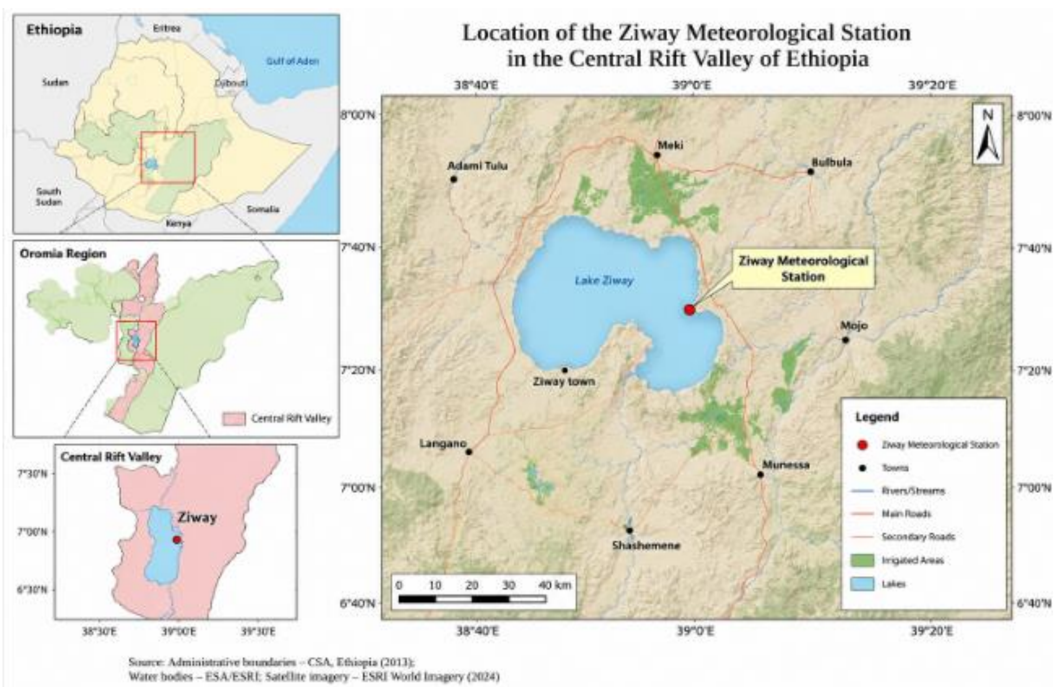


Figure 1 – Geographical location of the Ziway meteorological station

Solar radiation required for the FAO-56 Penman–Monteith and Radiation methods was estimated from sunshine duration using procedures incorporated in CROPWAT 8.0 based on Food and Agriculture Organization of the United Nations (FAO, 1990, 2016) recommendations (Allen *et al.*, 1998; Smith, 1992). ET_O calculations and climatic data processing were performed using CROPWAT 8.0 developed by FAO, while statistical analyses were conducted using Microsoft Excel.

Data quality control

Prior to analysis, the meteorological dataset was subjected to quality control following the recommendations of the World Meteorological Organization (WMO, 2017) and FAO guidelines for evapotranspiration estimation (Allen *et al.*, 1998).

Climatic variables including maximum temperature, minimum temperature, relative humidity, wind speed, sunshine duration, and rainfall were screened for missing values, outliers, and inconsistencies.

Missing values represented less than 2% of the complete dataset. They were estimated using long-term monthly averages and consistency checks based on neighbouring observations. Data consistency and homogeneity were evaluated through graphical inspection and comparison with long-term climatic patterns.

Sunshine duration was converted to solar radiation using procedures implemented within CROPWAT 8.0 (Smith, 1992). Wind-speed observations were standardised to the FAO-recommended height of 2m before calculating ET_O (Allen *et al.*, 1998).

Estimation of ET_O

ET_O was estimated using four empirical methods (Modified Penman, Hargreaves, Blaney–Criddle, and Radiation) and compared with the FAO-56 Penman–Monteith method, which served as the benchmark (Allen *et al.*, 1998).

The FAO-56 Penman–Monteith equation is expressed as (*Equation 1*):

$$ETo = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}u_2(es-ea))}{\Delta+\gamma(1+0.34u_2)} \quad (1)$$

where: ET_O = reference evapotranspiration (mm day^{-1}); Rn = net radiation at the crop surface (MJ m^{-2} day^{-1}); G= soil heat flux density (MJ m^{-2} day^{-1}); T = mean daily air temperature at a height of 2 m (°C); u_2 = wind speed at height of 2 m (m s^{-1}); es = saturation vapour pressure (kPa); ea = actual vapour pressure (kPa); (es – ea) = vapour pressure deficit (kPa); Δ=slope vapour pressure curve (kPa °C^{-1}); γ = psychrometric constant (kPa °C^{-1}).

Table 1 summarises the four empirical methods used to estimate ET_O. The Hargreaves method uses the following temperature-based equation to estimate ET_O (Hargreaves and Samani, 1985) (*Equation 2*):

$$ETo = 0.0023(T_{mean} + 1.78)(T_{max} - T_{min})^{0.5}R_a \quad (2)$$

The Blaney–Criddle method uses the following formula to estimate ET_O (Blaney and Criddle, 1950) (*Equation 3*):

$$ETo = p(0.46\mathrm{T}_{\mathrm{mean}} + 8) \quad (3)$$

The Radiation method was determined by following the FAO-24 procedures described by Doorenbos and Pruitt (1977). The Modified Penman method was estimated using the FAO-24 procedure incorporated in CROPWAT 8.0 (Doorenbos and Pruitt, 1977; Smith, 1991). Because the software internally computes the radiation and aerodynamic components, the complete equation is not presented here. The Modified Penman method combines energy balance and aerodynamic components and requires climatic variables including temperature, relative humidity, wind speed, and solar radiation. All ET_O estimates do not include crop coefficients (Kc) or crop evapotranspiration calculations.

Table 1 – Summary of the reference evapotranspiration estimation methods

Method	Equation (simplified)	Required inputs	Key assumptions/ notes
Blaney–Criddle	$ETo = p(0.46\mathrm{T}_{\mathrm{mean}} + 8)$	Mean air temperature (T_{mean}), percentage of annual daytime hours (p)	Temperature-based empirical method; assumes evapotranspiration is proportional to temperature and daylight duration
Hargreaves	$ETo = 0.0023(T_{mean} + 1.78)(T_{max} - T_{min})^{0.5}R_a$	Maximum temperature (T_{max}), minimum temperature (T_{min}), extra-terrestrial radiation (Ra)	Suitable for data-scarce conditions; does not explicitly account for humidity or wind speed
FAO-56 Penman–Monteith	Standard FAO-56 Penman–Monteith equation	Temperature, relative humidity, wind speed, and solar radiation	Internationally accepted benchmark method for estimating reference evapotranspiration; integrates energy balance and aerodynamic processes; crop coefficients (Kc) are not required for ET_O estimation
Radiation	$ETo = cWRs$	Solar radiation, temperature	Radiation-based method; assumes radiation is the dominant driver of evapotranspiration and gives limited consideration to aerodynamic effects
Modified Penman	FAO-24 Modified Penman procedure implemented in CROPWAT 8.0	Temperature, relative humidity, wind speed, and solar radiation	Combines energy balance and aerodynamic components; generally performs better than simple temperature-based methods under semi-arid conditions

Evaluation of model performance

The performance of the empirical evapotranspiration methods was evaluated by comparing their ET_O estimates with those obtained from the FAO-56 Penman–Monteith benchmark. Statistical analyses were conducted using 12 long-term mean monthly values derived from the 1990–2023 climatic record. Because the statistical evaluation was based on 12 climatological monthly mean values rather than the complete daily dataset, the performance indicators describe the agreement among the seasonal climatological patterns of the evaluated methods. Consequently, the reported statistics should be interpreted as representing long-term monthly agreement rather than day-to-day model performance.

The statistical indicators used included root mean square error (RMSE), mean absolute error (MAE), mean bias error (MBE), coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), Willmott's index of agreement (d), mean absolute percentage error (MAPE), and normalised root mean square error (NRMSE). These indicators are commonly used for evaluating the performance of evapotranspiration estimation models (Allen *et al.*, 1998; Koç and Can, 2023; Nash and Sutcliffe, 1970; Raja *et al.*, 2024; Willmott, 1982). Lower RMSE, MAE, MBE, MAPE, and NRMSE values indicate better agreement with the benchmark method, whereas higher R^2, NSE, and d values indicate stronger correspondence between the empirical methods and the FAO-56 Penman–Monteith benchmark (Allen *et al.*, 1998; Koç and Can, 2023; Raja *et al.*, 2024).

RESULTS

Monthly ET_O estimates

Table 2 presents the monthly ET_O estimated using the FAO-56 Penman–Monteith method (the benchmark) and the four selected empirical methods. The FAO-56 Penman–Monteith method produced the highest ET_O estimates for most months of the year, with values ranging from 2.87 mm day^{-1} in July to 5.00 mm day^{-1} in March. ET_O estimates were higher during the dry season and lower during the rainy season. The empirical methods produced similar seasonal patterns but generally produced lower ET_O estimates than the FAO-56 Penman–Monteith method. The Modified Penman method generated estimates closest to the FAO-56 Penman–Monteith values, whereas the Radiation method consistently produced the lowest ET_O estimates. The Hargreaves and Blaney–Criddle methods showed intermediate performance.

Statistical performance of empirical models

Table 3 presents the statistical performance of the empirical methods relative to the FAO-56 Penman–Monteith benchmark. The Hargreaves method presented the highest R^2 value (0.319), followed by the Radiation method (R^2= 0.267), indicating relatively stronger relationships with the benchmark method. The Modified Penman and Blaney–Criddle methods showed the lowest R^2 values (0.093 and 0.071, respectively). The Modified Penman method produced the lowest RMSE (0.948 mm day^{-1}), MAE (0.717 mm day^{-1}), and MBE (–0.717 mm day^{-1}). The Hargreaves method had an RMSE of

1.121mm day^{-1}, an MAE of1.031mm day^{-1}, and an MBE of –1.017 mm day^{-1}, while the Blaney–Criddle method produced and RMSE of 1.144mm day^{-1}, an MAE of 0.975mm day^{-1}, and an MBE of –0.965mm day^{-1}. The Radiation method produced the highest error values, with an RMSE of 2.170mm day^{-1}, an MAE of 2.111mm day^{-1}, and an MBE of –2.111 mm day^{-1}.

All empirical methods produced negative MBE values, indicating systematic underestimation of ET_O relative to the FAO-56 Penman–Monteith benchmark. Additional statistical indicators further revealed differences among the evaluated methods. The Modified Penman method exhibited the lowest MAPE (16.22%) and NRMSE (23.14%), while the Radiation method recorded the highest MAPE (50.71%) and NRMSE (52.96%). Willmott's index of agreement (d) ranged from 0.302 to 0.468. The Modified Penman method produced the highest value (d = 0.468), followed by the Blaney–Criddle (d = 0.466), Hargreaves (d = 0.464), and Radiation (d = 0.302) methods. NSE was negative for all empirical methods, ranging from –13.493 for the Radiation method to –1.767 for the Modified Penman method.

Scatter plot analysis

Figure 2 shows scatter plots illustrating the relationship between monthly ET_O estimates obtained from each empirical method and the FAO-56 Penman–Monteith benchmark.

Based on simple linear regression, the Hargreaves method exhibited the strongest correlation with the benchmark (r = 0.564), followed by the Radiation method (r = 0.517), the modified Penman method (r = 0.305), and the Blaney–Criddle method (r = 0.267).

Although the Hargreaves method demonstrated the strongest linear relationship, all empirical methods underestimated ET_O relative to the benchmark method.

These results indicate that model agreement varied considerably among the evaluated methods under the semi-arid climatic conditions of the Ziway area.

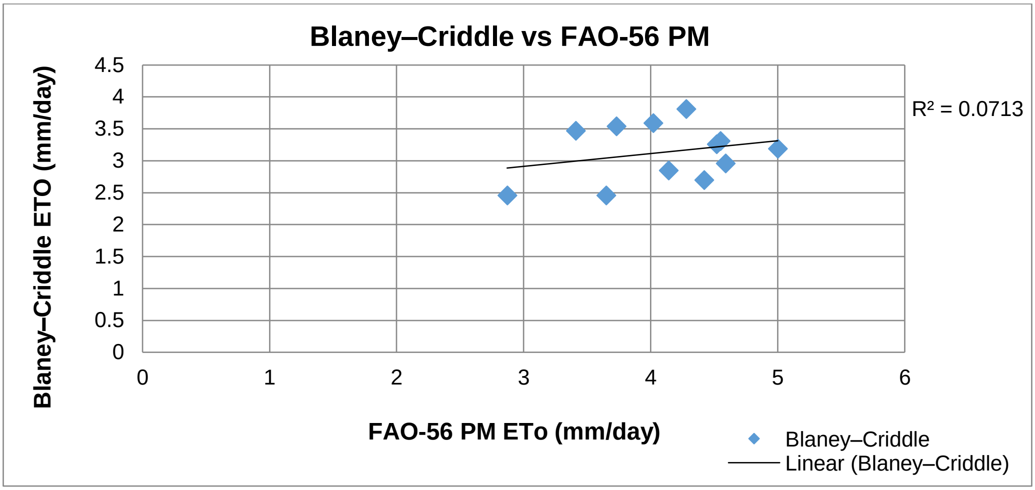
Table 2 – Mean monthly rainfall and reference evapotranspiration (ET_O) estimated with various methods

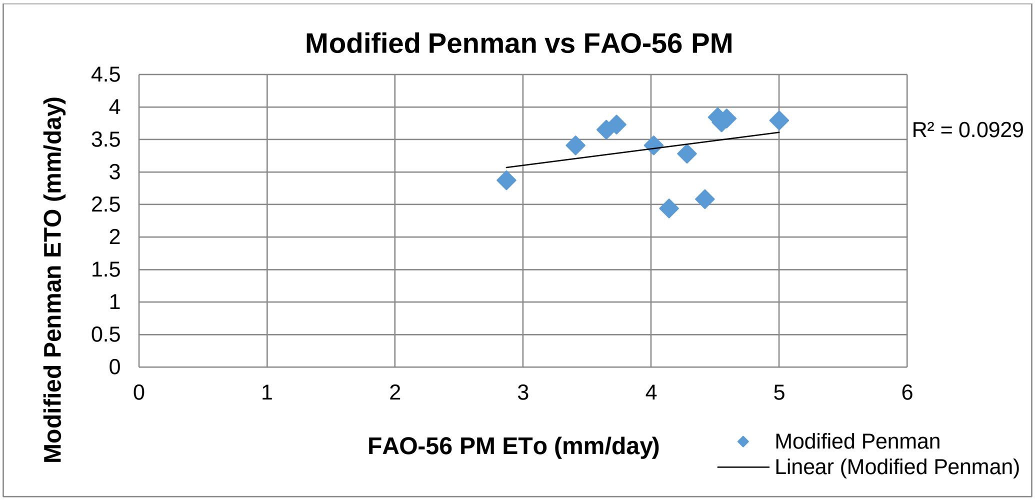
Month	Mean daily rainfall (mm/day)	Blaney–Criddle ET_O (mm/day)	Modified Penman ET_O (mm/day)	Radiation ET_O (mm/day)	Hargreaves ET_O (mm/day)	FAO-56 Penman–Monteith ET_O (mm/day)
Jan	0.57	3.59	3.41	1.79	2.85	4.02
Feb	1.07	3.26	3.84	2.01	3.08	4.52
Mar	1.63	2.96	3.82	2.20	3.45	4.59
Apr	2.69	3.31	3.76	2.23	3.50	4.55
May	2.16	3.19	3.79	2.24	3.62	5.00
Jun	2.81	3.81	3.28	2.06	3.25	4.28
Jul	4.95	2.85	2.44	1.80	2.68	4.14
Aug	3.93	2.70	2.58	1.84	2.74	4.42
Sep	2.33	2.46	2.87	1.99	2.95	2.87
Oct	1.17	2.46	3.65	2.04	3.15	3.65
Nov	0.10	3.54	3.73	1.88	2.89	3.73
Dec	0.13	3.47	3.41	1.77	2.81	3.41

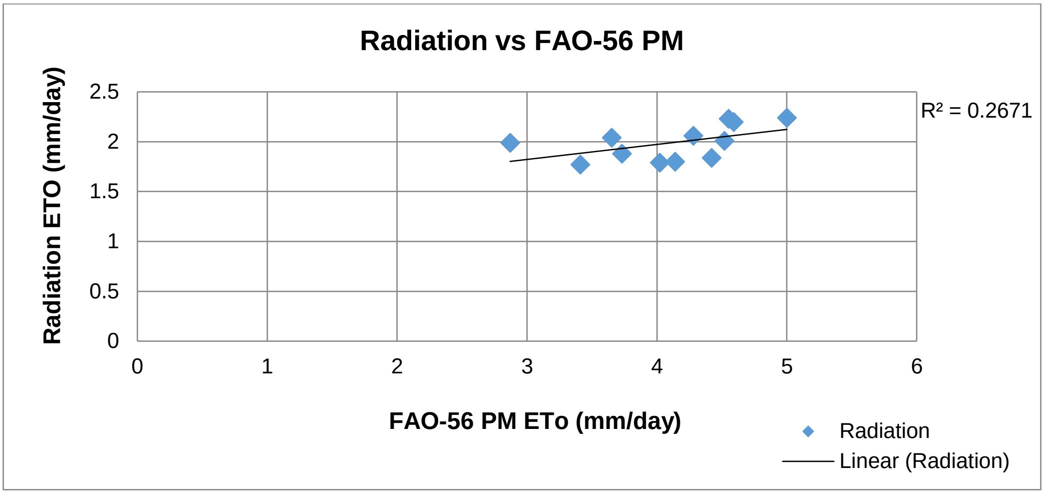
Table 3 – Statistical performance of the empirical reference evapotranspiration (ET_O) models

Model	RMSE (mm day⁻¹)	MAE (mm day⁻¹)	MBE (mm day⁻¹)	R^2	NSE	d	MAPE (%)	NRMSE (%)
Blaney–Criddle	1.14	0.98	-0.97	0.07	–3.03	0.47	22.69	27.92
Radiation	2.17	2.11	-2.11	0.27	–13.49	0.30	50.71	52.96
Hargreaves	1.12	1.03	-1.02	0.32	–2.87	0.46	24.20	27.36
Modified Penman	0.95	0.72	-0.72	0.09	–1.77	0.47	16.22	23.14
FAO-56 Penman–Monteith	–	–	–	–	–	–	–	–

D. Willmott's index of agreement; MAE, mean absolute error; MAPE, mean absolute percentage error; MBE, mean bias error; NRMSE, normalised root means square error; NSE, Nash–Sutcliffe efficiency; R^2, coefficient of determination; RMSE, root mean square error mean absolute error







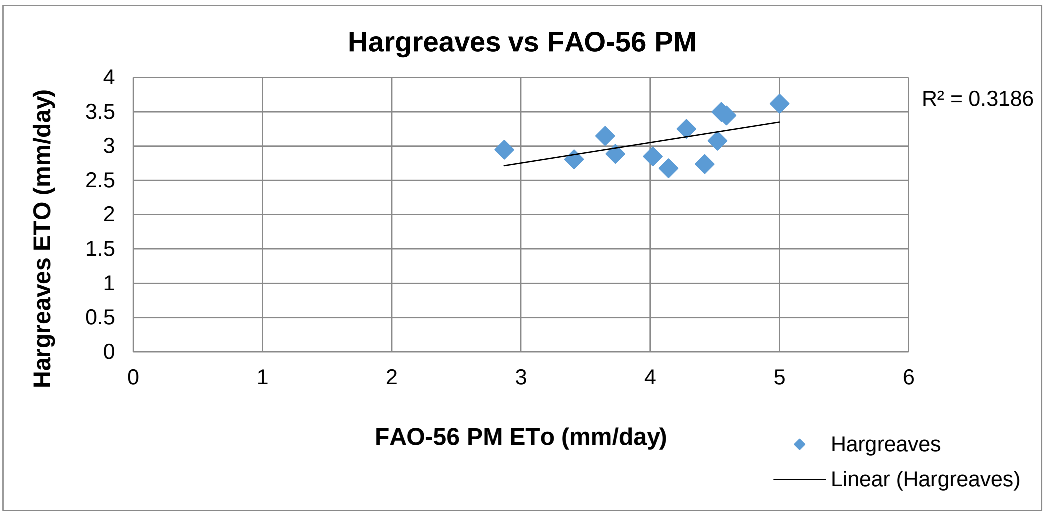


Figure 2 – Relationship between monthly reference evapotranspiration (ET_O) estimated by the empirical methods and the FAO-56 Penman–Monteith benchmark method for the Ziway area (1990–2023)

Comparison of rainfall and ET_O estimates

Figure 3 presents the comparison between monthly rainfall and ET_O estimates. Monthly ET_O estimated by the FAO-56 Penman–Monteith method exceeded rainfall during most months of the year.

The largest differences occurred during the dry season, particularly from January to May, when rainfall was substantially lower than atmospheric evaporative demand. Rainfall exceeded ET_O only during a limited period of the main rainy season.

These results indicate a persistent atmospheric water deficit during most months and highlight the importance of supplementary irrigation for agricultural production in the Ziway area.

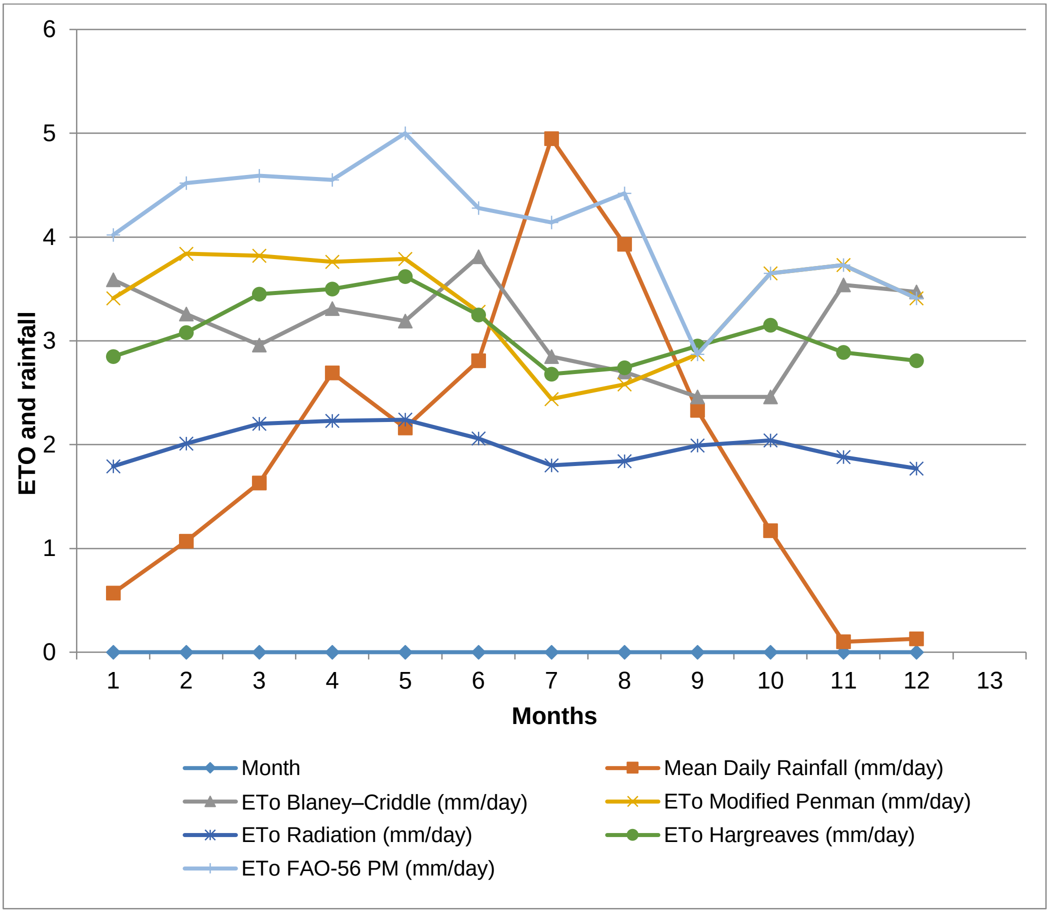


Figure 3 – Comparison of monthly rainfall and reference evapotranspiration (ET_O) estimates in the Ziway area (1990–2023)

DISCUSSION

Performance of the empirical ET_O estimation methods

The variation observed among the empirical methods demonstrates the influence of climatic variables on the accuracy of evapotranspiration estimation. The FAO-56 Penman–Monteith method is internationally recognised as the standard to estimate ET_O because it integrates radiation, temperature, humidity, and wind speed into a physically based framework (Allen *et al.*, 1998). Consequently, it provides a reliable benchmark for evaluating simplified empirical approaches. The Hargreaves method exhibited the highest R^2 value among the evaluated models, suggesting a relatively stronger ability to reproduce temporal variations in ET_O.

Similar findings have been reported in data-limited and semi-arid environments where temperature-based methods performed reasonably well when complete climatic datasets were unavailable (Koç and Can, 2023; Raja *et al.*, 2024).

Performance of temperature-based methods

The Hargreaves and Blaney–Criddle methods rely primarily on temperature-related variables to estimate ET_O. The relatively stronger performance of the Hargreaves method among the evaluated empirical methods indicates that temperature is a major driver of evapotranspiration variability in the Ziway area.

Similar results have been reported in semi-arid regions where the Hargreaves method has provided acceptable estimates under limited climatic data conditions (Bautista and Bautista, 2009; López-Urrea *et al.*, 2024). However, temperature-based methods do not explicitly account for the effects of humidity and wind speed. Consequently, these methods may not adequately represent evapotranspiration dynamics during periods of high atmospheric demand.

Performance of the Modified Penman method

The Modified Penman method produced the lowest RMSE, MAE, MBE, MAPE, and NRMSE values among the evaluated empirical methods, indicating the closest overall agreement with the FAO-56 Penman–Monteith benchmark. This improved performance is likely attributable to the inclusion of additional climatic variables, including temperature, relative humidity, wind speed, and solar radiation, which enable a more comprehensive representation of atmospheric evaporative demand than simpler empirical approaches.

These findings are consistent with previous studies reporting that combination methods generally outperform temperature-based methods under semi-arid conditions (Allen *et al.*, 1998; Doorenbos and Pruitt, 1977). Similar results have been reported in recent studies conducted under Mediterranean, Asian, and African semi-arid climates, where combination methods generally outperformed temperature-based empirical equations because they better represent both radiative and aerodynamic controls on evapotranspiration.

The consistency of these findings suggests that the superior performance of the Modified Penman approach is not limited to the Ziway area but reflects its stronger physical representation of atmospheric evaporative demand under water-limited environments.

Although the Hargreaves method exhibited the highest R^2 of the evaluated methods (0.319), its larger prediction errors indicate that the Modified Penman method provides a more reliable alternative for ET_O estimation in the Ziway area when complete meteorological data are available.

Performance of the Radiation method

The Radiation method consistently underestimated ET_O and produced the largest prediction errors. This underestimation is likely attributable to the method's limited representation of aerodynamic processes. In semi-arid environments, evapotranspiration is influenced not only by available energy but also by wind speed and vapor pressure deficit.

Consequently, radiation-based approaches may fail to adequately represent actual atmospheric evaporative demand.

Similar limitations have been reported in recent studies evaluating empirical ET_O methods under water-limited climatic conditions (Raja *et al.*, 2024).

Implications for irrigation water management

The consistent underestimation of ET_O by the evaluated empirical methods has important implications for irrigation scheduling. Underestimation of crop water requirements may result in inadequate irrigation, potentially leading to crop water stress and reduced agricultural productivity. Therefore, careful selection of evapotranspiration estimation methods is necessary when planning irrigation water use in semi-arid environments (Awulachew *et al.*, 2007; Tadese *et al.*, 2020).

The comparison between rainfall and ET_O further indicates that atmospheric evaporative demand exceeds precipitation during most months of the year. This finding emphasises the importance of supplementary irrigation for sustaining agricultural production in the Ziway area.

Study limitations

The present study evaluated empirical ET_O estimation methods using the FAO-56 Penman–Monteith method as a benchmark rather than direct field measurements. Consequently, the results should be interpreted as agreement with the benchmark method rather than as a measure of absolute estimation accuracy.

Direct measurements of evapotranspiration using lysimeters, eddy-covariance systems, or pan-evaporation observations were unavailable for the study area. Therefore, uncertainty associated with the benchmark method could not be quantified.

Future studies should incorporate observed evapotranspiration data and locally calibrated empirical models to improve the assessment of evapotranspiration estimation methods under the semi-arid conditions of Ethiopia (Allen *et al.*, 1998; Koç and Can, 2023; López-Urrea *et al.*, 2024).

CONCLUSIONS

This study evaluated four empirical ET_O estimation methods against the FAO-56 Penman–Monteith benchmark using long-term climatic data from the Ziway area of Ethiopia. Monthly ET_O estimated by the benchmark method ranged from 2.87 to 5.00 mm day^{-1} and exceeded rainfall during most months of the year, indicating persistent atmospheric water deficits and a strong dependence on supplementary irrigation.

Overall, the Modified Penman method demonstrated the best agreement with the FAO-56 Penman–Monteith benchmark based on combined error statistics, whereas the Hargreaves method showed the strongest correlation with the benchmark. The Radiation method consistently exhibited the poorest performance.

Because direct measurements of evapotranspiration were unavailable, the findings should be interpreted as agreement with the FAO-56 Penman–Monteith benchmark rather than absolute estimation accuracy.

The results support previous studies indicating that empirical evapotranspiration models require local evaluation and calibration before application in irrigation planning because their performance is strongly influenced by climatic conditions and data availability (Tessema *et al.*, 2024; Trajkovic *et al.*, 2023).

Future studies should incorporate lysimeter or eddy-covariance measurements and evaluate local calibration procedures to improve ET_O estimation under Ethiopian semi-arid conditions.

RECOMMENDATIONS

Based on the findings of this study, the FAO-56 Penman–Monteith method is recommended as the preferred approach for estimating ET_O in the Ziway area whenever complete meteorological data are available because it incorporates the major climatic variables influencing atmospheric evaporative demand and serves as the internationally accepted benchmark.

Under data-limited conditions, the Hargreaves method may be used as a practical alternative because it exhibited the strongest correlation with the benchmark estimates. In contrast, the Radiation method is not recommended for irrigation planning in the Ziway area because it consistently under estimates ET_O. The persistent atmospheric water deficit observed during most months underscores the need for supplementary irrigation to meet crop water requirements.

Future research should incorporate direct evapotranspiration measurements, such as lysimeter or eddy-covariance observations, and evaluate locally calibrated empirical models to improve the reliability of ET_O estimation under the semi-arid conditions of Ethiopia.

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