



Monthly Vs Daily Penman–Monteith Estimates of Reference Evapotranspiration: A 65-Year Record from Adana, Türkiye

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Abstract. This study evaluates reference evapotranspiration (ET_o) using a long-term meteorological record acquired from the Adana meteorological station in southern Turkey. The standardised FAO-56 Penman–Monteith method was applied at two temporal resolutions: (i) ET_o computed directly from monthly climatic data, and (ii) ET_o obtained by aggregating ET_o estimated from daily climatic data. Agreement between the two approaches was assessed using Pearson's correlation and paired t-tests. The results showed a very close correspondence, with a high correlation ($r = 0.99$), a mean bias of -0.92 mm per month (defined as the difference between the monthly input and the daily aggregated ET_o), and no statistically significant difference (paired t-test, $p > 0.05$). These results suggest that where daily climate records are unavailable, the standardised FAO-56 Penman–Monteith method driven by monthly inputs can reliably estimate monthly ET_o. Furthermore, study findings highlight the applicability of the technique in regions with long-term but coarse-resolution data, with valuable implications for water resource management and agricultural planning.

Keywords: Reference Evapotranspiration (ET_o), Climate Variability, Planning of Irrigation Systems, Water Resources Management.

1 Introduction

Reference evapotranspiration (ET_o) is a key component of the hydrological cycle that quantifies the atmospheric demand for water from a reference surface, typically a hypothetical, well-watered grass field (Gocic & Trajkovic, 2014; Cetin et al., 2023a). It represents the combined processes of soil evaporation and plant transpiration. Accurate estimation of ET_o underpins irrigation scheduling, drought assessment, drought mitigation, optimal allocation of water resources, rational water-resources management,

and studies on climate-change impacts (Alsenjar et al., 2023a, 2023b). In irrigated agricultural systems, understanding ETo dynamics is essential for optimizing water use efficiency, sustaining crop yields, and ensuring a reliable water supply.

The FAO-56 standardised Penman–Monteith formulation, recommended by the Food and Agriculture Organization (FAO) as the reference method for ETo, incorporates key climatic variables — air temperature, radiation, wind speed, and humidity — by balancing energy and aerodynamic components (Allen et al., 1998). Although it is robust across diverse climates and regions, it often requires access to high-resolution daily weather data, which is limited in many areas of the world.

Despite growing data availability, daily records frequently remain incomplete, inconsistent, or unavailable over long periods, especially in developing regions or historical archives. In contrast, monthly climate summaries are more commonly preserved and span longer periods, yet their lower temporal resolution may affect ETo precision. Given the emphasis on long-term climate variability and its implications for water resources, there is a practical need to evaluate whether monthly climatic data can serve as a reliable substitute for daily inputs when estimating monthly ETo.

This question is particularly salient in semi-arid Mediterranean settings such as Adana, Türkiye, where irrigated agriculture is a significant economic driver and water scarcity is intensifying (Cetin et al., 2020). The region’s pronounced seasonality—hot, dry summers and mild, wetter winters—produces significant intra-annual variability in atmospheric demand, with peak ETo and irrigation requirements concentrated in summer. Consistent, multi-decadal quantification of ETo is therefore critical for evidence-based irrigation scheduling, drought-risk assessment, climate-adaptation planning, and operational decisions on water allocation across competing sectors.

Previous studies have compared monthly and daily ETo estimates using the FAO-56 Penman–Monteith method across diverse regions, generally reporting strong correlations alongside biases introduced by temporal aggregation (see, among others, Irmak et al., 2003). However, such evaluations remain limited for Türkiye and comparable Mediterranean climates, and much of the literature focuses on short time windows or specific seasons rather than continuous, long-term records.

This study addresses this gap by comparing monthly ETo computed from monthly climatic summaries using the FAO-56 Penman–Monteith method with monthly ETo obtained by aggregating daily ETo derived from daily inputs at the Adana meteorological station over 1960–2024. The objectives are to quantify agreement and potential bias between the two approaches and to assess the statistical significance of any observed differences.

More broadly, the findings are intended to inform practitioners and researchers working with limited daily meteorological records about the reliability of monthly-input ETo estimation. The evidence supports the use of historical datasets in climate-impact assessments and the design of adaptive irrigation-scheduling strategies, and it clarifies how temporal data resolution influences hydrological modeling and decision-making in semi-arid agricultural systems.

2 Materials and Methods

Figure 1 shows the flowcharts used to estimate ET_o monthly, based on the FAO-56 Penman–Monteith method. The figure summarises the overall procedure followed in this study, including the data sources, input variables, methods, and outputs used. The subsequent sections offer a comprehensive description of the datasets and methodologies employed.

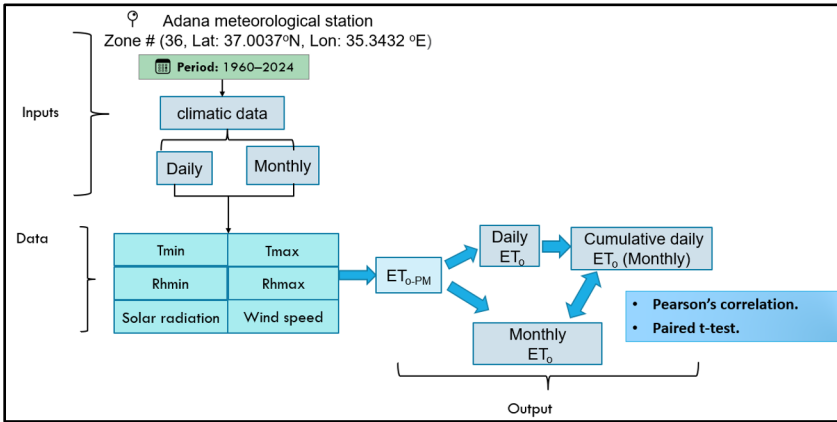


Fig. 1. Workflow for reference evapotranspiration (ET_o) at the Adana meteorological station (1960–2024): from daily and monthly climatic inputs to FAO-56 Penman–Monteith ET_o computation and detection of statistical differences between the two approaches.

2.1 Study Area

This analysis uses long-term meteorological observations (1960–2024) from the Adana meteorological station (ID: 17351; 37.0° N, 35.3° E; 23 m a.s.l.; Figure 2). Adana city center and its surroundings have a Mediterranean climate with hot, dry summers and mild, wet winters. Mean annual precipitation is approximately 650 mm, most of which occurs from November to March; mean temperatures range from about 9 °C in winter to >29 °C in summer (Cetin et al., 2023b; Alsenjar et al., 2023a). Agriculture is a significant economic sector—cotton, citrus, and cereals are widely cultivated (Alsenjar et al., 2023b). In this semi-arid setting, reliable estimates of reference evapotranspiration (ET_o) are necessary to support efficient irrigation scheduling and water resource planning amid increasing pressures on water availability.

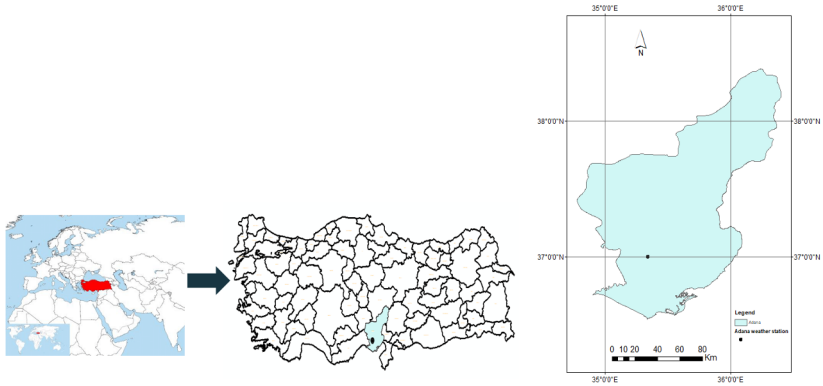


Fig. 2. Study area showing the location of the city of Adana and the Adana meteorological station (ID: 17351) in southern Türkiye (37.0° N, 35.3° E; 23 m a.s.l.).

2.2 Meteorological Data: Acquisition, Gap-Filling, and Quality Assurance/Quality Control (QA/QC)

Daily and monthly meteorological data for 1960–2024 were obtained from the Adana meteorological station (ID: 17351). The dataset comprises the variables, as time series, required for reference evapotranspiration (ET_0): minimum and maximum air temperature (T_{min} , T_{max}), relative humidity (RH_{min} , RH_{max}), solar radiation (R_s), wind speed at 2 m (u_2), and atmospheric pressure (P). Quality control involved screening for missing, physically implausible, or internally inconsistent values and correcting flagged entries using interpolation procedures consistent with established climatological practice (Jerez et al., 2010; Keskiner & Cetin, 2022). Missing daily values in the datasets were identified, and their counts and percentages are summarized in Table 1. Gap filling followed the procedures described by Jerez et al. (2010) and Hirca & Eryılmaz-Türkkan (2024), among others. In this context, when a single daily observation was missing, it was imputed by a simple averaging method, replacing the value for that day with the mean of the preceding and following days. Due to extended gaps in the daily solar radiation record series in some years (in certain cases of at least one month), averaging was not applicable. Instead, missing R_s values were estimated using a regression between daily global solar radiation and sunshine duration (the Ångström–Prescott approach; Jerez et al., 2010; Keskiner & Cetin, 2022), resulting in a continuous time series. The most significant gaps occurred in solar radiation (4,729 values; 19.91%) and sunshine duration (1,338 values; 5.64%), whereas wind speed (1.24%), relative humidity (0.04–0.16%), and temperature (<0.03%) exhibited comparatively few missing observations.

Table 1. Counts and percentages of missing daily meteorological observations by variable at the Adana meteorological station (1960–2024).

Meteorological parameters	Number of missing data	Percentage of missing data (%)
Solar radiation (Cal/cm ²)	4729	19.91
Minimum temperature (°C)	6	0.03

Maximum temperature (°C)	6	0.03
Mean temperature (°C)	7	0.03
Minimum relative humidity (%)	10	0.04
Maximum relative humidity (%)	10	0.04
Mean relative humidity (%)	39	0.16
Mean wind speed (m/s)	294	1.24
Sunshine duration (hours)	1338	5.64

2.3 Reference Evapotranspiration (ET_o) Estimation

Reference evapotranspiration (ET_o) time series was computed using the standardized FAO-56 Penman–Monteith formulation (Allen et al., 1998), which combines energy-balance and aerodynamic terms for a short, well-watered grass reference, and is expressed as:

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

Where: ET_o is the reference evapotranspiration (mm day⁻¹), R_n is the net radiation at the crop surface (MJ m⁻² day⁻¹), G is the soil heat flux density (MJ m⁻² day⁻¹), T is the mean daily air temperature at 2 m height (°C), u₂ is the wind speed at 2 m height (m s⁻¹), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), e_s - e_a is the saturation vapour pressure deficit (kPa), Δ and γ are the slope (kPa °C⁻¹) of the vapour pressure curve and the psychrometric constant (kPa °C⁻¹), respectively.

The calculations were performed using two temporal-resolution approaches: Daily-based approach (daily to monthly aggregation): Daily climatic variables were input to the FAO-56 Penman–Monteith equation to compute daily ET_o. These values were then summed to monthly totals for each month from January 1960 to December 2024. Monthly-input approach (direct monthly computation): Monthly climatic summaries were used directly in the FAO-56 Penman–Monteith equation to estimate monthly ET_o, assuming that applying the formulation to monthly-averaged variables approximates the monthly total. In both approaches, the following auxiliary terms were computed in strict accordance with FAO-56 procedures: saturation vapor pressure, the slope of the saturation vapor-pressure curve, and the psychrometric constant. These quantities were evaluated using FAO-56 algorithms and constants in SI units to ensure internal consistency across time steps; the daily workflow employed the daily formulation, whereas the monthly workflow used the monthly formulation recommended by FAO-56. All calculations followed FAO-56 conventions for handling temperature and humidity statistics and were applied uniformly throughout the period of record.

2.4 Statistical Analysis

To evaluate the consistency between the two ETo estimation approaches, we compared monthly ETo totals obtained by aggregating daily ETo with monthly ETo computed directly from monthly climatic summaries (Wilcoxon, 1992; Alazba et al., 2025). Agreement and differences were assessed as follows :

Pearson's correlation (r): Quantified the strength of the linear association between the two monthly ETo series (values near 1 indicate strong positive correlation).

Paired t-test: Tested whether the mean difference between the two monthly ETo series differed from zero at the 95% confidence level (two-sided) (Field, 2024). Normality of paired differences was checked (Shapiro–Wilk); if not supported, the Wilcoxon signed-rank test was used as a nonparametric alternative.

All analyses were implemented in Microsoft Excel. Results were visualized with scatterplots (including a 1:1 reference line) and time-series graphs to facilitate comparison and interpretation.

3 Results and Discussion

3.1 Comparison of Monthly ETo Estimates from Daily-Aggregated and Monthly-Input Data

Figure 3 and Table 1 depict monthly reference evapotranspiration (ETo) at the Adana meteorological station for 1960–2024. Mean monthly ETo ranges from 41.30 mm in December to 178.64 mm in July, reflecting the strong influence of temperature and solar radiation in this semi-arid Mediterranean climate. Medians closely match the means, indicating near-symmetric distributions, while dispersion or variability is larger in summer (e.g., SD = 18.87 mm and range = 88.17 mm in August), consistent with greater interannual variability. Skewness values are generally small, and kurtosis shows occasional departures from mesokurtic behavior (e.g., December = 1.39, April = -0.78). Seasonal extremes are evident in the minima and maxima (January = 23.71 mm, July = 220.43 mm). Precision of the monthly means is high, with standard errors of 0.93–2.36 mm and corresponding 95% CI half-widths of 1.87–4.71 mm across months.

High summer ETo values are associated with prolonged sunshine, elevated temperatures, and low cloud cover, whereas lower winter values reflect reduced solar radiation, shorter daylength, and cooler air masses. Considerable interannual variability, particularly in summer, is plausibly influenced by large-scale circulation patterns such as the North Atlantic Oscillation (NAO) and the Eastern Mediterranean Pattern (EMP), which modulate regional temperature, humidity, and wind fields (Hurrell, 1995). Overall, these patterns indicate that ETo in the Lower Seyhan Plain is shaped by multiple interacting climatic drivers, underscoring the need for adaptive water-management strategies.

To summarize briefly, across 1960–2024, monthly ETo at the Adana station exhibits pronounced seasonality—from 41.30 mm in December to 178.64 mm in July. Distributions are near-symmetric (medians \approx means), with greater dispersion in summer (e.g., SD 18.87 mm in August; range 88.17 mm) than in winter; seasonal extremes span 23.71–220.43 mm. Standard

errors of the monthly means are minor (0.93–2.36 mm) with 95% confidence-interval half-widths of 1.87–4.71 mm, indicating precise monthly means. Taken together, these characteristics provide a consistent baseline for the method comparison and suggest that applying the FAO-56 Penman–Monteith formulation to monthly-averaged inputs can closely reproduce the monthly totals obtained by aggregating daily ETo under this semi-arid Mediterranean climate.

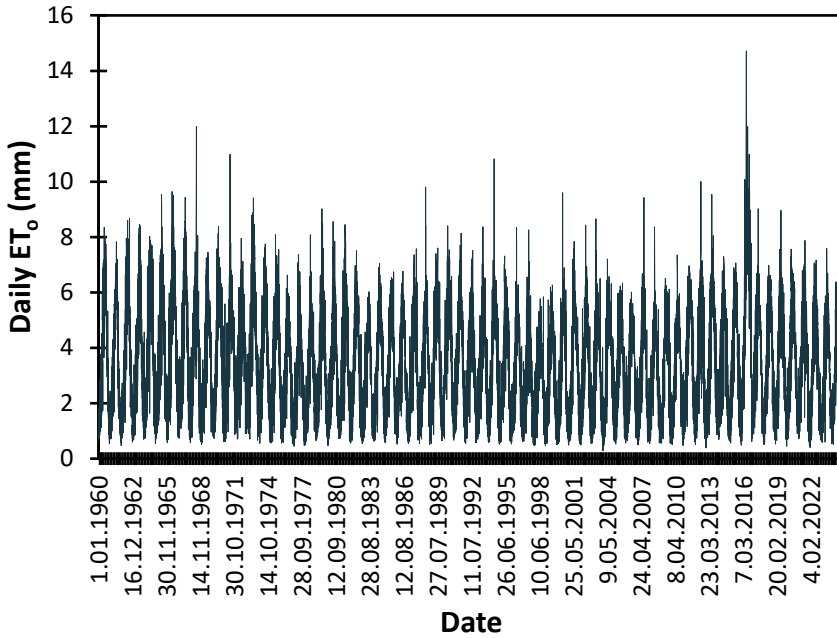


Fig. 3. Time series of daily reference evapotranspiration (ET₀; mm day⁻¹) estimated with the FAO-56 Penman–Monteith method at the Adana meteorological station, 1960–2024.

Table 2. Descriptive statistics of monthly reference evapotranspiration (ET₀; mm month⁻¹) at the Adana meteorological station, 1960–2024.

Months	January	February	March	April	May	June
Mean	43.79	53.05	81.84	107.14	142.43	165.00
Standard Error	0.93	0.94	1.13	1.73	1.98	2.00
Median	43.27	52.48	81.02	106.30	142.82	164.95
Standard Deviation	7.47	7.48	9.08	13.86	15.87	15.97
Kurtosis	0.78	0.39	-0.48	-0.78	0.03	0.75
Skewness	0.37	0.46	-0.09	0.21	-0.03	0.45
Range	41.37	37.57	37.47	55.65	73.27	83.26
Minimum	23.71	36.98	60.77	82.81	105.60	133.90
Maximum	65.09	74.56	98.23	138.46	178.86	217.16
Confidence Level	1.87	1.87	2.27	3.46	3.96	3.99

(95.0%)						
Months	July	August	September	October	November	December
Mean	178.64	164.55	130.67	92.49	55.13	41.30
Standard Error	2.00	2.36	1.88	1.60	1.05	0.97
Median	177.20	164.64	131.53	92.11	56.05	40.67
Standard Deviation	16.03	18.87	15.01	12.81	8.39	7.79
Kurtosis	0.23	-0.01	-0.21	-0.57	-0.17	1.39
Skewness	0.32	0.31	-0.14	0.16	0.02	0.60
Range	81.15	88.17	72.36	56.87	38.36	41.58
Minimum	139.28	125.78	89.62	62.88	37.89	25.49
Maximum	220.43	213.95	161.98	119.75	76.25	67.06
Confidence Level (95.0%)	4.00	4.71	3.75	3.20	2.10	1.94

The primary objective of this study was to assess whether applying the FAO-56 Penman–Monteith formulation to monthly climatic summaries can reliably reproduce monthly reference evapotranspiration (ET_o) obtained from the daily-aggregated approach. Figure 4 shows a scatterplot of monthly ET_o from daily-aggregated calculations versus monthly-input calculations for 1960–2024. Points cluster tightly along the 1:1 line, indicating excellent agreement. Ordinary least squares regression yielded a slope of 1.0075, $R^2 = 0.99$, and $r = 0.99$, confirming an almost perfectly linear relationship.

To further quantify agreement, the variances of the two monthly ET_o series (daily-aggregated 2635.80 mm²; monthly-input 2648.72 mm²) were compared using an F-test ($F = 0.995$, $p = 0.47$; Table 2), showing no evidence of unequal variances. A two-sided paired t-test likewise indicated no statistically significant mean difference between approaches ($t = -0.365$, $p = 0.715$; Table 3), with a small bias of -0.92 mm month⁻¹ (defined as monthly-input minus daily-aggregated). Time-series comparisons confirm that both methods capture seasonal and interannual variability consistently, with only minor deviations. Overall, the monthly-input method provides monthly ET_o estimates that closely match those from daily aggregation and is suitable for practical applications in this setting.

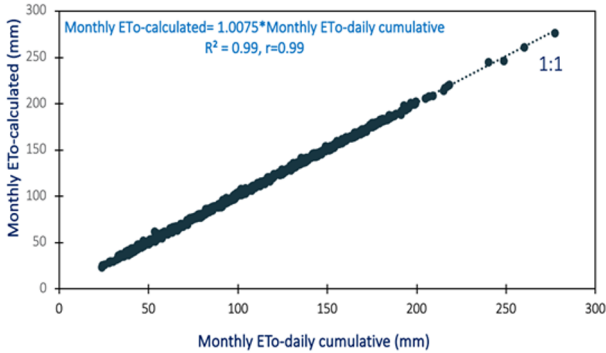


Fig. 4. Scatterplot of monthly reference evapotranspiration (ET₀; mm month⁻¹): daily-aggregated FAO-56 Penman–Monteith estimates versus monthly-input FAO-56 Penman–Monteith estimates at the Adana meteorological station (1960–2024). The dotted line shows the 1:1 reference line.

Table 3. F-test for equality of variances between monthly reference evapotranspiration (ET₀) series: daily-aggregated vs monthly-input (FAO-56 Penman–Monteith) at the Adana meteorological station, 1960–2024.

	<i>Monthly ET₀-daily cumulative (mm)</i>	<i>Monthly ET₀-calculated (mm)</i>
Mean	104.65	105.57
Variance	2635.80	2648.72
Observations	780	780
df	779	779
F	0.995	
P(F<=f) one-tailed	0.47	
F Critical one-tailed	0.89	

Table 4. Paired t-test (two-sided) for the **mean monthly difference** in reference evapotranspiration (ET₀; monthly-input – daily-aggregated) at the Adana meteorological station (FAO-56 Penman–Monteith), 1960–2024.

	<i>Monthly ET₀-daily cumulative</i>	<i>Monthly ET₀-calculated</i>
Mean	104.65	105.57
Variance	2635.80	2648.72
Observations	780	780
Pooled Variance	2642.17	
Hypothesized Mean Difference	0	
df	1558	
t Stat	-0.365	
P(T<=t) one-tailed	0.358	
t Critical one-tailed	1.646	
P(T<=t) two-tailed	0.715	

t Critical two-tailed	1.961
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This study demonstrates that monthly reference evapotranspiration (ET_0) in the Eastern Mediterranean of Türkiye—specifically the Adana Plain—can be reliably estimated from monthly climatic summaries when daily data are unavailable. Consistent with Figure 4, a simple proportional fit for this dataset is: Monthly ET_0 -calculated = $1.0075 \times$ Monthly ET_0 -daily cumulative, which succinctly reflects the near-1:1 agreement between approaches. Statistical tests indicate no evidence of unequal variances (Table 2) and no statistically significant mean difference (Table 3), with an average bias of $-0.92 \text{ mm month}^{-1}$ (defined as monthly-input minus daily-aggregated).

Minor deviations arise during periods of high day-to-day variability or extreme events due to the nonlinear terms in the FAO-56 Penman–Monteith formulation: daily peaks in temperature, radiation, and humidity that elevate ET_0 can be smoothed when using monthly averages, yielding slight under- or overestimation. In practice, the residual underestimation is small and operationally negligible, yet a conservative margin can be incorporated into irrigation scheduling to cover peak demands.

These findings have clear practical value for historical archives and data-sparse locations. The high agreement between the monthly-input and daily-aggregated methods enables water managers and agronomists to use monthly data to estimate crop water requirements, support irrigation planning, and conduct long-term assessments of water resources in semi-arid settings like Adana. Overall, the results echo prior studies reporting strong consistency for FAO-56 Penman–Monteith at monthly resolution (e.g., Allen et al., 1998; Irmak et al., 2003), with correlations typically ≥ 0.95 .

4 Conclusions and Recommendations

This study evaluated the applicability of the FAO-56 Penman–Monteith method for estimating monthly reference evapotranspiration (ET_0) from monthly climatic summaries, benchmarked against a daily-aggregated approach, using the 1960–2024 record for Adana, Türkiye. The analyses showed very high agreement between approaches ($r = 0.99$) and no statistically significant mean differences, with a slight average bias of $-0.92 \text{ mm month}^{-1}$ for the monthly-input method. Thus, where daily meteorological data are unavailable, applying FAO-56 Penman–Monteith to monthly data provides a reliable and practical alternative for estimating monthly ET_0 .

These findings are especially relevant for semi-arid regions with sparse daily observations. By enabling accurate estimation of crop water requirements from widely available monthly datasets, the monthly-input approach can support irrigation scheduling, water-resources allocation, and climate-adaptation planning based on long-term ET_0 assessments. That said, monthly-based estimates are best suited to long-term planning and trend analyses. For day-to-day irrigation management—where intra-monthly variability can be significant, users should apply caution and, where feasible, incorporate conservative safety margins or complementary higher-frequency data/methods.

Future work could extend these results by incorporating spatially distributed drivers (e.g., remote sensing or reanalysis) to refine regional ETo fields and by evaluating the performance of simplified empirical ETo models with monthly inputs for data-scarce settings. Overall, the study results echo prior studies reporting strong performance of FAO-56 Penman–Monteith at monthly resolution. The take-home conclusion is that, in the absence of daily meteorological records, applying the FAO-56 Penman–Monteith formulation to monthly climatic summaries yields monthly ETo estimates that closely match daily-aggregated totals—exhibiting negligible bias and no significant differences—thereby supporting robust irrigation planning and water-resources management in data-scarce regions.

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