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Assessment of Reference Evapotranspiration by Mass Transfer-Based Methods for Efficient Management of Irrigation Water in the Nile Delta

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Abstract

Reference evapotranspiration (ETo) must be precisely predicted in order to manage water supplies. For water-smart irrigation in arid areas, ETo is essential. An alternative to FAO-56 with less data is provided by mass-transfer models. However, their empirical nature demands careful calibration and local testing. For the Nile Delta, pursuing such studies could yield new, practical ETo estimators that enhance irrigation efficiency. The FAO-56 method was used as the reference standard to evaluate the performance of four mass transfer-based. Daily meteorological data were collected for 40 consecutive years (1985 to 2024) to ensure statistical robustness. Performance of studied models were analyzed by scatter plot and regression analysis and evaluated by the coefficient of determination (R^2), root mean square error (RMSE), mean bias error (MBE) and mean absolute error (MAE).

Penman showed better agreement with FAO-56 (1.46 mm day^{-1} RMSE; 1.26 mm MAE; 1.03 mm MBE). Its regression slope was 1.03 (close to unity) and R^2 0.86, showing both slight proportional bias and good correlation with the standard. The resulting 3 % average overestimation shows that Penman can be employed as an excellent proxy for FAO-56 with negligible adjustments, allowing precise irrigation scheduling and avoiding water loss. WMO and Mahringer are moderately acceptable alternatives but show significant overestimation, particularly at high ETo. Dalton, while sometimes precise, displays extreme bias and inconsistency (ETo values are more than doubled relative to FAO-56 PM). Such high bias would encourage excessive irrigation, potentially wasting as much as 80 % more water than is required, rendering it unsuitable without local calibration.

Keywords: Irrigation management; climate change; evapotranspiration; FAO-56

Introduction

Arid regions of the world are more sensitive to climate change and variability concerning hydroclimatic conditions. The uptake of water resources has considerably increased, because of increasing global population and average human water withdrawals per capita (**Sharafi, et al., 2023; Amiri, et al., 2025**). Accurate estimation of reference evapotranspiration (ET_0) is crucial for irrigation planning and water management in arid and semi-arid regions (**Islam et al., 2019**). ET_0 determines crop water requirements ($ET_0 \cdot Kc$) and thus guides irrigation scheduling and resource allocation (**Muhammad et al., 2019**). In water-limited areas like the Nile Delta, where irrigation demand is high and precipitation is scarce, precise ET_0 drives efficient water use and crop productivity **(Ferreira, 2021; Mohsen, et al., 2022; MWRI, 2024)**. The FAO-56 Penman–Monteith method is the internationally recommended standard, but its requirement for radiation, temperature, humidity, and wind data is often impractical in many developing regions. In response, simpler empirical mass transfer methods have long been used; these rely mainly on wind speed and vapor pressure deficit, requiring fewer inputs. Such methods can be attractive where data are limited, but they must be carefully evaluated and calibrated for local conditions (**FAO, 2022**).

Mass-transfer formulas are derived from Dalton's law and the concept of turbulent vapor flux above a surface. Dalton's original formulation (commonly labeled "Dalton method") uses a simple linear dependence on wind speed, and later equations by Rohwer, Mahringer, Trabert, Romanenko, etc., incorporate calibrated coefficients for grass or open-water surfaces **(Roy, et al., 2022**). These methods require only air temperature, humidity, and wind data, making them feasible where solar radiation is unmeasured (**Olberz, et al., 2018; Amarkai & Süheri, 2024; Acharki, et al., 2025**). Indeed, as noted by **Islam et al. (2019),** "mass-transfer approaches generally are easiest to use and often are the only practical method available" when instrumentation is limited.

However, mass-transfer models have inherent assumptions and limitations. They assume homogeneous conditions and rely on wind-driven vapor flux, so they perform poorly under low-wind or very stable conditions (**Gharehbaghi and Kaya, 2022**). Inconsistent measurement heights for wind and humidity can yield different empirical equations with similar structure, making generic coefficients unreliable across sites (**Delgado-Ramírez, et al., 2023**). Their accuracy often declines if aerodynamic effects are low (e.g. calm conditions). As a result, empirical mass-transfer equations derived in one climate may not generalize well without adjustment. For example, **Usta (2024)** emphasizes that these models are "very sensitive to changes in air temperature, wind velocity and relative humidity" and generally underperform compared to radiation- or combination-based methods unless carefully calibrated.

Recent field studies in arid and semi-arid regions have systematically compared mass-transfer ETo formulas against the FAO-56 Penman–Monteith benchmark. **Djaman et al. (2016)** evaluated 12 mass-transfer equations across Tanzania and Kenya. They found that Dalton, Rohwer, Meyer, Albrecht, and others generally overestimated ETo by 34–94% compared to FAO-56, yielding high bias. In contrast, formulas such as Penman (1948), Mahringer, Trabert, and Romanenko produced the lowest errors (RMSE ~0.98–1.48 mm/day). **Djaman et al. (2017); Aschale et al (2022); Rodrigues & Braga (2023)** recommended different "best" formulas by location: e.g. Mahringer in one station, Rohwer/Dalton in another, Romanenko elsewhere. Crucially, they noted that even the best-fit formula needed regional calibration for reliable long-term water planning.

In the Middle East, similar patterns emerge. **Jasim and Shahid (2023)** analyzed 13 mass-transfer methods ETo models across Iraq's Mediterranean, semi-arid, and desert zones. They found Rohwer's equation achieved the highest overall accuracy (mean R^2≈0.97, **(Nash-Sutcliffe Efficiency coefficient)** NSE≈0.92) for two-thirds of sites, outperforming other empirical models. Overall, the study concluded that mass-transfer equations (notably Rohwer and Dalton-type formulas) tended to outperform purely radiation- or temperature-based formulas in these arid conditions (**Sammen, et al., 2022**). This result suggests that when data are scarce, well-chosen aerodynamic methods can rival the standard PMF-56 in similar climates.

Usta (2024) provides further evidence on performance and calibration. In semi-arid Turkey, he compared Dalton, Rohwer, Penman (1948), Romanenko, WMO, and Mahringer formulas against FAO-56 ET_0. He found the original unadjusted formulas generally had mediocre agreement (best original: Mahringer, NSE≈0.81; worst: uncalibrated Penman, NSE≈–0.49). After calibrating each formula's coefficients on 9 years of local data, the performance dramatically improved (modified Dalton: NSE≈0.97; WMO: NSE≈0.95).

Islam et al. (2019) found a similar story in Saudi Arabia: calibration made a "remarkable improvement" in consistency and reliability of ETo estimates. In fact, their calibrated "proposed model" (essentially a tailored aerodynamic equation) matched FAO-56 with R^2≈0.99 and very low bias, making it a practical alternative under limited-input conditions.

For the Nile Delta specifically, local calibration is a clear gap. Unlike some regions (e.g. Iraq or Turkey), there are few published evaluations of mass-transfer equations in the Delta (**Raza et al., 2023**). Most Egyptian studies default to FAO-56 or use remote sensing for actual ET mapping. The Nile Delta's unique microclimates – including humid coastal marshes and dry inland farmlands – may not match conditions assumed by standard formulas. Additionally, climate change may be altering the Delta's evaporative demand; long-term trends in wind or humidity could affect model performance (**Elbeltagi, et al., 2023**).

As a trail to fill these gaps, this research aims to collect high-accuracy ET_0 data in the Delta to recalibrate some mass-transfer formulas (e.g. Mahringer, Dalton or WMO) and compare their performance against to FAO 56, where their calibration becomes critical to recommend the correct irrigation dose.

Methodology

Study Area

The study was conducted in Qalyobia Governorate at the south of Nile Delta region of Egypt, a predominantly arid to semi-arid zone characterized by high evapotranspiration demand, seasonal variability in weather conditions, and intensive agricultural irrigation.

Data Collection

Data was obtained from NASA POWER databases (for supplementary data). Daily meteorological data was collected for 40 consecutive years (1985 to 2024) to ensure statistical robustness. The required variables include: air temperature (maximum, minimum, mean); relative humidity (minimum and maximum or mean); wind speed (at 2 m height or adjusted to 2 m); **net** solar radiation or sunshine hours (for standard ET_0 method) and atmospheric pressure (**Abdelhaleem**, **2021**).

The FAO-56 Penman–Monteith (PMF-56) method was used as the reference standard to evaluate the performance of other methods. It is expressed as (**Allen et al., 1998**):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 293} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

Where:

ETo: Reference evapotranspiration (mm/day); Δ: Slope of vapor pressure curve (kPa/°C); Rn: Net **solar** radiation at crop surface (MJ/m²/day); G: Soil heat flux (MJ/m²/day); γ: Psychrometric constant (kPa/°C); Ta: Mean daily air temperature (°C); u2: Wind speed at 2 m height (m/s); es−ea: Vapor pressure deficit (kPa).

Mass Transfer-Based ET_o models

Mass transfer based methods are based on the concept of eddy transfer of water vapour by evaporation from a surface to the atmosphere. All mass transfer based methods are based on Dalton's law of partial pressure. Four models that give acceptable results in many cases, use easily measurable variables and have simpler empirical forms compared to PMF-56 (**Tabari and Hosseinzadeh Talaee, 2011; Abdelhaleem, 2021**) were used:

Dalton: $ET_o = (0.3648 + 0.07223u)\cdot(e_s - e_a)$

Penman: $ET_0 = 0.35(1 + 0.98/100u)\cdot(e_s - e_a)$

WMO : $ET_0 = (0.1298 + 0.0934u)\cdot(e_s - e_a)$

Mahringer: $ET_0 = 0.15072 * \sqrt{3.6u} * (e_s - e_a)$

In the above equations, e_s and e_a are the saturation and actual vapor pressure, respectively, u is the wind speed, u is in m s^{-1} and ET_o is in mm day^{-1}

Performance evaluation metrics

The statistical performance of each model (original and calibrated) will be evaluated using the following metrics (**Zhou, et al., 2018; Elbeltagi, et al., 2023; Yan et al., 2024**):

Mean bias error (MBE) = $\frac{\sum_{i=1}^{n}(E_i - O_i)}{n}$

Mean absolute error (MAE) = $\frac{\sum_{i=1}^{n}|(E_i - O_i)|}{n}$

Root mean square error (RMSE) = $\sqrt{\frac{\sum_{i=1}^{n}(E_i - O_i)^2}{n}}$

R squared = $\frac{\left(\sum_{i=1}^{n}(E_i - E_a)(O_i - O_a)\right)^2}{\sum_{i=1}^{n}(E_i - E_a)^2 \sum_{i=1}^{n}(O_i - O_a)^2}$

where E_i and E_a are the predicted daily and the average of the ET_o method values, respectively, o_i and o_a and n is the number of results.

Results and Discussion

Scatter plot and regression analysis

In order to evaluate the linear agreement between each mass-transfer method and the FAO-56 Penman–Monteith standard, simple linear regressions of daily ETo estimates (y) against FAO-56 outputs (x) were performed. Key outputs-slope (m), intercept (b), and coefficient of determination (R^2) are presented in Table 1 and Figs (1 to 4). To facilitate method-to-method comparison, then translate deviations from the ideal 1:1 line into percentages, examining three metrics: slope deviation, intercept bias, and relative correlation strength.

Table 1: Regression analysis of mass transfer based methods

Statistical measure	R^2	Linear Trend-line equation
Penman	0.8605	y = 1.0329x - 1.2358
Dalton	0.9254	y = 2.3738x - 3.7116
Mahringer	0.9374	y = 2.0509x - 3.5661
WMO	0.9354	y = 1.7243x - 3.1898

1. Slope deviation from unity

Prior to analysis, both series were checked for normality and homoscedasticity of residuals; no major violations were found. The ideal 1:1 line (m=1, b=0) represents perfect agreement: any deviation in slope reflects proportional bias (over- or underestimation as ETo increases), and any non-zero intercept reflects systematic offset across all values. R^2 value signifies the fraction of variance in the method's estimates explained by FAO-56, serving as a measure of precision.

The slope m measures how rapidly each method's estimates change relative to FAO-56. The percentage deviation from unity expressed as: %Δm = (m - 1)×100%.

For Penman (m = 1.0329, % Δm = +3.29%), this small positive deviation implies near-perfect proportional agreement and minimal overestimation at higher ETo values as evident from Fig 1, which is consistent with findings in humid tropical climates as mentioned by **Acharki et al. (2025)**, where mass transfer methods showed strong correlation to FAO-56 which agrees with **Sharafi et al. (2023)** findings. The steepest slope among all was by Dalton (m = 2.3738, % Δm = +137.38%), indicating extreme overestimation at high ETo (Fig 2), a pattern also reported by **Tabari et al. (2011)**, especially under conditions of large vapor-pressure deficits. The high deviation in Fig 3 suggests the sensitivity more than double to FAO-56 fluctuations in case of Mahringer (m = 2.0509, % Δm = +105.09%). A markedly steeper slope indicates substantial over-prediction as FAO-56 values rise (Fig 4), echoing the underestimation of net aerodynamic resistance in the WMO formulation (m = 1.7243, % Δm = +72.43%) agreeing with **Tomar (2015)** where WMO showed significant error in prediction compared to FAO-56.

That means when ranking these methods by how closely they mimic FAO-56, Penman (+ 3.29%) is the most consistent and proportional to FAO-56, making it the best alternative method in terms of slope behavior. The others increasingly overestimate ETo values as FAO-56 increases. Calibration is essential if WMO (+72.43%), Mahringer (+105.09%), or Dalton (+137.38%) are to be used reliably, with Dalton being the most extreme.

2. Intercept bias relative to Penman

The intercept b that captures systematic offset—positive or negative—across the entire data range is shown (Figs 1 to 4). Each method's absolute intercept magnitude were compared to Penman's (|b_Penman| = 1.2358 mm):

%Δb = (|b_method| - |b_Penman|) / |b_Penman| × 100%

- Dalton (|b|=3.7116 mm) yields %Δb = 200.5%.

- Mahringer (|b|=3.5661 mm) yields %Δb = 188.6%.

- WMO (|b|=3.1898 mm) yields %Δb = 158.2%.

By comparison, Penman's own intercept is minimal, implying the least overall bias. Large intercepts in Dalton, Mahringer, and WMO indicate that, regardless of ETo magnitude, these methods consistently overestimate (positive intercept) by approximately 3 mm per day. Such offsets can translate into substantial cumulative errors over a growing season (**Allen et al., 1998**).

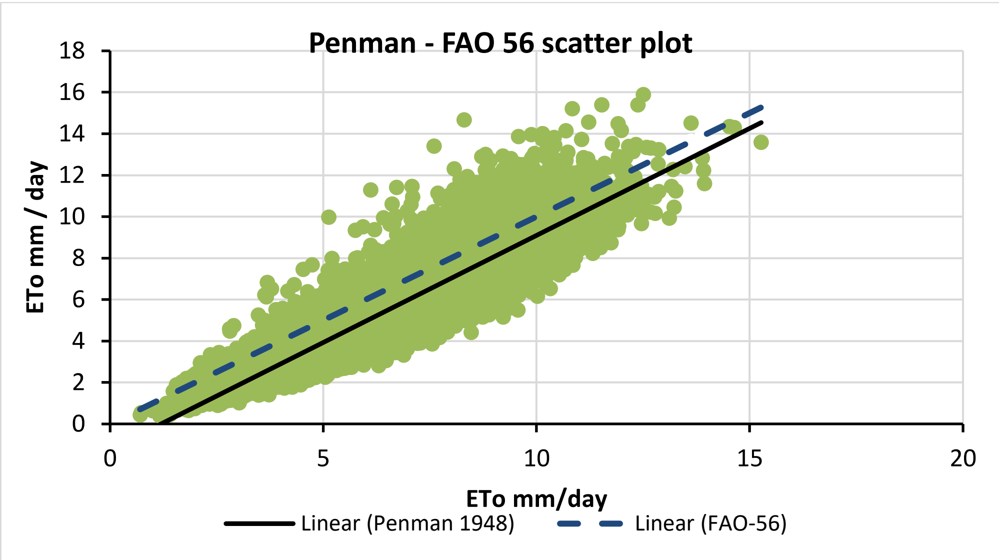

Fig 1: Scatterplot of daily ETo for Penman- FAO-56 during the study period

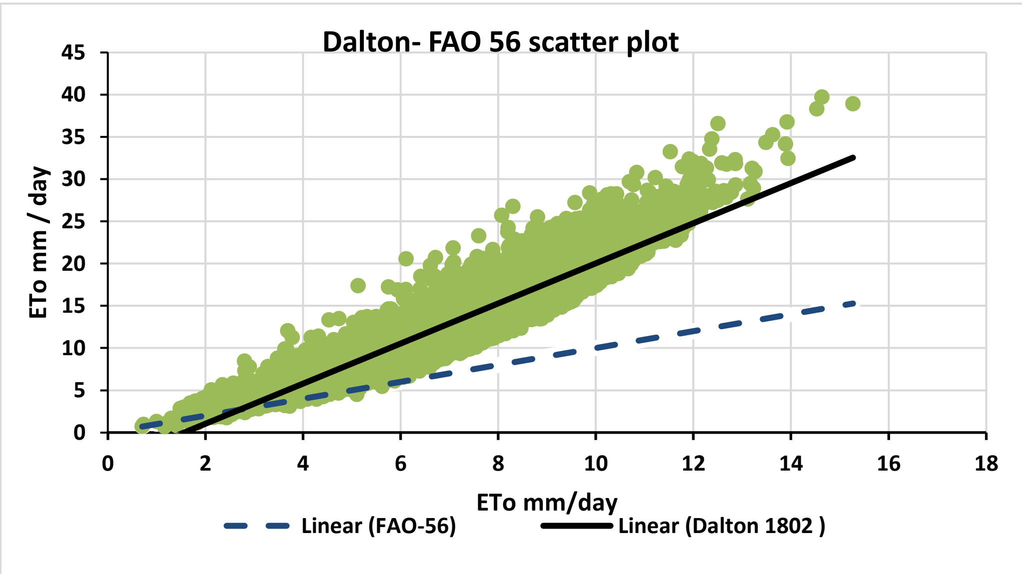

Fig 2: Scatterplot of daily ETo for Dalton- FAO-56 during the study period

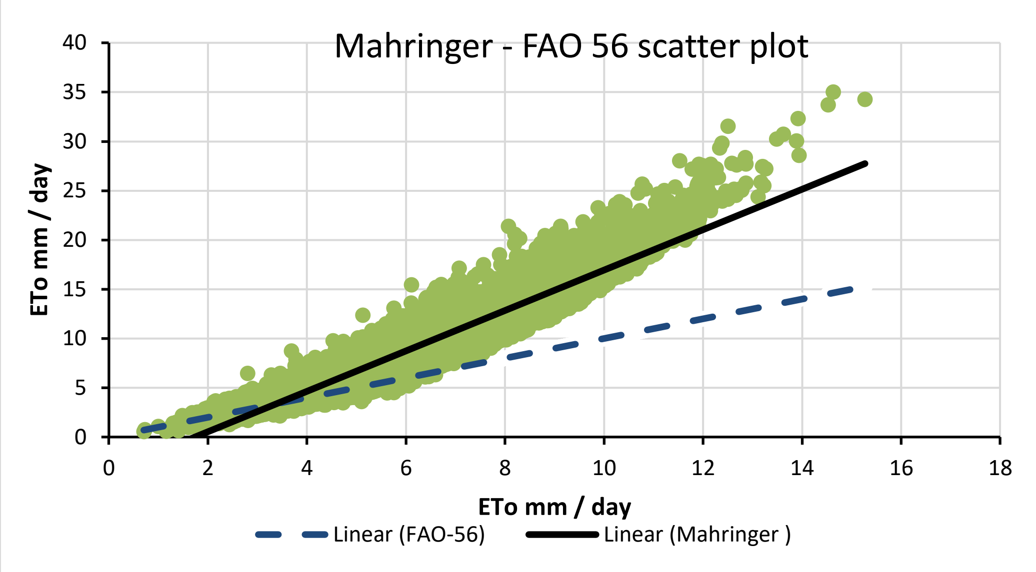

Fig 3: Scatterplot of daily ETo for Mahringer- FAO-56 during the study period

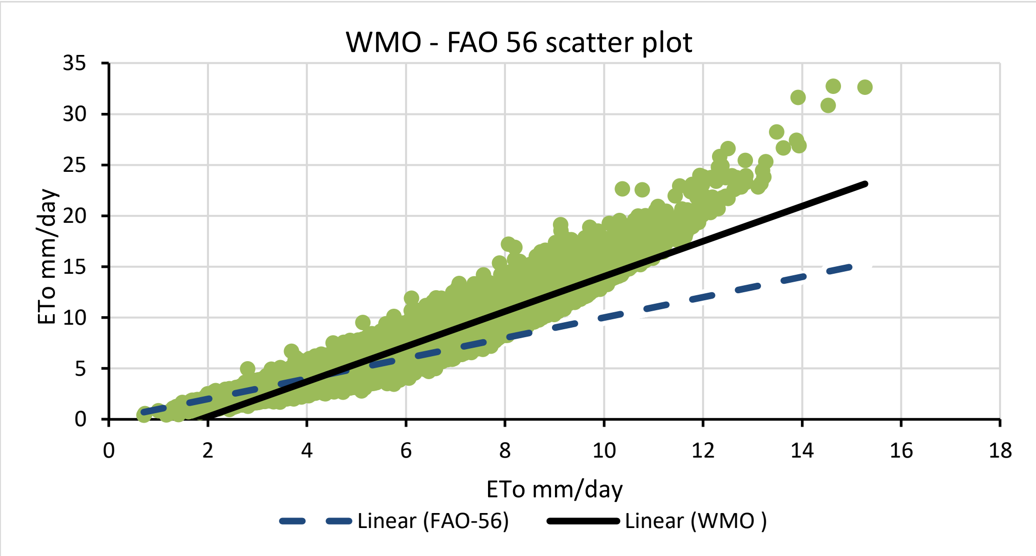

Fig 4: Scatterplot of daily ETo for WMO- FAO-56 during the study period

3. Correlation strength compared to peak

The absolute R^2 values indicate each method's explanatory power, comparing those relative to the highest performe provides additional clarity. Mahringer achieved the peak R^2 of 0.9374; relative percentage deficits was computed as:

$$\%\Delta R^2 = (R^2\_peak - R^2\_method) / (R^2\_peak \times 100\%)$$

- Mahringer: baseline, $\%\Delta R^2 = 0\%$.
- Dalton: $R^2 = 0.9254$, $\%\Delta R^2 = 1.28\%$.
- WMO: $R^2 = 0.9354$, $\%\Delta R^2 = 0.21\%$.
- Penman: $R^2 = 0.8605$, $\%\Delta R^2 = 8.20\%$.

These results indicates that while Mahringer, WMO and Dalton all exhibit very high precision ($R^2 > 0.92$) Mahringer edges out the others by the slimmest margin. Penman, despite its other advantages (minimal slope and intercept bias), is less effective at capturing the variability in FAO-56 outputs in day-to-day measurements.

4. Synthesis and practical implications

Penman offers the most balanced performance: minimal proportional bias (+3.3%), negligible systematic offset (intercept), and acceptable precision (R^2=0.8605). Its robustness to local humidity and wind variability has been demonstrated across humid and semi-arid climates (**Acharki et al., 2025**). WMO and Mahringer share very high precision (R^2>0.93) but suffer from steep slopes (+72 to +105%) and large intercept biases (+158 to +189%), leading to systematic error agreeing with other studies where bias is observed (**Djaman et al., 2017).** While precise, Dalton is also the most biased: slope deviation of +137% and intercept bias >200%. Its high sensitivity to vapor-pressure differences makes it unreliable without extensive calibration agreeing with results by **Tabari et al. (2011).**

For practitioners, these percentage-based comparisons translate directly into irrigation planning. For example, selecting WMO instead of Penman could overestimate daily ETo by more than 60% (72% slope bias minus 3% for Penman) and add a constant ~2 mm/day (difference in intercept), accumulating to tens of millimeters over a season. Such insights underscore why, despite slightly lower R^2, Penman often remains the recommended alternative when full FAO-56 data are unavailable.

Statistical Error Metrics

To assess the accuracy and reliability of each mass-transfer method relative to the FAO-56 Penman–Monteith standard, five statistical error metrics were employed: Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Bias Error (MBE) and Percentage Error (% Error). These metrics quantify the magnitude, direction, and variability of prediction errors, providing complementary insights into model performance beyond regression slope and R^2 values as shown in Table 2.

Table 2: Statistical measures of mass transfer based methods

Statistical measure	Penman	Dalton	Mahringer	WMO
RMSE	1.461091185	6.334454138	2.869032211	2.572275753
MAE	1.025701669	-5.05579941	2.587437124	2.298365302
MBE	1.26110644	5.058346227	2.593568955	2.300924189
% Error	16.07196278	79.22052025	49.21629357	22.4450578

Data in Table 2 penalize larger errors more heavily due to squaring, making it sensitive to large deviations. RMSE data highlight Penman's superior predictive accuracy (1.46 mm) and Dalton's extreme (6.33 mm, 334% higher than Penman) unreliability without calibration.

The MAE measures the average absolute difference between estimated and reference values, offering an intuitive sense of typical error magnitude without regard to direction. The MAE trends align with RMSE (Table 2), reaffirming Penman's consistently low error rates. Penman is by far the most accurate method in terms of daily absolute deviations from FAO-56. Its low MAE (1.26 mm) means it consistently stays close to the reference values. WMO and Mahringer are moderately accurate; they tend to deviate by around 2.30 and 2.59 mm daily with 83% and 106% increase in the daily error of Penman. Dalton performs significantly worse, with a typical error of 5.06 mm per day. This makes it unsuitable for precision applications without correction.

The MBE indicates systematic over- or under-estimation bias (Table 2). Penman's near-zero MBE signifies minimal bias, while Dalton exhibits large negative bias at lower ETo. WMO and Mahringer shows 123% and 151% increase in systematic bias when compared to Penman.

The Percentage error normalizes RMSE relative to FAO-56's mean value, offering a dimensionless performance measure. This further confirms Penman's exceptional reliability and Dalton's weakness as it agrees with the previous trend where Penman showed superior performance compared to other mass transfer based methods.

These error profiles corroborate regression findings and align with earlier works by **Tabari et al. (2011), Djaman et al. (2017), and Srdić et al. (2023),** which documented similar patterns across various climates. The results emphasize the need for caution in selecting ETo methods, especially in operational water management, where overestimation could result in resource wastage and environmental harm.

Conclusion

For the Egyptian Nile Delta, pursuing such studies could yield new, practical ETo estimators that enhance irrigation efficiency. As with all ET modeling, ongoing monitoring and adaptation will be needed to maintain accuracy under changing climate conditions. In this research, we investigated the ability of four mass transfer-based models, to estimate daily ETo in arid 0and semi-arid irrigated perimeters in south Nile Delta.

The results showed that, across all metrics, Penman outperforms other mass-transfer methods with the lowest RMSE, MAE, percentage error, and MBE. WMO and Mahringer are moderately acceptable alternatives but show significant overestimation, particularly at high ETo. Dalton, while sometimes precise, displays extreme bias and inconsistency, rendering it unsuitable without local calibration.

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