World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(RESEARCH ARTICLE)

Evapotranspiration estimation in Jeddah using FAO and Hargreaves methods

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World Journal of Advanced Engineering Technology and Sciences, 2025, 15(03), 2038-2046

Publication history: Received on 13 May 2025; revised on 18 June 2025; accepted on 21 June 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.15.3.1157

Abstract

The purpose of this study was to compare two well-known techniques for calculating evapotranspiration (ET_0), which is an important component of the hydrological cycle, particularly in arid and semi-arid areas such as Jeddah, Saudi Arabia. The simplified, temperature-dependent Hargreaves equation and the physically based FAO Penman-Monteith equation (PME) were the main subjects of the study. Reference ET_0 was calculated using daily meteorological data from station 41024 (1997-2011), which included temperature, humidity, and wind speed. PME produced more detailed and typically higher ET_0 values since it took into account a wide range of climatic factors, according to the analysis that compared the estimates from the two methodologies. The Hargreaves approach, which just used temperature, on the other hand, generated estimates that were lower and less variable.

This study provides these results in context by contrasting them with earlier studies, such the work done by Al-Subhi (2012) utilizing Dalton's equation. The results illustrate the necessity for reliable ET_0 estimation techniques in water-scarce ecosystems subject to climatic extremes, underscoring the crucial balance between data availability and estimation accuracy.

Keywords: Evapotranspiration; Penman-Monteith equation; Hargreaves equation; Dalton's equation; Jeddah

1. Introduction

The process of evaporation, which converts water from a liquid to a vapor, is essential to the hydrological cycle of the planet, particularly in arid and semi-arid areas like Jeddah, Saudi Arabia. Climate modeling, irrigation planning, and efficient water resource management all depend on precise evaporation rate estimation. Although direct measurements can be made with devices like evaporation pans, they can be time-consuming and cannot always accurately represent evaporation in natural settings. As a result, several indirect techniques have been created to use meteorological data to estimate evaporation.

The most reliable model for predicting reference ET_0, especially when extensive meteorological datasets are available, is the PME, which was formally developed by Allen, Pereira et al. (1998). This approach, which combines the surface's aerodynamic characteristics and energy balance, has shown promise in a number of experiments conducted in arid areas (Shahidian[1], Serralheiro[1] et al. 2012, Djaman, Lombard et al. 2018). Alkhuzai (2025) investigated the effectiveness of four simple temperature-dependent equations for estimating ET_0 against the Penman–Monteith equation, concluding that the Linacre equation (LE) provided the best estimates, despite overestimating the ET_0 rate, with the modified LE producing values closest to the Penman–Monteith results for the Al-Baha region.

The Hargreaves-Samani model (Hargreaves and Samani 1985), on the other hand, was created for situations in which temperature data is the only available information and has been well validated in tropical and semi-arid regions. Its

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simplicity makes it useful in situations with little data, even though it lacks humidity and wind components. Hargreaves is still a viable alternative, according to recent evaluations as those by Fu, Luo and Li (2018), even though it may occasionally overestimate or underestimate ET_0 in extremely hot or cold temperatures.

Other traditional models include:

The Thornthwaite technique (Thornthwaite 1948): This approach, based on latitude-dependent daylight hours and mean monthly temperature, is still employed in climatological studies. However, it often works poorly in arid settings since it disregards wind and sun radiation.

The Blaney-Criddle method (Doorenbos, Pruitt et al. 1977), which was once widely used in the US, is now generally considered to be less reliable than the PME in most weather conditions. Temperature and sunshine affect it. The formula of Priestley-Taylor (Priestley and Taylor 1972) is designed for humid climates and computes ET_0 solely based on radiation. Although it is sometimes used in conjunction with remedial factors, its use in arid environments is limited.

Artificial intelligence (AI) methods and data-driven models have become increasingly effective tools for ET_0 prediction in the last ten years. Aghelpour, Varshavian et al. (2022) developed and evaluated a hybrid Adaptive Neuro-Fuzzy Inference System with Differential Evolution (ANFIS-DE) model and compared it to stochastic time series models for forecasting monthly reference ET_0 across diverse Iranian climates, ultimately recommending the simpler Seasonal Autoregressive Integrated Moving Average (SARIMA) model as most appropriate due to its superior performance and parsimony, with all models performing better in drier climates. ANNs have shown high prediction accuracy when used to estimate ET_0 (Abdel-Fattah, Kotb Abd-Elmabod et al. 2023).

Atiea and El-Agha (2025)tested 20 ML models across 14 stations using daily meteorological data from 1943 to 2024, with the PME serving as a benchmark. The Categorical Boosting (CatBoost) regressor consistently showed the best performance, even when using a reduced set of features.

Bouregaa (2025) evaluated several ML models, including LASSO (Linear Regression), k-Nearest Neighbors (KNN), Random Forest (RF), Adaptive Boosting (AdaBoost), Gradient Boosting Machine (GBM), and Support Vector Machine (SVM), under different input scenarios. The SVM model achieved near-perfect predictions in Sidi Bel Abbes and Tiaret. Random Forest and AdaBoost performed best in Oum El Bouaghi, while KNN showed strong performance with minimal inputs in Setif. LASSO regression also demonstrated high accuracy in Tiaret when mean temperature and relative humidity were included.

The goal of Saudi Arabia's ET_0 estimation efforts has been to balance model performance with regional climate constraints. Al-Subhi (2012), for instance, examined the Penman and Dalton approaches in Jeddah and found notable seasonal differences in accuracy. For station 41024 in Jeddah,

Despite these advancements, the balance between data availability and model complexity remains a significant challenge. Even though the PME offers greater accuracy when comprehensive data is available, simpler methods like Hargreaves are essential in locations with poor infrastructure or data availability. Modern modeling techniques must be combined with field validation to produce an accurate ET_0 calculation for effective water resource planning in places like Jeddah.

2. Available metrological data

The standard meteorological data, such as air temperature, relative humidity, and wind speed, were supplied by the Saudi Presidency of Meteorology and Environment (PME) for station 41024 (21.68N, 39.15E) at Jeddah Airport. The study station's location is shown in Figure 1.

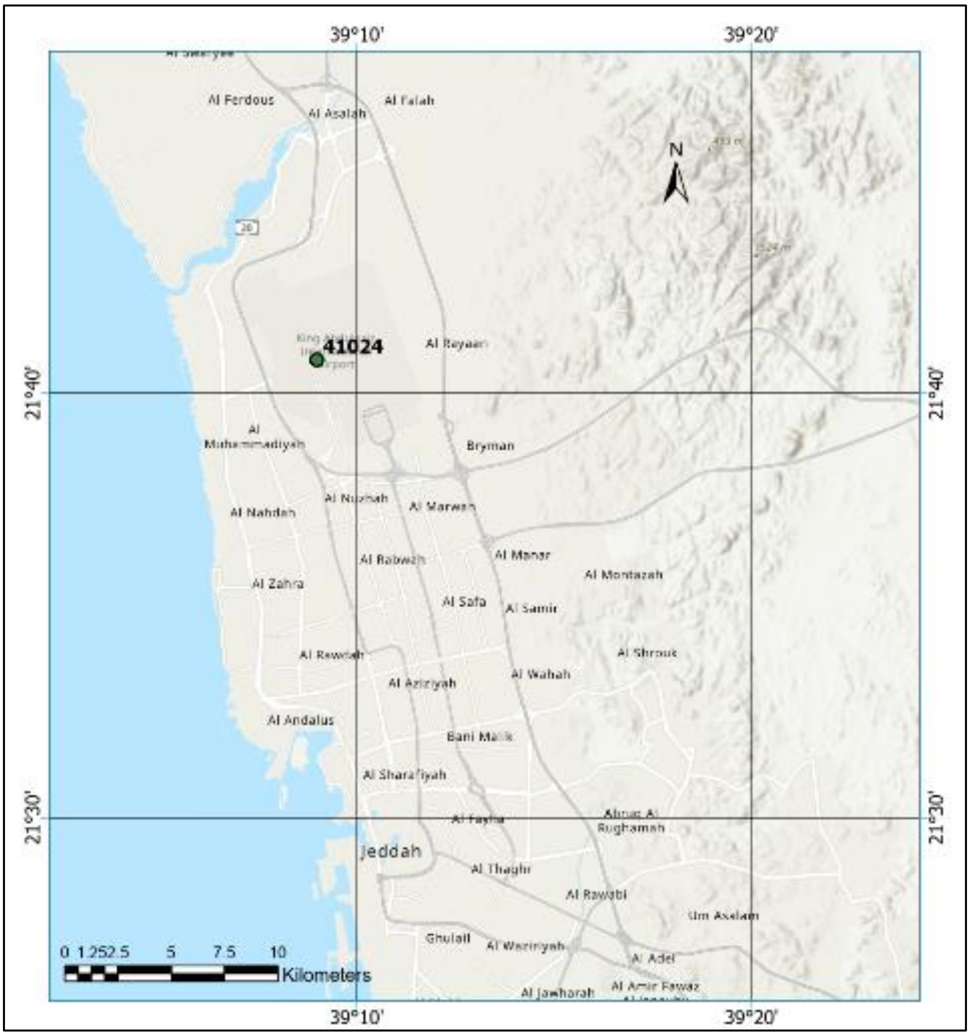

Figure 1 Location of station 41024

The meteorological data for station 41024, collected daily from 1997 to 2011, includes minimum, mean, and maximum temperature; minimum, mean, and maximum humidity; and mean wind speed. These parameters are visually presented across Figure 2, Figure 3 and Figure 4 respectively.

Figure 2 illustrates the distinct seasonal fluctuations in Jeddah's daily temperatures. During summer months (June-September), daily maximums consistently exceed 40°C, with the highest recorded at 42°C. Conversely, winter months (December-February) see minimum daily temperatures occasionally drop below 20°C, with the lowest recorded at 11.5°C. The mean temperature, which averaged 28.97°C over the period, follows this consistent annual cycle, characteristic of an arid climate with hot summers and milder winters.

Figure 3, on the other hand, highlights significant daily and seasonal fluctuations in Jeddah's relative humidity. Humidity levels varied widely, with minimum values dropping as low as 3% and maximums reaching 100%. The mean relative humidity for the period was 60.38%. These humidity changes directly influence ET_0, a critical part of the hydrological cycle. Higher humidity signifies more atmospheric moisture, which reduces the vapor pressure deficit between the evaporating surface and the air. This diminished deficit slows ET_0 rates, as there is less driving force for water to vaporize. Conversely, lower humidity increases this deficit, leading to higher ET_0 rates.

Figure 4 displays the daily mean wind speed for station 41024, showing considerable variability and occasional strong events over the 1997-2011 period. Wind speeds generally fluctuated, with the mean speed recorded at 6.87 m/s , though daily values frequently showed spikes, sometimes exceeding 15-20 m/s, and a maximum recorded value of 22 m/s. Wind speed is a crucial factor in ET_0, as higher wind speeds increase the rate at which saturated air near the evaporating surface is replaced with drier air. This removal of moist air enhances the vapor pressure gradient, thereby accelerating the rate of water vapor transport away from the surface and increasing ET_0. The physically based PME explicitly incorporates wind speed in its calculation to account for this effect.

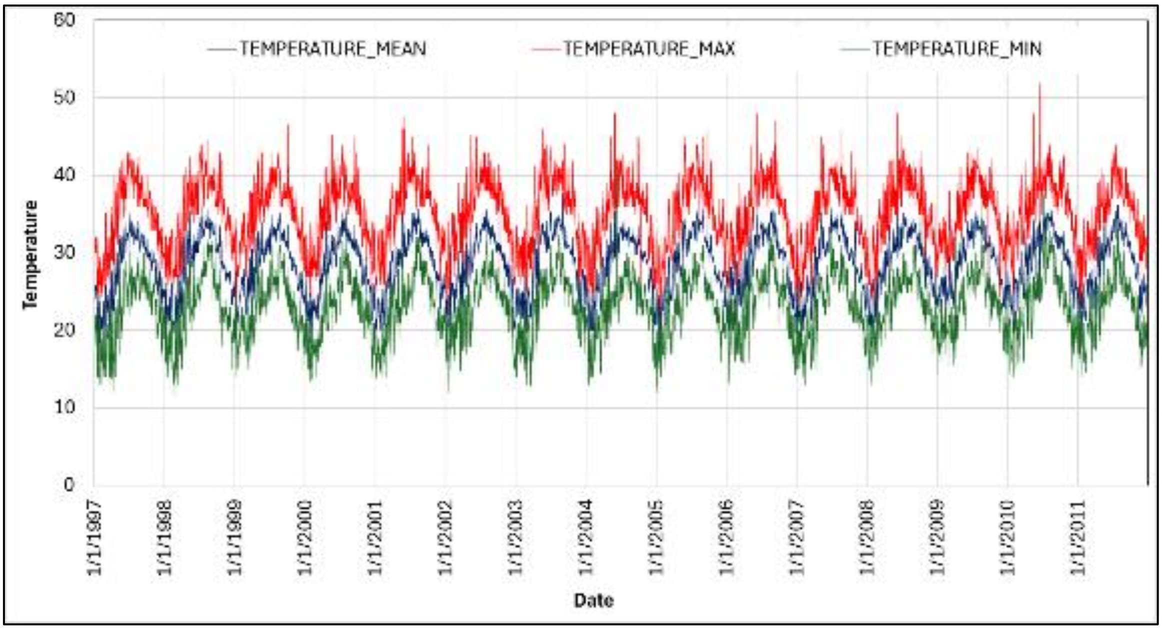

Figure 2 Daily min, average and max temperature in (°C) for station 41024**.**

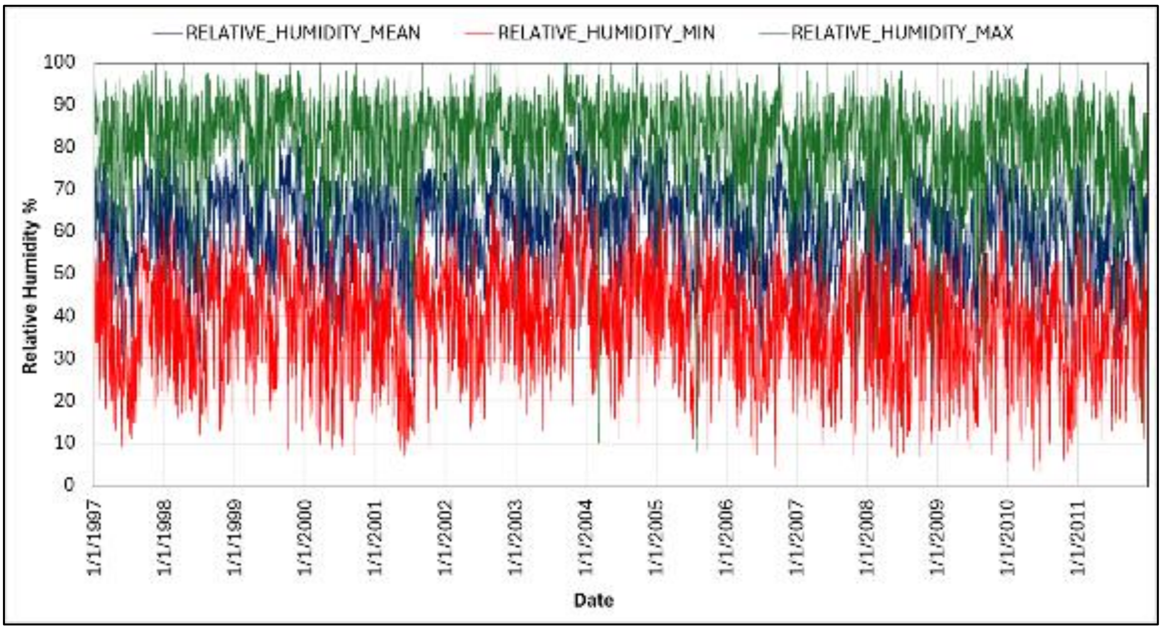

Figure 3 Daily min, average and max humidity in (°C) for station 41024.

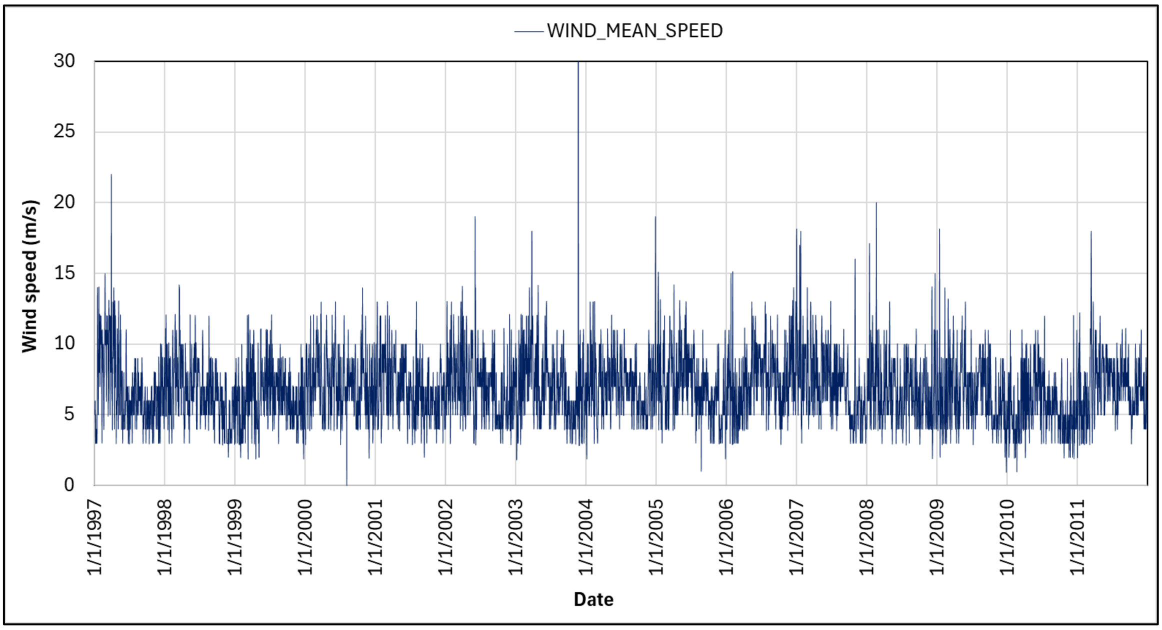

Figure 4 Daily average wind speed in (m/s) for station 41024**.**

3. Methodology

The PME considers a range of meteorological factors, making it more robust and applicable across diverse climates compared to simpler empirical equations. The core equation for estimating reference ET_0 using the PME is:

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

where:

ET_0: Reference evapotranspiration (mm/day)
Rn: Net radiation at the crop surface ($MJ/m^2/day$)
G: Soil heat flux ($MJ/m^2/day$)
Tmean: Mean daily air temperature at 2 m height (°C)
u_2: Wind speed at 2 m height (m/s)
e_s: Saturation vapor pressure (kPa)
e_a: Actual vapor pressure (kPa)
Δ: Slope of the vapor pressure curve (kPa/°C)
γ: Psychrometric constant (kPa/°C)

The Hargreaves equation is another method for estimating ET_0 which is used as a simpler alternative to the PME. It is an empirical formula used to estimate reference ET_0. It is particularly useful when you have limited meteorological data, as it primarily relies on temperature data. This makes it more accessible in situations where more complex data like solar radiation, humidity, and wind speed are not readily available.

$$ET_o = 0.0023(T_{mean} - 17.8)(T_{max} - T_{min})^{0.5} R_a$$

Where:

Ra: Extraterrestrial radiation ($MJ/m^2/day$) – obtained from tables or calculators based on latitude and day of year.
T_{max}: Maximum daily temperature (°C)
T_{min}: Minimum daily temperature (°C)

4. Results and analysis

The study calculated daily reference ET_0 in Jeddah, Saudi Arabia, using both the PME and Hargreaves methods, with the outcomes visually represented in Figure 5. A clear distinction emerged between the two approaches: the PME consistently produced higher and more variable ET_0 estimates, while the Hargreaves method yielded generally lower and smoother daily values. Both methods, however, exhibited pronounced seasonal patterns, with ET_0 peaking in warmer months and decreasing during cooler periods.

Statistical analysis, summarized in Table 1, further quantified these differences. For the study period, the PME's ET_0 ranged from a minimum of 2.45 mm/day to a maximum of 22.26 mm/day, with a mean of 8.31 mm/day. In contrast, the Hargreaves method's ET_0 varied from 0.00 mm/day to 11.73 mm/day, with a lower mean of 5.17 mm/day. This substantial difference underscores the impact of the input parameters considered by each method.

Temperature is a primary driver for both methods, but especially for the Hargreaves equation, which relies solely on it. As depicted in Figure 1, Jeddah experiences high summer temperatures, often exceeding 40°C. The statistical maximum temperature recorded was 42°C^0. These high temperatures directly contribute to the elevated ET_0 values observed during these months, particularly for the Hargreaves method.

Humidity, specifically incorporated in the PME, plays a crucial role. Periods of lower humidity increase the vapor pressure deficit, which in turn enhances the driving force for evaporation, leading to higher ET_0 estimates by the PME. Conversely, higher humidity reduces this deficit, slowing down ET_0 rates.

Wind speed is another critical factor accounted for by the PME. The mean wind speed was 6.87 m/s, with considerable daily variability and occasional spikes, reaching a maximum of 22 m/s. Higher wind speeds actively remove saturated air near the evaporating surface, thereby maintaining a steeper vapor pressure gradient and promoting increased ET_0. The PME, by integrating temperature, humidity, and wind speed, provides a more comprehensive and generally higher estimation of ET_0, reflecting the complex interplay of these meteorological variables. The Hargreaves method, while simpler and useful with limited data, consistently provides lower and less dynamic estimates due to its exclusive reliance on temperature.

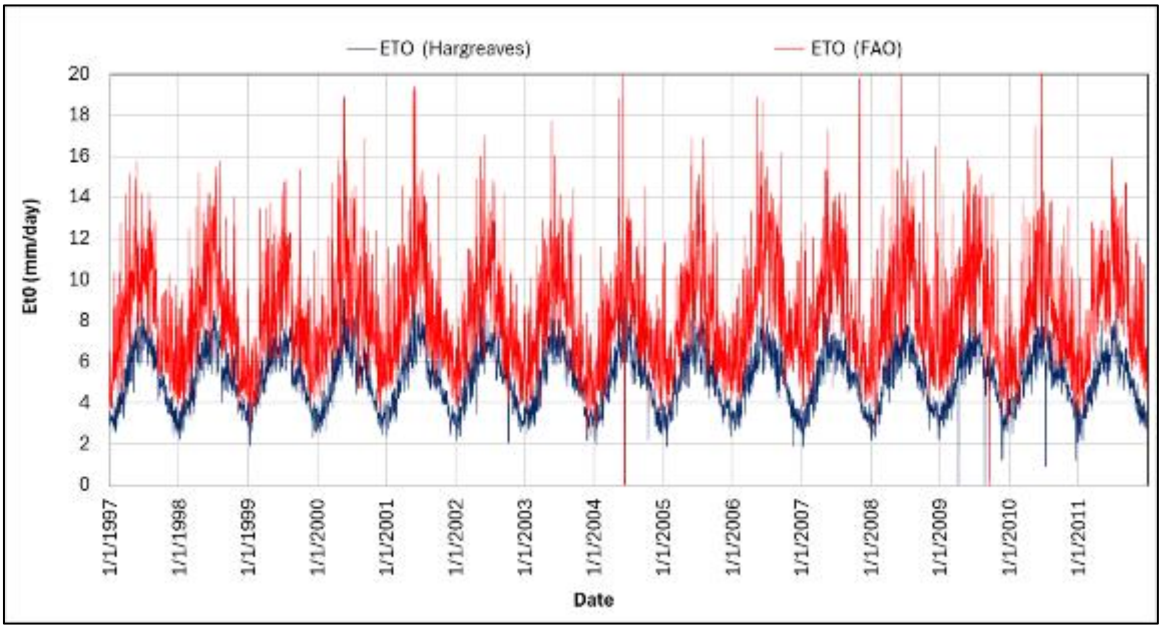

Figure 5 Results of daily evapotranspiration (mm/day).

Table 1 Statistical analysis of resulted evapotranspiration**.**

	Temperature (°C)	Rel. Humidity %	Wind speed	ETO (PME)	ETO (Hargreaves)
Min	11.5	3	0	2.45	0.00
Mean	28.97	60.38	6.87	8.31	5.17
Max	42	100	22	22.26	11.73
Stdv	3.93	20.95	2.49	2.62	1.43

Al-Subhi (2012) estimated monthly evaporation in Jeddah using Dalton's equation during the period from 1997 to 2007. Figure 6 provides a comparative analysis of monthly ET_0 results from the PME, the Hargreaves method, and Dalton's equation as estimated by Al-Subhi (2012) for Jeddah. The figure clearly illustrates the distinct performance of each method over the annual cycle.

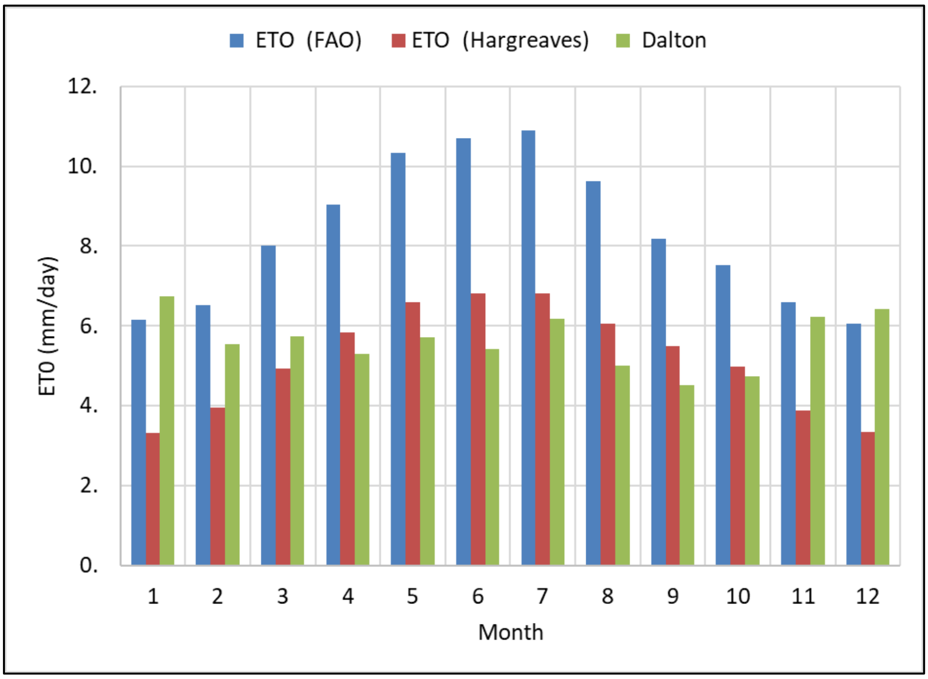

Figure 6 Comparing monthly evapotranspiration with the three equations

Overall, the PME consistently yields the highest monthly ET_0 values, especially during the summer months (e.g., reaching over 10 mm/day in June and July). Dalton's equation, as used by Al-Subhi (2012), generally produces ET_0 values that fall between the PME and Hargreaves estimates. For instance, in colder months (e.g., January and February), Dalton's estimates are quite close to, or even slightly higher than, the PME results. However, during the peak summer months, Dalton's values tend to be lower than PME but notably higher than Hargreaves.

The Hargreaves method consistently shows the lowest monthly ET_0 values across the entire year, a trend observed throughout the daily comparisons as well. This is particularly evident during the hot summer, where its estimates are significantly lower than both PME and Dalton's equation. All three methods, however, capture the pronounced seasonal variation in ET_0, with values peaking in mid-summer and declining during winter months. The differences in magnitude likely stem from the varying complexities and input parameters of each model, with PME being the most comprehensive and Hargreaves relying solely on temperature.

5. Conclusion

This study successfully computed reference evapotranspiration (ET_0) in Jeddah, Saudi Arabia, utilizing both the PME and Hargreaves methods, providing valuable insights into their applicability within arid and semi-arid environments. The findings confirm that the PME, by integrating multiple meteorological parameters (temperature, humidity, and wind speed), consistently offers more comprehensive and generally higher ET_0 estimates. In contrast, the Hargreaves method, while simpler and useful when only temperature data is available, produced lower and less variable estimates.

Statistical analysis underscored these differences: the mean ET_0 was 8.31 mm/day for PME, compared to 5.17 mm/day for Hargreaves, reflecting the distinct influences of their input parameters. The comparison with Al-Subhi's (2012) work using Dalton's equation further contextualized these results, showing Dalton's estimates generally fall between the PME and Hargreaves methods, though sometimes aligning closely with PME in colder months.

The research highlights the critical trade-off between data availability and estimation accuracy, emphasizing the necessity for robust ET_0 estimation techniques in water-scarce regions facing climatic extremes. Future efforts in water resource planning for areas like Jeddah should consider integrating advanced modeling approaches with field validation to ensure reliable ET_0 estimations.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflicts of interest.

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