# Performance Evaluation of Reference Evapotranspiration Equations across a Range of Indian Climates

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**Abstract:** Reference crop evapotranspiration ($ET_0$) is a key variable in procedures established for estimation of evapotranspiration rates of agricultural crops. In recent years, there is growing evidence to show that the more physically based FAO-56 Penman–Monteith (PM) combination method yields consistently more accurate $ET_0$ estimates across a wide range of climates and is being proposed as the sole method for $ET_0$ computations. However, other methods continue to remain popular among Indian practitioners either because of traditional usage or because of their simpler input data requirements. In this study, we evaluated the performances of several $ET_0$ methods in the major climate regimes of India with a view to quantify differences in $ET_0$ estimates as influenced by climatic conditions and also to identify methods that yield results closest to the FAO-56 PM method. Performances of seven $ET_0$ methods, representing temperature-based, radiation-based, pan evaporation-based, and combination-type equations, were compared with the FAO-56 PM method using historical climate data from four stations located one each in arid (Jodhpur), semiarid (Hyderabad), subhumid (Bangalore), and humid (Pattambi) climates of India. For each location, $ET_0$ estimates by all the methods for assumed hypothetical grass reference crop were statistically compared using daily climate records extending over periods of 3–4 years. Comparisons were performed for daily and monthly computational time steps. Overall results while providing information on variations in FAO-56 PM $ET_0$ values across climates also indicated climate-specific differences in $ET_0$ estimates obtained by the various methods. Among the $ET_0$ methods evaluated, the FAO-56 Hargreaves (temperature-based) method yielded $ET_0$ estimates closest to the FAO-56 PM method both for daily and monthly time steps, in all climates except the humid one where the Turc (radiation-based) was best. Considering daily comparisons, the associated minimum standard errors of estimate (SEE) were 1.35, 0.78, 0.67, and 0.31 mm/day, for the arid, semiarid, subhumid, and humid locations, respectively. For monthly comparisons, minimum SEE values were smaller at 0.95, 0.59, 0.38, and 0.20 mm/day for arid, semiarid, subhumid, and humid locations, respectively. These results indicate that the choice of an alternative simpler equation in a particular climate on the basis of SEE is dictated by the time step adopted and also it appears that the simpler equations yield much smaller errors when monthly computations are made. In order to provide simple $ET_0$ estimation tools for practitioners, linear regression equations for preferred FAO-56 PM $ET_0$ estimates in terms of $ET_0$ estimates by the simpler methods were developed and validated for each climate. A novel attempt was made to investigate the reasons for the climate-dependent success of the simpler alternative $ET_0$ equations using multivariate factor analysis techniques. For each climate, datasets comprising FAO-56 PM $ET_0$ estimates and the climatic variables were subject to factor analysis and the resulting rotated factor loadings were used to interpret the relative importance of climatic variables in explaining the observed variabilities in $ET_0$ estimates. Results of factor analysis more or less conformed the results of the statistical comparisons and provided a statistical justification for the ranking of alternative methods based on performance indices. Factor analysis also indicated that windspeed appears to be an important variable in the arid climate, whereas sunshine hours appear to be more dominant in subhumid and humid climates. Temperature related variables appear to be the most crucial inputs required to obtain $ET_0$ estimates comparable to those from the FAO-56 PM method across all the climates considered.

**DOI:** 10.1061/(ASCE)0733-9437(2006)132:3(238)

**CE Database subject headings:** Evapotranspiration; Performance characteristics; Evaluation; Statistics; Validation; India.

## Introduction

Estimates of evapotranspiration (ET) flux occurring from cropped land surfaces are essential in studies relating to hydrology, climate, and agricultural water management. The procedure for estimation of ET rates of agricultural crops is well established and involves as a first step, computation of reference crop evapotranspiration ($ET_0$) using regularly recorded climatological data. $ET_0$ is defined as "the rate at which water, if readily available, would be removed from soil and plant surfaces of a specific crop, arbitrarily called the reference crop" (Jensen et al. 1990). Owing to difficulties in direct measurement, several temperature-based, radiation-based, pan evaporation-based, and combination-type equations are commonly used to derive estimates of $ET_0$. Innumerable worldwide studies have evaluated the performances of these methods under different climatological conditions

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Note. Discussion open until November 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 31, 2005; approved on August 16, 2005. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 132, No. 3, June 1, 2006. ©ASCE, ISSN 0733-9437/2006/3-238–249/$25.00.

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(e.g., Clothier et al. 1982; Michalopoulou and Papaloannou 1991; Amatya et al. 1995; Ventura et al. 1999; Xu and Singh 2002). While there is a broad consensus that combination-type methods are more accurate, performances of most methods have been found to vary from one climate to another (e.g., Jensen et al. 1990; Katul et al. 1992).

Studies carried out in India have identified the FAO-24 (Doorenbos and Pruitt 1977) Penman combination method to be the most accurate one (Subramaniam and Rao 1985; Mall and Gupta 2002). However, owing to the fact that the FAO-24 Penman method requires input data of humidity and windspeed that may not be available at all locations, efforts have been made to identify simpler methods for a few climate regimes of India (Gunston and Batchelor 1983; Mohan 1991). For instance, Mohan (1991) on the basis of comparisons with FAO-24 Penman $ET_0$ estimates recommends the use of the FAO-24 radiation method in per-humid climates, the Hargreaves and Samani (1985) temperature-based equation in humid climates, and the FAO-24 Blaney–Criddle temperature-based equation in subhumid and semiarid climates of Tamil Nadu state, India.

However, such findings may have limited relevance in view of the significant changes that have taken place in the past decade with regard to procedures for estimation of $ET_0$. Following an improved understanding of the physics involved in crop evapotranspiration responses to vegetation characteristics, the Penman–Monteith (PM) method has been proposed as the best estimator of $ET_0$ (Allen et al. 1994). The PM method is considered to be more "physically based" since it incorporates the effects of physiological and aerodynamic characteristics of the reference surface. Several worldwide studies have proved the superiority of the PM method across a wide range of climatic conditions (e.g., Jensen et al. 1990; Irmak et al. 2003; Itenfisu et al. 2003). Accordingly, the recent version of the FAO methodology for estimation of crop water requirements (Allen et al. 1998) (hereinafter referred to as FAO-56), recommends the sole use of the PM method for $ET_0$ estimation in all climates.

Interestingly, in a recent study carried out at a subhumid location in India, Kashyap and Panda (2001) found that FAO-56 PM estimates compared most favorably with $ET_0$ values measured in a grass lysimeter and yielded average root mean square error (RMSE) of 0.08 mm/day. In contrast, the popular FAO-24 Penman method yielded an average RMSE of 0.76 mm/day. George et al. (2002) evaluated $ET_0$ estimates by nine popular methods relative to the FAO-56 PM method at two humid locations in India.

In view of such proven superiority of the FAO-56 PM method, it is imperative that this method be adopted by Indian practitioners as a standard in all analysis requiring computation of crop evapotranspiration. Use of the FAO-56 PM method will lead to the much required improvement in irrigation water-use efficiencies, allow global $ET_0$ comparisons to be carried out, and permit unambiguous definition of crop coefficients, which are known to vary with the method adopted for computing $ET_0$ (e.g., Itenfisu et al. 2003; Tyagi et al. 2003).

However, on account of being a combination-type method, routine use of the FAO-56 PM method is also constrained by nonavailability of humidity and windspeed data at all locations. Consequently, simpler temperature-based, radiation-based, and pan evaporation-based methods will be used until the density of climate stations in India improves substantially. Therefore, there is an urgent need to reevaluate the performances of simpler and traditionally used $ET_0$ methods relative to the FAO-56 PM method under climatic conditions most commonly encountered in India. Indian researchers and practitioners need to be provided guidance on the choice of the most appropriate $ET_0$ equation to be adopted in a particular climate when input data are insufficient to apply the preferred FAO-56 PM method. To our knowledge no such comparative study involving the FAO-56 PM method has previously been attempted for a range of Indian climates.

The present study was taken up to evaluate the performances of several $ET_0$ methods relative to the FAO-56 PM method at four locations representing the major climate regimes of India. The objective was to derive information on variations in FAO-56 PM $ET_0$ estimates across these climates and also to identify alternative methods that yield results closest to the FAO-56 PM method for each climate. Performances of seven methods, representing temperature-based, radiation-based, pan evaporation-based, and combination-type equations, were compared with the FAO-56 PM method. $ET_0$ calculations were performed using historical climate data of four stations located one each in arid (Jodhpur), semiarid (Hyderabad), subhumid (Bangalore), and humid (Pattambi) climates of India. For each location, $ET_0$ estimates by all the methods for assumed hypothetical grass reference crop were statistically compared with the FAO-56 PM method using daily climate records extending over periods of 3–4 years.

Upon identification of the best alternative methods for each climate, our intention was to develop regression equations, which could serve as practical tools for estimation of FAO-56 PM $ET_0$ from $ET_0$ values estimated by the simpler methods. It is envisaged that this study would provide important information to Indian researchers/practitioners and at the same time make a contribution to ongoing efforts for standardization of the reference evapotranspiration estimation method (Allen et al. 2000; Itenfisu et al. 2003).

Although several of the previous studies cited earlier have shown that some of the simpler $ET_0$ equations perform well in some climates and not so well in others, the likely causes for such behavior have not been investigated. Given that such equations are empirically derived using regression procedures without taking into account physical laws governing the evapotranspiration phenomenon, the success of a method in a particular climate can only be explained through statistical analysis of the underlying climatic dataset. For instance, the fact that Mohan (1991) found the temperature-based FAO-24 Blaney–Criddle method to yield more accurate $ET_0$ estimates in semiarid climates of Tamil Nadu state, India, is evidently due to the higher degrees of correlation between FAO-24 Penman $ET_0$ estimates and temperature variables in his dataset. However, owing to the presence of intercorrelations between climatic variables, simple correlation analysis may not be appropriate in seeking such explanations. Therefore, in this study we used the multivariate statistical method of factor analysis with the objective of establishing the likely reasons for the climate-dependent success of simpler methods in yielding $ET_0$ estimates comparable to the FAO-56 PM method. Mohan and Arumugam (1996) did use factor analysis to evaluate the relative importance of climatic variables on the evapotranspiration process but our study was different in that we included FAO-56 PM $ET_0$ as a dependent variable in the factor analysis. This enabled the use of results from factor analysis to provide a statistical explanation as to why a particular simpler equation was able to yield results closer to the FAO-56 PM method in a particular climate in comparison to other methods.

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**Table 1.** Details of Climate Stations

| Station | State | Latitude (north) | Longitude (east) | Altitude (m amsl) | Climate | Data period |
|---|---|---|---|---|---|---|
| Jodhpur | Rajasthan | 26°18′ | 73°01′ | 224.00 | Arid | 1984–1987 |
| Hyderabad | Andhra Pradesh | 17°32′ | 78°16′ | 545.00 | Semiarid | 1988–1990 |
| Bangalore | Karnataka | 13°00′ | 77°37′ | 899.00 | Subhumid | 1982–1985 |
| Pattambi | Kerala | 10°48′ | 76°12′ | 253.60 | Humid | 1985–1988 |

Note: amsl=above mean sea level.

## Methodology

### *Climate Data*

Table 1 lists details of the climate stations considered in the analysis. These stations are drawn from a network of over 550 surface observatories operated and maintained by the India Meteorological Department (IMD), Government of India. The stations were selected to represent the major climate types prevalent in India (Subrahmanyam 1983): arid (Jodhpur), semiarid (Hyderabad), subhumid (Bangalore), and humid (Pattambi).

All stations are equipped with standard ground-based instruments; alcohol and wet-bulb thermometers, sunshine recorder, cup anemometer, and mercury thermometers. Readings are taken twice a day at 0830 and 1730 hrs. Records are transmitted from the stations to the IMD Data Centre at Pune where data archives are maintained. Data is scrutinized and subjected to quality checks prior to supply to users.

Historical data was procured from IMD for the periods shown against each station in Table 1. Unfortunately, good quality data were unavailable for a common period for all the stations. For each station, the data set used in this study comprised daily values of maximum air temperature ($T_{\max}$), minimum air temperature ($T_{\min}$), maximum relative humidity ($\mathrm{RH}_{\max}$), minimum relative humidity ($\mathrm{RH}_{\min}$), actual hours of sunshine ($n$), 24 h wind speed ($u_z$) at 3 m height, and pan evaporation depth ($e_{\mathrm{pan}}$). Site details required in $\mathrm{ET}_0$ calculations are: altitude ($z$) above mean sea level, height ($z_w$) at which windspeed is measured and latitude ($\phi$) of the station. Day to night windspeed ratios ($u_r$) for these locations were taken from Subba Rao (1983).

Individual data records were subjected to further screening and integrity checks were performed on the climatic variables as per procedures described in FAO-56 (results not presented here for brevity). After discarding obvious outliers and accounting for missing records, the number of days for which complete records were available for each station is: Jodhpur (1,453), Hyderabad (1,044), Bangalore (1,368), and Pattambi (1,275). Two thirds of this data set, i.e., Jodhpur (969), Hyderabad (696), Bangalore (912), and Pattambi (850), was used as input to derive $\mathrm{ET}_0$ estimates by the various methods, development of regression equations, and also in the factor analysis. The remaining data set was set apart for the validation of the regression equations developed.

### *$\mathrm{ET}_0$ Methods and Calculations*

$\mathrm{ET}_0$ estimation methods included in the comparative analysis are listed in Table 2. Other than the FAO-56 PM combination method that was used as the benchmark method, seven other $\mathrm{ET}_0$ estimation methods included in the analysis are: FAO-56 Hargreaves, FAO-24 Blaney–Criddle (temperature based); FAO-24 radiation, Priestley–Taylor, Turc (radiation-based); FAO-56 Pan evaporation; and FAO-24 Penman (combination type). For brevity, detailed computational procedures are not included in this paper and the reader may refer to the publications listed in Table 2 for details regarding the basic equation and supporting equations associated with each method. Based on the findings of Nandagiri and Kovoor (2005), we ensured that recommended computational procedures for each method were followed so as to avoid erroneous results arising on account of using nonrecommended supporting equations. However, tables and nomograms for some parameters in FAO-24 procedures were replaced with equivalent regression equations developed by earlier investigators (see Table 2). The reference crop was assumed to be green grass. Table 3 summarizes the input data requirements of each method.

A computer program that uses daily climate variables and other site data and calculates daily average $\mathrm{ET}_0$ (mm/day) by all eight methods was developed for use in this study. The program was validated using numerical examples given in FAO-24 and FAO-56.

For each location, differences between $\mathrm{ET}_0$ estimates by the FAO-56 PM method and each of the other seven methods were quantified using the standard error of estimate (SEE) statistic. Also computed were the standard deviations of the estimates (STDEV), coefficient of determination ($R^2$), and slope ($S$) of a linear regression fit (forced through the origin) between FAO-56 PM $\mathrm{ET}_0$ estimates and estimates by the other methods. SEE is a measure of the precision of the estimates whereas STDEV is a powerful measure of dispersion. The coefficient of determination $R^2$ is the ratio of the explained variance to the total variance and is a measure of the linear covariance between the two variables. The best model is one with the smallest SEE, the smallest STDEV, and the highest $R^2$. Statistical comparisons were made separately for daily and monthly time steps. In the case of monthly calculations, we had a choice of either using daily average climate inputs and averaging the resulting daily $\mathrm{ET}_0$ estimates over each calendar month or using daily climate inputs averaged over each month and deriving monthly mean daily $\mathrm{ET}_0$ estimates. Although our investigations revealed differences as low as 2.3% (Pattambi) to as high as 9.02% (Jodhpur) between $\mathrm{ET}_0$ values obtained by both approaches, we preferred to adopt the latter approach (monthly mean daily inputs) since it represents a more realistic situation from the practitioners' viewpoint.

### *Factor Analysis*

Principal components analysis (PCA) and factor analysis are statistical techniques that can be used to analyze the matrix of correlation coefficients of a set of variates and provide better understanding and interpretability of the structure of the matrix. These methods employ eigenvalue-eigenvector analysis to derive a smaller number of derived variables (or factors) that are linear combinations of the original variables and are uncorrelated (orthogonal) to one another. The elements of the transformed

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**Table 2.** Details of Different Evapotranspiration Methods Used

| Method | Basic equation | Basic reference | Supporting equations | Reference |
|---|---|---|---|---|
| FAO-56 Penman Monteith | $\mathrm{ET}_0=\dfrac{0.408\Delta(R_n-G)+\gamma\dfrac{900}{\bar{T}+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)}$ | Allen et al. (1998) | $\Delta$, $\gamma$, $R_n$, $G$, $u_2$, $e_s$, $e_a$ | Allen et al. (1998) |
| FAO-24 Penman | $\mathrm{ET}_p=C\left[\dfrac{\Delta'}{\Delta'+\gamma'}R_n'+\dfrac{\gamma'}{\Delta'+\gamma'}f(u)(e_s'-e_a')\right]$ | Doorenbos and Pruitt (1977) | $\gamma'$, $f(u)$ | Doorenbos and Pruitt (1977) |
| | | | $\Delta' e_s'$, $e_a'$ | Lowe (1977) |
| | | | $R_a$ | Kreider (1979) |
| | | | $C$ | Kotsopoulos and Babajimopoulos (1997) |
| FAO-24 Blaney–Criddle | $\mathrm{ET}_{bc}=a_b+b_b[p(0.46\bar{T}+8.13)]$ | Doorenbos and Pruitt (1977) | $a_b$ | Doorenbos and Pruitt (1977) |
| | | | $b_b$ | Frevert et al. (1983) |
| FAO-24 Radiation | $\mathrm{ET}_r=b_R\left(\dfrac{\Delta'}{\Delta'+\gamma'}R_s'\right)-0.3$ | Doorenbos and Pruitt (1977) | $b_R$ | Frevert et al. (1983) |
| | | | $\Delta'$ | Lowe (1977) |
| | | | $\gamma'$ | Doorenbos and Pruitt (1977) |
| | | | $R_a$ | Kreider (1979) |
| Priestley–Taylor | $\mathrm{ET}_{pt}=\beta\dfrac{\Delta}{\Delta+\gamma}(R_n')$ | Shuttleworth (1992) | $\Delta$, $\gamma$, $R_n$ | Allen et al. (1998) |
| Turc | $\mathrm{ET}_t=0.31\left(\dfrac{\bar{T}}{\bar{T}+15}\right)(R_s'+2.09)\left(1+\dfrac{50-\mathrm{RH}_{\mathrm{mean}}}{70}\right)$<br>for $\mathrm{RH}<50$<br>$\mathrm{ET}_t=0.31\left(\dfrac{\bar{T}}{\bar{T}+15}\right)(R_s'+2.09)$<br>for $\mathrm{RH}>50$ | Shuttleworth (1992) | $R_s$ | Allen et al. (1998) |
| FAO-56 Hargreaves | $\mathrm{ET}_h=0.0023(\bar{T}+17.8)(T_{\max}-T_{\min})^{0.5}*R_a'$ | Allen et al. (1998) | $R_a$ | Allen et al. (1998) |
| FAO-56 Pan evaporation | $\mathrm{ET}_{\mathrm{pan}}=k_p*e_{\mathrm{pan}}$ | Allen et al. (1998) | $k_p$ | Allen et al. (1998) |

eigenvector matrix are called factor loadings and are indicative of the amount by which each original variable contributes to the total variance. In an effort aimed at improving the interpretability of results, the large elements in the factor loadings are made as large as possible and the small elements are made as small as possible through an exercise called rotation. Mathematical details and steps involved in performing PCA and factor analysis are given in Haan (1995) and McCuen and Snyder (1986). Conventionally, these analyses are performed on data sets comprising of carefully selected independent variables that the analyst believes have an influence on the dependent variable. However, McCuen and Snyder (1986) demonstrate how the dependent variable can also be included in factor analysis. Independent variables that have a high loading in a factor in which the dependent variable also has high loadings may then be identified as the most important ones explaining the total variability.

In the present study, factor analysis was performed using SPSS software which was available at the Department of Community Medicine, MAHE, Manipal, India. The analysis was performed separately on the four climate data sets (Table 1). $\mathrm{ET}_0$ estimated by the FAO-56 PM method for each day of the record was considered to be the dependent variable. Independent variables considered were the climatic variables required in computation of FAO-56 PM $\mathrm{ET}_0$, i.e., $T_{\max}$, $T_{\min}$, $\mathrm{RH}_{\max}$, $\mathrm{RH}_{\min}$, $n/N$ (ratio of

**Table 3.** Input Data Requirements of $ET_0$ Methods Considered

| | | Input data requirements | | |
|---|---|---|---|---|
| | | | Climate | |
| Method | Method (acronym) | Site | Primary | Secondary |
| FAO-56 Penman Monteith | PM | $z$, $z_w$, $\phi$ | $T_{max}$, $T_{min}$, $RH_{max}$, $RH_{min}$, $u_z$, $n$ | — |
| FAO-24 Penman | PEN | $z$, $z_w$, $\phi$ | $T_{max}$, $T_{min}$, $RH_{max}$, $RH_{min}$, $n$ | $u_z$, $u_r$ |
| FAO-24 Blaney- Criddle | BC | $z_w$, $\phi$ | $T_{max}$, $T_{min}$ | $RH_{min}$, $u_z$, $u_r$, $n$ |
| FAO-24 Radiation | RAD | $z$, $z_w$, $\phi$ | $T_{max}$, $T_{min}$, $n$ | $RH_{max}$, $RH_{min}$, $u_z$, $u_r$ |
| Priestley–Taylor | PT | $z$, $\phi$ | $T_{max}$,$T_{min}$, $n$ | — |
| Turc | TC | $\phi$ | $T_{max}$, $T_{min}$, $RH_{max}$, $RH_{min}$, $n$ | — |
| FAO-56 Hargreaves | HAR | $\phi$ | $T_{max}$, $T_{min}$, $n$ | — |
| FAO-56 Pan evaporation | PAN | $z_w$ | $e_{pan}$ | FET, $RH_{max}$, $RH_{min}$, $u_z$ |

actual hours of sunshine to maximum possible), and 24 h wind speed ($u_2$) at 2 m height. The varimax method of rotation was employed.

## Results and Discussion

### Comparisons of Daily $ET_0$

Mean daily $ET_0$ estimates obtained by averaging results across the period of record for each of the four stations are shown in Table 4. FAO-56 PM estimates vary from a low of 4.39 mm/day at the humid location (Pattambi) to a high of 5.63 mm/day at the arid location (Jodhpur). Most other methods also indicate similar differences between these two extreme climates, except for the Priestley–Taylor, Turc, and Hargreaves methods, which yield lower $ET_0$ values for the subhumid climate (Bangalore) rather than the humid climate (Pattambi). For a given climate, large differences in $ET_0$ estimates by the various methods are evident. In comparison to FAO-56 PM estimates, the FAO-24 Penman and FAO-24 radiation methods consistently overestimate $ET_0$ across all the stations, while the FAO-56 pan evaporation method yields consistently lower values. The performances of the other methods relative to the FAO-56 PM method appear to vary with climate. For instance, the FAO-24 Blaney–Criddle method which provides very close estimates in subhumid and humid climates, deviates the most among all methods at the arid location.

Comparisons between the FAO-56 PM method and the FAO-24 Penman method are particularly relevant, given the popularity of the latter method among Indian practitioners. The FAO-24 Penman method yields consistently higher estimates at all the locations. This is more clearly evident from the scatter plots shown in Fig. 1 in which daily comparisons for the individual days of record are shown. Given the similarity in input data requirements, the FAO-24 Penman method was not included in further statistical comparisons with the FAO-56 PM method.

Results of comparisons between $ET_0$ estimates for individual days of record for the remaining methods are shown in Table 5. Various performance statistics mentioned earlier were computed for each station on the basis of individual comparisons between daily $ET_0$ estimated by the FAO-56 PM method and each of the other methods. Methods were ranked separately on the basis of SEE, STDEV, and $R^2$ values. Since each statistic highlights a different aspect of model performance, an "overall" rank number calculated as the average of rank numbers from the three statistics was also computed for each method. From these results (Table 5), it is evident that for a given $ET_0$ method, considerable differences exist in rank numbers derived from the performance statistics and, therefore, the overall rank may prove useful in selecting the best method. For instance, at the arid Jodhpur site, the FAO-56 Hargreaves method yielded the highest overall rank followed by the FAO-24 radiation and the FAO-24 Blaney–Criddle methods in second and third place, respectively. On the other hand, considering ranking based on SEE, the FAO-56 Hargreaves method retained its first place, whereas the Priestley–Taylor method was ranked second and the FAO-24 radiation method was ranked third. At this site, the FAO-56 Hargreaves method was ranked first even on the basis of STDEV but based on the $R^2$ statistic the best method relative to the FAO-56 PM values was the FAO-24 Blaney–Criddle method. At the semiarid location (Hyderabad), the FAO-56 Hargreaves method was overall best, the FAO-24 Blaney–Criddle method was second best, and the Turc method was third best. The FAO-24 Blaney–Criddle temperature-based method yielded the smallest SEE followed by the FAO-24 radiation method and the FAO-56 Hargreaves method. At this site, the FAO-56 Hargreaves method yielded the lowest value of STDEV but the FAO-24 Blaney–Criddle method yielded the

**Table 4.** Mean Daily $ET_0$ Estimates

| | Mean daily $ET_0$ values (mm/day) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Combination methods | | Radiation-based methods | | | Temperature -based methods | | |
| Station | PM | PEN | RAD | PT | TC | BC | HAR | PAN |
| Jodhpur | 5.63 | 6.39 | 6.32 | 5.36 | 5.37 | 6.72 | 5.05 | 4.46 |
| Hyderabad | 5.16 | 5.91 | 5.60 | 5.97 | 4.53 | 5.42 | 4.81 | 3.59 |
| Bangalore | 4.73 | 5.49 | 5.41 | 4.39 | 4.29 | 4.70 | 4.69 | 3.93 |
| Pattambi | 4.39 | 5.27 | 4.97 | 4.92 | 4.50 | 4.41 | 4.91 | 2.77 |

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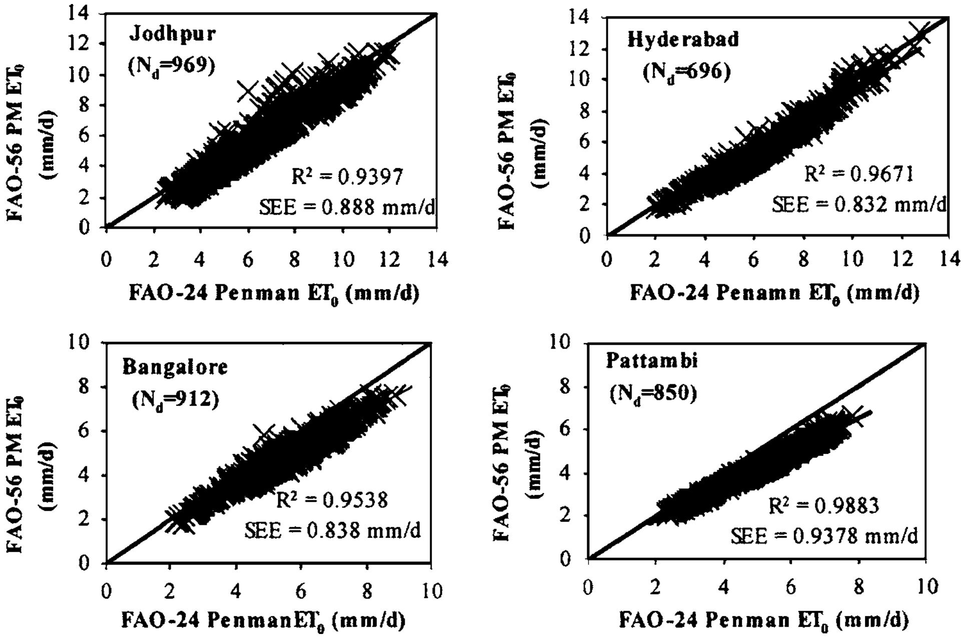

**Fig. 1.** Comparison between daily $ET_0$ estimates by FAO-56 PM and FAO-24 Penman methods

**Table 5.** Regression Statistics for Daily $ET_0$ Comparisons

| Station | Method | SEE (mm/day) | STDEV (mm/day) | $R^2$ | Slope $S$ (zero intercept) | Overall rank | SEE of peak month (mm/day)[a] |
|---|---|---|---|---|---|---|---|
| Jodhpur ($N_d$=969) | HAR | 1.35 (1) | 1.57 (1) | 0.72 (3) | 0.86 | 1.67 | 1.88 |
| | RAD | 1.38 (3) | 1.91 (4) | 0.73(2) | 1.26 | 3 | 2.01 |
| | BC | 1.53 (4) | 2.17 (5) | 0.83(1) | 1.04 | 3.33 | 2.27 |
| | PAN | 1.59 (5) | 1.85 (3) | 0.69(4) | 0.91 | 4 | 1.67 |
| | TC | 1.73 (6) | 1.68 (2) | 0.68(5) | 1.01 | 4.33 | 1.3 |
| | PT | 1.36 (2) | 2.29 (6) | 0.42(6) | 1.12 | 4.67 | 1.73 |
| Hyderabad ($N_d$=696) | HAR | 1.10 (3) | 1.17 (1) | 0.87 (2) | 0.89 | 2 | 1.17 |
| | BC | 0.78 (1) | 1.99 (6) | 0.88 (1) | 1.44 | 2.67 | 3.16 |
| | TC | 1.27 (4) | 1.32 (3) | 0.81 (3) | 1.15 | 3.33 | 2.46 |
| | PAN | 1.84 (6) | 1.29 (2) | 0.79 (4) | 1.11 | 4 | 1.86 |
| | RAD | 1.00 (2) | 1.85 (5) | 0.62 (6) | 0.94 | 4.33 | 0.92 |
| | PT | 1.41 (5) | 1.43 (4) | 0.72 (5) | 0.92 | 4.67 | 2.57 |
| Bangalore ($N_d$=129) | HAR | 0.67 (1) | 0.87 (1) | 0.64 (3) | 1.07 | 1.67 | 0.59 |
| | PT | 0.77 (3) | 0.98 (2) | 0.77 (1) | 1.16 | 2 | 0.56 |
| | BC | 0.70 (2) | 1.42 (5) | 0.68 (2) | 0.85 | 3 | 0.8 |
| | TC | 0.93 (4) | 1.05 (3) | 0.64 (4) | 1.09 | 3.67 | 0.68 |
| | PAN | 1.30 (6) | 1.06 (4) | 0.53 (5) | 0.97 | 5 | 1.24 |
| | RAD | 1.14 (5) | 1.57 (6) | 0.31 (6) | 1 | 5.67 | 1.23 |
| Pattambi ($N_d$=850) | TC | 0.31 (1) | 0.84 (2) | 0.84 (3) | 0.87 | 2 | 0.37 |
| | BC | 0.57 (2) | 1.28 (4) | 0.92 (1) | 1.35 | 2.33 | 0.85 |
| | HAR | 0.79 (5) | 0.83 (1) | 0.90 (2) | 0.91 | 2.67 | 0.88 |
| | PT | 0.67 (3) | 0.94 (3) | 0.78 (4) | 0.9 | 3.33 | 0.62 |
| | RAD | 0.78 (4) | 1.32 (5) | 0.53 (5) | 0.96 | 4.67 | 0.56 |
| | PAN | 1.84 (6) | 1.32 (6) | 0.43 (6) | 0.99 | 6 | 1.38 |

Note: Numbers in parentheses=rank numbers of $ET_0$ methods based on performance statistic considered.

[a] Peak months: May for Jodhpur and Hyderabad, April for Bangalore, and March for Pattambi.

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highest correlation with FAO-56 PM estimates. The FAO-56 Hargreaves method yielded the highest overall rank at the subhumid Bangalore site followed by the Priestley–Taylor and the FAO-24 Blaney–Criddle method. The FAO-24 Blaney–Criddle method was the second best when SEE was used as the criterion for ranking. The Turc method was the overall best at the humid location (Pattambi) and yielded SEE of 0.31 mm/day which was the lowest by any method across all the sites considered. In this climate, the FAO-24 Blaney–Criddle method was second best overall followed by the FAO-56 Hargreaves method at third position.

The performance of the FAO-56 Pan evaporation method was consistently poor at all locations and gave rise to extremely low $ET_0$ estimates. Pan coefficients, necessary for converting measured pan evaporation depths to $ET_0$ estimates, were calculated as per procedures laid out in FAO-56 and based on our findings, there may be a need to reassess these procedures for Indian climates. It is interesting to note that the performances of all the $ET_0$ methods (except the pan evaporation) were best at the humid location and appeared to worsen progressively toward the arid climate, where all of them performed poorly.

Given the importance of peak $ET_0$ estimates in irrigation planning and design, performances of the simpler methods were evaluated separately by comparing daily $ET_0$ estimates of the summer months. Performances relative to the FAO-56 PM method for the months of May for Jodhpur and Hyderabad; April for Bangalore; and March for Pattambi are quantified in terms of SEE which are shown in the last column of Table 5. It is evident that relative performances of the methods in estimating peak $ET_0$ are somewhat different in comparison to the rankings obtained from the daily estimates.

## Comparisons of Monthly Mean $ET_0$

Monthly mean daily $ET_0$ estimates obtained by all eight methods at all four locations are plotted in Fig. 2. The seasonal variability in the performances of the $ET_0$ methods relative to the FAO-56 PM estimates are clearly evident in this graphical representation. While the overall trend of the monthly march in $ET_0$ values is reproduced by all the methods at all the sites, the FAO-24 Penman estimates form the upper envelope and the lower envelope is formed by the Pan evaporation method estimates. Differences of the order of 3 mm/day between these two methods are common for certain months at all the locations. The other methods produce estimates that lie in between these extremes.

A clearer picture of the performances of the various methods (again excluding the FAO-24 Penman method) relative to the FAO-56 PM method for each month can be seen in the regression statistics presented in Table 6. As in the case of daily comparisons, $ET_0$ methods were ranked separately on the basis of SEE, STDEV, and $R^2$ statistics and also using an overall (average) rank. Based on overall ranking, the FAO-56 Hargreaves method was the best alternative to the FAO-56 PM method in all climates except humid (Pattambi) where it was ranked second to the Turc method. The performance of the Turc method appeared to worsen progressively from the wetter climates to the drier ones. On the other hand, the FAO-24 radiation method which performed reasonably well at the arid and humid climates, performed poorly in the semiarid and subhumid climates. While the performance of the Priestley–Taylor method was reasonably good in the wetter climates and poor in the drier climates, the opposite was true for the FAO-24 Blaney–Criddle method. Interestingly, the Pan evaporation method exhibited a much better performance in the semiarid and subhumid climates in comparison to its poor performance in the other extreme climates. Considering the SEE performance statistic, it is immediately apparent that the values of SEE for monthly comparisons (Table 6) are lower than for the daily comparisons (Table 5). This may due to the reduction in

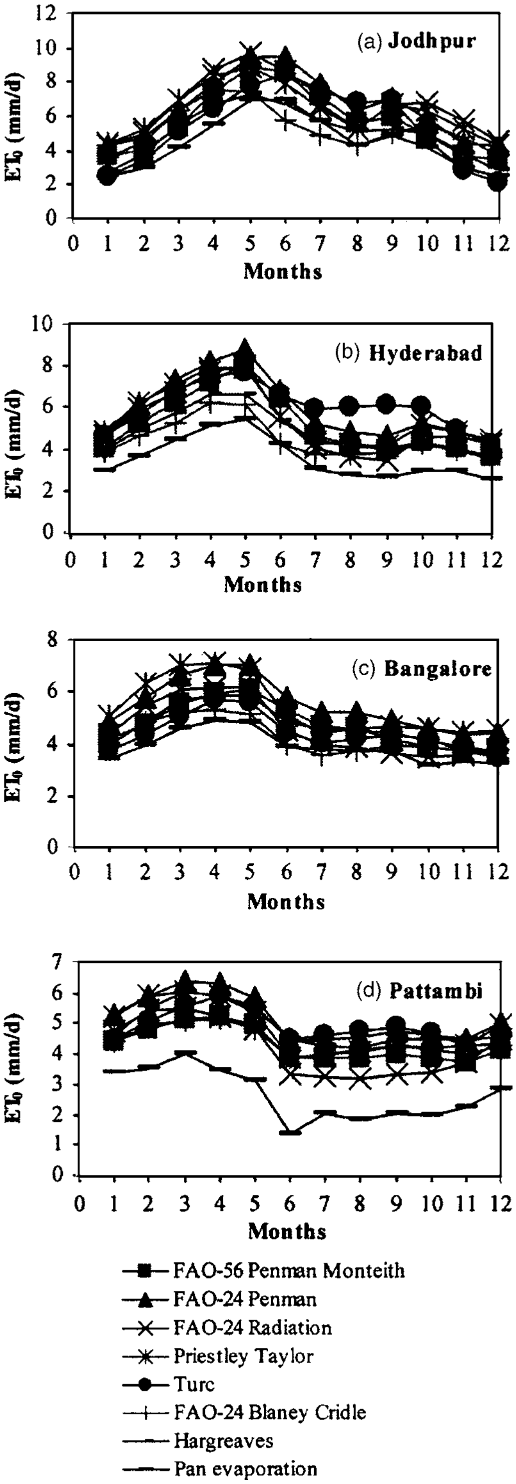


**Fig. 2.** Mean monthly $ET_0$ for four stations by all methods

**Table 6.** Regression Statistics for Monthly $ET_0$ Comparisons

| Station | Method | SEE (mm/day) | STDEV (mm/day) | $R^2$ | Slope $S$ (zero intercept) | Overall rank |
|---|---|---|---|---|---|---|
| Jodhpur ($N_d=48$) | HAR | 1.01 (2) | 1.46 (2) | 0.87 (2) | 1.27 | 2 |
| | RAD | 1.03 (3) | 1.53 (3) | 0.82 (4) | 0.92 | 3.33 |
| | BC | 1.24 (4) | 1.76 (5) | 0.95 (1) | 1.08 | 3.33 |
| | TC | 1.4 (6) | 1.32 (1) | 0.84 (3) | 0.87 | 3.33 |
| | PT | 0.95 (1) | 2.19 (6) | 0.51 (6) | 1.02 | 4.33 |
| | PAN | 1.36 (5) | 1.62 (4) | 0.79 (5) | 1.14 | 4.67 |
| Hyderabad ($N_d=36$) | HAR | 0.67 (2) | 1.05 (2) | 0.94 (2) | 0.87 | 2 |
| | BC | 0.59 (1) | 1.62 (6) | 0.97 (1) | 1.44 | 2.67 |
| | TC | 1.05 (4) | 0.97 (1) | 0.86 (3) | 1.17 | 2.67 |
| | PAN | 1.67 (6) | 1.05 (3) | 0.83 (4) | 0.93 | 4.33 |
| | RAD | 0.73 (3) | 1.47 (5) | 0.73 (6) | 0.97 | 4.67 |
| | PT | 1.16 (5) | 1.08 (4) | 0.81 (5) | 1.09 | 4.67 |
| Bangalore ($N_d=48$) | HAR | 0.38 (1) | 0.78 (3) | 0.78 (2) | 0.87 | 2 |
| | TC | 0.74 (4) | 0.72 (1) | 0.81 (1) | 1.20 | 2 |
| | PT | 0.56 (2) | 0.73 (2) | 0.74 (3) | 1.11 | 2.33 |
| | BC | 0.57 (3) | 1.12 (5) | 0.68 (4) | 1.01 | 4 |
| | PAN | 1.1 (6) | 0.79 (4) | 0.6 (5) | 1.07 | 5 |
| | RAD | 0.93 (5) | 1.14 (6) | 0.42 (6) | 1.01 | 5.67 |
| Pattambi ($N_d=48$) | TC | 0.2 (1) | 0.48 (1) | 0.96 (1) | 1.53 | 1 |
| | HAR | 0.62 (3) | 0.68 (3) | 0.82 (3) | 0.88 | 3 |
| | RAD | 0.64 (4) | 0.86 (4) | 0.9 (2) | 0.88 | 3.33 |
| | PT | 0.64 (5) | 0.57 (2) | 0.82 (4) | 0.89 | 3.67 |
| | BC | 0.48 (2) | 0.94 (6) | 0.72 (6) | 0.98 | 4.67 |
| | PAN | 1.77 (6) | 0.9 (5) | 0.78 (5) | 1.01 | 5.33 |

Note: Monthly analysis has been done for the entire data set as there are only a maximum of 48 values. Numbers in parentheses=rank numbers of $ET_0$ methods based on performance statistic considered.

variabilities of climatic variables due to the averaging process which may also explain smaller STDEV and higher $R^2$ values for monthly comparisons. Undoubtedly, all $ET_0$ methods considered in this study yielded much better monthly estimates relative to the FAO-56 PM method than daily ones. As in the case of daily comparisons, the popular FAO-24 Penman method consistently overpredicted monthly mean $ET_0$ and yielded SEE values in excess of 1.0 mm/day in all the climates (results not shown for brevity).

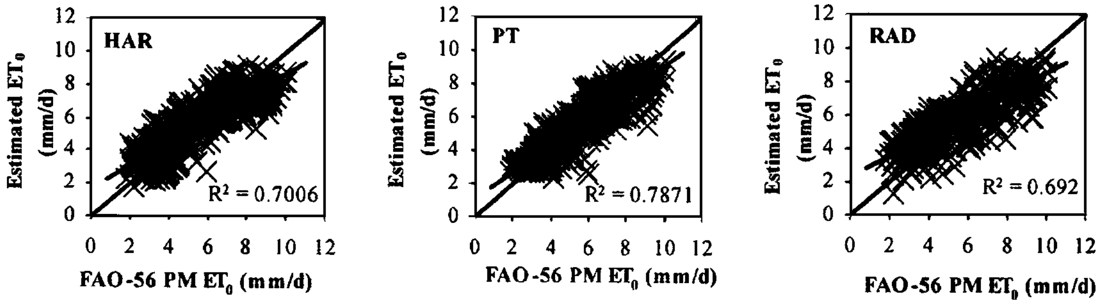
### Regression Equations

For each climate station, separate linear regression equations were established with FAO-56 PM daily $ET_0$ estimates as the dependent variable and daily $ET_0$ values estimated by the alternative simpler methods as an independent variable. Equations were developed for only those methods which were ranked among the top three on the basis of daily SEE values (Table 5). A part of the available climate data set for each location (Table 1) was used for

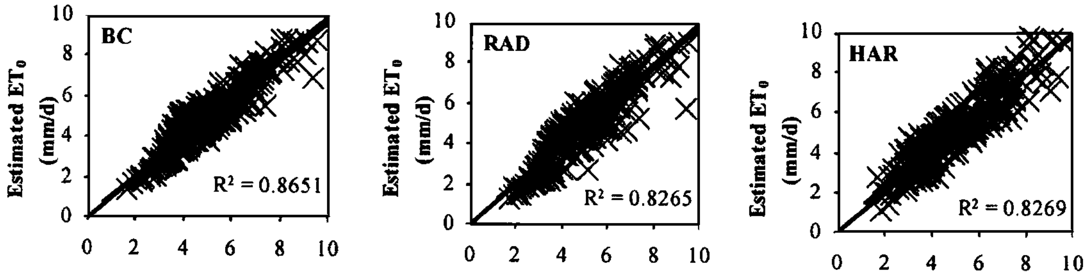
**Table 7.** Developed Regression Equations and Validation Statistics

| Station | Method | Regression | SEE | $R^2$ |
|---|---|---|---|---|
| Jodhpur ($N=484$) | HAR | $y=1.1924x-0.3827$ | 1.1476 | 0.7006 |
| | PT | $y=0.7940x+1.3796$ | 0.9684 | 0.7871 |
| | RAD | $y=0.9554x-0.3341$ | 1.1956 | 0.6920 |
| Hyderabad ($N=348$) | BC | $y=0.9089x+0.2209$ | 0.5976 | 0.8651 |
| | RAD | $y=0.9333x-0.0708$ | 0.6966 | 0.8265 |
| | HAR | $y=1.4898x-1.9684$ | 0.6968 | 0.8269 |
| Bangalore ($N=456$) | HAR | $y=1.0244x-0.1063$ | 0.6838 | 0.7055 |
| | BC | $y=0.692x+1.4804$ | 0.4758 | 0.8545 |
| | PT | $y=0.9069x+0.7654$ | 0.7301 | 0.6477 |
| Pattambi ($N=425$) | TC | $y=1.0532x-0.3119$ | 0.2476 | 0.9147 |
| | BC | $y=0.6665x+1.4416$ | 0.3772 | 0.7624 |
| | PT | $y=0.8785x+0.1073$ | 0.3548 | 0.8091 |

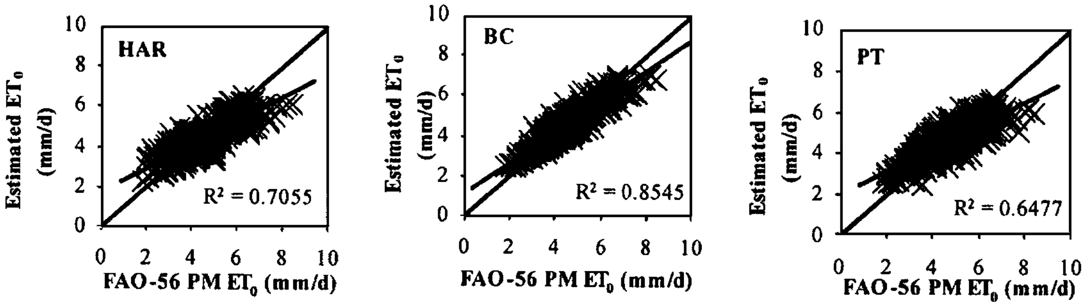
Note: $y$= daily $ET_0$ (mm/day) by FAO-56 PM method; and $x$= daily $ET_0$ (mm/day) by alternative method considered.



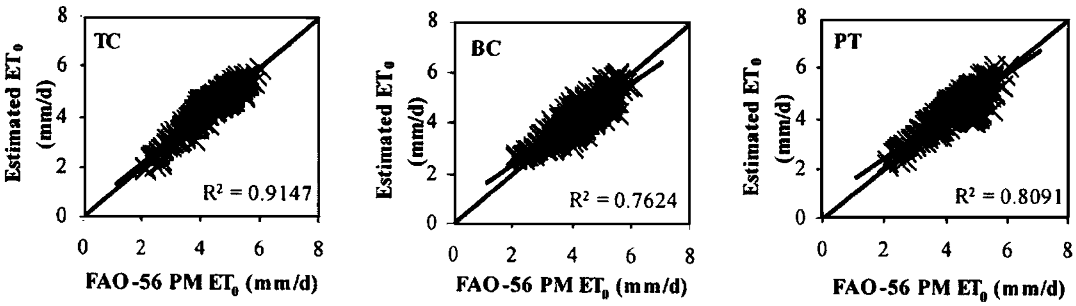
(a) Jodhpur ($N_d$=484)



(b) Hyderabad ($N_d$=348)



(c) Bangalore ($N_d$=456)



(d) Pattambi ($N_d$=425)

**Fig. 3.** Validation of regression equations developed for four stations: (a) Jodhpur; (b) Hyderabad; (c) Bangalore; (d) Pattambi

establishing the regression coefficients and the remaining part was used for validating the developed equations. Performances of the regression equations were assessed in terms of the SEE and $R^2$ values obtained in the validation phase through comparison of daily PM $ET_0$ values estimated by FAO-56 procedures and those obtained from the regression equations.

The forms of the established regression equations and their associated validation performance statistics are listed in Table 7. Fig. 3 shows scatter plots of these comparisons for each of the three top methods (based on SEE) for the climate stations considered. On comparing these statistics with the ones listed in Table 5, it can be seen that in all cases the developed regression equations perform much better than the original equations in yielding daily $ET_0$ estimates comparable to the FAO-56 PM method. Also, as in the earlier comparisons, the performances of the regression equations appear to progressively worsen from the humid climate to the arid one. In any case, we expect the regression equations developed in this study to be useful tools to Indian practitioners and researchers in obtaining reasonably accurate FAO-56 PM $ET_0$ estimates from simple climatic inputs.

**Table 8.** Results of Factor Analysis for Four Stations

| | Rotated component matrix | | | |
|---|---|---|---|---|
| | | Components | | |
| Station | Variable | 1 | 2 | 3 |
| Jodhpur | $T_{\max}$ | −0.0660 | 0.9801 | 0.0709 |
| | $T_{\min}$ | 0.3705 | 0.8798 | 0.2253 |
| | $\mathrm{RH}_{\max}$ | 0.8896 | 0.0046 | 0.1165 |
| | $\mathrm{RH}_{\min}$ | 0.9513 | −0.0161 | 0.0631 |
| | $u_2$ | 0.2893 | 0.2152 | 0.9265 |
| | $n/N$ | −0.7849 | −0.1362 | −0.1313 |
| | FAO-56 PM $\mathrm{ET}_0$ | −0.1280 | 0.7565 | 0.6180 |
| Hyderabad | $T_{\max}$ | 0.9379 | 0.1952 | — |
| | $T_{\min}$ | 0.4056 | 0.8243 | — |
| | $\mathrm{RH}_{\max}$ | −0.8716 | −0.0274 | — |
| | $\mathrm{RH}_{\min}$ | −0.7434 | 0.6044 | — |
| | $u_2$ | 0.2748 | 0.7353 | — |
| | $n/N$ | 0.4235 | −0.8135 | — |
| | FAO-56 PM $\mathrm{ET}_0$ | 0.9555 | 0.1939 | — |
| Bangalore | $T_{\max}$ | 0.6071 | 0.7345 | −0.1424 |
| | $T_{\min}$ | −0.1762 | 0.9569 | 0.0783 |
| | $\mathrm{RH}_{\max}$ | −0.6903 | −0.0531 | 0.0761 |
| | $\mathrm{RH}_{\min}$ | −0.8848 | −0.0651 | 0.1184 |
| | $u_2$ | −0.2249 | 0.0237 | 0.9684 |
| | $n/N$ | 0.8057 | -0.0882 | −0.2729 |
| | FAO-56 PM $\mathrm{ET}_0$ | 0.6864 | 0.5452 | 0.4073 |
| Pattambi | $T_{\max}$ | 0.8324 | 0.0649 | — |
| | $T_{\min}$ | 0.1633 | 0.9402 | — |
| | $\mathrm{RH}_{\max}$ | −0.5110 | 0.4610 | — |
| | $\mathrm{RH}_{\min}$ | −0.7807 | 0.4164 | — |
| | $u_2$ | 0.5959 | 0.0997 | — |
| | $n/N$ | 0.7572 | −0.3545 | — |
| | FAO-56 PM $\mathrm{ET}_0$ | 0.9446 | 0.0742 | — |

## *Factor Analysis*

As a first step, the matrix of correlation coefficients between the variables included in the analysis (FAO-56 PM $\mathrm{ET}_0$, $T_{\max}$, $T_{\min}$, $\mathrm{RH}_{\max}$, $\mathrm{RH}_{\min}$, $n/N$, $u_2$) was computed (not shown here for brevity) separately for the data sets of each climate station (Table 1). As was to be expected, significant correlations existed between some of the variables. Particularly notable were significantly large correlation coefficients ($> \pm 0.6$) between the temperature variables ($T_{\max}$ and $T_{\min}$) and humidity variables ($\mathrm{RH}_{\max}$ and $\mathrm{RH}_{\min}$) and also between FAO-56 PM $\mathrm{ET}_0$ and $T_{\max}$. Variables $n/N$ and $u_2$ appeared to be mutually weakly correlated but exhibited significant correlation with FAO-56 PM $\mathrm{ET}_0$ only in some climates. Each of these matrices was subjected to eigenvalue-eigenvector analysis. In all cases, it was found that only the first four components (out of a maximum possible of seven) were significant and accounted for 97% (Jodhpur), 97% (Hyderabad), 93% (Bangalore), and 92% (Pattambi) of the total variability present in the original data sets for each climate. Accordingly, the eigenvector matrices of only these four factors were considered for varimax rotation. This exercise was implemented in stages by first rotating only the first two factors, then the first three factors, and finally all four factors. For two stations (Hyderabad and Pattambi) the two-factor rotation provided the best solution for interpreting the relative importance of independent variables on the dependent variable. For the Jodhpur and Bangalore sites, the best interpretation could be obtained from the three-factor solution. These results are shown in Table 8.

Considering the rotated three-factor solution for the Jodhpur site, it can be seen that the dependent variable (FAO-56 PM $\mathrm{ET}_0$) has the highest loading in the second factor in which $T_{\max}$ and $T_{\min}$ are the only other variables with high loadings. This implies that these two climatic variables have the most dominant effect on $\mathrm{ET}_0$ estimates at this site. Since these two variables exhibit a high degree of correlation (0.827), either one of them could be considered as a dominant variable. The next highest loading for $\mathrm{ET}_0$ occurs in the third factor and windspeed ($u_2$) is the dominant variable on account of its high loading. The first factor has a small negative loading for the dependent variable and may therefore be ignored. In summary, the results of factor analysis for the arid Jodhpur site indicate that temperature ($T_{\max}$ or $T_{\min}$) and to a lesser degree, windspeed ($u_2$) explain most of the variability associated with FAO-56 PM $\mathrm{ET}_0$ estimates. This interpretation implies that any alternative $\mathrm{ET}_0$ method that uses these climatic inputs will yield results closest to those by the FAO-56 PM method. Examination of the results shown in Table 5 indicate that for this climate the FAO-56 Hargreaves and FAO-24 Blaney–Criddle methods, which are both temperature based and primarily use $T_{\max}$ and $T_{\min}$ as inputs performed well. However, we cannot explain the almost equally good performance of the FAO-24 radiation method (overall rank, 2) from the results of factor analysis. Surprisingly, the FAO-24 Penman method provided the best estimates at this location (Fig. 1), probably because it uses windspeed data, which was identified as the second most important input variable through factor analysis. The fact that none of the remaining methods use windspeed data explains why the ranks for all the methods are highest in the arid climate.

Using a similar reasoning the two-factor solution for Hyderabad (Table 8) may be interpreted. The loading for $\mathrm{ET}_0$ is quite high in the first factor and negligible in the second factor. Variables $T_{\max}$, $\mathrm{RH}_{\max}$, and $\mathrm{RH}_{\min}$ also exhibit high loadings in the first factor. The correlation coefficients between these variables are: $T_{\max}$: $\mathrm{RH}_{\max}=-0.786$, $T_{\max}$: $\mathrm{RH}_{\min}=-0.567$, and $\mathrm{RH}_{\max}$: $\mathrm{RH}_{\min}=0.608$. Since correlations are significantly high, we may deduce that only one of these three variables needs to be considered in explaining the variability of FAO-56 PM $\mathrm{ET}_0$ values. If $T_{\max}$ is considered as the primary variable, it provides an explanation as to why the temperature-based FAO-56 Hargreaves method and the FAO-24 Blaney–Criddle method provide $\mathrm{ET}_0$ estimates with the highest rankings (Table 5) for the semiarid (Hyderabad) site.

The three-factor rotation for the subhumid Bangalore site (Table 8) revealed highest loading for $\mathrm{ET}_0$ in the first factor in which $\mathrm{RH}_{\min}$ and $n/N$ also had relatively high loadings. The second factor had the next highest loading for the dependent variable and here the temperature variables appeared to be dominant. The last factor with the smallest loading for $\mathrm{ET}_0$ indicated high loading for the wind speed variable. Based on the high degree of correlation that existed between the temperature variables and humidity variables even at this location, it was concluded that the most important climatic variables that influence FAO-56 PM $\mathrm{ET}_0$ estimates in the subhumid climate are $T_{\max}$ (or $T_{\min}$) and $n/N$. This finding provides an explanation for the success of the temperature-based FAO-56 Hargreaves methods and to a slightly lesser degree, the success of the radiation-based Priestley–Taylor method in this climate (Table 5).

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At the humid Pattambi site, the two-factor solution (Table 8) indicated the existence of high loadings for $T_{\max}$ and $n/N$ variables in the first factor which had the highest loading for the dependent variable. The second factor did not contain any useful information since the loading for $\mathrm{ET}_0$ was negligible. Since $n/N$ is an important input in radiation-based methods, the results of factor analysis provide a justification to the extremely good performance of the Turc method in this climate (Table 5).

While accepting that the ability of the alternative methods to produce $\mathrm{ET}_0$ estimates close to the FAO-56 PM method may be partly linked to the correct choice of numerical values of coefficients in the equations, one cannot deny the role of correlations between climate variables and the dependent variable. Although not explicit in all cases, factor analysis still provides a reasonably good description of the relative importance of climatic variables on $\mathrm{ET}_0$ in distinctly different climates and was able to substantiate the success of the simpler $\mathrm{ET}_0$ methods. Also one may broadly conclude that windspeed appears to be an important variable in the arid climate, whereas sunshine hours appear to be more dominant in subhumid and humid climates. In any case, temperature related variables are the most crucial inputs required to obtain $\mathrm{ET}_0$ estimates comparable to those from the FAO-56 PM method in all the climates considered.

## Conclusions

Performances of several commonly used $\mathrm{ET}_0$ methods were evaluated relative to the FAO-56 recommended Penman–Monteith method for a range of climatic conditions prevalent in India. Due to nonavailability of measured data from grass lysimeters, $\mathrm{ET}_0$ comparisons could be made only on a relative basis. Daily and monthly average $\mathrm{ET}_0$ values (mm/day) estimated by all the methods were statistically compared with the preferred FAO-56 PM method using historical daily climate data from four stations located at Jodhpur (arid), Hyderabad (semiarid), Bangalore (subhumid), and Pattambi (humid). Overall results indicate that some of the simpler temperature-based and radiation-based $\mathrm{ET}_0$ methods provide reasonably good comparisons with the FAO-56 PM method, especially for monthly $\mathrm{ET}_0$ estimates in the humid climate. In an effort to provide guidance on the choice of the most appropriate $\mathrm{ET}_0$ equation to be adopted in a particular Indian climate when input data are insufficient to apply the preferred FAO-56 PM method, alternative $\mathrm{ET}_0$ methods were ranked on the basis of SEE, STDEV, $R^2$, and also on the basis of an overall rank that considered all the performance statistics. For each climate, simple regression equations were developed for deriving preferred FAO-56 PM $\mathrm{ET}_0$ estimates from estimates obtained from the methods involving simpler climatic inputs. Validation tests revealed that PM $\mathrm{ET}_0$ estimates from these regression equations were more accurate than those obtained from the original equations and could therefore serve as useful practical $\mathrm{ET}_0$ estimation tools for practitioners/researchers. For the first time, an attempt has been made in this paper to seek an explanation for the climate-dependent success of some of the simpler temperature-based and radiation-based equations. This was achieved through application of multivariate factor analysis techniques on the climate data sets used in the comparative analysis. Results of factor analysis provided extremely useful information on the relative importance of climatic variables in explaining the variabilities associated with FAO-56 PM $\mathrm{ET}_0$ estimates at each station and provided a statistical justification for the successful performance of some of the simpler $\mathrm{ET}_0$ methods in the various climates considered in this study.

## Notation

*The following symbols are used in this paper:*

$a_b$ = adjustment factor used in FAO-24 Blaney–Criddle method which depends on minimum relative humidity ($\mathrm{RH}_{\min}$) and ratio of actual to possible sunshine hours ($n/N$);
$b_b$ = adjustment factor used in FAO-24 Blaney–Criddle method which depends on minimum relative humidity ($\mathrm{RH}_{\min}$), ratio of actual to possible sunshine hours (n/N) and daytime windspeed ($u_d$);
$b_R$ = adjustment factor used in FAO-24 radiation method which depends on mean relative humidity ($\mathrm{RH}_{\mathrm{mean}}$) and day time windspeed($u_d$);
$C$ = adjustment factor used in FAO-24 Penman equation to incorporate differences between day and night weather conditions;
$\mathrm{ET}_{\mathrm{bc}}$ = reference crop ET (mm/day) by FAO-24 Blaney–Criddle method;
$\mathrm{ET}_h$ = reference crop ET (mm/day) by FAO-56 Hargreaves method;
$\mathrm{ET}_p$ = reference crop ET (mm/day) by FAO-24 Penman method;
$\mathrm{ET}_{\mathrm{pan}}$ = reference crop ET (mm/day) by FAO-56 Pan evaporation method;
$\mathrm{ET}_{\mathrm{pt}}$ = reference crop ET (mm/day) by Priestley–Taylor method;
$\mathrm{ET}_r$ = reference crop ET (mm/day) by FAO-24 radiation method;
$\mathrm{ET}_t$ = reference crop ET (mm/day) by Turc method;
$\mathrm{ET}_0$ = reference crop ET (mm/day) by FAO-56 Penman–Monteith method;
$e_a$ = actual vapor pressure (kPa);
$e'_a$ = actual vapor pressure at mean temperature (mbar);
$e_{\mathrm{pan}}$ = pan evaporation (mm/day);
$e_s$ = saturation vapor pressure (kPa);
$e'_s$ = saturation vapor pressure at mean temperature (mbar);
FET = fetch (m);
$f(u)$ = wind function used in FAO-24 Penman method;
$G$ = soil heat flux density $[\mathrm{MJ}/(\mathrm{m}^2\,\mathrm{day})]$;
$k_p$ = pan coefficient;
$N$ = maximum possible duration of sunshine (h);
$N_d$ = number of data points;
$n$ = actual duration of sunshine (h);
$p$ = ratio of actual daily day time hours to annual mean daily day time hours (%);
$R^2$ = coefficient of determination of linear fit;
$R_a$ = extraterrestrial solar radiation at top of atmosphere $[\mathrm{MJ}/(\mathrm{m}^2\,\mathrm{day})]$;
$R'_{a,}$ = extraterrestrial radiation at top of atmosphere (mm/day);
$\mathrm{R}_n$ = net radiation at crop surface $[\mathrm{MJ}/(\mathrm{m}^2\,\mathrm{day})]$;
$R'_n$ = net radiation at crop surface (mm/day);
$R_s$ = incoming solar radiation $[\mathrm{MJ}/(\mathrm{m}^2\,\mathrm{day})]$;
$R'_s$ = incoming solar radiation (mm/day);
$\mathrm{RH}_{\max}$ = maximum relative humidity (%);
$\mathrm{RH}_{\mathrm{mean}}$ = mean relative humidity (%);

$\mathrm{RH}_{\min}$ = minimum relative humidity (%);

$S$ = slope of linear fit (forced through origin) between FAO-56 PM $\mathrm{ET}_0$ values and those estimated by other methods;

$\bar{T}$ = mean air temperature at 2 m height (°C);

$T^*$ = either $T_{\max}$ or $T_{\min}$;

$T_{\max}$ = maximum air temperatures (°C);

$T_{\min}$ = minimum air temperatures (°C);

$u_r$ = ratio of day to night time windspeed;

$u_z$ = windspeed measured at any other height (m/s);

$u_2$ = 24 h windspeed at 2 m height (m/s);

$z$ = elevation of site above mean sea level (m);

$z_w$ = height of wind measurement (m);

$\beta$ = Priestley–Taylor coefficient;

$\gamma$ = psychrometric constant (kPa/°C);

$\gamma'$ = psychrometric constant (mbar/°C);

$\Delta$ = slope of vapor pressure versus temperature curve at mean temperature (kPa/°C);

$\Delta'$ = slope of vapor pressure versus temperature curve at mean temperature (mbar/°C); and

$\phi$ = latitude of place (rad).

## References

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