Evaluation of FAO-56 Penman–Monteith and alternative methods for estimating reference evapotranspiration using limited climatic data at Pusa

SUDARSHAN PRASAD and VISHAL KUMAR

College of Agricultural Engineering, Rajendra Agricultural University, Pusa (Bihar)

e-mail: sp_28783@yahoo.com

ABSTRACT

The FAO-56 Penman–Monteith method (FAO-56 PM) is standard method recognized by the Food and Agriculture Organization of the United Nations for estimating reference evapotranspiration (ET₀). Unfortunately, some of climatic variables, especially relative humidity, solar radiation and wind speed are often missing which could impede the estimation of ET₀ with the FAO-56 PM method. To overcome the problem of availability of climatic variables, procedures to estimate ET₀ with missing climate data are proposed as part of the FAO methodology. Therefore, assessing the accuracy of these procedures for Pusa Observatory is important.

The comparison of ET₀ estimates using limited data to those computed with full data set revealed that the difference between ET₀ obtained from full and limited data set is small. Both the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) of the comparison were less than 0.35 and 1.00 with a minimum of 0.11 and 0.29 mm day⁻¹, respectively, leading to small errors in the ET₀ estimates. R² and ÷²-test and index of agreement values confirmed strong relationships among data for the year 1998 to 2006.

Keywords: Reference evapotranspiration; FAO-56 Penman-Monteith model; Limited data.

The need for an accurate and standard method to estimate reference evapotranspiration (ET₀), to predict crop water requirements, has been stated by several authors (Allen, 1996; Chiew et al., 1995; and Martinez-Cob and Tejero-Juste, 2004). A great number of equations for estimating ET₀ are reported in literature (Alexandris et al., 2005; DehghaniSanij et al., 2004; Gavilán et al., 2006; and Pereira and Pruitt, 2004), but the international scientific community has accepted the FAO-56 Penman–Monteith (FAO-56 PM) equation as the most precise one for its good results when compared with other equations in various regions of the entire world (Chiew et al., 1995; Garcia et al., 2004; and Gavilán et al., 2006). Subsequent papers have demonstrated the superiority of the FAO-56 PM equation over other methods (Allen et al., 1998) when comparing it with lysimetric measurements especially for daily computations (Cai et al., 2007; Chiew et al., 1995; Garcia et al., 2004; and López-Urrea et al., 2006).

The FAO-56 PM method requires daily data on maximum and minimum air temperature (T_max and T_min), relative humidity (RH), solar radiation (Rₚ) and wind speed (u) for daily ET₀ calculation. Unfortunately, for many locations in India, such meteorological variables are often incomplete and/or not available. But estimation methods for limited weather data are outlined by Allen et al. (1998) and found appropriate for Bulgaria (Popova et al., 2006) making their use applicable under various conditions. It is therefore important to assess the accuracy of the procedures to estimate ET₀ from missing data. Thus, the present study has been carried out to assess the validity of the estimates of ET₀ obtained using limited data against ET₀ computed with a complete data set under the environmental conditions of Pusa (India).

MATERIALS AND METHODS

Climate data

To evaluate the performance of ET₀ estimated from limited climatic data using the FAO-56 PM method, daily data recorded at Pusa meteorological station (latitude 25.98° N; longitude 85.67° E; 52.0 meters above the mean sea level) were used. The weather stations have good quality of daily data from 1998 to 2006 for estimating ET₀ with the FAO-56 PM method including sunshine duration, relative humidity, wind speed and daily maximum and minimum temperatures. FAO-56 PM method was applied...
with the observed data sets to assess the accuracy of using limited data on the estimation of $ET_o$.

**The FAO-56 Penman–Monteith equation and its computational procedures**

The Penman–Monteith equation for computation of daily reference evapotranspiration assumes the reference crop evapotranspiration as that from a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m$^{-1}$ and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered. It is expressed as (Allen et al., 1998):

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

where $ET_o$ is the grass reference evapotranspiration (mm day$^{-1}$); $\Delta$ is the slope of the saturated vapor pressure curve (kPa °C$^{-1}$); $R_s$ is the net radiation (MJ m$^{-2}$ day$^{-1}$); $G$ is the soil heat flux density (MJ m$^{-2}$ day$^{-1}$); considered as null for daily estimates; $T$ is the daily mean air temperature (°C) at 2 m height, based on the average of maximum and minimum temperatures; $u_2$ is the average wind speed at 2 m height (m s$^{-1}$); $e_s$ is the saturation vapor pressure (kPa); $e_a$ is the actual vapor pressure (kPa); and $(e_a - e_s)$ is the saturation vapor pressure deficit (kPa) at temperature $T$; and $\tilde{\alpha}$ is the psychrometric constant (0.0677 kPa °C$^{-1}$).

**Missing climatic data**

The procedures for computing reference evapotranspiration using limited climatic data stated in Allen et al., (1998) were used and these procedures are as follow:

**Relative humidity**

If the air humidity data is not available, the actual vapour pressure ($e_a$) could be obtained by assuming that the dew point temperature is close to the daily minimum air temperature ($T_{min}$) which is usually found at the time of sunrise in a location. The $e_a$ is estimated by:

$$e_a = e^a(T_{min}) = 0.6108 \times e^{(17.27 \times T_{min} + 237.3)} \quad \text{... (2)}$$

$T_{min}$ might be greater than $T_{dew}$ in a non-reference weather station, as in a station located inside a town. Where $T_{min}$ may require correction (Allen, 1996 and Allen et al., 1998) proposed that the estimate for $e_a$ from $T_{min}$ should be checked and that, when the prediction by Eq. (2) is validated for a region, it can be used for daily estimates of $e_a$.

**Solar radiation**

Allen et al. (1998) suggested a simple method to estimate $R_s$ in the absence of solar radiation or sunshine radiation using the difference method based on the fact that differences between maximum and minimum air temperature are closely related to the existing daily solar radiation for a given location:

$$R_s = K_{rs} \left( \sqrt{T_{max} - T_{min}} \right) R_o \quad \text{... (3)}$$

Where, $R_s$ is the extraterrestrial radiation (MJ m$^{-2}$ day$^{-1}$) and $K_{rs}$ is an empirical adjustment coefficient (°C$^{-0.5}$). The value of $K_{rs}$ ranges from 0.16 °C$^{-0.5}$ for interior region to 0.19 °C$^{-0.5}$ for coastal region depending upon the case (Hargreaves and Samani, 1982).

**Wind speed**

Where wind speed data are lacking, Allen et al. (1998) proposed to use default value of wind speed to compute reference evapotranspiration. In fact, impact of wind speed on the estimated $ET_o$ is relatively small except for arid and windy areas (Martinez-Cob and Tejero-Juste, 2004). Thus, the authors refer the possibility to use with caution the default value of 2 m/s, which is the average value over 2000 weather stations around the globe.

**Data analysis**

The results from $ET_o$ estimated by the FAO-56 PM method with missing Rs, $e_a$ and $u_2$ obtained with the procedures mentioned above were compared with $ET_o$ data computed with full data sets. The empirical calibration of the parameters of each method was performed by minimizing $ET_o$ errors between the calibrated methods and the full-data FAO-56 PM method, approximating the slope of the regression analysis to one. The performance of the methods for each location was determined by regression analysis, always forcing the linear coefficient through the origin ($a = 0$). The slope ($b$) was used as a measure of accuracy, while coefficient of determination ($R^2$) was considered as a measure of precision. A perfect method should result in $b = 1$ and $R^2 = 1$. Following the suggestion of Jacovides and Kontoyiannis (1995) and
Jabloun and Sahli (2008), the performance of the ET\textsubscript{o} estimates was also evaluated using root mean square error (RMSE) and mean bias error (MBE). The RMSE and MBE were calculated by the following equations:

\[
\text{RMSE} = \left[ \frac{1}{N} \sum_{i=1}^{N} (ET_{o-est} - ET_{o-ref})^2 \right]^{1/2}, \text{ mm day}^{-1} \quad \ldots (4)
\]

\[
\text{MBE} = \frac{1}{N} \sum_{i=1}^{N} (ET_{o-est} - ET_{o-ref}), \text{ mm day}^{-1} \quad \ldots (5)
\]

Other statistical parameters such as the Chi-Square (\(\chi^2\)) -test and the correlation between ET\textsubscript{o} estimated using full data set and ET\textsubscript{o} estimated using limited data were used to evaluate the performance of the described method for the computation of ET\textsubscript{o}.

\[
\chi^2 = \sum_{i=1}^{N} \left( \frac{(ET_{O-ref} - ET_{O-est})^2}{ET_{O-est}} \right) \quad \ldots (6)
\]

Where, ET\textsubscript{o-ref} is the reference evapotranspiration computed with full data sets and ET\textsubscript{o-est} is the ET\textsubscript{o} estimated from limited data and N is the number of data.

The Willmott index of agreement (d) was used as a relative measure of the difference among variables and is written as (Zhou and Zhou, 2009 and Lopez-Urera et al., 2006):

\[
d = 1 - \frac{\sum_i (ET_{o-ref} - ET_{o-est})^2}{\sum_i (ET_{o-ref} - \text{ave}(ET_{o-ref}))^2 + \sum_i (ET_{o-est} - \text{ave}(ET_{o-est}))^2} \quad \ldots (7)
\]

where, \(\text{ave}(ET_{o-ref})\) is the mean value of the observed variable. Perfect agreement would exist between observed and estimated variables if d is equal to 1.

**RESULTS AND DISCUSSION**

**Computation of reference evapotranspiration from complete meteorological data**

Reference evapotranspiration (ET\textsubscript{o}) from daily meteorological data from the years 1998 to 2006 was computed using Eq. (1) for Pusa (North-Bihar). In the computational procedure complete data set including daily maximum and minimum air temperature, daily maximum and minimum relative humidity, solar radiation and wind speed were used. Results of the analysis revealed that maximum value of ET\textsubscript{o} was found during monsoon season while minimum value of ET\textsubscript{o} was observed during winter (kharif) season. The annual minimum values of ET\textsubscript{o} estimated by FAO-56 PM method oscillates between 0.88 to 1.17 mm day\(^{-1}\) whereas the annual maximum between 6.38 to 8.95 mm day\(^{-1}\) at Pusa Station. The normal value of ET\textsubscript{o} for the period 1998 to 2006 at Pusa Station was observed to be 3.78 mm day\(^{-1}\) while it ranged from 3.66 (2002) to 3.97 (1999 & 2006) mm day\(^{-1}\) during the period from 1998 to 2006.

**Computation of reference evapotranspiration using limited meteorological data**

When relative humidity data are missing

When relative humidity data are absent, Allen et al., (1998) stated that the actual vapour pressure (\(e_a\)) can be determined by assuming that the dew point temperature (\(T_{\text{dew}}\)) is close to the daily minimum temperature i.e., (\(T_{\text{dew}} = T_{\text{min}}\)). ET\textsubscript{oh} values computed using Eq. (1) assuming \(e_a\) estimated from \(T_{\text{min}}\) using Eq. (2) shows that range of annual minimum and maximum values of ET\textsubscript{oh} for the region are 0.96 (1999) to 1.21 (2005) and 6.40 (2001) to 8.20 (1998) mm day\(^{-1}\), respectively. The daily average ET\textsubscript{oh} values ranges from 3.61 (2002) to 3.95 (1999) mm day\(^{-1}\).

The scatter plot Fig. 1(a) between the values of ET\textsubscript{oh} computed when relative humidity data were not available and the values of ET\textsubscript{o} computed from full data set shows a strong relationship between the two methods. The \(R^2\) values were close to 1.0 (higher than 0.95) for the Pusa region. However, the scatter plot illustrates systematic underestimation for high ET\textsubscript{o} rates (ET\textsubscript{o} > 3.33 mm day\(^{-1}\)). The errors associated with this condition are presented in Fig. 2(a) for MBE which shows dispersion of ET\textsubscript{oh} when estimating ET\textsubscript{o} when relative humidity data were not available.

Table 1 summarizes the statistical indices for comparing ET\textsubscript{oh} computed when relative humidity data were not available with ET\textsubscript{o-ref}. The RMSE and MBE values were very low as ET\textsubscript{oh} tends to overestimate ET\textsubscript{o} for high ET\textsubscript{o} rates (ET\textsubscript{o} > 3.33 mm day\(^{-1}\)). The values of RMSE and MBE between ET\textsubscript{o} and ET\textsubscript{oh} ranged from 0.291 (2001) to 0.380 (2005) mm day\(^{-1}\) and from 0.02 (1999) to 0.10 (2006) mm day\(^{-1}\), respectively.
Fig. 1: Scatter plots between reference evapotranspiration ($ET_o$) estimated from full data set and that computed (a) when humidity is missing ($ET_{oh}$); (b) when solar radiation is missing ($ET_{os}$); and (c) when wind speed is missing ($ET_{os}$).
Fig. 2: Mean Bias Error (MBE) between computed $\text{ET}_\text{O}$ from full data set and those computed (a) when $e_a$ is estimated from $T_{\text{min}}$, (b) when $Rs$ is estimated from air temperature and (c) when default value of wind speed is used (2 m s$^{-1}$) for the Pusa.
Table 1: Comparison between \( ET_0 \) computed from full data set and when \( e_c \) is estimated by considering \( T_{dew} = T_{min} \) for different years at Pusa station.

| Years | RMSE (mm day\(^{-1}\)) | MBE (mm day\(^{-1}\)) | Correlation | Index of agreement | \( \chi^2 \)-test statistics |
|-------|--------------------------|-------------------------|-------------|-------------------|----------------------------|
| 1998  | 0.348                    | 0.035                   | 0.981       | 0.99              | 10.27                      |
| 1999  | 0.323                    | 0.020                   | 0.983       | 0.99              | 8.68                       |
| 2000  | 0.326                    | 0.056                   | 0.979       | 0.99              | 8.39                       |
| 2001  | 0.291                    | 0.038                   | 0.979       | 0.99              | 7.46                       |
| 2002  | 0.335                    | 0.049                   | 0.970       | 0.98              | 9.68                       |
| 2003  | 0.338                    | 0.050                   | 0.972       | 0.98              | 9.82                       |
| 2004  | 0.325                    | 0.075                   | 0.983       | 0.99              | 9.72                       |
| 2005  | 0.380                    | 0.083                   | 0.975       | 0.98              | 12.37                      |
| 2006  | 0.372                    | 0.100                   | 0.984       | 0.99              | 11.60                      |

Table 2: Comparison between \( ET_0 \) computed from full data set and estimated when \( R_s \) is computed from air temperature for different years at Pusa station.

| Years | RMSE (mm day\(^{-1}\)) | MBE (mm day\(^{-1}\)) | Correlation | Index of agreement | \( \chi^2 \)-test statistics |
|-------|--------------------------|-------------------------|-------------|-------------------|----------------------------|
| 1998  | 0.842                    | 0.220                   | 0.891       | 0.94              | 71.20                      |
| 1999  | 0.949                    | 0.326                   | 0.858       | 0.91              | 93.70                      |
| 2000  | 0.797                    | 0.173                   | 0.870       | 0.93              | 62.01                      |
| 2001  | 0.774                    | 0.256                   | 0.845       | 0.90              | 68.48                      |
| 2002  | 0.749                    | 0.277                   | 0.855       | 0.90              | 62.32                      |
| 2003  | 0.770                    | 0.305                   | 0.867       | 0.91              | 73.97                      |
| 2004  | 0.712                    | 0.282                   | 0.917       | 0.94              | 50.58                      |
| 2005  | 0.598                    | 0.150                   | 0.928       | 0.96              | 32.91                      |
| 2006  | 0.712                    | 0.291                   | 0.936       | 0.95              | 44.59                      |

\( R^2 \); \( \chi^2 \)-test value for goodness of fit and index of agreement values show strong relationships among data which can be seen by high \( R^2 \) values around 0.95; lowest average \( \chi^2 \)-test value of 11.60 and index of agreement value around unity for all the years of observation. The values for the statistical indices are of the same order and magnitude of those referred by Cai et al., (2007) and Popova et al., (2006) in their computations of \( ET_0 \) with limited data. Thus, there is a reasonably good agreement between these two methods i.e. the methods to compute \( ET_{oh} \) when relative humidity is absent and \( ET_0 \) computed from full data set. These lowest values of RMSE and MBE and high values of correlation between \( ET_0 \) and \( ET_{oh} \) indicate that it may be an appropriate method to compute \( ET_0 \) when relative humidity is absent.

**When solar radiation data are missing**

The missing data \( \text{Rs} \) was computed using Eq. (3) with an assumption that difference between maximum and minimum temperatures are closely related to the existing daily solar radiation in a given location (Allen et al., 1998). The results of the analysis revealed that the range of annual minimum value of \( ET_{or} \) was observed to be 0.90 (2004) to 1.59 (2005) mm day\(^{-1}\) while that of annual maximum was 6.71 (2002) to 9.06 (1998) mm day\(^{-1}\). The values of daily average \( ET_{or} \) ranges from 3.36 (2003) to 3.68 (2006) mm day\(^{-1}\).

The weak performance of FAO-56 PM method to estimate when solar radiation is missing can be better understood by analyzing the relationship between observed (ref \( ET_0 \)) and estimated \( SR \) data (\( ET_{or} \)) (Fig. 1(b)). The method recommended by Allen et al. (1998) to estimate \( SR \) proved to be fairly poor option for Pusa conditions, presenting high dispersion \((R^2 = 0.78)\) and systematic overestimation from \( SR \) below 3.50 mm day\(^{-1}\) and underestimation above the \( ET_{or} \) values of 3.50 mm day\(^{-1}\). The errors associated with this condition are presented in Fig. 2(b) for MBE which shows an underestimation at the majority of the observations when estimating \( ET_0 \) using \( T_{max} \) and \( T_{min} \) to assess \( R_s \).

The RMSE and MBE values were larger than those when \( R_s \) is estimated using temperature difference method. The values of MBE between \( ET_0 \) and \( ET_{or} \) ranged from 0.150 (2005) to 0.326 (1999) mm day\(^{-1}\). There is a reasonably good agreement between the two methods since the RMSE values were less than 0.949 mm day\(^{-1}\). These values are consistent with the results presented by Popova et al., (2006). These lower values of RMSE and MBE and corresponding high \( \chi^2 \)-test values indicate that it is appropriate to compute \( ET_0 \) when estimating \( R_s \) with Eq. (3). Furthermore, the values of index of agreement between the two methods for estimating \( ET_0 \) using temperature difference method were relatively higher. It ranged from 0.90 (2001 & 2002) to 0.96 (2005) which are close to unity (Table 2).

**When wind speed data are missing**

Wind speed is not always available in agro-
Table 3: Comparison between $ET_0$ computed from full data set and estimated using default value of wind speed for different years at Pusa station.

| Years | RMSE (mm day$^{-1}$) | MBE (mm day$^{-1}$) | Correlation | Index of agreement $\chi^2$-test | Statistics |
|-------|----------------------|---------------------|--------------|----------------------------------|------------|
| 1998  | 0.491 0.275          | 0.975 0.98          |              |                                  | 25.12      |
| 1999  | 0.533 0.328          | 0.971 0.97          |              |                                  | 28.56      |
| 2000  | 0.490 0.321          | 0.975 0.97          |              |                                  | 26.28      |
| 2001  | 0.478 0.250          | 0.969 0.96          |              |                                  | 25.12      |
| 2002  | 0.527 0.312          | 0.964 0.95          |              |                                  | 30.36      |
| 2003  | 0.504 0.245          | 0.966 0.96          |              |                                  | 27.59      |
| 2004  | 0.471 0.306          | 0.976 0.98          |              |                                  | 23.18      |
| 2005  | 0.566 0.198          | 0.969 0.95          |              |                                  | 32.38      |
| 2006  | 0.530 0.348          | 0.975 0.98          |              |                                  | 27.29      |

Meteorological stations that could impede the $ET_0$ estimation using Eq. (1). An alternatives given by Allen et al. (1998) were followed in order to estimate $ET_0$ when default world average value of wind speed was taken 2 m s$^{-1}$ i.e. $u_2 = 2$ m s$^{-1}$. The plot shows the aerodynamic effect on $ET_0$ especially in the coldest period of the year ($ET_0 < 4.5$ mm day$^{-1}$). The range of annual minimum and maximum values of $ET_0$ observed to be 1.01 to 1.16 (2005) and 6.00 (2001) to 8.63 (1998) mm day$^{-1}$, respectively. The average value of $ET_0$ for the years 1998 to 2006 was 4.07 mm day$^{-1}$.

Analysis of the results indicate that there is a high correlation between $ET_0$-ref and $ET_0$-os (R$^2$ exceed 0.90) (Fig. 1(c)). The actual values of the estimates are very similar (R$^2$ values are close to unity). However, it can be seen from Fig. 2(c) depicting the MBE values between $ET_0$-ref and $ET_0$-os that computed $ET_0$ values overestimates below 5.68 mm day$^{-1}$ while underestimates above 5.68 mm day$^{-1}$ (Fig. 1(c)).

Table 3 summarizes the statistical indices for comparing $ET_0$ computed when $u_2$ is missing as outlined above with $ET_0$-os. The RMSE and MBE values were larger than those when using the default value of wind speed as $ET_0$ tends to overestimate $ET_0$ for the different evapotranspiration rates. When using default value of wind speed, the RMSE and MBE values ranged from 0.478 (2001) to 0.566 (2005) mm day$^{-1}$ and from 0.198 (2005) to 0.348 (2006) mm day$^{-1}$, respectively.

$R^2$, $\chi^2$-test and index of agreement values show strong relationships among data which can be seen by high R$^2$ values around 0.96; average $\chi^2$-test value of 27.32 and degree of agreement values around unity for all the years of observation. Concluding, when wind speed is not available the procedure of using default value of wind speed for every years produced the best results for estimating $ET_0$.

**SUMMARY AND CONCLUSIONS**

Different methods outlined by Allen et al. (1998) to compute $ET_0$ with limited climate data were evaluated for Pusa Observatory. The comparison over 9 years of climatic data from 1998 to 2006 revealed that the average values of reference evapotranspiration computed by the use of $T_{\text{min}} = T_{\text{dew}}$ in FAO-56 PM method (3.74 mm day$^{-1}$) were close to that computed by FAO-56 PM method (3.78 mm day$^{-1}$) for the region. However, the $ET_0$ computed when $R_s$ is estimated from temperature difference method was observed to be 3.53 mm day$^{-1}$. Hence, it was concluded that when $e_s$ is estimated from $T_{\text{min}} = T_{\text{dew}}$ in FAO-56 PM method yielded accurate values of reference evapotranspiration. The use of $R_s$ estimated from maximum and minimum daily temperature in FAO-56 PM method could be a good alternative to compute reference evapotranspiration. As far as the use of default value of wind speed is concerned, it led to relatively high average value of $ET_0$ (4.07 mm day$^{-1}$) in the region.

**REFERENCES**

Alexandris, S., Kerkides, P., Liakatas, A. (2005). Daily reference evapotranspiration estimates by the “Copais” approach. *Agric. Water Manage.*, 82:371–386.

Allen, R. G. (1996). Assessing integrity of weather data for reference evapotranspiration estimation. *J. Irrig. Drainage Engg.*, ASCE 122 (2):97–106.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998). Crop evapotranspiration: guidelines for computing crop water requirements. *FAO Irrig. Drainage Paper no. 56*, Rome, Italy.

Cai, J., Liu, Y., Lei, T., Pereira, L. S. (2007). Estimating reference evapotranspiration with the FAO Penman–Monteith equation using daily weather forecast messages. *Agric. Forest Meteorol.*, 145:22–35.

Chiew, F. H. S., Kamaladasa, N. N., Malano, H. M., McMahon,
T. A. (1995). Penman-Monteith, FAO-24 reference crop evapotranspiration and class-A pan data in Australia. *Agric. Water Manage.*, 28:9–21.

DehghaniSanij, H., Yamamotoa, T., Rasiah, V. (2004). Assessment of ET estimation models for use in semi-arid environments. *Agric. Water Manage.*, 64:91–106.

Fischer, G., Tubiello, H., Veithuizen, V., Wiberg, D. (2006). Climate change impacts on irrigation water requirements: global and regional effects of mitigation. *Tec. Forecasting Soc. Ch*, 74, 1990-2080.

Garcia, M., Raes, D., Allen, R., Herbas, C. (2004). Dynamics of reference evapotranspiration in the Bolivian highlands (Altiplano). *Agric. Forest Meteorol.*, 125:67–82.

Gavilán, P., Lorite, I. J., Tornero, S., Berengena, J. (2006). Regional calibration of Hargreaves equation for estimating reference ET in a semiarid environment. *Agric. Water Management*, 81, 257-281.

Hargreaves, G. L., Samani, Z. A. (1982). Estimating potential evapotranspiration. *J Irri. Drainage Engg., ASCE*, 108 (3):225–230.

Jacovides, C. P. and Kontoyiannis, H. (1995). Statistical procedures for the evaluation of evapotranspiration computing models. *Agric. Water Manage.*, 27:365–371.

Jabloun, M. and Sahli, A. (2008). Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data Application to Tunisia. *Agric. Water Management.*, 95 :707 –715.

López-Urrera, R., Olala, F. M. S., Fabeiro, O., Moratalla, A. (2006). Testing evapotranspiration equations using lysimeter observation in a semiarid climate. *Agric. Water Management.*, 85:15-26.

Martinez-Cob, A., Tejero-Juste, M. (2004). A wind-based qualitative calibration of the Hargreaves ETo estimation equation in semiarid regions. *Agric. Water Manage.*, 64:251–264.

Pereira, A. R., Pruitt, W. O. (2004). Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration. *Agric. Water Manage.*, 66:251–257.

Popova, Z., Kercheva, M., Pereira, L.S. (2006). Validation of the FAO methodology for computing ET, with missing climatic data application to South Bulgaria. *Irrig. Drain.*, 55:201–215.

Zhou, L. and Zhou, G. (2009). Measurement and modeling of evapotranspiration over a reed (*Phragmites australis*) marsh in Northeast China. *J. Hydrology.*, 372:41-47.

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