Article

Calibration and evaluation of mathematical models to calculate reference evapotranspiration in greenhouses

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Abstract

With the reference evapotranspiration (ETo) and the Kc of a crop, the volumes of irrigation water and frequency of application are estimated and planned. In Mexico, the area of protected agriculture increases from 20 to 25% annually, 44% are greenhouses and production units less than 0.5 ha predominate, suggesting that they have limited technology. For greenhouses there is no standard method for estimating ETo such as Penman-Monteith for open field. With a Campbell automatic station installed inside a greenhouse on the grounds of the Chapingo Autonomous University, two series of meteorological data were measured. With the first one, the parameters of several models reported in the literature were modified to calculate ETo, some based on temperature (Baier-Robertson, Romanenko and Hargreaves) and others on radiation (Abtew, Jensen-Haise, Caprio, Irmak, Sthepen, Priestley-Taylor and Makkink) and with the second all were evaluated. The ETo obtained by each of the methods with its modified parameters was compared with the ETo calculated with the Penman-Monteith method, determining that the radiation models showed better adjustments than those of temperature. In the evaluation, those based on temperature showed inadequate adjustments with R^2 less than 0.461 and RSE greater than 0.31 mm d^{-1} and those of radiation had R^2 greater than 0.909 and RSE less than 0.21. The modified Abtew model was the best for estimating ETo in a greenhouse with an R^2 of 0.947 and an RSE of 0.06 mm d^{-1}.

Keywords: greenhouse irrigation management, irrigation requirement, Penman-Monteith.

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Introduction

Juárez *et al*. (2011) indicate that the area of protected agriculture in Mexico has an annual growth of 20 to 25 percent, 44 percent are greenhouses. The average area per unit of production in Mexico is less than 1 ha, but production units less than 0.5 ha limit access to technology, training and technical assistance, as well as to more demanding markets (Cedillo and Calzada, 2012). Therefore, for structures that modify microclimate conditions where crops are produced, specific studies are necessary to estimate their water needs, improve irrigation management and water use efficiency (Morán *et al*., 2014).

Knowing the ETc is essential to adjust the volumes and frequency of irrigation to the needs of the crop. Proper irrigation management leads to high yields, optimum quality and rational use of resources by minimizing waste of water and energy (Puppo and García, 2010).

The crop evapotranspiration (ETc) and the reference (ETo) defined in FAO Bulletin 56 (Allen *et al*., 2006) for a crop are related through a so-called crop coefficient (Kc) that depends on features of this. ETo incorporates most meteorological effects and is an indicator of atmospheric demand (Allen *et al*., 2006). De la Casa and Ovando (2016) mention that in many weather stations there are no complete measurements of temperature (T), relative humidity (RH), solar radiation (Rs) and wind speed, so models with a smaller number of variables.

The Penman-Monteith method (P-M) is the standard method for outdoor crops, it has also given good results to estimate the ETo inside the greenhouses in regions with Mediterranean climate (Fernández *et al*., 2010). For greenhouses there is no similar method, especially when these structures have a great variability in their geometry (Gavilán *et al*., 2014).

If the conditions outside the greenhouse condition the microclimate inside, it is possible to adjust the parameters of the models that were generated to estimate outdoor evapotranspiration, to predict the ETo inside the greenhouse.

The objective of this work was to calibrate and evaluate mathematical models to calculate reference evapotranspiration inside a greenhouse which were: Makkink (1957); Romanenko (1961); Turc (1961); Haise (1963); Baier-Robertson (1965); Stephen (1965); Priestley and Taylor (1972); Jensen and Caprio (1974); Hargreaves and Samani (1985); Abtew (1996); Irmak *et al*. (2003).

Materials and methods

The work was carried out in the weather station of the Irrigation Department of the Chapingo Autonomous University in a greenhouse (Figure 1) with dimensions 8 x 15 m, maximum height of 6.5 m, height of the walls of 4.5 m, a useful area for cultivation of 105 m^2, an approximate volume of air 550 m^3, lateral ventilation, plastic cover and metal structure with North-South orientation. The geographical location is latitude 19.483° north latitude and west longitude 98.900° with a height of 2 250 meters above sea level.

The climate of the locality is of type Cb (Wo)(W)(i') g, temperate subhumid with rains in summer, a dry season in winter and with thermal oscillation that varies between 5 to 7 °C. The average annual temperature is 17.2 °C, the hottest month is May with an average temperature of 19.7 °C and with 14.1 °C January is the coldest. The average annual rainfall is 598 mm with dominant winds from the South (Pulido and García, 2018).

Figure 1. Panoramic view of the greenhouse.

Figure 2. Automatic station inside the greenhouse.

The measurement of the data was carried out with a Campbell CR10x automatic weather station located inside the greenhouse on bare ground partially covered with nopal vegetables in plastic bags (Figure 2), the variables recorded were: temperature (°C), relative humidity (%), speed (m s^{-1}) and wind direction (^{o}) and solar radiation (MJ m^{-2} d^{-1}). The automatic station was located in the central part of the greenhouse.

The Penman-Monteith equation (P-M)

The CR10x team of Campbell (1995) has programmed the algorithm to calculate the ETo with the Penman Monteith (P-M) model presented by Allen *et al*. (2006).

For manual calculation of ETo with the Penman-Monteith method for conditions similar to greenhouses, in FAO Bulletin 56 (Allen *et al*., 2006) it is recommended to use 0.5 m s^{-1} as the minimum value for speed of wind, which improves ETo estimates.

Models selected to calculate ETo

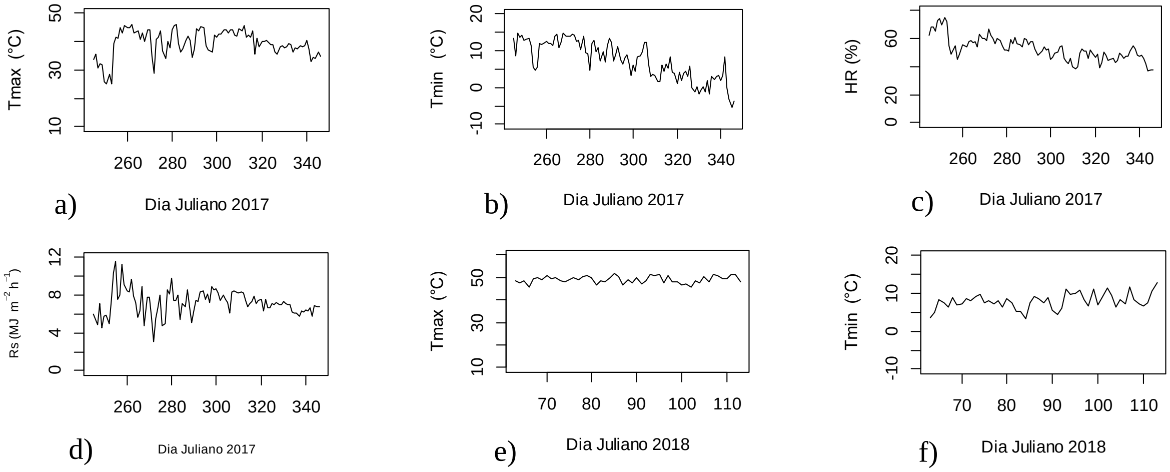
Several models based on temperature and radiation are included (Table 1), which were proposed for conditions other than those of a greenhouse, but that do not include wind speed, to estimate ETo on a daily basis.

ETo is the reference evapotranspiration in (mm d^{-1}), Tmed the average temperature (°C), Tmax is the maximum temperature (°C), Tmin the minimum temperature (°C), TD is the daily thermal oscillation (°C), RH the relative humidity in (%), is the saturation vapor pressure (kPa) e_a the real vapor pressure (kPa), Δ is the slope of the saturation pressure curve γ is the psychometric constant, Ra is the solar radiation extraterrestrial in MJ m^{-2} d^{-1}, Rs is the solar radiation in MJ m^{-2} d^{-1}, Rn is the net radiation in MJ m^{-2} d^{-1}, G is heat flow in the ground [MJ m^{-2} d^{-1}] and T1 is an empirical coefficient.

Table 1. Original parameters of the empirical models and their reference.

Model	Reference	Formula	Variables
		Temperature based	
Baier-Robertson	Baier and Robertson (1965)	$ETo= 0.157*Tmax+0.158(TD)+0.109*Ra-5.39$	Tmax, TD, Ra
Romanenko	Romanenko (1961)	$ETo= 0.00006(Tmed+25)^2 (100- HR)$	Tmed, RH
Hargreaves	Hargreves and Samani (1985)	$ETo= 0.0023*Ra(Tmed+17.8)\ (Tmax-Tmin)^{0.5}$	Ra, Tmed, Tmax, Tmin
		Radiation based	
Turc	Turc (1961)	$ETo= (0.3107\ Rs+0.65)\ (\frac{T1}{Tmed*15})$	Rs, Tmed, T1
Abtew	Abtew (1996)	$ETo= 0.408\ \ 0.01786\ Rs\ Tmax$	Rs, Tmax
Jensen-Haise	Jensen-Haise (1963)	$ETo= 0.408*Rs\ (0.025\ Tmed+0.08)$	Rs, Tmed
Caprio	Caprio (1974)	$ETo= (0.01092708Tmed+0.0060706)Rs$	Tmed, Rs
Irmak	Irmak *et al*. (2003)	$ETo= 0.149\ Rs+0.079*Tmed-0.611$	Rs, Tmed
Stephen	Stephen *(1965)*	$ETo= 0.408(0.0158*Tmed+0.09)Rs$	Rs, Tmed
Priestley-Taylor	Priestley-Taylor (1972)	$ETo= 0.408(1.26\left(\frac{\Delta}{\Delta+\gamma}\right)(Rn-G))$	Δ, γ, Rn, G
Makkink	Makkink (1957)	$ETo= 0.408*0.61\left(\frac{\Delta}{\Delta+\gamma}\right)Rs-0.12$	Δ, γ, Rs

Two series of daily meteorological data of (T, RH, Rs) and calculated (ETo P-M) were determined: one from September 2 to December 12, 2017 and another from March 4 to April 23, 2018. With the data of the first one, the parameters (Table 1) of the models were modified and with those of the second the models were evaluated with the parameters defined in this work. The data used for parameter estimation and evaluation are presented in Figure 3.



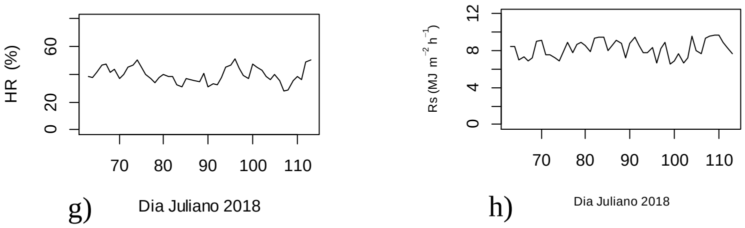


Figure 3. Data used for the estimation of parameters from (a) to (d) with n= 102 and those used for the evaluation of (e) to (h) with n= 51.

With the values obtained from ETo with the models of Table 1 and calculated with the first series of data and those of P-M that were calculated by the automatic station, dispersion diagrams were constructed between the ETo data of the models and P-M, and the statistics were calculated: root of the mean square of the error (RSE) and coefficient of determination R^2.

Parameter estimation

To estimate the parameters of the ETo models (Table 1), the meteorological data of the first series and those calculated by the Campbell CR10x station for this task were used. An R language program was carried out for this purpose, in which one model was worked at a time, with the following procedure.

The parameters of one of the proposed models (ETox) were identified for modification. For each parameter a range was defined in which the lower limit was the nominal value of the parameter minus 10 and the upper limit the nominal value plus 10. Once defined the ranges were divided into 80 000 parts with which a vector was constructed, which defined parameter proposals with increments of 0.00025.

20 000 cycles were programmed for each model, where the program assigned a value to each parameter randomly taken from the corresponding vector. The values of the parameters selected in the model were replaced and evaluated with the 2017 meteorological data, obtaining 102 ETox data. With the ETox data and ETo data calculated with the Penman-Monteith method (P-M), the correlation coefficient (R) between them was determined.

The numerical value of R is compared with the value of Ro (which at the beginning of the program was assigned the numerical value of zero), if R> Ro, then Ro= R and the parameter values are stored in defined programming variables For this purpose, these values are updated only if in the cycle an R greater than the one stored in Ro is obtained. The cycle is repeated 20 000 times and at the end of this computational process the correlation coefficient value and the corresponding randomly proposed parameter values are obtained.

In the model, the parameters stored at the end of the 20 000 cycles are replaced, which correspond to those that generated the highest value of R and with the meteorological data the ETox were generated. With the data of ETo P-M (dependent variable) and those calculated with the model and the stored parameters (ETox independent variable) a linear regression was performed. Finally, the numerical values of the parameters were obtained by being affected by the regression coefficient and with the sum of the independent term.

The models obtained to be used in the estimation of the ETo in greenhouse, were validated with data estimated with Penman-Monteith with the series (second) of 2018 (51 data) the coefficient of determination (R^2) and the root of the square medium of error (RSE) were determined (Draper and Smith, 2014).

Results and discussion

The models based on temperature of Figures 4a to 4c) show that they overestimate the ETo values calculated with P-M. Those based on radiation in Figures 4e, 4f, 4g, 4h and 4j it is determined that the data calculated with the models of Abtew, Jensen and Haise (J and H), Caprio, Irmak and Priestley-Taylor (P and T) overestimate the values of the ETo P-M, in Figure 4d) Turc’s method has data that overestimate and underestimate, it is also appreciated that the data have a greater dispersion to the other methods and in Figures 4i and 4k the data of Makkink and Stephen underestimate the values of ETo P-M.

The coefficients of determination (R2) and the root of the mean square of the error (RSE) of the dispersion diagrams (Figure 4), indicate that the data calculated with the models of Abtew, Jensen-Haise, Caprio, Irmak, Priestley-Taylor and Makkink are similar to those of P-M. They have coefficients of determination ranging from 0.625 to 0.939 and the RSE are less than 0.72 mm d^{-1}, the best model with its original parameters is Makkink. The Turc model has a RSE value of 0.34 and R^2 of 0.198. The data of the models based on temperature obtained lower values of the coefficients of determination than those of radiation. The RSE were higher for the models based on temperature, where the Hargreaves model obtained the highest RSE value of 15.26 mm d^{-1} (Figure 4).

The errors were calculated according to e_i=ETo PM_i-X_i where X_i is the value obtained with the model with its original parameters, ETo PM_i is the value of ETo calculated with the Penman-Monteith method. For the calculation of RSE, the mean of the errors was equal to zero, n= 102.

The coefficient of determination (R^2) does not depend on the units of measurement of the independent and dependent variables, so even though there was an RSE value between the data of ETo P-M and Abtew of 0.53, that of R^2 was 0.918 (Figure 4). Therefore, the R^2 statistical analysis should not be used by itself to decide whether the model is correct or not (Infante and Zárate, 2011).

The models in Table 1 are not of general application due to their local meteorological dependence, studies in different conditions indicate that they should be calibrated (Xu and Singh, 2001; Irmak *et al*., 2003; Trajkovic, 2005). It is appreciated (Figure 4) that if the ETo data is calculated with the models based on radiation and temperature without calibrating the constants or parameters of the formulas, errors are obtained in the estimation of the ETo which agrees with the indicated by Xu and Singh (2001).

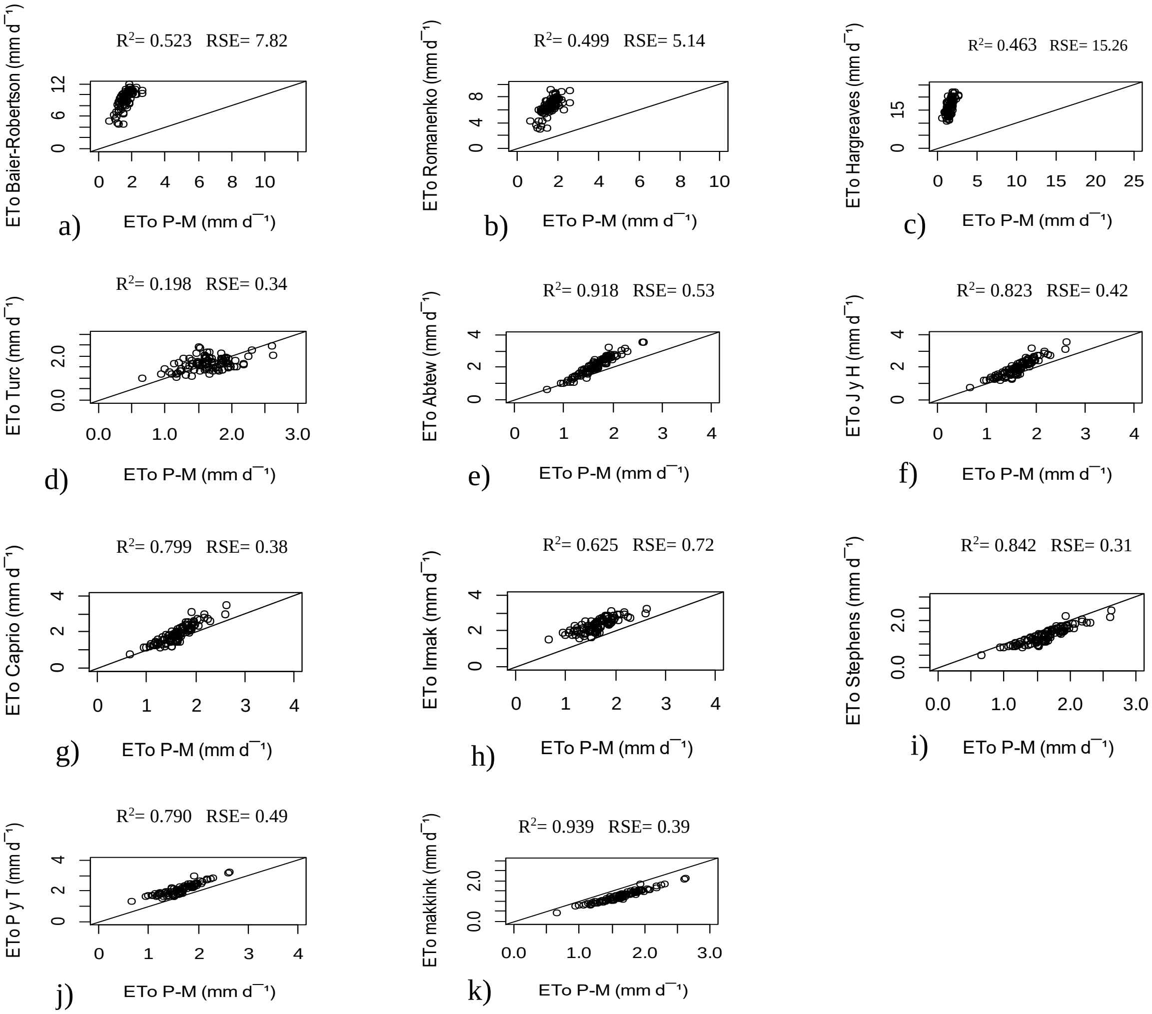


Figure 4. Scatter diagrams between ETo values calculated with the models in Table 1 and those of the P-M method: (a), (b) and (c) based on temperature and from (d) to (k) in radiation (n=102).

ETo estimation with the models with their modified parameters

The root values of the mean square of the error (RSE) of the ETo models with their modified parameters based on Baier-Robertson, Romanenko and Hargreaves temperature were: 0.21, 0.23, 0.20 mm d^{-1} and the R^2 of 0.501, 0.599 and 0.626 respectively (Table 2).

Of the models for estimating ETo based on radiation, the RSEs were: 0.19 and 0.09 mm d^{-1} for Priestley-Tylor and Abtew respectively and 0.08 mm d^{-1} for the others. The Irmak method presented the largest adjustment to ETo values calculated with Penman-Monteith. In general, radiation-based methods were better than with respect to temperature (Table 2).

With the values calculated with the modified models of Turc, Abtew, Jensen-Haise, Caprio, Irmak, Stephens and Makkink and those estimated by the P-M method, a good fit was obtained, in all (R^2) they were greater than 0.918. According to the statistics in Table 2, the ETo data obtained with the radiation-based models have a better level of adjustment with those of ETo P-M than those based on temperature. The coefficients of determination (R^2), being all smaller than the unit, indicate that the data have dispersion with respect to the 1:1 line.

Table 2. The models with their modified parameters to estimate the daily ETo (mm) inside the greenhouse n= 102.

Model	Modified formula	R^2	RSE (mm d^{-1})
	Based on temperature		
Baier-Robertson	$ETo= 0.0160\ Tmax + 0.0344(TD) + 0.0471\ Ra - 1.559$	0.599	0.21
Romanenko	$ETo= 0.0000202752(Tmed11+18.68)^{1.909}(100 - HR11)+0.4345$	0.501	0.23
Hargreaves	$ETo= 2.086 \ast 10^{-5}\ Ra\ (Tmed+27.64)\ (Tmax-Tmin)^{1.031}+0.4694$	0.626	0.2
	Based on radiation		
Turc	$ETo= (0.2570\ Rs-2.0772)\ \left(\frac{303.2}{15Tmed}\right)+1.851$	0.934	0.08
Abtew	$ETo= 0.408 \ast 0.0099Rs\ Tmax+0.473$	0.918	0.09
Jensen-Haise	$ETo= 0.4081 \ast 0.0542\ Rs\ (0.0784\ Tmed+8.002)+0.068$	0.945	0.08
Caprio	$ETo= (0.0017\ Tmed+0.1780)\ Rs+0.067$	0.945	0.08
Irmak	$ETo= 0.2189 \ast Rs+0.0127 \ast Tmed-0.233$	0.946	0.08
Stephen	$ETo= 0.408 \ast Rs\ (0.0041 \ast Tmed20+0.4389)+0.065$	0.945	0.08
Priestley-Taylor	$ETo= 0.408\left(1.0269\left(\frac{\Delta}{\Delta+\gamma}\right)(Rn)\right)-0.023$	0.665	0.19
Makkink	$ETo= 0.408{*}0.6695\left(\frac{\Delta}{\Delta+\gamma}\right)Rs+0.122$	0.939	0.08

From the statistics (Figure 4 and Table 2), the behavior of the models to predict the values of ETo P-M inside a greenhouse is observed, with its original parameters (Figure 4) and the modified ones (Table 2). The models based on temperature went from R^2 values between 0.463 and 0.523 to values between 0.501 and 0.626 and their RSE from 5.14 to 15.26 to values between 0.2 and 0.23. In all these models there was an improvement of the model with the parameters modified in the estimation of the ETo.

Those based on radiation also showed an improvement to predict the values of ETo P-M, went from RSE with values between 0.31 to 0.72 to values between 0.08 to 0.19 and R^2 were improved from values between 0.198 to 0.939 to values from 0.665 to 0.946.

Performance evaluation of models based on temperature

In the temporal march of the values of the ETo obtained with the models based on temperature and those obtained with the expression of Penman-Monteith (P-M), it is observed that the three models overestimated the P-M values during the 51 days used to evaluate the models (Figure 5). In Table 2 the ones that show the best fit are the estimates made with the Baier-Robertson and Hargreaves models, but the data of the two models overestimate the P-M values (Figures 6a and 6c). The Romanenko Model in most of its data overestimates P-M and only in four underestimated data (Figure 6b).

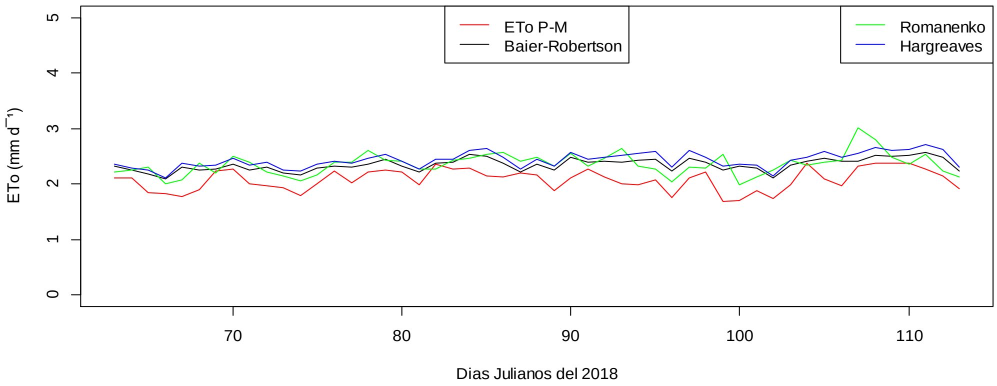


Figure 5. Temporary adjustment between the ETo measurements of the automatic station (P-M) and the modified temperature-based models to predict the daily ETo inside a greenhouse of: Baier-Robertson, Romanenko and Hargreaves, n= 51.

The dispersion diagrams between the ETo estimates of the models based on temperature and the estimation of ETo P-M are shown in Figure 6a, 6b and 6c. The one that presented the best trend was the one that corresponds to the data between the method of P-M and Baier-Roberston's and the diagram has the most attached points to the 1:1 line.

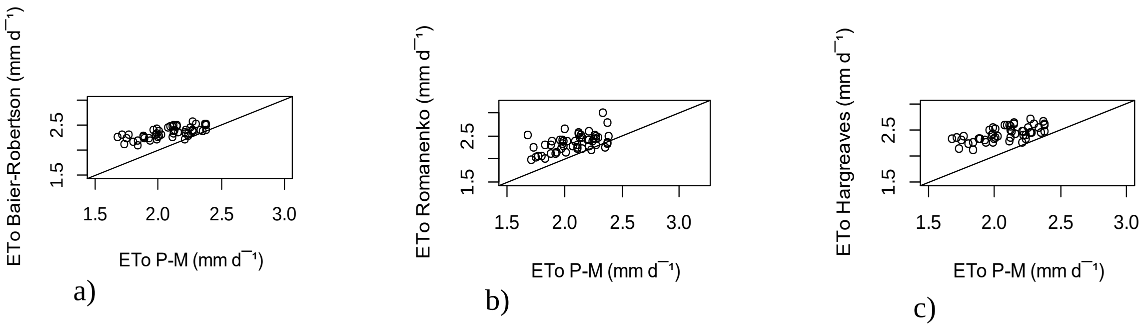


Figure 6. Scatter diagrams between the values predicted by the modified models and the measurements inside the greenhouse with the automatic station (P-M): a) between the Baier-Robertson method and P-M; b) between Romanenko and P-M; and c) between Hargreaves and P-M, n= 51.

The statistics of the evaluation of the models with 51-day data, the Baier-Robertson and Hargreaves models obtained coefficients of determination (R^2) of 0.461 and 0.411 and their RSE of 0.31 and 0.39 mm d^{-1} respectively. The statistics of the Romanenko method are (R^2) of 0.3 and RSE of 0.34 mm d^{-1} was the best method based on temperature.

Performance evaluation of radiation-based models

The temporal relationship between ETo of the radiation-based models and the Penman-Monteith (P-M) method, in the evaluation period, the one that showed the least adjustment was that of Turc (green line) since in all its data it underestimated the ETo P-M value (red line). The Abtew method data adhered to those of P-M and in general terms the model has adjustment to P-M values.

The models of Jensen-Haise, Caprio, Irmak, Stephens, Makkink, showed temporary marches of their data that underestimate those of P-M. In its temporary march, the Priestley-Taylor method showed adherence to the P-M model data, in values of ETo less than 1.9 mm d^{-1} overestimated and greater than 2.1 mm d^{-1} underestimate (Figure 7).

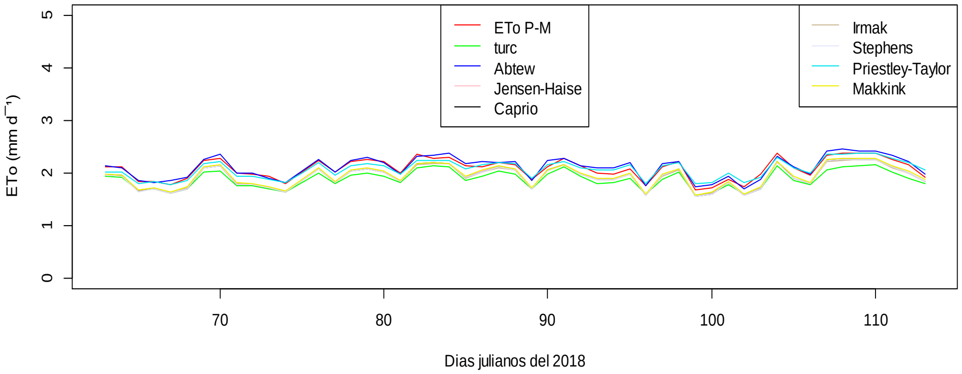


Figure 7. Temporary adjustment between the ETo measurements of the automatic station (P-M) and the modified models based on radiation to predict the daily ETo inside a greenhouse, n= 51.

In the dispersion diagrams between the estimates of the modified models based on radiation and Penman-Monteith, it can be seen that they generally showed a trend and six of the eight models underestimated the P-M of ETo values (Figure 8). The models that performed better in the evaluation stage were: Abtew, Priestley-Tylor and Makkink (Figures 8 b, 8g and 8h).

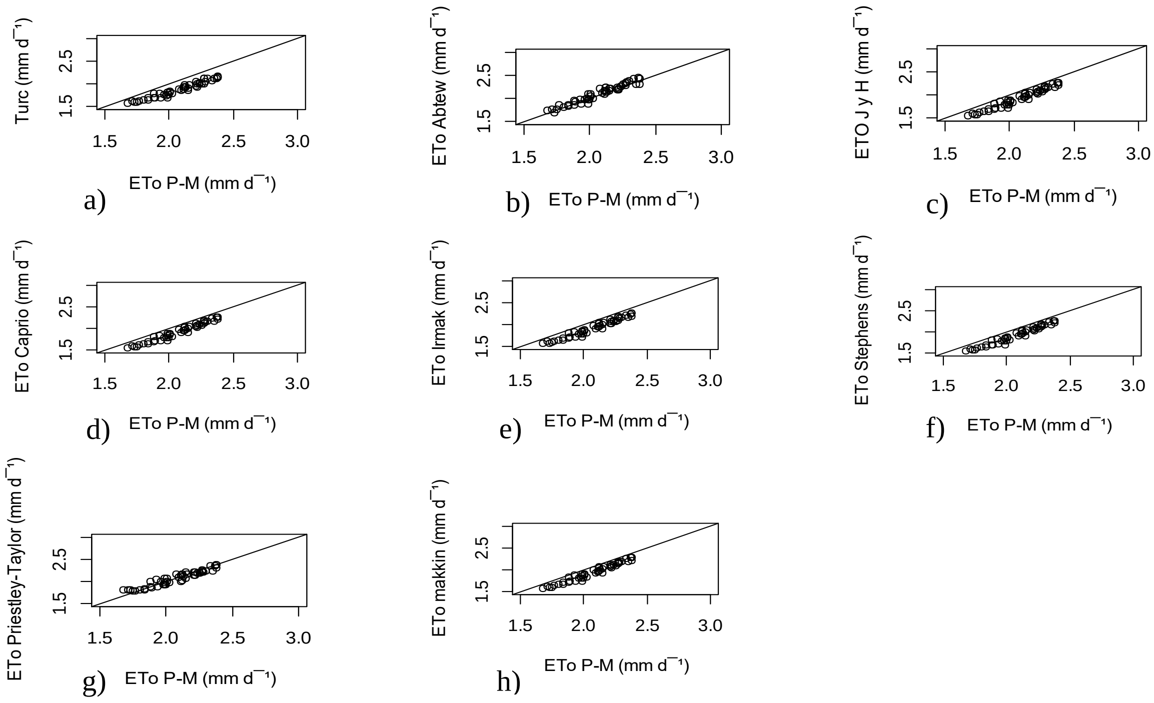


Figure 8. Scatter diagrams between the values predicted by the modified models and the measurements inside the greenhouse with the automatic station (P-M): a) Turc and P-M; b) Abtew and P-M; c) Jensen-Haise and P-M; d) Caprio and P-M; e) Irmark and P-M; f) Stephens and P-M; g) Pristley-Taylor and P-M; and h) Makkink and P-M, n= 51.

The Turc model with an R^2 of 0.943 and an RSE of 0.21 mm d^{-1} was the one that was least adjusted, the rest of the models obtained R^2 greater than 0.787 and RSE less than 0.16 mm d^{-1} (Table 3).

Table 3. Statistics obtained between the values of the modified models to estimate ETo inside the greenhouse and the ETo measurements of the automatic weather station (P-M method).

Modified model	R^2	RSE (mm d^{-1})
Turc	0.943	0.21
Abtew	0.947	0.06
Jensen-Haise	0.956	0.15
Caprio	0.956	0.16
Irmak	0.956	0.16
Stephen	0.956	0.16
Priestley–Taylor	0.909	0.06
Makkink	0.956	0.14

When comparing the statistics of the modified models, it is appreciated that the radiation-based models are more closely attached to the values calculated with Penman-Monteith. The Abtew and Priestley-Taylor models with R^2 of 0.947 and 0.909 respectively and RSE of 0.06 for both were the ones that best predicted the ETo of P-M values in the greenhouse.

Conclusions

In the circumstances in which this work was carried out without the standard reference conditions for the calculation of ETo and evaluation of the equations, the results obtained may be an alternative to estimate the water requirements of the crops.

To use models to estimate reference evapotranspiration in conditions for which they were not developed, it is necessary to calibrate and evaluate them.

Under greenhouse conditions and with original parameters the temperature-based evapotranspiration models did not give good results and those based on radiation the Makkink model was the best. The models to estimate the reference evapotranspiration in greenhouse based on radiation and modified parameters were the best. In Mexico, most greenhouses are less than 0.5 ha, so it is important that this type of work is carried out as they have different types of structures and climatic conditions.

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