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COMPARISON OF METHODS FOR ESTIMATING REFERENCE EVAPOTRANSPIRATION IN SOUTHERN CALIFORNIA

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A significant part of precipitation returns back to the atmosphere by evapotranspiration. Developing formulations aimed at accurately quantifying evapotranspiration over a given region can aid a wide variety of audiences, including water managers and hydrologists. In this study, the accuracy of four existing evapotranspiration methods (Thornthwaite, Blaney-Criddle, Turc and Makkink) for southern California is investigated. The end results are compared with those of the FAO Penman-Monteith method, which is taken as the benchmark solution for comparison purposes. The meteorological data from a California Irrigation Management Information System (CIMIS) station in southern California has been used. The comparison is first made by using the original constant coefficients in the above four methods and subsequently using recalibrated constant values. Based on statistical analysis, the methods that performed best in estimating daily and monthly evapotranspiration are recommended with their recalibrated constants for potential use in Southern California.

INTRODUCTION

Evapotranspiration (ET) is a major component in terrestrial water balance and an important parameter in different numerical and analytical models in the fields of hydrology, water-management, and crop-growth disciplines. Decision makers also use this parameter in predicting drought and desertification situations. ET can be broadly defined as the cumulative sum of water that is evaporated from surface and transpired by plants as a part of their metabolic processes. The evapotranspiration rate from a reference surface that is abundantly watered is called reference evapotranspiration (ETo) (Allen et al., 1998). The concept of ETo was developed to study the evaporative potential of the atmosphere independently of surface or crop type, crop stage of development, and management practices.

Given the importance of quantifying evapotranspiration in water balance studies, many researchers over the last few years have either derived or improved existing formulations for the geographical area of their interest. The results reported in this category include Amatya et al. (1995) who compared different methods for estimating ETo in three locations in eastern North Carolina. Savadel and Decker (1999) evaluated and compared results from three different models used by different agricultural agencies in the state of Missouri. Jacob and Satti (2001) compared more than ten different methods using meteorological data from Florida. Xu and Singh (2002) evaluated and compared ETo results from three different methods with four years of meteorological data from Switzerland, and Lu et al. (2003) developed an empirical model to estimate long-term annual actual evapotranspiration (AET) for forested watersheds to quantify spatial AET patterns across the southeast United States. Irmak and Harman (2003) compared the reliability of five methods to compare evaporation rates for Florida. Kumar et al. (2002) investigated the performance of artificial neural networks (ANNs) for estimating evapotranspiration and compared the performance of ANN methods with the results of Penman-Monteith method. Lott and Hunt (2002) compared the measured values of ET with the results of Penman method in natural and constructed wetland system.

In 1990, FAO in collaboration with the International Commission for Irrigation and Drainage and the World Meteorological Organization, recommended the FAO Penman-Monteith method (Allen et al., 1998) as a standard method for the definition and computation of ETo. To maintain continuity in the discussion, the FAO Penman-Monteith method and the four empirical methods compared in this investigation are briefly covered here, with more details present in the references cited.

FAO PENMAN-MONTEITH METHOD

The FAO Penman-Monteith (FAO-PM) method for calculating reference evapotranspiration can be written as

$$ETo = (0.408\,\Delta\,(Rn-G) + \gamma\,(900/T+273)u2(e_s-e_a) \,/\, (\Delta+\gamma\,(1+0.34u2) \qquad (1)$$

where

ETo = reference evapotranspiration (mm day^{-1})

Δ = slope of the vapor pressure curve (kPa $^oC^{-1}$)

Rn = net radiation at the crop surface (MJ m^{-2} day^{-1})

G = soil heat flux density (MJ m^{-2} day^{-1})

γ = psychometric constant (kPa $^oC^{-1}$)

T = mean daily air temperature at 2 m height (^oC)

u2 = wind speed at 2 m height ($m\ s^{-1}$)

e_s - e_a = saturation vapor pressure deficit (kPa)

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

All the variables in Equation (1) were calculated using the standard procedure outlined by Allen et al. (1998).

EMPIRICAL METHODS

While a common advantage in using empirical methods (Turc, Makkink, Thornthwaite, Blaney-Criddle) is the availability of the associated data, a limitation arises at the geographical location of the station of interest. As these methods were originally developed for a particular geographical location, their application to a different geographical region requires calibrating their constants.

The Turc method can be written as:

$$ETo = 0.013\ (T/T+15)(0.484Rs+50) \qquad \text{for } Rh>50\% \qquad (2)$$

$$ETo=0.013(T/T+15)(0.484Rs+50)(1+(50-Rh)/70) \qquad \text{for } Rh<50\% \qquad (3)$$

where ETo is in mm/day, T is temperature in ^oC, Rs is the solar radiation in watts per square meter ($W\ m^{-2}$), and Rh is the average relative humidity for the day of interest.

According to the Makkink approach:

$$ETo= 0.61(\Delta/\Delta+\gamma)(Rs/58.5)-0.12 \qquad (4)$$

where ETo is given in mm/day, Δ is the slope of the saturation vapor pressure curve in millibars/°C, and gamma (γ) is a psychrometric constant in millibars/°C. For $T \geq -23°C$, Δ can be calculated from,

$$\Delta = 33.8639[0.05904(0.00738T+0.8072)^7 - 0.0000342] \qquad (5)$$

and

$$\gamma = c_pP/0.622\lambda \qquad (6)$$

where C_p (= 0.242) is the specific heat of air at constant pressure in calories/gram, P is the atmospheric pressure in millibars and is related to the elevation (EL) in meters as P=1013-0.1055EL, λ is the latent head of vaporization in calories/gram, given as λ=595-.51T, where T is the average air temperature in °C.

In the Thornthwaite method, the variable is computed as:

$$ETo = 1.6\ L_d\ (100T/I)^a \qquad (7)$$

where ETo is in mm/month, T is the average monthly temperature in °C, L_d is an adjustment factor related to number of hours of daylight and latitude, I is the heat index computed as $I=(T/5)^{1.514}$, a is a function of the heat index, and is related to heat index as:

$$a = 0.49 + 0.0179\ I - 0.0000771\ I^2 + 0.000000675\ I^3 \qquad (8)$$

The Blaney-Criddle equation when converted to the International System of Units (SI) is written as:

$$ETo = kp\,(0.46T + 8.13) \qquad (9)$$

where ETo = potential evapotranspiration from a reference crop, in mm, for the period in which p is expressed, T = mean temperature in ^{o}C, p = percentage of total daytime hours for the period used (daily or monthly) out of total daytime hours of the year (365×12), and k = monthly consumptive use coefficient which depends on vegetation type, location and season.

RESULTS AND DISCUSSION

Meteorological data obtained from California Irrigation Management Information System (CIMIS) station 78 Pomona, was used to calculate daily ETo values for the period 1999-2002 by the FAO-PM as well as four empirical methods; Thornthwaite, Blaney-Criddle, Turc and Makkink. Station 78 Pomona is located at 34.058^{o} N latitude and 117.812^{o} W longitude in Los Angeles County in Southern California (Figure 1). CIMIS is a program unit in the Office of Water Use Efficiency (OWUE), Department of Water Resources (DWR) of California. CIMIS (http:// www.cimis.water.ca.gov) operates an integrated network of 118 automated active weather stations all over California, which gather and record hourly, daily, and monthly data used to estimate ETo. Station 78 Pomona has been active since March 14 of 1989. During this period, continuous data was recorded for several hydrometeorological variables including air temperature, grass temperature, soil temperature (at -5 cm), wind speed (at 2 m), relative humidity, solar radiation and vapor pressure among others. In this investigation, daily evapotranspiration values were calculated from 1999 to 2002 by using the four empirical methods with their initial constant values and by the

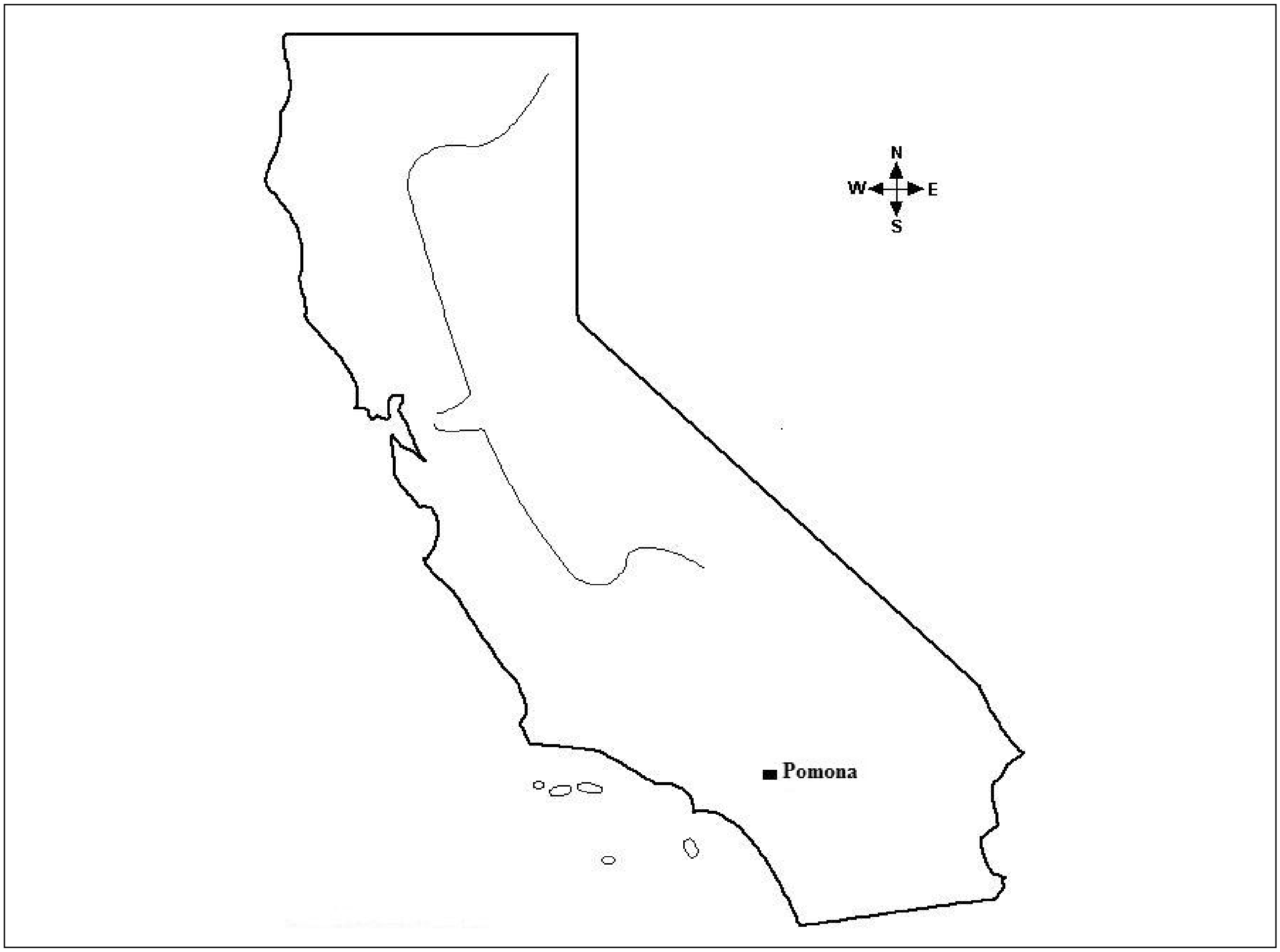

Figure 1. Location CIMIS station 78 Pomona in California.

FAO-PM method. Figure 2 plots the monthly values of the four methods with the FAO-PM solution.

A visual comparison of the results in Figure 2 shows that the initial constant value of 1.6 (Equation 7) in the Thornthwaite method and a 0.61 value in the Makkink method (Equation 4) appear to be too low for Southern California. The results indicate that the end solution from the initial constant values in the Blaney-Criddle method (Equation 9) and the Turc method (Equations 2 and 3) perform well. Figure 3 (season variability) plots the mean monthly ETo values averaged over four years (1999–2002) from the four empirical methods using the original parameters. The plot indicates that generally all four methods underestimate ETo with respect to FAO-PM. Variability of the Turc method closely matches the FAO-PM method for the year, even though it slightly over estimates FAO-PM from October to April and underestimates it from June to August. The Makkink method consistently underestimates FAO-PM. Variability of these two methods followed the same pattern displayed by FAO-PM. The Blaney-Criddle method overestimated FAO-PM in April, May and September, but remained below the FAO-PM estimate in the rest of the months.

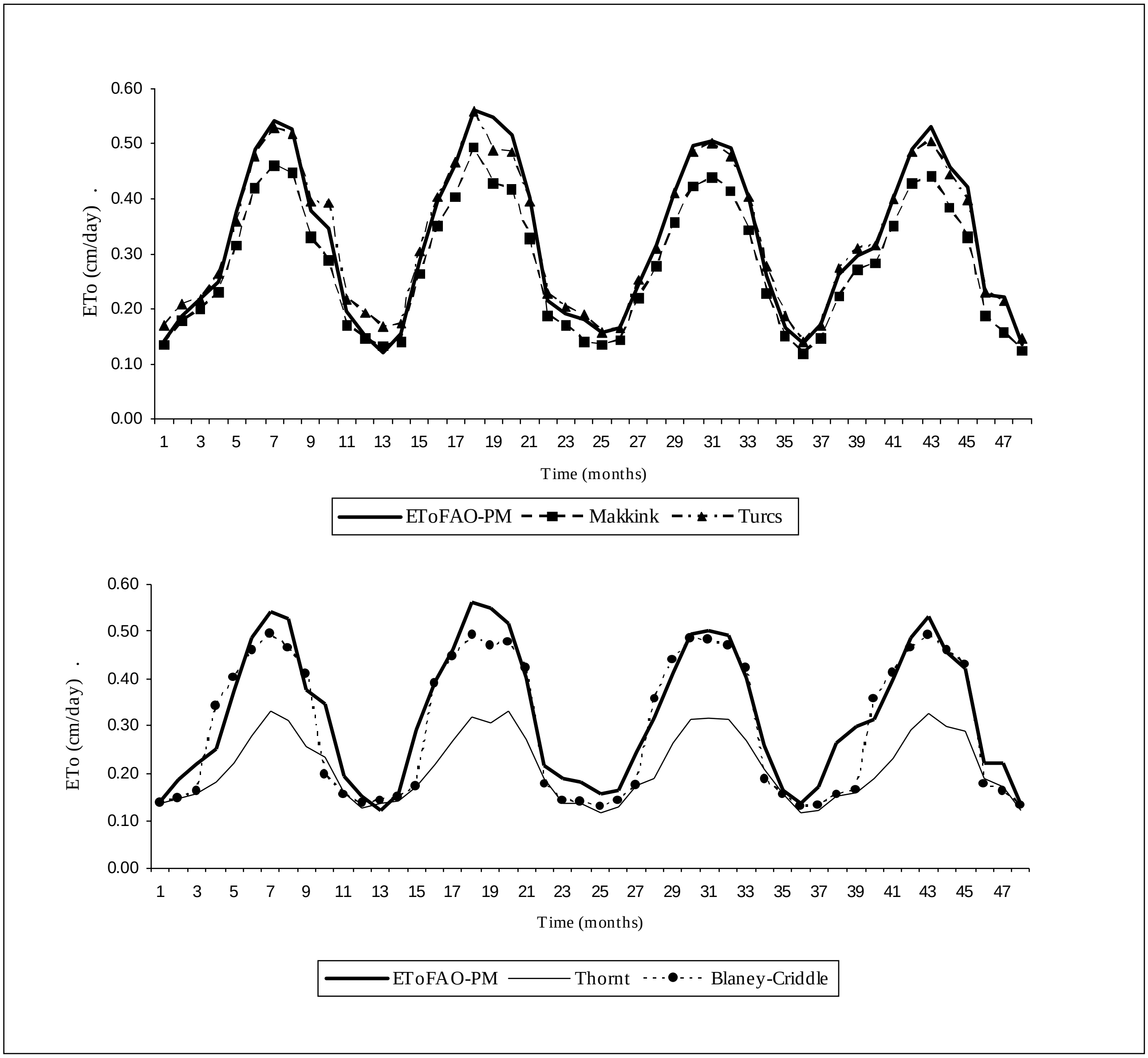

Figure 2. Comparison of the monthly evapotranspiration rates of the four empirical methods with the original parameters against the FAO Penman-Monteith method.

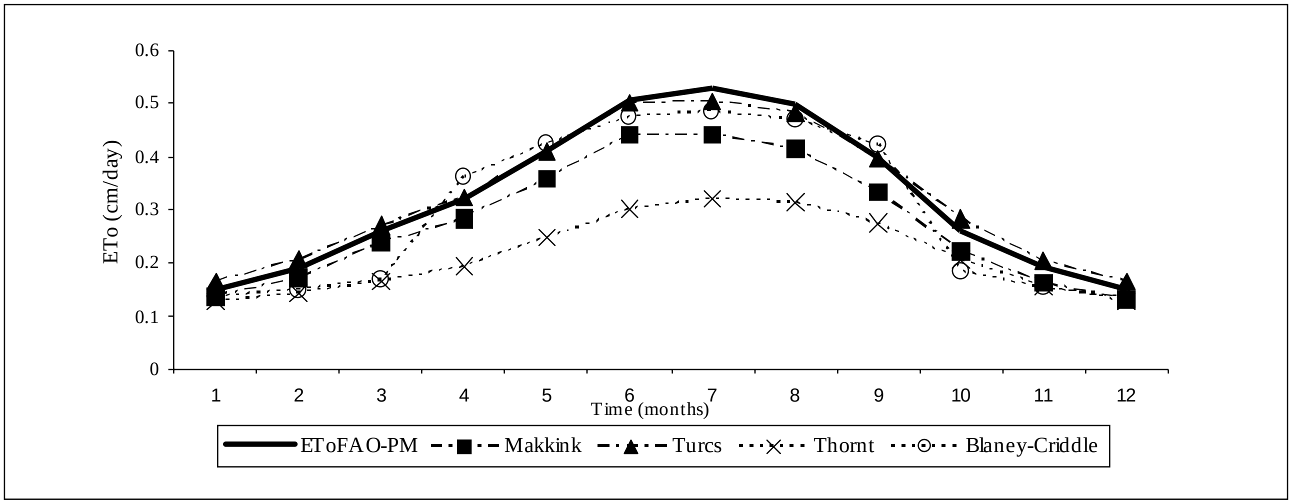

Figure 3. Season variability of the four methods with original parameters.

Regression analysis was conducted to examine the relationships of the monthly evapotranspiration estimates from the four empirical equations with the monthly values calculated by the FAO-PM method. The regression equation is given by

$$Y = mX + c \tag{10}$$

where, Y represents ETo computed by FAO-PM (Equation 1) and X is the ET estimated from each of the other four methods, and m and c are constants representing the slope and intercept of the regression equation, respectively. The end regression equations together with the coefficient of determination (R^2) are presented in Figure 4. Characteristic features of the best method include (i) a c value closest to zero (ii) a m value close to 1.0 and (iii) a high value of R^2. The regression analysis indicates that the performance details of the Turc method is superior to the other three methods, which is in agreement with the results illustrated in Figure 2. Turc's regression matched very closely to the FAO-PM with a slope (m) of 0.91, an interception point (c) of 0.03 and a coefficient R^2 of 0.99. The Makkink method displayed the second best regression with m of 0.83, c of 0.41 and R^2 of 0.99. The

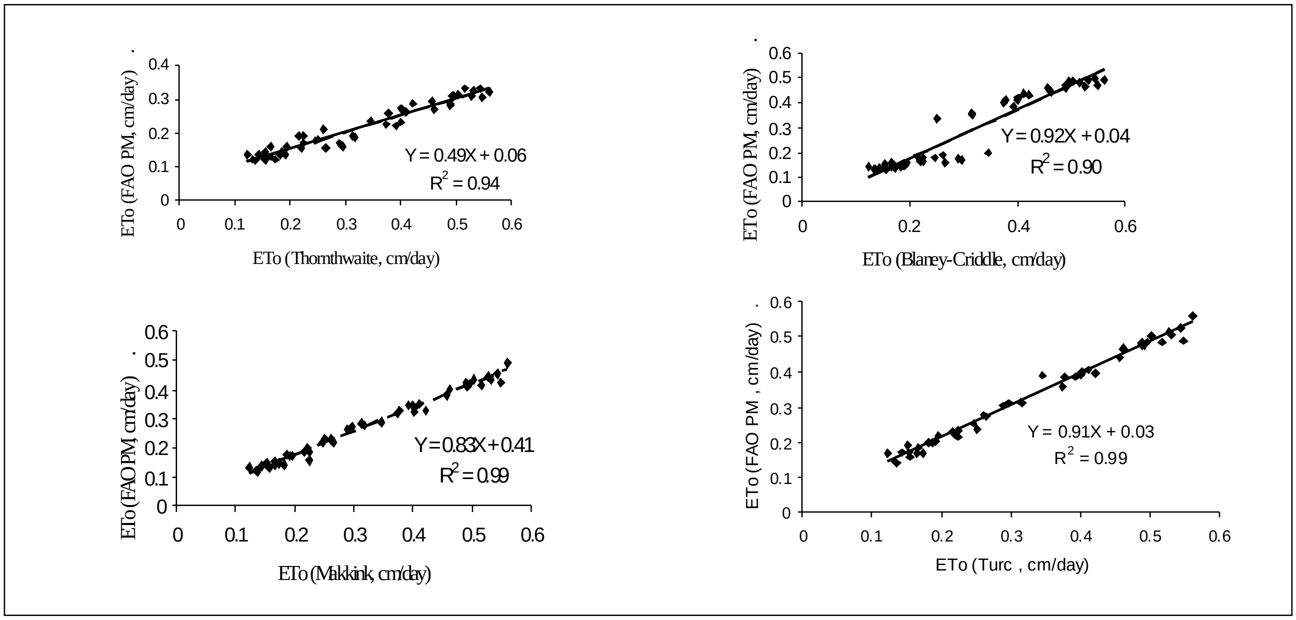

Figure 4. Regression performance details of the evapotranspiration methods with original parameters.

Table 1. Initial and Calibrated Parameter Values

Method	**Equation**	**Initial Parameter Values**	**Recalibrated Parameter Values**
Thornthwaite	$ET=k\ Ld\ (10T/I)^a$	k=1.6	k=2.35
Blaney-Criddle	ET=k p (0.46T+8.13)	k=0.85 (April to Sept.) k=0.45 (Oct. to March)	k=0.9 (Apr. to Sept.) k=0.6 (Oct. to Mar.)
Turcs	ET= k(T/T+15)(Rs+50) or ET=k(T/T+15)(Rs+50)(1+(50-Rh)/70)	k=0.013	k=0.013 (not recalibrated)
Makkink	ET= k (? /? +γ)(Rs/58.5)-0.12	k=0.61	k=0.70

Blaney-Criddle method displayed a higher dispersion in its regression values, m of 0.92, c of 0.04 and R^2 of 0.90. The Thornthwaite method displayed the weakest values overall with a m of 0.49, c of 0.06 and R^2 of 0.94.

Theoretically, it is plausible that one can improve the end solutions, by recalibrating the values of these constants, for the geographical area of interest. To this end, we have utilized the "automatic optimization" process as presented in Singh and Xu (2002). In the automatic optimization process, a statistical parameter is often chosen as a criterion to determine the level of dispersion in a data series, and when the value of the statistical parameter is at a minimum, optimization is achieved. The optimal parameter chosen in this investigation is the least square error, which is related to Et_{PM} (evapotranspiration computed by the FAO-PM) and Et_{Emp} (computed evapotranspiration by four other methods which is a function of model parameters) as:

$$OF=\Sigma(Et_{PM} - Et_{Emp})^2 \tag{11}$$

Minimizing the above objective function for the set of conditions can lead to the optimal constant parameters. Table 1 illustrates the initial and adopted parameter values after recalibration. The results indicate that in the Thornthwaite method, the original parameter of 1.6 was increased to 2.35. For Blaney-Criddle method, the k value for the growing season (April to September) was adjusted from 0.85 to 0.90, in the non-growing season (October to March) the k value was increased from 0.45 to 0.60. The Makkink method could be improved slightly after the recalibration where the original value of 0.61 was changed to 0.70. As no significant improvement could be obtained for the Turc method the initial parameter values were retained.

Comparison was conducted again with the recalibrated empirical equations; results are presented in Figures 5, 6 and 7. The best improvement was achieved for the Thornthwaite method where recalibrating the initial constant value from 1.6 to 2.35 reduced the objective function from 0.02 to 0.005. The Blaney-Criddle method slightly improved in the linear regression cross-relation R^2 from 0.90 to 0.93. For the Makkink method, the OF function in this method was reduced from 0.0025 to 0.0015. Meanwhile, m and c were improved from 0.83 and 0.41 to 0.97 and 0.02, respectively.

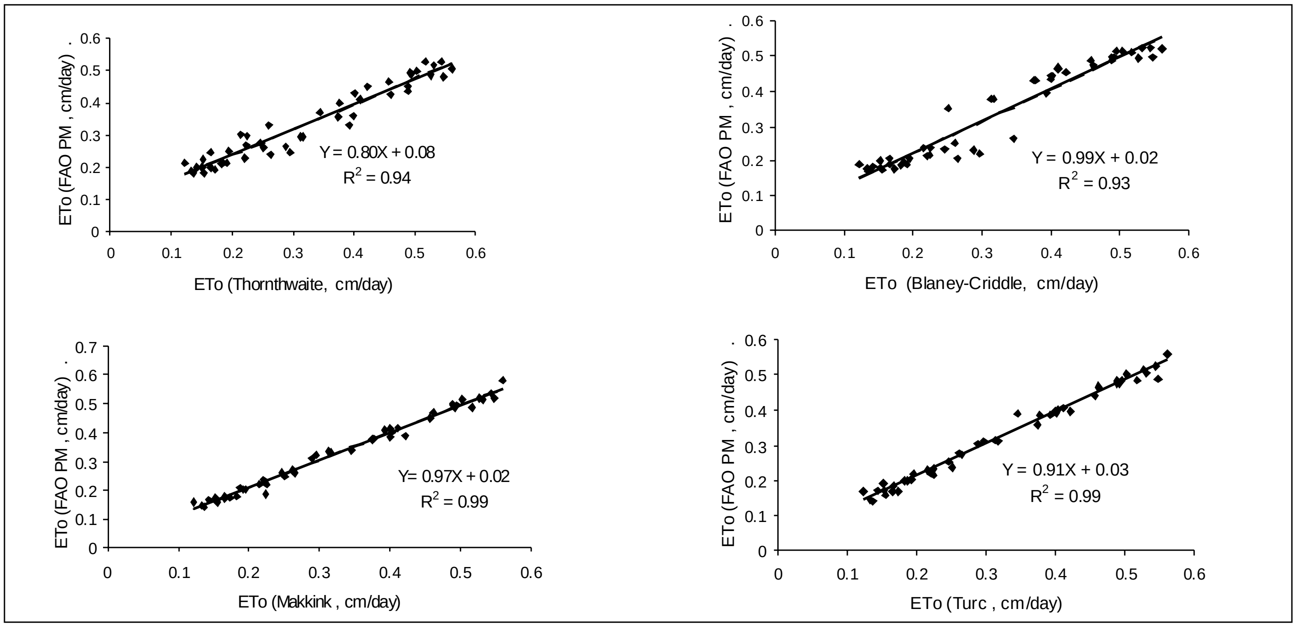

Figure 5. Regression performance details of the evapotranspiration methods with recalibrated parameters.

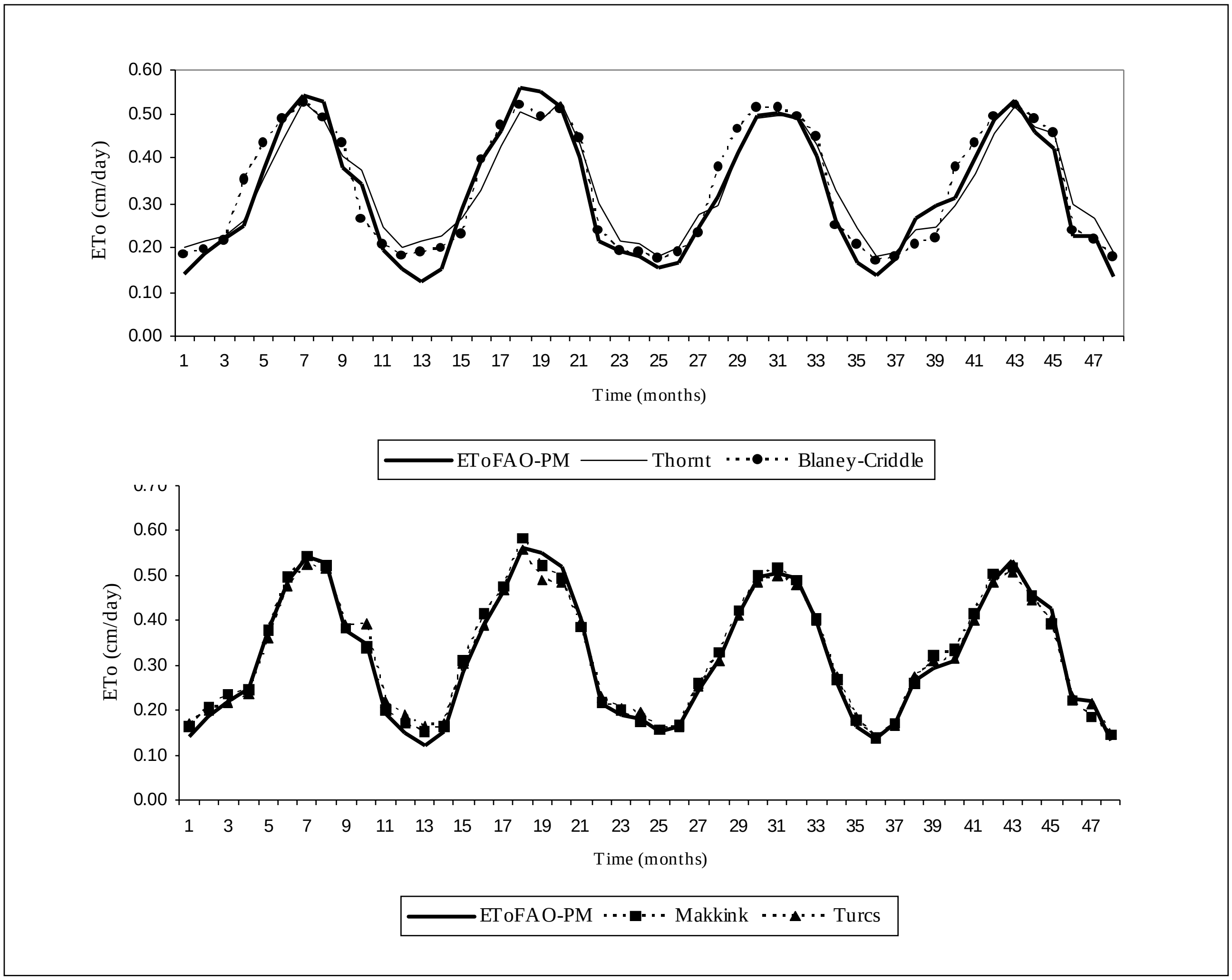

Figure 6. Comparison of the monthly evapotranspiration rates of the four empirical methods with the recalibrated parameters against the FAO Penman-Monteith method.

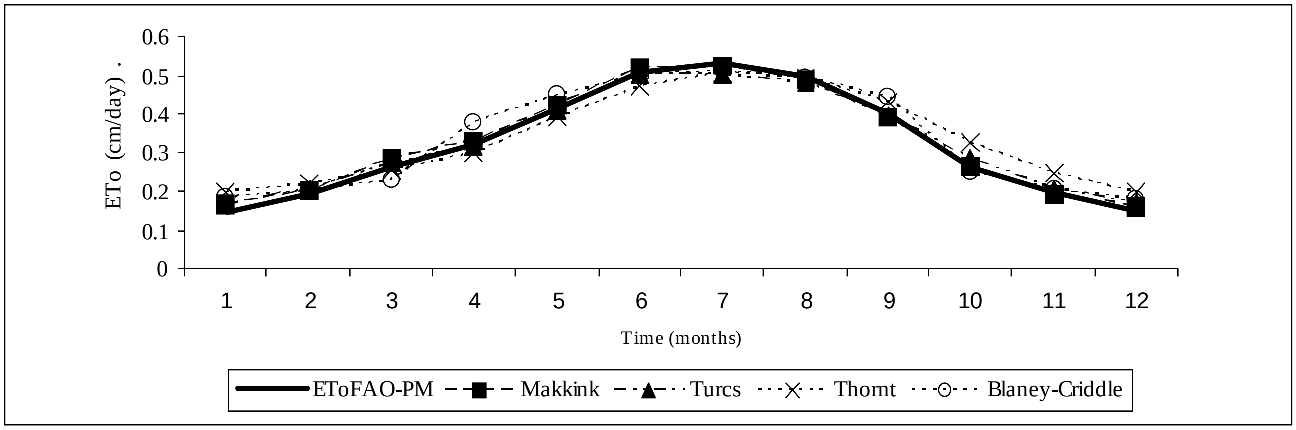

Figure 7. Season variability of the four methods with recalibrated parameters.

CONCLUSIONS

Four empirical methods for calculating reference evapotranspiration (ETo) were evaluated using meteorological data from station 78 Pomona of the CIMIS network in the state of California. The FAO Penman-Monteith method (FAO-PM) was taken as a standard in evaluating the four empirical methods. The comparison was first made with the initial constant values involved in each method.

After the first comparison, the four methods were calibrated against the FAO-PM method to determine best constant values for each empirical method to be used in southern California. The results indicated that the value of 1.6 in the Thornthwaite method was too low for the study region, and a value of 2.35 was the appropriate value compared with FAO Penman-Monteith method. The Blaney-Criddle method was improved when the initial constant values of the monthly consumptive use coefficient (k) were adjusted from 0.85 and 0.45 for the growing and non-growing seasons respectively to 0.90 and 0.60. The climatic condition in the semiarid region of southern California increases the value of this coefficient.

The method which best predicted ETo as compared to the FAO-PM method was the Turc method; its value was closest to the ETo computed by the FAO-PM method before recalibration. The Makkink method displayed the best improvement after recalibration. All the empirical methods displayed a very good performance with the recalibrated value. Using locally determined parameter values, all four empirical methods (Makkink, Turc, Thornthwaite and Blaney-Criddle) display acceptable estimates of daily reference evapotranspiration as compared with that of FAO-PM method.

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