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Substantiation of the daily FAO-56 reference evapotranspiration with data from automatic and conventional weather stations

Comprovação da evapotranspiração de referência diária FAO-56 com dados de estações meteorológicas automática e convencional

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Abstract *- Daily grass reference evapotranspiration (ETo) computed following the FAO-56 guidelines and parameterization of the Penman-Monteith big leaf model (P-M) were compared with lysimetric evapotranspiration (ET) measurements in an irrigated grass field. ETo was computed using two independent weather data sets. One, from an automatic weather station (AWS), located at the lysimeter site, with a complete set of data as required by the P-M model. Another, from a regional conventional weather station (CWS), about 2 km away from the lysimeter, and lacking measurements of net radiation and wind speed at 2 m above the ground, being both estimated empirically. Results with data from both weather stations substantiates the FAO-56 scheme and the proposal that the big leaf P-M model should be preferred even when some of the required weather data are missing and have to be estimated empirically. On the average, the CWS incomplete data set resulted in better estimates of ETo than the complete data from the AWS. The decoupling factor W was, on average, close to 0.8 indicating that grass ET was indeed strongly dependent on the net radiation as suggested elsewhere.*

Key words*: grass reference evapotranspiration, Penman-Monteith, big leaf model, decoupling factor*

Resumo *- Evapotranspiração de referência diária (ETo) computada seguindo-se as prescrições e parametrizações FAO-56 do modelo "big leaf" de Penman-Monteith (P-M) foi comparada com medidas lisimétricas de evapotranspiração (ET) de um gramado irrigado. ETo foi computada usando-se dois conjuntos independentes de dados meteorológicos. Um, fornecido por uma estação meteorológica eletrônica automática (AWS), localizada próxima ao lisímetro, continha todas as informações exigidas pelo modelo de P-M. Outro, oriundo de uma estação convencional (CWS), representativa da região e distante cerca de 2 km do lisímetro, mas sem medidas de saldo de radiação e velocidade do vento a 2 m acima da superfície, necessitando de suas estimativas. Os resultados obtidos com os dados fornecidos pelas duas estações meteorológicas comprovam a adequação do esquema FAO-56 e a proposta de que o modelo de P-M deve ser usado mesmo em situações de dados incompletos, necessitando de suas estimativas. Em média, os resultados oriundos do conjunto incompleto de dados da CWS foram melhores do que aqueles dados pelo conjunto completo da AWS. O fator de desacoplamento W foi, em média, próximo de 0,8 confirmando que a ET do gramado foi, de fato, fortemente dependente do saldo de radiação, como sugerido na literatura.*

Palavras-chave*: evapotranspiração de referência, Penman-Monteith, modelo "big leaf", fator de desacoplamento*

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Introduction

With the technology advance, irrigation of agricultural fields became one of the major users of water, affecting substantially the hydrological balance of watersheds. Such technology is responsible for transforming rain defficient regions but of high input of solar energy into high productive fields. Besides the availability of water from permanent rivers and reservoirs, irrigation management requires the correct dimensioning of the water use by crops. Present days method for estimating the water used by a field crop (ETc, crop evapotranspiration) depends on the knowledge of the evapotranspiration from a reference surface (ETo) and of an appropriate crop coefficient (Kc), i.e., ETc = ETo Kc. Known as the two-step approach, this method, proposed by JENSEN (1968), is described by DOORENBOS & PRUITT (1975) and ALLEN et al. (1998).

ETo represents the evapotranspiration of an extense non-stressed grass field, completely covering the ground, and growing actively, being limited only by the local weather conditions. According to this definition ETo can be interpreted as a hypothetical evapotranspiration, and as such it can be computed by the guidelines prescribed by the Food and Agriculture Organization Irrigation and Drainage Paper No. 56 (ALLEN et al., 1998), here referred to as FAO-56, which was based on the work of ALLEN et al. (1989).

The FAO-56 recommends the use of the parameterized Penman-Monteith equation (big leaf model) for estimating ETo even if some of the required meteorological data are missing and need to be estimated empirically. Lack of complete set of weather data is a fairly common situation in both conventional (CWS) and automated (AWS) weather stations. Net radiation is rarely measured continously for a long period of time because the instrument needs frequent professional care and calibration, and its use is only common in research projects. In CWS, the wind speed is measured only at 10 m above the ground and it needs to be reduced empirically to the 2 m level required by the parameterization scheme used for ETo models. Consequently, the objective here is to follow the FAO-56 guidelines using both, a local AWS and a regional CWS weather data sets to estimate ETo, and compare them against lysimetric measurements in a weather station-like grass surface in a tropical environment. The motivation for this work comes also from the fact that AWS is not available everywhere, mainly at remote locations with large irrigation projects in developing countries where ETo estimatives are needed and only possible with incomplete data from the regional CWS.

Material and methods

The FAO-56 Penman-Monteith equation parameterization

The FAO-56 Penman-Monteith (P-M) equation (ALLEN et at., 1998) estimates the evapotranspiration from a hypothetical grass surface with an average resistance of 70 s m^{-1} for water vapour transport to the atmosphere, with a mean height of 0.12 m, and albedo equal to 0.23. When parameterized to be applied on a 24-h calculation time step the P-M equation can be expressed as

$$ETo = \frac{0.408\ s\ (Rn - G) + \dfrac{g\ 900\ u_2\ \Delta e}{T + 273}}{[s + g\ \ (1 + 0.34\ u_2)]} \qquad (1)$$

where ETo is the reference evapotranspiration [kg m^{-2} d^{-1} = mm d^{-1}]; Rn is the daily total net radiation [MJ m^{-2} d^{-1}]; G is the daily total soil heat flux [MJ m^{-2} d^{-1}], assumed to be negligible on a 24-h cycle (G = 0); T is the daily average air temperature at 2 m height [°C]; u_2 is the daily average wind speed at 2 m height [m s^{-1}]; *s* is the slope of the saturation vapour pressure-temperature curve [kPa °C^{-1}]; γ is the psychrometric coefficient [kPa °C^{-1}]; and Δe is the daily average saturation vapour pressure deficit [kPa].

The slope *s* of the saturation vapour pressure-temperature curve is computed at the point of the daily average temperature T (°C) by the equation

$$s = \frac{4098\ e_s}{[237.3 + T]^2} \qquad (2)$$

where e_s is the saturation vapour pressure at the daily average temperature T, given by

$$e_s = 0.6108 \exp\left[\frac{17.27\,T}{237.3 + T}\right] \qquad (3)$$

For standardization, FAO-56 recommends that the daily mean temperature be computed from the daily maximum (Tmax) and minimum (Tmin) temperatures as (Tmax + Tmin)/2 rather than 24-hour records.

The psychrometric coefficient γ is a very weak function of the atmospheric pressure (≈ 95 kPa for the local) and of the latent heat of vaporization (2.45 MJ kg^{-1}), and it was set to 0.0632 kPa $°C^{-1}$.

The daily average saturation vapour pressure deficit Δe was taken from following equations

$$\Delta e = e_s - e_a \quad (4)$$

$$e_s = [e_s\{Tmax\} + e_s\{Tmin\}] / 2 \quad (5)$$

$$e_a = [e_s\{Tmin\}\ RHmax + e_s\{Tmax\}\ RHmin] / 200 \quad (6)$$

where $e_s\{..\}$ represents the saturation vapour pressure, respectively, at the daily maximum (Tmax) and minimum (Tmin) air temperatures; RHmax and RHmin are the daily maximum and minimum relative humidity (%).

Lysimetric measurements

The experimental site was close to an irrigation project field located at Piracicaba, SP, Brazil (geographical coordinates: 22° 42´ S, 47° 30´ W, 546 m amsl). The weighing lysimeter (three load cells Omega Engineering, model LCCA-2K, full capacity of 910 kg, precision of 0.037%) had the following dimensions: 0.65 m depth, 1.08 m length, 0.85 m width (0.92 m^2 of confined area), and was covered with and surrounded by a 35 m x 90 m field of *Paspalum notatum* L. grass. The minimum fetch area was close to 10 m from the NE direction, the least frequent wind direction at the site. Soil moisture was monitored by tensiometers inside and outside the lysimeter and kept near field capacity by frequent irrigations from January to December 1996. The soil of the experimental site was classified as an alfisol (“Terra roxa estruturada”), series “Luiz de Queiroz”. To obtain the evapotranspiration as close as possible to the ETo conditions the grass was clipped to keep its average height close to the 0.12 m recommended by FAO-56 (ALLEN et al., 1998). The electric signal output from the load cells was recorded by a datalogger every second starting at midnight, resulting in 48 consecutives 30-min averages. The difference in lysimeter weight (Δkg) between the first and last 30-min averages was corrected using the lysimeter exposed area (0.92 m^2) to express it on a unit ground surface area basis, i.e., ET = Δkg/0.92.

The experiment began in the middle of the 1995/96 growing (rainy) season, ran through the fall and winter (dry period), and ended at the middle of the following growing season. Lysimetric measurements were not taken during June and July (winter months) since at that period the grass was not growing actively as requested by the definition of ETo.

Data from the Automatic Weather Station (AWS)

The AWS was a Campbell Scientific model installed in the same grass area of the lysimeter, and it consisted of the following sensors: REBS Q7.1 net radiometer at 1 m above the ground; temperature/relative humidity probe (Vaisala HMP35C, ± 0.2 °C, ± 3%) at 2 m from the ground; wind speed sensor (Met-One Instuments, model 014A, starting speed of 0.45 m s^{-1}) at 2 m above the ground; tipping bucket rain gauge (model TE525 Weather Bureau, 0.1 mm) at 1.5 m above the ground. The signals from all sensors were collected every second by a datalogger (Campbell Scientific CR10) storing totals, averages, and extreme values every 30 min, starting at midnight. Rainy days were discarded due to uncertainties in the net radiation measurements with a wet sensor dome.

Data and Computations with the Conventional Weather Station (CWS)

The CWS was about 2 km away from the experimental site and it is the regional weather station, a standard condition where net radiation and wind speed at 2 m above the ground are not measured and have to be estimated. Estimates of the missing data followed the guidelines proposed by FAO-56 even though local relationships were available.

Air temperature and relative humidity were measured inside the Stevenson screens weather shelter at 1.7 m above the ground, following the WMO (1983) recommendation. Maximum (Tmax) and minimum (Tmin) air temperatures were measured, respectively, by a mercury and an alcohol filled thermometer (R. Fuess, 0.1 °C). Relative humidity was recorded by a hair thermohygrograph (R. Fuess, 2.5 %), and RHmax and RHmin were extracted from the daily graphs.

Wind speed was measured at 10 m above the ground by an Universal anemograph (R. Fuess, starting speed of 0.5 m/s). Daily average wind speed (u_{10}, m s^{-1}) was computed converting the daily wind run (km d^{-1}). The corresponding wind speed at 2 m above the ground (u_2) was estimated by the reduction formula recommended by FAO-56, where z = 10 m, i.e.,

$$u_2 = u_z \frac{4.87}{Ln(67.8\,z - 5.42)} = 0.75\,u_{10} \quad (7)$$

This reduction in wind speed is equivalent to that originated from the application of the empirical power law for the wind speed profile in the turbulent boundary layer as a function of the heights of measurements (PLATE, 1971), that is, $u_z = u_h\,(z / h)^p$ with p = 0.18.

At the CWS the net radiation (Rn, MJ m^{-2} d^{-1}) was not measured and it had to be estimated applying the following equations (ALLEN et al., 1998):

$$Rn = Rs\,(1 - \alpha) - (0.34 - 0.14\,\sqrt{e_a})\,4.903\,10^{-9}\,(Tmax,K^4 + Tmin,K^4)/2\,(1.35\,Rs/Rso - 0.35) \quad (8)$$

$$Rs = Ra\,(a + b\,n/N), \quad (9)$$

$$Rso = Ra\,(a + b) \quad (10)$$

$$Ra = 37.586\,d_r\,(\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s) \quad (11)$$

$$d_r = 1 + 0.0333 \cos(2\pi\,J/365) \quad (12)$$

$$\delta = 0.4093 \sin[(2\pi\,/365)\,J - 1.405] \quad (13)$$

$$\omega_s = \cos^{-1}(-\tan\varphi \tan\delta) \quad (14)$$

$$N = 24\,\omega_s/\pi \quad (15)$$

where a = 0.26 and b = 0.51 are the local coefficients (OMETTO, 1981); n is the number of sunshine hours given by a Campbell-Stokes sunshine recorder (R. Fuess); φ is the local latitude (= -0.3962 rad); J is the julian day (day of the year, DOY); α = 0.23 is the albedo for the grass surface; Tmax,K and Tmin,K represents the maximum and the minimum absolute air temperature (K).

Results and discussion

The FAO-56 guidelines for predicting reference evapotranspiration (ETo) were followed and the results tested against daily measurements of grass ET using a weighing lysimeter. Before ETo vs ET comparisons are presented and discussed it is important to describe the environmental conditions at the experimental site during the period of measurements.

Climatically, there were two very distinctive periods, which are better illustrated by the rainfall distribuition throughout 1996, and by a 5-day Thornthwaite-Mather climatological soil water budget with a 100 mm field capacity (Figure 1). During the first period (from January 1 to May 24, DOY 1 to 145), there were 68 rainy days, amounting to 703 mm, with plenty of soil water at the beginning and gradually decreasing to a regional condition of soil water deficit. During the second period (from August 2 to December 9, DOY 215 to 344), the above situation was reversed with a regional soil water deficit at the beginning and going to a surplus towards the end of the period, with 46 rain events amounting to 565 mm. Averages and standard deviations of the means of the weather elements given by the AWS, during the two periods, are presented in Table 1. On average, the first period had higher net radiation (+6%), Tmax (+3%), Tmin (+22%), URmin (+22%), URmean (+12%), but lower Δe (-12%) and u_2 (-16%) than the second period. The sunshine ratio was about the same in both periods. Lysimeter ET measurements varied from 1.8 to 6.2 mm d^1 (4.1 ± 1.2 mm d^1) during the first period, and from 2.2 to 7.0 mm d^1 (4.6 ± 1.2 mm d^1) during the second period. Since ET were measured with plenty of soil water at the lysimeter, the higher values observed during the

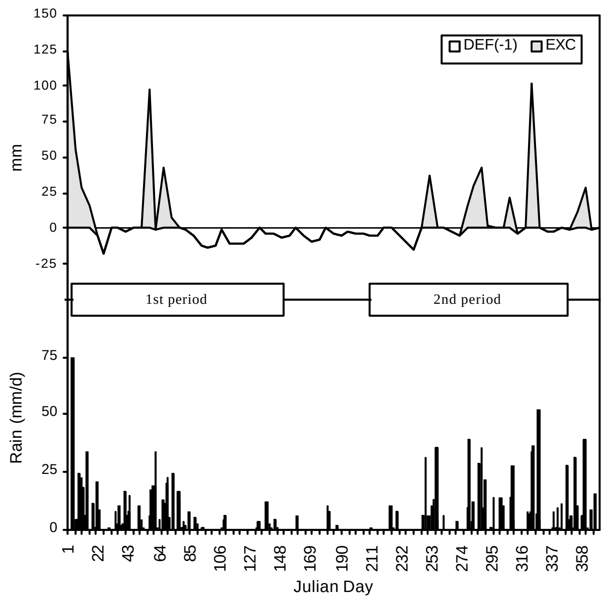

Figure 1 Daily rainfall at the lysimeter site (lower panel), and excess (EXC) and deficit (DEF) of the regional soil water based on a 5-day Thornthwaite-Mather climatological water budget (upper panel) during 1996, in Piracicaba, SP, Brazil.

Table 1. Averages and standard deviations of the mean (Avg. ± s.d.) of the weather elements at the automatic weather station, during the experiment (1996, Piracicaba, SP, BR).

Weather Elements	Period[1]	
	1 Jan – 24 May	2 Aug – 9 Dec
Rn (MJ m^2 d^{-1})	12.22 ± 2.99	11.45 ± 2.92
Tmax (°C)	30.0 ± 3.1	29.0 ± 3.0
Tmin (°C)	18.1 ± 3.1	14.8 ± 3.8
RHmin (%)	48.2 ± 7.8	39.6 ± 12.9
RHmed (%)	78.8 ± 5.0	70.4 ± 8.7
Δe (kPa)	1.13 ± 0.31	1.28 ± 0.41
u_2 (m s^{-1})	1.75 ± 0.47	2.09 ± 0.22
n/N[2]	0.68 ± 0.18	0.70 ± 0.22

[1] 41 days for the 1st period; 86 days for the 2nd period.
[2] from the CWS data set.

second period were determined by the combination of the higher Δe and u_2 prevailing at that time in comparison with the first period.

If the Penman-Monteith (P-M) equation is split in two terms (conventionally called radiative and aerodynamic terms), the combination of the average weather elements shown in Table 1 indicates that the relative contribution of the aerodynamic term increased from about 30% during the first period, to 38% during the second period. The first figure is very close to the 26% determined by PRIESTLEY & TAYLOR (1972) as an indicative of conditions for potential evapotranspiration, and during the first period fetch was not a problem. During the second period there was an increase of advection from the surrounding dry areas where the soil water was below field capacity, but the irrigated fetch area around the lysimeter reduced the effect of advection at the measurement site. On average, the lysimeter ET consumed about 82% (r^2 = 0.9130) of the net radiation during the first period, and 91% (r^2 = 0.8691) during the second.

Another way to inspect the relative importance of each term to the overall ET is expressed by the decoupling factor defined as $\Omega = \{1 + [\gamma/(s + \gamma)\ r_s/r_a]\}^{-1}$ by McNAUGHTON & JARVIS (1983) rearranging the P-M equation, being r_s and r_a the (bulk) surface and aerodynamic resistances, respectively. Conceptually, the extreme values for the decoupling factor are: a) $\Omega \rightarrow 1$ as $r_s/r_a \rightarrow 0$, implying that the radiation term is the only contributor to the ET process, and ET is completely decoupled from the atmospheric conditions; b) $\Omega \rightarrow 0$ as $r_s/r_a \rightarrow \infty$, indicating a complete coupling of ET with the atmospheric vapor pressure deficit and wind speed. With r_s/r_a computed by inverting the P-M equation using the lysimeter ET as input, it was found that Ω = 0.78 ± 0.09 for both periods, ranging from 0.56 to 0.93, during the first period, and from 0.58 to 1.05, during the second period, indicating moderate to strong decoupling in both periods. The average Ω = 0.8 was suggested as characteristic for grass field by McNAUGHTON & JARVIS (1983). Theoretically impossible, since $\Omega > 1$ implies $r_s/r_a < 0$, it is computationally possible whenever $[0.408\ s\ Rn + (\gamma\ 900\ \Delta e\ U_2)/(273 + T)]/(\gamma\ ET) < (s + \gamma)/\gamma$, and it occurred in only two days. It is difficult to pinpoint a single cause for such discrepancy, but both days had a very low sunshine ratio (n/N < 0.25) and radiative input, even though five other days had similar n/N values without such problem.

As above, assuming $r_a = 208/u_2$, derived by FAO-56, then r_s was computed with the P-M equation using the lysimeter ET as input. The computed r_s becomes the value necessary for the P-M equation give a perfect fit against the lysimeter ET. During the first period, it was obtained $50 \leq r_s \leq 230$ s m^{-1} averaging 136 ± 50 s m^{-1}; during the second period, the results were $-25 \leq r_s \leq 260$ s m^{-1}, and 100 ± 56 s m^{-1}. The occurrence of a negative value for r_s is computationally possible as discussed before, and ALVES et al. (1998) suggested that it indicates that the virtual evaporating surface is above the presumed level of the big leaf as implied in the computation of the aerodynamic resistance (r_a), because this fictitious surface is considered to possess the physiological properties of a leaf (LHOMME, 1991). It is obvious that such surface resistance bears little, if any, physiological significance as discussed by LHOMME (1991), and in both periods the averages were a little higher than the 70 s m^{-1} prescribed by the FAO-56 guidelines.

Linear regression analysis was performed taking the measured ET as independent variable (X), the FAO-56 ETo as dependent variable (Y), forcing the regression line to pass through the origin since the Y-intercept was not statistically different from zero (Y = b X), simplifying the comparisons. Using AWS data set, the results from both periods indicate that they could be pooled and represented by ETo = 1.07 ET_{lys} (r^2 = 0.8485; n = 127) with a standard error of estimate of 0.46 mm d^{-1} (Figure 2). This equation is practically identical to the ETo = 1.08 ET_{lys} (r = 0.90;

s.e. = 0.32 mm d^{-1}; n = 127) reported by ALLEN et al. (1989) for the semi-arid conditions of Davis, CA. The slight overprediction of 7%, on average, observed here can also be considered as a good practical estimate, as was the case in Davis, CA.

With the CWS data set, the agreement between ETo and the lysimeter ET can be considered even better since the points spread more evenly around the perfect fit line (Figure 3). Pooling the results from both periods, the unbiased regression line is ETo = 1.002 ET_{lys} (r^2 = 0.8126; s.e. = 0.50 mm d^{-1}; n = 127). However, the results for the two periods were slightly different, with the points of the first period consistently above the 1:1 line. For the first period, the relationship was identical to the one presented above for the AWS data, or ETo = 1.07 ET_{lys} (r^2 = 0.7894; s.e. = 0.47 mm d^{-1}; n = 41), while for the second period there was a minor underprediction with ETo = 0.97 ET_{lys} (r^2 = 0.8237; s.e. = 0.46 mm d^{-1}; n = 86).

Comparing the ETo obtained with the data from the two weather stations, those predicted by the AWS (ETo_A) were slightly higher than those from the CWS (ETo_C). On average, ETo_A = 1.06 ETo_C (r^2 = 0.8876; n = 127), caused mainly by the difference in net radiation (Rn_A = 1.05 Rn_C; r^2 = 0.8514; n = 127), and wind speed (u_A = 1.05 u_C; r^2 = 0.5258; n = 127) because there were no difference in vapour pressure deficit (Δe_A = 1.01 Δe_C; r^2 = 0.8759; n = 127) and average temperature (T_A = 0.98 T_C; r^2 = 0.9515; n = 127).

Conclusions

The reference evapotranspiration given by the Penman-Monteith big leaf model parameterized by FAO-56 guidelines was very close to the lysimetric measurements obtained on an irrigated grass field prepared to have a physical aspect similar to those prescribed on the definition of ETo. In general, ETo given by the conventional weather station (with estimated net radiation) were closer to the lysimeter ET than those resulted from the on-site automatic weather station data set with measured net radiation. On average, the overprediction was less than 7% for both weather stations. It can be concluded that FAO-56 parameterization scheme and guidelines can be adopted for practical applications.

The data set from a regional weather station located about 2 km away gave reliable estimates of ETo because the FAO-56 scheme requires only daily extreme values for air temperature and relative humidity regardless of the data set available.

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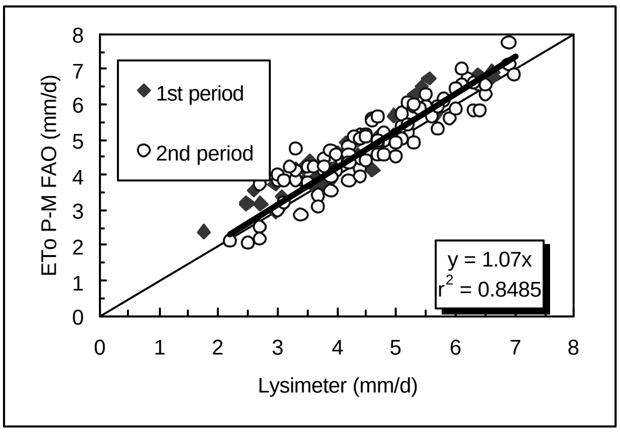

Figure 2 Daily FAO-56 reference evapotranspiration (ETo), with data from the automatic weather station (AWS) vs. daily lysimeter ET, at Piracicaba, SP, Brazil.

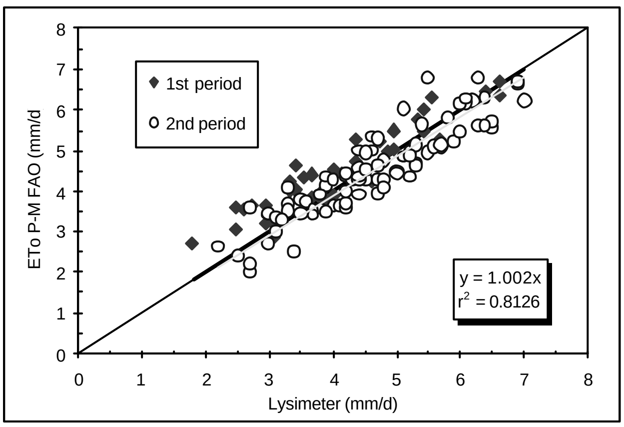

Figure 3. Daily FAO-56 reference evapotranspiration (ETo), with data from the conventional weather station (CWS) vs daily lysimeter ET, at Piracicaba, SP, Brazil

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