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AN HOURLY REFERENCE EVAPOTRANSPIRATION MODEL AS A TOOL FOR ESTIMATING PLANT WATER REQUIREMENTS

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Abstract

The usefulness of estimating hourly reference evapotranspiration for assessing the water requirements of plants over a 24-hour period was determined in the study. The values of hourly ($ET_{0,h}$) and daily ($ET_{0,d}$) evapotranspiration were calculated using the Penman-Monteith (PM) model. The daily ET_0 was calculated automatically by the meteorological station, and the evapotranspiration values for individual hours were calculated using spreadsheet software. To verify the values of evapotranspiration calculated with these two approaches in relation to the actual water needs of grass, lysimetric measurements were performed. Additionally, substrate moisture content and temperature were measured using capacitance probes. The values of evapotranspiration estimated with the hourly PM model were higher than those determined with the daily model. An accuracy of the hourly model in relation to the data measured with a weighing lysimeter depended largely on the quality of the reproduction of meteorological parameters at the site of the crop. Observed underestimation of the actual daily evapotranspiration was presumably due to the use of air temperature values in the calculations (measured at a height of 2 m by the weather station). During strong solar radiation the air temperature was much lower than the temperature of the upper layer of the substrate in the weighing lysimeter. Reference evapotranspiration was recalculated by introducing into the hourly PM model the measured values of substrate temperature. After taking into consideration the higher temperatures, the calculated values of evapotranspiration increased, and the regression model took the form: $y = 1.01x + 0.014$ ($R^2 = 0.90$), which proves the proportionality of the calculated and measured (actual water needs determined with the weighing lysimeter) data. Reliable data on the hourly variations in evapotranspiration over a 24-hour period can be a great tool for use in controlling the irrigation of plants grown in a limited volume of substrate.

Keywords: weighting lysimeter, Penman-Monteith model, irrigation

INTRODUCTION

Water availability is a limiting factor in agricultural production in Poland (Żarski 2009, Łabędzki 2007, Rolbiecki et al., 2009, Treder et al. 2009). Consequently, all irrigation water use needs to be optimized. Increasing the efficiency of irrigation water use requires practical application of precise methods of determining plant water needs and irrigation scheduling. The timing of irrigation can be determined using soil, plant and/or climatic criteria (Doorenbos and Pruitt 1977, Jones et al. 1996, Treder and Klamkowski 2008, Sentelhas et al. 2010). Climatic criteria are based on the assumption that the consumption of water by plants is determined mainly by weather conditions and crop characteristics (Thornthwaite 1948, Blaney and Criddle 1950, Ley et al. 1994). Plant water requirements are determined by the rate of evapotranspiration (ET). The term evapotranspiration is used to describe two processes of water loss from land surface to atmosphere, evaporation and transpiration. Both processes depend on solar radiation, air temperature, relative humidity and wind speed. Because direct measurement of ET is difficult, time consuming, and costly, the most common procedure is to estimate it using climatic data. Reference evapotranspiration (ET_0) is defined as the rate at which readily available soil water is vaporized from specified vegetation-covered surfaces under the conditions of sufficient soil water availability (no water shortage). The evaporative demand of the atmosphere is independent of crop type, crop development and management practices (Jensen et al. 1990). ET_0, computed from weather data, together with crop coefficients for specific crops, is a widely accepted indicator for estimating crop water use. (Doorenbos and Pruitt 1977, Allen et al. 1996, Xing et al. 2008). Numerous methods have been introduced for computing ET_0 in daily (24-h) time steps. (Doorenbos and Puitt 1977, Hargreaves and Samani 1985, Grabarczyk and Żarski 1992, Allen 1993, Gocic and Trajkowic 2010, Sentelhas et al. 2010). The Food and Agriculture Organization (FAO) recommends determining the reference evapotranspiration with the Penman-Monteith equation (Allen et al. 1998). A 24-h period is the basic time step for this type of calculation. With the increased development and installation of electronic weather stations around the world, weather data are becoming increasingly available for calculating ET_0 also in hourly time steps (Allen et al. 2006).

The data on the water needs of plants determined in hourly time steps can be useful for controlling the irrigation of shallow-rooted plants and also plants grown in small containers. In the case of this type of plants, we need to run at least a few watering cycles per day, which is why reliable data on hourly evapotranspiration can have a crucial impact on improving irrigation performance.

The quality of the models for estimating evapotranspiration can be assessed by means of lysimeters. Lysimeters are classified as weighing or non-weighing. Non-weighing lysimeters are useful for studying solute leaching, the weighing ones can monitor the weight continuously (Xiao et al. 2009). A weighing lysimeter is fabricated as a box with impermeable walls that is filled with a soil or substrate and placed in a field or vegetation-covered area. A load cell measures the variation in weight (Viana et al. 2003). This type of lysimeters is commonly used to measure evapotranspiration from agronomic crops (Allen et al. 1991, Yang et al. 2000, Marek et al. 2006). In water balance studies, lysimeters are used to quantify rainfall, drainage and evapotranspiration (Lazarovitch et al. 2006, Meissner et al. 2010). With the current technical advancement, lysimeters can accurately measure short-time ET rates with an accuracy of ±0.05 mm/h, daily ET, or irrigation and rainfall with an accuracy of ±0.1 mm (Howell et al. 1995).

The aim of this study was to determine the usefulness of estimating hourly reference evapotranspiration for assessing the water requirements of plants over a 24-hour period.

MATERIAL AND METHODS

The study was carried out during the growing season (May-September) of 2016 in Skierniewice, Poland. The geographical coordinates are 51°57′17″ N latitude and 20°09′30″ E longitude. Elevation – 128 m above sea level. Skierniewice has a humid continental climate with winter and summer time. The annual mean temperature is about 8°C, and the annual precipitation averages 515 mm. During summer, the average high temperature is 22.7°C, and the average low temperature is 12°C.

Meteorological data were obtained using an agro-meteorological station iMetos (Pessl Instruments, Austria) equipped with the necessary sensors to record data required for calculating ET_0: air temperature, relative humidity, solar radiation, and wind velocity. Recordings were made of all the climatic data and stored every 60 minutes.

The values of hourly ($ET_{0,h}$) and daily ($ET_{0,d}$) evapotranspiration were calculated using the Penman-Monteith (PM) model:

The FAO-56 Penman-Monteith equation used for ET$_0$ calculation in daily (24-h) and hourly time steps:

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{C_n}{T + 273}\,u_2\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

ET$_0$ – standardized grass-reference ET (mm d^{-1} or mm h^{-1})

Δ – slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1})

R_n – net radiation (MJ m^{-2} d^{-}1 for 24-h time steps, or MJ m^{-2} h^{-1} for hourly time steps)

G – heat flux density at the soil surface (MJ m^{-2} d^{-1} for 24-h time steps, or MJ m^{-2} h^{-1} for hourly time steps)

T – mean daily or hourly air temperature (°C)

u$_2$ – mean daily or hourly wind speed (m s^{-1})

e_s – saturation vapour pressure (kPa)

e_a – actual vapour pressure (kPa)

$e_s - e_a$ – vapour pressure deficit (kPa)

γ – psychrometric constant (kPa °C^{-1})

C_n – numerator constant that changes with reference surface and calculation time step (900°C mm s^3 Mg^{-1} d^{-1} for 24-h time steps, and 37°C mm s^3 Mg^{-1} h^{-1} for hourly time steps for the grass-reference surface).

The daily ET$_0$ was calculated automatically by the meteorological station, and the evapotranspiration values for individual hours were calculated using an Excel spreadsheet (Microsoft, USA). To verify the values of evapotranspiration calculated with these two approaches in relation to the actual water needs of grass, lysimetric measurements were performed. The measurements of grass water needs were carried out in micro-weighing lysimeters. The lysimetric station has two weighing lysimeters with continuous electronic data reading devices and a temperature compensation system. The daily resolution of measurements was ±0.01 mm. The surface area of each lysimeter was equal to 1 m^2. The lysimeters were irrigated by capillary action, providing the grass with an unrestricted access to water. Data were recorded every 15 minutes.

Substrate moisture content and temperature were measured using 5TE capacitance probes (Decagon Devices, USA). Data were collected (5 min. sampling interval) by a logger unit (EM-50G, Decagon Devices, USA) and wirelessly transmitted to a personal computer (access to the data was granted through a dedicated web site).

RESULTS AND DISCUSSION

In order to compare the values of reference evapotranspiration calculated with the PM model in hourly and 24-h time steps, the hourly values for individual days were added up. The statistical analysis carried out separately for each month (May-September) showed a high correlation between the values of evapotranspiration determined with the daily and hourly models (Fig. 1). Because the parameters *a* and *b* in the linear regression equation $y = ax + b$ describing in individual months the relationship between the daily ET_0 values determined with the models under comparison were similar, the correlation coefficient and the regression equation parameters were calculated for the combined data from the entire growing season (Fig. 2). The coefficient *r* reached a value of 0.99, which is evidence of a very strong correlation between the analyzed data. The values of $ET_{0,h}$ were higher than those of $ET_{0,d}$. The formula describing the correlation for the data from the entire growing season took the form of: $ET_{0,h} = 1.2 \times ET_{0,d} - 0.27$, with the standard error of the estimate equal to 0.14. Determining the linear regression equation without the free term (Y intercept), we obtained the formula: $ET_{0,h} = 1.11 \times ET_{0,d}$, with the standard error of the estimate equal to 0.18. It thus became apparent that the hourly PM model produces higher daily values of evapotranspiration by an average of 11% in relation to the values determined with the daily model. Irmak et al. (2005) had also observed a difference between the evapotranspiration values determined with hourly and daily models. They compared the PM model standardized by the American Society of Civil Engineers (ASCE-PM). Analysis of data from six meteorological stations located throughout the United States showed that higher $ET_{0,h}$ values (by 2.7%) were obtained only in one case in Santa Barbara (CA).

To verify which version of the PM model, the daily or the hourly one, better described the daily values of actual evapotranspiration (ET_r) of grass, the calculated data were compared with lysimetric measurements (Fig. 3). The values of the coefficients of determination between the data measured with lysimeters and the values of $ET_{0,h}$ and $ET_{0,d}$ were high. The slopes of the regression lines showed that for values > 2 mm/day the values of ET_r were increasingly higher, even higher than those determined with the hourly PM model. Both models give values lower than the actual evapotranspiration of grass, but in the case of the hourly PM model the error is much smaller (Fig. 4). From June to May, it takes on the values of -0.53 to -0.48 mm/day, respectively, while in September it is already very small, reaching only -0.08 mm/day.

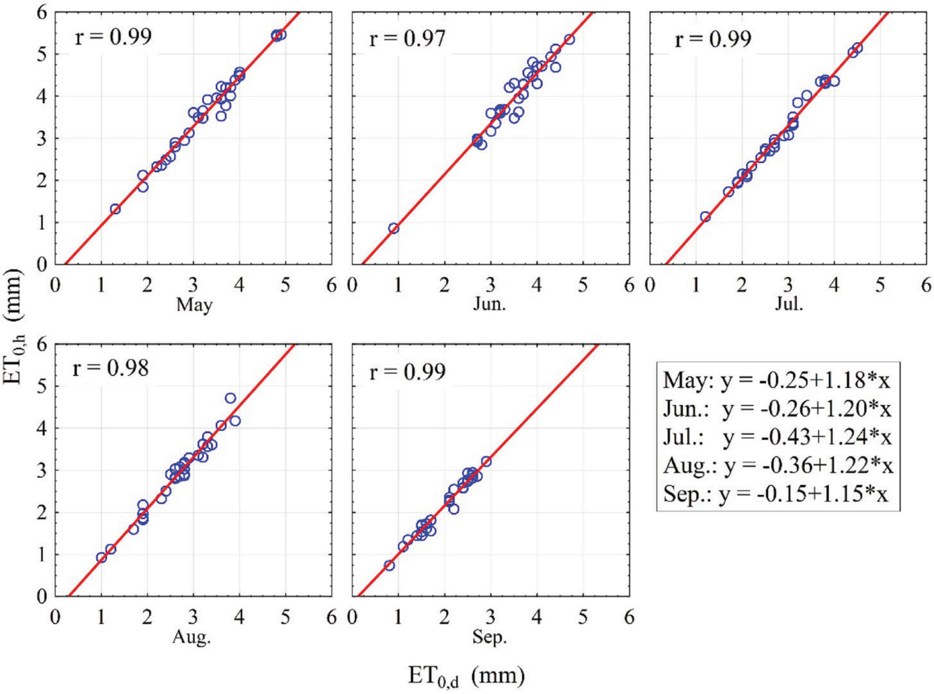

Figure 1. Correlation, in each month of the growing season, between the daily evapotranspiration values calculated with the Penman-Monteith model in hourly and 24-h time steps. Year 2016.

Both the lysimeter measurements and the calculated values of $ET_{0,h}$ allow the changes in evapotranspiration to be reproduced in hourly time steps as well as shown in terms of their cumulative progress (Fig. 5). Analyzing the courses of the hourly values of $ET_{r,h}$ and $ET_{0,h}$ in the individual days, it was found that there was a slight overestimation of the ET_0 value with respect to the reference standard (ET_r) in the morning hours and a marked underestimation of them in the midday and afternoon hours, the consequence of which were lower values of the calculated daily evapotranspiration in relation to the values measured with the lysimeter. Examples of the temporal courses of measurements and estimates for days 11-13 June are shown in Figure 5.

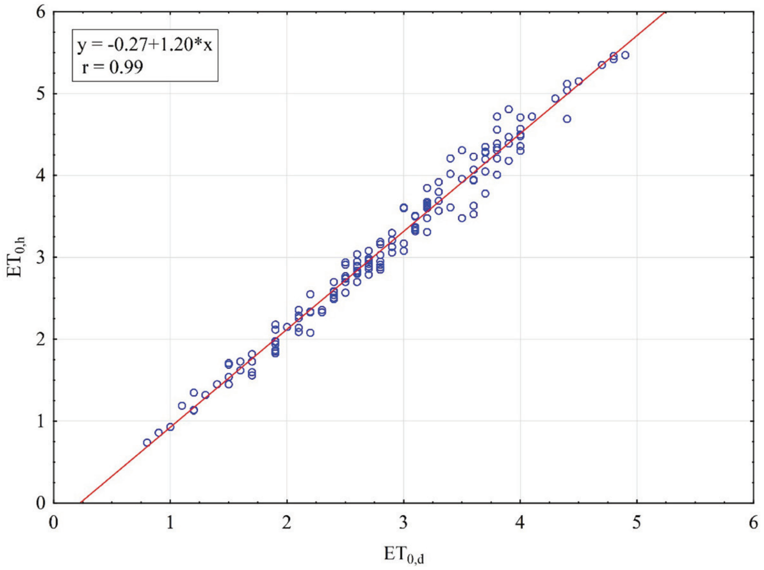

Figure 2. Correlation between the daily evapotranspiration values calculated with the Penman-Monteith model in hourly and 24-h time steps. May-September 2016.

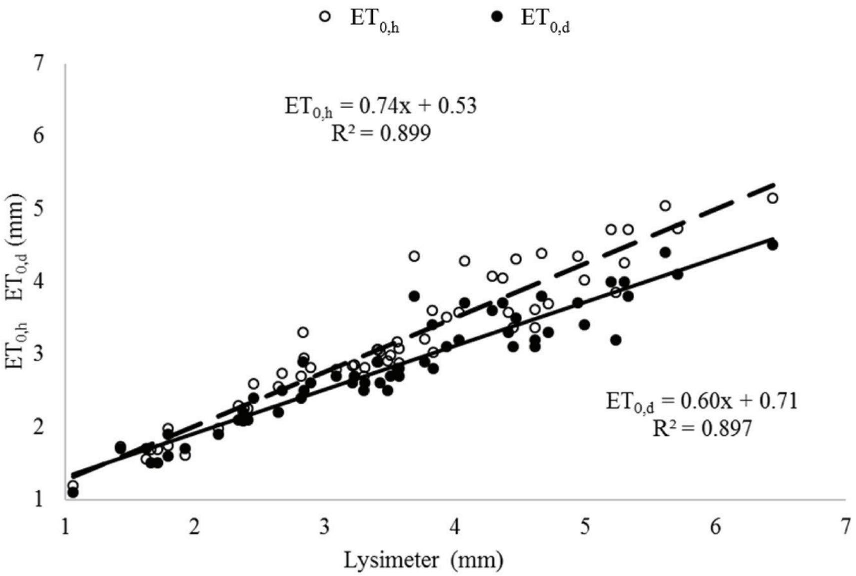

Figure 3. Correlation between lysimetric measurements and values calculated with the daily (24-h) and hourly Penman-Monteith models.

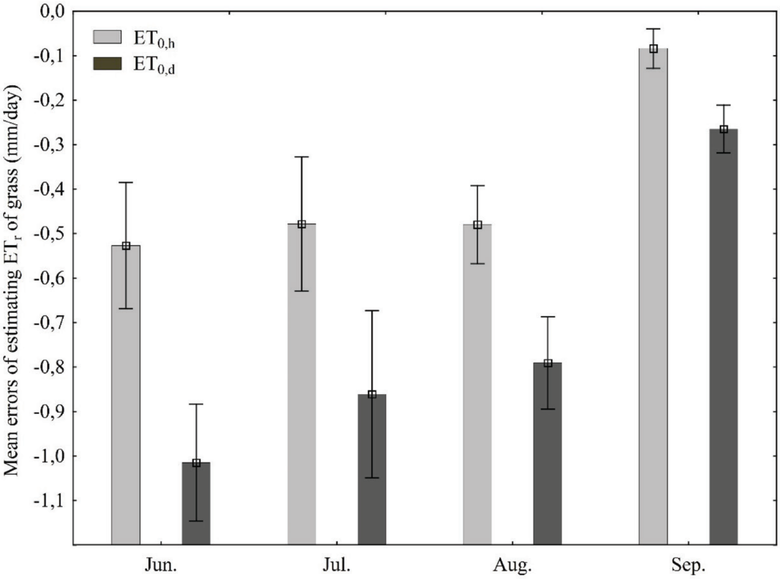

Figure 4. Mean errors of estimating ET_r of grass (mm/day) with the Penman-Monteith model in hourly and 24-h time steps.

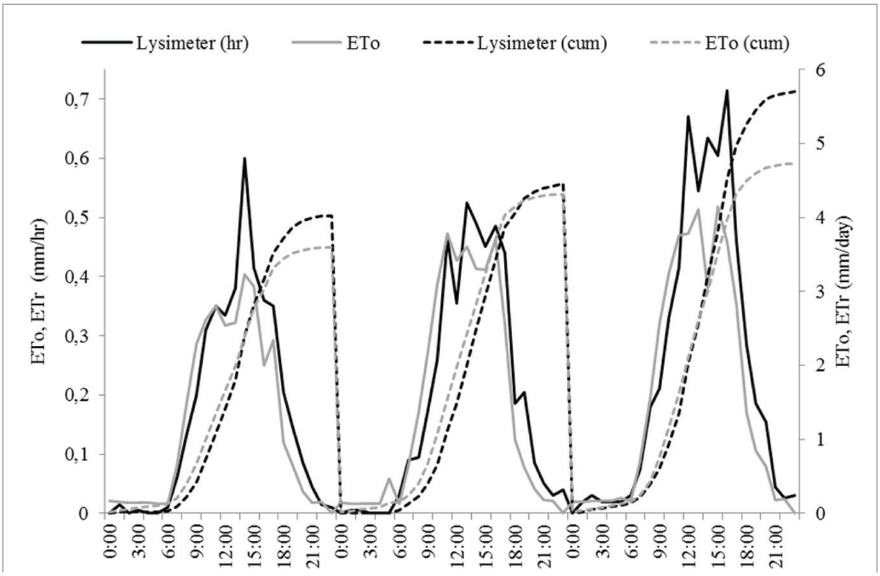

Figure 5. Hourly and cumulative variation in ET_r – lysimetric measurements, and ET_0 – determined with the PM model, 11-13 June 2016.

To explain the reasons for the existing differences, meteorological data were analyzed, which showed considerable differences between the temperatures measured by the meteorological station and the temperature of the surface layer of the substrate in the lysimeter (Fig. 6). The surface temperatures of the substrate were higher than the air temperature, and the stronger the solar radiation was, the higher they were. The data obtained explain why the error in the estimation of evapotranspiration of grass was smallest in September, when the level of solar radiation was relatively low, and why in the summer at high levels of insolation during the day that error was largest. Widmoser (2009) reports the difference between the measured air temperature and the temperature of a standing crop as one of the causes of errors in the calculation of evapotranspiration.

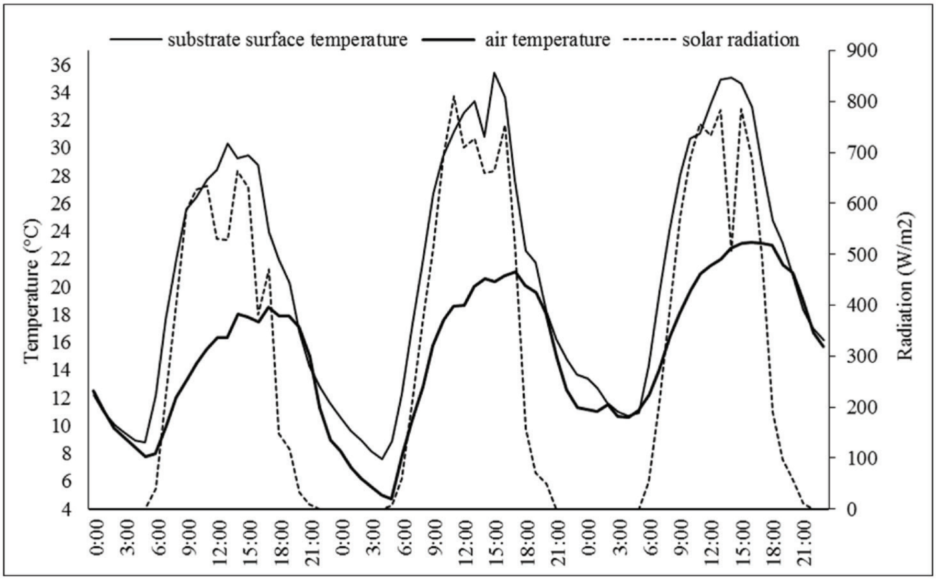

Figure 6. Solar radiation and the variations in air temperature and the substrate surface temperature in the lysimeter (11-13 June 2016)

After observing such large differences between the air temperature measured at a height of 2 m (weather station) and the temperature of the substrate (lysimeter), the reference evapotranspiration was recalculated by introducing into the PM model the measured values of substrate temperature. Figure 7 shows the relationship between the hourly values of $ET_{0,h}$ determined for the temperature from the weather station and the surface temperature of the substrate in relation to the lysimetric measurements. The analysis included data from three consecutive days, from 11 to 13 June 2016. After taking into consideration the higher temperatures, the calculated values of evapotranspiration increased, and the regression model took the form: $y = 1.01x + 0.014$, with $R^2 = 0.90$, which proves the proportionality of the calculated and measured data. An almost identical correlation: $y = 1.022x - 0.0055$, with $R^2 = 0.93$, had been obtained by Lopez-Urrea et al. (2006) in a similar study conducted in Spain.

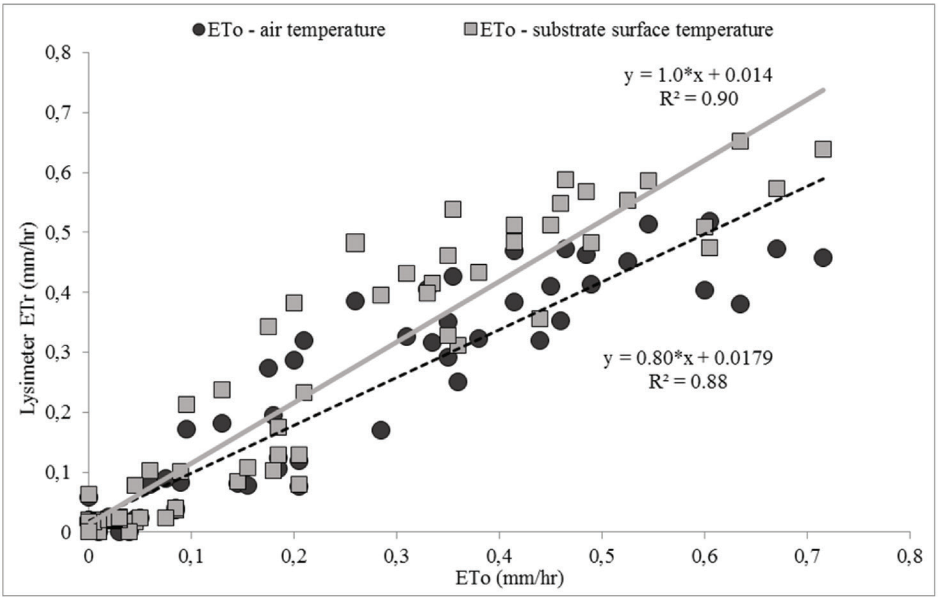

Figure 7. Correlation between the measured ET_r values of grass and the values calculated with the PM model (data for days 11-13 June).

CONCLUSIONS

The values of evapotranspiration estimated with the hourly PM model were higher than those determined with the daily model. The hourly model describes very well the daily variation in actual grass evapotranspiration. Its accuracy in relation to the data measured with a weighing lysimeter depended largely on the quality of the reproduction of meteorological parameters at the site of the crop. In the case of our tests, the underestimation of the actual daily evapotranspiration was presumably due to the use of air temperature values in the calculations (measured at a height of 2 m by the weather station). During strong solar radiation the air temperature was much lower than the temperature of the upper layer of the substrate in the weighing lysimeter.

Reliable data on the hourly variations in evapotranspiration over a 24-hour period can be a great tool for use in controlling the irrigation of plants grown in a limited volume of substrate. In the case of such crops, we generate not one but several irrigation events daily, and that is why information on the water needs of plants on an hourly basis, on the maximum needs in the afternoon hours, and the cumulative evapotranspiration after a specified period of time is very useful.

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