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Solar radiation and relative humidity based, empirical method, to estimate hourly reference evapotranspiration

C.D. Chatzithomas*, S.G. Alexandris

Laboratory of Agricultural Hydraulics, Department of Natural Resources Management & Agricultural Engineering, Agricultural University of Athens, Iera Odos 75, 118 55 Athens, Greece

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ABSTRACT

A new empirical method which estimates hourly reference evapotranspiration is proposed, that utilizes two meteorological variables, namely incoming solar radiation and relative humidity. It also utilizes a term that combines both variables. The inverse of the natural logarithm of relative humidity and the vapor pressure deficit of the atmosphere were investigated and were found to correlate quite well. The equation was calibrated in a semi arid environment, using data from Davis station (year 2000), of the CIMIS network. The estimations of both, the empirical method and the ASCE PM method, were compared. Validation of the method was performed with hourly data from the same station for 8 years, using various statistical indices. The hourly empirical equation was investigated for the whole period, for each year separately and for the summer period. It was found that it performed satisfactorily in all cases. Yearly RMSE ranged from 0.036 to 0.045 mm/h with an average for the whole period 0.042 mm/h. For the summer period RMSE ranged from 0.040 mm/h to 0.055 mm/h with an average for all the values of the summer period 0.047 mm/h. It was also validated with data from the grass reference meteorological station in the experimental field of the Agricultural University of Athens in Copais, Greece and was found to perform satisfactorily with RMSE equal to 0.043 mm/h. The deviations of the new empirical method from the ASCE PM method were investigated for various ranges of wind speed and vapor pressure deficit data values. It was found that the empirical method estimates were acceptable for practically all cases when 0.073 mm/h was considered as the threshold RMSE value. The proposed hourly empirical equation is recommended for use in semi arid climates.

1. Introduction

The largest part of the total amount of water resources consumed goes to agriculture. The consumption can be reduced with improved irrigation efficiency which in turn depends on accurate knowledge of reference evapotranspiration (ET_o).

ET_o can be either measured e.g. with the use of lysimeters or it can be estimated. Lysimeter measurements in most cases are used to compare the estimations of the various methods and assess their accuracy and true reliability (Abtew, 2007; Allen et al., 1989; Hargreaves, 1994; Hargreaves and Allen, 2003; Jensen et al., 1990; López-Urrea et al., 2006; Makkink, 1957; Snyder et al., 2005; Ventura et al., 1999). There are few sites maintaining lysimeters and therefore only few data are available. Furthermore, proper maintenance of a lysimeter is costly and demanding. Poor data may result as a consequence of mismanaging a lysimeter, (Allen et al., 1994; Allen et al., 2011). In such cases methods for estimating ET_o from meteorological data, may give better results.

Combination methods for estimating ET_o, are the most accurate and data intensive. They are based on theoretical considerations which combine the aerodynamic and the energy balance methods. Penman (1948) first introduced such a method which needed data only from the air above an open water surface, bypassing the need for surface measurements. Various forms were later developed, e.g. FAO 24 Penman (Doorenbos and Pruitt, 1977), CIMIS Penman, (George et al., 1985; Snyder and Pruitt, 1985; Snyder and Pruitt, 1992), Kimberly Penman (Wright and Jensen, 1972; Wright, 1982). Monteith (1965) introduced the properties of the canopy and proposed a new more complete form of the equation, the Penman–Monteith (PM) equation. It was further modified with the FAO56 PM, Allen et al. (1998) and ASCE-EWRI PM (ASCE-EWRI, 2005) *equation.* Combination methods can estimate ET_o for any period of time e.g. hourly, daily, monthly etc. The reliability of these methods makes them suitable for benchmarks against which other

* Corresponding author. Tel.: +30 1 210 529 4076.
E-mail addresses: Costas@aua.gr, lhyd7hak@gmail.com (C.D. Chatzithomas).

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methods can be compared and evaluated (Alexandris et al., 2008; Amatya et al., 1995; Gavilán et al., 2008; Irmak et al., 2008a; Irmak and Irmak, 2008b; Itenfisu et al., 2003; Rojas and Sheffield, 2013; Temesgen et al., 2005; Trajkovic and Kolakovic, 2009; Xu and Singh, 2002; Xystrakis and Matzarakis, 2011).

The need for standardization of the PM equations was suggested, Allen et al. (1998) and Allen et al. (2000), to enable commonality and comparability between estimations. Computational procedures of the ASCE-EWRI PM (ASCE-EWRI, 2005) have been fixed, in other words it is a standardized method.

In many instances however, where only limited data are available, the use of the ASCE PM method is not possible. Estimations of ET_o in this case can come either from estimating missing data (Amatya et al., 1995; Popova et al., 2006; Rojas and Sheffield, 2013; Todorovic et al., 2013), although there is no method that predicts wind speed with total confidence Irmak et al. (2003a), or from empirical methods (Alexandris et al., 2006; Blaney and Criddle, 1950; Irmak et al., 2003a; Jensen and Haise, 1963; Kharrufa, 1985; Makkink, 1957; Linacre, 1977; Priestley and Taylor, 1972; Thornthwaite, 1948), that need less data to estimate evapotranspiration. All empirical methods have limitations which depend on the variables they use and the climatic conditions of their calibration, e.g. the radiation methods tend to be more accurate in humid climates where the aerodynamic term of the PM equation is less significant Allen et al. (1998). Studies indicate that empirical methods cannot estimate accurately under all climatic regimes without some calibration (Irmak et al., 2003b; Meyer, 1999).

Most empirical formulas use multiplicative expressions to calculate ET_o (Blaney and Criddle, 1950; Hargreaves and Samani, 1985; Turc, 1961). Exponentials are used in the form of fixed exponent values e.g. quadratic terms, (Alexandris and Kerkides, 2003; Hamon, 1961; Romanenko, 1961), square roots Hargreaves and Samani (1985) or in the form of a function which depend on another variable e.g. Thornthwaite (1948) calculates the exponent as a function of monthly mean temperature. Pereira and Pruitt (2004) introduced the daylight duration into the exponent of the Thornthwaite (1948) formula, thus giving different values of the exponent for every day of the year.

Empirical methods generally estimate ET for daily periods or greater, e.g. weekly, ten day period, monthly etc. An exception to this generalization is the Copais method, Alexandris and Kerkides (2003). This method uses three meteorological variables, incoming solar radiation (R_s), relative humidity (RH) and temperature (T), to make the estimate of hourly reference evapotranspiration. It was calibrated in a semi arid climate (Copais, Greece) and validated with data from the meteorological station of Davis, California which is part of the California Irrigation and Management and Information System (CIMIS). The form of the equation is Multivariable Linear Regression (MLR), with linear and quadratic terms, and a term with a multiplication by R_s which distributes over addition of RH and T terms.

In this paper we propose a new empirical method for estimating hourly reference evapotranspiration with the use of two meteorological variables, solar radiation (R_s) and relative humidity (RH). Maximum possible duration of sunshine (daylight hours, N) of each day are also taken into account. We use MLR with two linear and a multiplicative term. In the multiplicative term, the inverse of the natural logarithm of the relative humidity is multiplied by the exponential of the incoming solar radiation to a power of a function of daylight hours. The method has been calibrated with data from the meteorological station of Davis, California, from the CIMIS network, for the year 2000. The validation of the empirical method was made with data from Davis station, for specific years selected on the basis of average temperature, precipitation and wind speed. The new empirical method is also validated with data from the grass reference meteorological station of the experimental field of the Agricultural University of Athens, at Copais Greece. The method's estimates were compared with the ASCE PM method's estimates of reference evapotranspiration, as given by the CIMIS database.

2. Materials and methods

2.1. CIMIS network

The empirical relation was calibrated and validated with data from the CIMIS network. This network operates more than 120 stations throughout the state of California and is supervised by the California Department of Water Resources (CDWR) and the University of California, Davis (UCD). All stations of the network have similar sensors which are calibrated in the same way and are located at reference surfaces, so their meteorological measurements can be used to estimate reference evapotranspiration. Minute values are averaged on hourly and daily basis. Data retrieval, quality control and calculation of values of ET_o, Rn etc, are automated every 24 h. If a station fails to conform to the reference standards, it is disconnected from the network. Data access is free for registered users.

We used data from station no 6 (Davis) for the year 2000, to calibrate the empirical relation and from other years of the same station to evaluate it. The evaluation years appear in Table 1 and were the two consecutive years, (2001, 2002) and the years that the highest and lowest temperature, wind speed, and precipitation was observed. Maximum and minimum values were selected based on the averaged monthly values of each parameter. Monthly values were obtained from the CIMIS database. Years with missing data were avoided. After the selection, the hourly values of each year were downloaded from the CIMIS database (a total of 66.911 hourly values for the eight Davis years) and the estimations of the empirical formula were calculated.

Davis station is located within UCD, and is operative since 1982. It is a grass reference station with longitude 121°46′32″W, and latitude 38°32′09″N. Its altitude is 18 m a.s.l.

2.2. Copais grass reference meteorological station

The grass reference evapotranspiration station of the Agricultural University of Athens is located in central Greece, in the Copais basin. Its latitude is 38°23′N, its longitude is 23°05′E and its altitude is 110 m. It is located 72 km north-west of Athens. It is bounded from the Boeotikos Cephissus River Basin. The climate is Mediterranean semi arid. The station is installed in a well watered grass field (cool season) field, 25 m by 25 m (625 m^2).

A sub-Irrigation system is installed at the grass field in order to provide adequate water conditions for potential ET. On a 2 m high mast, a datalloger (CR10X Campbel) is installed along with Radiation sensors at 1,8 meters (albedometer with spectral range ≃ 280 to 2800 nm, a Net Radiometer, a photosyntheticaly active radiation sensor PAR with spectral range ≃ 400 to 700 nm),

Table 1
Years with max/min weather parameters for the Davis station. In the last row the data used from the Copais station. The formula was validated against these data.

Weather parameter	Year	No. of data
High wind	1996	8.447
High temperature	1997	8.361
High precipitation	1998	8.343
Low precipitation	1999	8.315
Validation	2001	8.273
Validation	2002	8.449
Low wind	2005	8.325
Low temperature	2011	8.398
Copais	2012	6.593