Computers and Electronics in Agriculture 132 (2017) 86–96

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Daily reference evapotranspiration estimates by artificial neural networks technique and empirical equations using limited input climate variables

Vassilis Z. Antonopoulos *, Athanasios V. Antonopoulos

School of Agriculture, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

ARTICLE INFO

Article history:
Received 25 July 2016
Received in revised form 8 November 2016
Accepted 13 November 2016
Available online 10 December 2016

Keywords:
Reference evapotranspiration
Penman–Monteith method
Neural networks
Empirical equations
Limited weather data

ABSTRACT

The artificial neural networks (ANN) and the empirical methods of Priestley-Taylor, Makkink, Hargreaves and mass transfer were used to estimate the reference evapotranspiration with daily meteorological data. These datasets consisted of daily meteorological measurements from a station in northern Greece, covering a period of five years (2009–2013). The daily values of the reference evapotranspiration were calculated using the Penman-Monteith equation. Those datasets were used for training and testing the ANN. The algorithm that was used is of the multi-layer feed forward artificial neural networks and of the back-propagation for optimization. The architecture that was finally chosen has the 4-6-1 structure, with 4 neurons in the input layer, 6 neurons in the hidden layer and 1 neuron in the output layer which corresponds to the reference evapotranspiration, using a sigmoid transfer function. The ANNs models estimate ET_o with an accuracy of a root mean square error (RMSE) ranged from 0.574 to 1.33 mm d^{-1}, and correlation coefficient (r) from 0.955 to 0.986. Using limited input variables (3 or 2) for training the ANNs result in ET_o values with slightly lower accuracy. The RMSE ranged from 0.598 to 0.954 mm d^{-1} and r ranged from 0.952 to 0.978 when 3 inputs variables were used, and RMSE of 0.846 to 1.326 mm d^{-1} and r of 0.910 to 0.956 when 2 input variables were used. The Priestley-Taylor and Makkink methods correlated very well with the Penman-Monteith method followed by the Hargreaves method which overestimates the higher values of ET_o. The mass transfer method also correlated satisfactorily but it underestimated the ET_o values.

1. Introduction

The reference evapotranspiration (ET_o) is one of the most important components of the hydrological cycle. The crop water requirements, which are essential in irrigation planning, scheduling, hydrologic balance studies and watershed hydrology is based on the accurate estimation of ET_o.

Numerous methods to estimate ET_o have been developed and are being used, depending upon the availability of meteorological variables. These range from empirical solar radiation or temperature based equations to complex methods based on physical processes of radiation and transport characteristics of natural surface. Among these methods are the Priestley-Taylor method (Priestley and Taylor, 1972), the corrected FAO-24 Penman method (Allen and Pruitt, 1991), the Hargreaves method (Hargreaves and Samani, 1985) and the FAO-56 Penman-Monteith method (Allen et al., 1998).

Significant efforts for the accurate estimation of ET_o under the Greek environmental-meteorological conditions have been carried out by several researchers, which focused on comparisons and sensitivity analysis between the aforementioned methods, their parameters and their calculation time step (Tsakiris and Vangelis, 2005; Sakellariou-Makrantonaki and Vagenas, 2006; Ampas et al., 2007; Aschonitis et al., 2012; Kitsara et al., 2015). Additional studies have been performed to develop new methodologies for the estimation of ET_o using empirical equations, such as the "Copais model" (Alexandris et al., 2006), equations based on Penman's formula with reduced parameters (Valiantzas, 2006) or with indirect estimation using pan evaporation measurements and pan coefficients (k_p) adapted to the surrounding environmental conditions (Aschonitis et al., 2012).

During the last decades there has been a widespread interest in the application of artificial intelligence techniques in the field of water sciences and technologies, as the artificial neural networks

* Corresponding author.
E-mail address: vasanton@agro.auth.gr (V.Z. Antonopoulos).

http://dx.doi.org/10.1016/j.compag.2016.11.011
0168-1699/

(ANN), fuzzy logic models, neuro-fuzzy models and support vector machines (Heddam, 2014). ANNs are being used to predict and forecast water resources variables in the last decades. ANNs have been successfully used in hydrological processes, water resources management, water quality prediction, and reservoir operation (Diamantopoulou et al., 2007; Piotrowski et al., 2012; Wu et al., 2014; Antonopoulos et al., 2015, 2016). An important feature of ANN is the ability to learn and generalize the relationships in complex data sets, which expands the scope of their applicability (Wu et al., 2014).

Recently a significant number of articles used ANN to simulate evaporation from free water surface as well as actual and reference evapotranspiration (Kumar et al., 2011). Jain et al. (2008) estimated ET_o using ANNs and examined these with limited input variables producing accurate results. Terzi and Keskin (2010) compared the ANN with four conventional methods to estimate daily pan evaporation and suggested that the conventional methods should be calibrated before being used and the ANN method gave better results. Diamantopoulou et al. (2011) tested two ANN models of back-propagation algorithm and the cascade correlation architecture to estimate daily reference evapotranspiration with minimum meteorological data. Ariapour and Zavarech (2011) developed an ANN model for the daily evaporation using a feed forward multiple layer network with a hidden layer and a sigmoid function. Benzaghta et al. (2012) estimated evaporation from the Batu Dam reservoir in Malaysia, using ANN, Penman and Priestley-Taylor methods. Goyal et al. (2014) estimated daily pan evaporation in sub-tropical climates using ANN and other machine learning approaches such as least squares support-vector regression (LS-SVR) and fussy logic. Laaboudi et al. (2012) examined the effectiveness of the use of artificial neural networks for the evaluation of ET_o using incomplete meteorological parameters. Antonopoulos et al. (2016) used ANNs technique to estimate daily evaporation from Lake Vegoritis in Northern Greece and they compared the results of ANNs with the classical empirical methods of Penman, Priestley-Taylor and the mass transfer method.

The aim of this study is to evaluate the applicability and validity of different evapotranspiration methods such as, Priestley-Taylor, Makkink, Hargreaves and mass transport and the ability of the Artificial Neural Networks technique to estimate daily reference evapotranspiration. Daily data from a meteorological station in northern Greece was used. The results are compared to the values of reference evapotranspiration estimated by the Penman – Monteith method.

2. Materials and methods

2.1. Daily reference crop evapotranspiration

The Food and Agricultural Organization of the United Nations (FAO) accepted the FAO Penman-Monteith as the standard equation for the estimation of ET (Allen et al., 1998). This method is a combination of the energy balance and the aerodynamic processes with two more resistance factors, the aerodynamic and the (bulk) surface resistances. Jensen et al. (1990) noted that the combination of energy balance and aerodynamic equations generally provides the most accurate results as a result of their foundation in physics and basis on rational relationships. The surface conductance/resistance term that accounted for the response of leaf stomata to their hydrologic environment was introduced by Monteith (1965).

The FAO-56 Penman-Monteith (PM) method of daily reference crop evapotranspiration ET_o estimation is described by the following equation (Allen et al. 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_\alpha - e_d)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_o is the daily reference crop evapotranspiration (mm d^{-1}), R_n is the net radiation (MJ m^{-2} d^{-1}), u_2 is the mean wind speed at 2 m above soil surface (m s^{-1}), T is the mean air temperature (°C), G is the soil heat flux density at the soil surface (MJ m^{-2} d^{-1}), e_a *is* the saturation vapour pressure (kPa), e_d is the actual vapour pressure (kPa), Δ is the slope of the saturation vapour pressure-temperature curve (kPa $°C^{-1}$), γ is the psychrometric constant (kPa $°C^{-1}$).

Many other formulas have been developed which are simplified methods of the Penman formula or other empirical equations, and are grouped according to method type (Rosenberry et al., 2007; Yao, 2009).

2.2. Priestley-Taylor method

The Priestley-Taylor method (Priestley and Taylor, 1972) is a modification and simplification of the Penman formula. Evaporation is estimated as a function only from the energy term of Penman equation. The aerodynamic term is approximated as a fixed fraction of the total evaporation over a suitable average period. The Priestley-Taylor equation has the following form:

$$ET_o = \alpha \frac{\Delta}{\Delta + \gamma} \frac{(R_n - G)}{\rho_w \lambda} \quad (2)$$

where λ is the latent heat of vaporization (MJ kg^{-1}), ρ_w is the water density (kg m^{-3}) and α is an empirically derived parameter with an average value of 1.26, which is the equivalent of suggesting that, for a water surface, the aerodynamic term in Penman equation contributes 21% of the total evaporation (Sene et al. 1991; Aschonitis et al., 2015). For the application of the Priestley-Taylor method there is no need for wind speed data. This method is a radiation based method. The Priestley-Taylor method has been used to estimate the reference crop evapotranspiration in many works (Utset et al., 2004; Bogawski and Bednorz, 2014; Aschonitis et al., 2015).

2.3. Hargreaves method

The Hargreaves method (Hargreaves and Samani, 1985) estimates daily ET_o, when solar radiation, relative humidity and wind speed data are missing by using only the maximum and minimum air temperature in the following equation

$$ET_o = a_h(T_{mean} + b_h)(T_{max} - T_{min})^{c_h} R_a \quad (3)$$

where T_{max}, T_{min} and T_{mean} are the maximum, minimum and mean temperature (°C), respectively, and R_a is the extraterrestrial radiation (mm day^{-1}) and α_h, b_h, and c_h empirical constants of Hargreaves equation ($a_h = 0.0023$ $°C^{-1.5}$, $b_h = 17.8$ °C, $c_h = 0.5$). This method is considered a temperature based method.

Hargreaves and Samani (1982) calculated solar radiation (R_s) as:

$$R_s = 0.162(T_{max} - T_{min})^{0.5} R_\alpha \quad (4)$$

The units of constant 0.162 of Eq. (4) are in $(°C)^{-0.5}$.

2.4. FAO-24 Makkink method

Makkink (1957) assumes that most of the evapotranspiration takes place due to the energy from radiation and the difference in temperature (hence energy) between the air above the surface and the surface (Doorenbos and Pruitt, 1977). Both energy sources are associated with and can be expressed by solar radiation. The equation is given as: