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A parsimonious regional parametric evapotranspiration model based on a simplification of the Penman–Monteith formula

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SUMMARY

Evapotranspiration is a key hydrometeorological process and its estimation is important in many fields of hydrological and agricultural sciences. Simplified estimation proves very useful in absence of a complete data set. In this respect, a parametric model based on simplification of the Penman–Monteith formulation is presented. The basic idea of the parametric model is the replacement of some of the variables and constants that are used in the standard Penman–Monteith model by regionally varying parameters, which are estimated through calibration. The model is implemented in various climates on monthly time step (USA, Germany, Spain) and compared on the same basis with four radiation-based methods (Jensen–Haise, McGuiness and Bordne, Hargreaves and Oudin) and two temperature-based (Thornthwaite and Blaney–Criddle). The methodology yields very good results with high efficiency indexes, outperforming the other models. Finally, a spatial analysis including the correlation of parameters with latitude and elevation together with their regionalization through three common spatial interpolation techniques along with a recent approach (Bilinear Surface Smoothing), is performed. Also, the model is validated against Penman–Monteith estimates in eleven stations of the well-known CIMIS network. The total framework which includes the development, the implementation, the comparison and the mapping of parameters illustrates a new parsimonious and high efficiency methodology in the assessment of potential evapotranspiration field.

1. Introduction

Accurate estimation of evapotranspiration has gained scientific interest due to high importance in hydrological modeling, irrigation planning and water resources management. According to Farquhar and Roderick (2007), changes in evaporative demand affect fresh water supplies and have impact on agriculture, the biggest consumer of fresh water. Estimating water requirements for irrigation purposes goes back to 1890 in the USA (Jensen and Haise, 1963).

The vast number of scientific attempts to estimate Potential Evapotranspiration (PET) or Reference Evapotranspiration (ETo) depicts the significant role of evapotranspiration in irrigation water management Those attempts yielded about 50 evapotranspiration models (Lu et al., 2005; McMahon et al., 2013) which can be grouped into seven classes: (i) empirical, (ii) water budget (iii) energy budget, (iv) mass transfer, (v) combination, (vi) radiation and (vii) measurement (Xu and Singh, 2001).

The plethora of models and frameworks arises from the complexity of the physical phenomenon, the availability of the necessary hydrometeorological data and the variability of local climatic conditions.

The Penman–Monteith formulation (Monteith, 1965,1981) was proposed by FAO as the standard method for computing Potential Evapotranspiration (PET) (Allen et al., 1989) and has had numerous successful applications in hydrology and agrometeorology in various hydroclimatic regimes (Wang and Georgakakos, 2007). Basic drawback of the model's applicability is the requirement of several climatic data like temperature, wind speed, relative humidity and radiation. Such measurements are not always easily available or accessible to researchers due to the sparse hydrometeorological stations networks in several regions, e.g. Africa, as well as the instability in the records of radiation and relative humidity (Samani, 2000).

Therefore, the demand of new simplified models in several time scales (Alexandris and Kerkides, 2003; Oudin et al., 2005; Valiantzas, 2013) like radiation-based and temperature-based models, is justified. Several publications (Tabari, 2010; Samaras et al., 2013) demonstrated that radiation-based methods are

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capable for PET estimation. Additionally, many researchers suggest the need for further model calibration (especially in the energy term of radiation) to improve the overall efficiency (Irmak et al., 2003; Zhai et al. 2010; Azhar and Perera, 2011; Thepadia and Martinez, 2012; Tabari and Hosseinzadeh Talaee, 2011; Pereira and Pruitt, 2004).

This study presents a radiation-based model that introduces an innovative approach in the estimation of potential evapotranspiration. This methodology that requires only temperature data incorporates a new concept concerning local calibration needs and produces a parsimonious expression for the potential evapotranspiration estimation by replacing some of the variables and constants that are used in the standard Penman–Monteith model by regionally varying parameters, which are estimated through calibration. The model is implemented and compared to established radiation and temperature based methods using the available data from 53 hydrometeorological stations of USA, Germany and Spain, representing different climate conditions, both arid and humid. Finally, analyses concerning: (a) the parameters' dependence on latitude and (b) the parameters' spatial variability, was performed based on data from the California Irrigation Management Information System (CIMIS – Hart et al., 2009) programme that was introduced by the California Department of Water Resource and the University of California, Davis, in 1982. For the latter, the calibration procedure incorporates 39 CIMIS stations, while the validation is made against the calculated parameter values from a set of 11 additional stations.

2. Materials and methods

2.1. Penman–Monteith model and radiation-based methods

The classic model of the Penman–Monteith (Monteith, 1965) equation to estimate potential evaporation or evapotranspiration is expressed as:

$$\mathrm{PET} = \frac{\Delta}{\Delta + \gamma'} \frac{R_n}{\gamma} + \frac{\gamma}{\Delta + \gamma'} F(u) D, \quad \gamma' = \gamma\left(1 + \frac{r_s}{r_a}\right) \tag{1}$$

where PET is potential evaporation or evapotranspiration (mm/d), R_n is net radiation at the surface Δ is the slope of the saturation vapor pressure curve, γ is psychometric coefficient while r_s and r_a are the surface and aerodynamic resistance factors.

Jensen and Haise (1963) evaluated 3000 observations of ET as determined by soil sampling procedures over a 35-year period, and developed an equation that requires only the average daily temperature and the extraterrestrial radiation, while one decade later, McGuiness and Bordne (1972) using lysimeter data suggested a slight modification to Jensen's formulation.

Another widely used approach is the Hargreaves model (Hargreaves and Samani, 1982) that estimates the reference evapotranspiration at monthly and daily scale. The method has received considerable attention because it can produce very acceptable results under diverse climates using only temperature and radiation measurements (Shahidian et al., 2013). According to several researchers (Samani, 2000; Xu and Singh, 2002) the method performs poorly in extreme humidity and wind conditions.

A recent study (Oudin et al., 2005), evaluated a number of evapotranspiration methods, on the basis of precipitation and streamflow data from a large sample of catchments in the USA, France and Australia. After extended analysis with the use of four hydrological models, the researchers modified the Jensen and McGuiness model and proposed a generalized radiation-based equation.

Table 1 summarizes the expressions that estimate PET according to the above-mentioned methodologies.

Table 1
Radiation-based methods for potential evapotranspiration estimation.

Method	Jensen and Haise	Mcguiness and Bordne	Hargreaves	Oudin
PET expression	$\frac{R_a T_a}{40\gamma\rho}$	$\frac{R_a T_a + 5}{68\gamma\rho}$	$0.0023 \frac{R_a}{\gamma}(T_\alpha + 17.8)(T_{max} - T_{min})^{0.5}$	$\frac{R_a T_a + 5}{100\gamma\rho}$

PET (mm d^{-1}, equivalent to kg m^{-2} d^{-1} of the dimensionally consistent Penman–Monteith equations) is the potential evapotranspiration, R_a (kJ m^{-2} d^{-1}) is the extraterrestrial shortwave radiation, T_a (°C) is the air temperature, λ is the latent heat of vaporization (kJ kg^{-1}) and ρ is the water density (kg L^{-1}).

2.2. Temperature-based methods

The Thornthwaite model (Thornthwaite, 1948) is the most simplified method and requires only temperature measurements. The model's form is:

$$\mathrm{PET} = 1.6 L_d \left(\frac{10 T_a}{I}\right)^a \tag{2}$$

where PET is the potential evapotranspiration (mm/month), L_d is the daytime length, T_a is the mean monthly air temperature (°C), I is the annual heat index and a is an empirically determined parameter which is function of I.

The Blaney–Criddle method (Blaney and Criddle, 1962) has received worldwide application for the estimation of irrigation demands. The model expression is:

$$\mathrm{PET} = K_p(0.46 T_a + 8.13) \tag{3}$$

where PET is the potential evapotranspiration (mm/month), T_a the mean temperature (°C), K is the monthly consumptive use coefficient and p is the mean daily percentage of annual daytime hours.

2.3. The parametric formula

The need of parsimonious model structure is essential in several fields of water resources sciences (Koutsoyiannis, 2009, 2014). This refers both to the model structure and to the input data, which should be easily available. Most of simplified formulas fail to describe the phenomenon of evapotranspiration due to its high complexity and the varying local climate conditions. Thus, the idea of replacing some variables and constants used in the standard Penman–Monteith (PM) formula by a number of parameters which are regionally varying and estimated through calibration from a reference evapotranspiration sample, constitutes a new appealing strategy for evapotranspiration estimation.

Koutsoyiannis and Xanthopoulos (1999) and Tegos et al. (2009, 2013) examined the structure and the sensitivity of input data in PM model. They concluded that extraterrestrial radiation and temperature dominate in determining potential evapotranspiration. Furthermore, Mamassis et al. (2014) reached to the conclusion that the influence of every meteorological parameter in evaporation is almost linear, with temperature having the greater influence.

By dividing both the numerator and the denominator by Δ, the PM equation can be written in the form:

$$\mathrm{PET} = \frac{1}{\gamma\rho} \frac{R_n + \gamma\lambda F(u) D}{1 + \gamma'/\Delta} \tag{4}$$

In the above expression, the numerator is the sum of a term related to solar radiation and a term related to the rest of meteorological variables, while the denominator is function of temperature.

Based on the previous analysis, a simplification of the Penman–Monteith formula, where the numerator is approximated by a