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Evaluation of a Parametric Approach for Estimating Potential Evapotranspiration across Different Climates

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Abstract

Potential evapotranspiration (PET) is key input in water resources, agricultural and environmental modelling. For many decades, numerous approaches have been proposed for the consistent estimation of PET at several time scales of interest. The most recognized is the Penman-Monteith formula, which is yet difficult to apply in data-scarce areas, since it requires simultaneous observations of four meteorological variables (temperature, sunshine duration, humidity, wind velocity). For this reason, parsimonious models with minimum input data requirements are strongly preferred. Typically, these have been developed and tested for specific hydroclimatic conditions, but when they are applied in different regimes they provide much less reliable (and in some cases misleading) estimates. Therefore, it is essential to develop generic methods that remain parsimonious, in terms of input data and parameterization, yet they also allow for some kind of local adjustment of their parameters, through calibration. In this study we present a recent parametric formula, based on a simplified formulation of the original Penman-Monteith expression, which only requires mean daily or monthly temperature data. The method is evaluated using meteorological records from different areas worldwide, at both the daily and monthly time scales. The outcomes of this extended analysis are very encouraging, as indicated by the substantially high validation scores of the proposed approach across all examined data sets. In general, the parametric model outperforms well-established methods of the everyday practice, since it ensures optimal approximation ofpotential evapotranspiration.

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Keywords: Potential evapotranspiration; Penman-Monteith formula; parametric model; calibration

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1. Introduction

The accurate estimation of evapotranspiration has a great importance in hydrological modeling, irrigation planning and water resources management. Several related studies have been performed during past decades and the attempts of estimating water requirements for irrigation purposes; go back to 1890 in U.S.A (Jensen and Haise, 1963).

More than 50 important evapotranspiration models can be found in literature (Lu et al., 2005, McMahon et al. 2013), which can be grouped into seven categories: (i) empirical, (ii) water budget (iii) energy budget, (iv) mass transfer, (v) combination, (vi) radiation and (vii) measurement (Xu and Singh, 2000).

The variety of models and frameworks is related to the complexity of the natural phenomenon and depends on the wide range of input climate data and local climate conditions.

The Penman-Monteith formulation (Monteith, 1981) for computing potential ET proposed from FAO as standardized method (Allen et al., 1998) That method had numerous successful applications in the fields of hydrology and agrometeorology and in a variety of hydroclimatic regimes (Wang and Georgakakos, 2007). Basic disadvantage of Penman–Monteith model is the simultaneous requirement of several meteorological data as temperature, wind speed, relative humidity and sunshine measures.

The interdependence of these meteorological parameters and their variability in space and time, lead in difficulties to formulate an equation that can be used to estimate ET from various crops under different climate conditions (Temesgen B. et al., 2005). Notably, the difficulties due the sparse hydrometeorological networks in several regions like Africa and the instability in the records of radiation and relative humidity (Samani, 2000) reveals the demand of new simplifies models.

Therefore parsimonious model developed and implemented worldwide, such as radiation-based or temperature-based models (Valiantzas, 2013). From numerous publications (Tabari, 2010; Samaras et al., 2014) demonstrated that radiation-based methods are powerful models for the ET estimation.

In this study a new radiation based model is proposed, which include a new strategy in the estimation of potential evapotranspiration (PET).

2. Overview of PET models

2.1. Penman- Monteith model

The classic model of the Penman-Monteith (1963) equation to estimate potential evaporation or evapotranspiration is represented from the form:

$$\mathrm{PET} = \text{——— \quad ——} \qquad , \ \gamma' = \gamma\,(1 + r_s/r_a) \tag{1}$$

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,$\gamma$is psychometric coefficient while r_s and r_a are the surface and aerodynamic resistance factors.

The FAO Penman–Monteith method was developed by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23.

2.2. Radiation- Based Methods

Jensen and Haise (1963)evaluated 3000 observations of PET as determined by soil sampling procedures over a 35-year period, and developed the following relation. This equation has only known the average daily temperature and extraterrestrial radiation and calculated easily form:

$$PET = \frac{R_a T_a}{40\lambda\rho} \tag{2}$$

One decade later Mcguiness and Bordne (1972) using measured values of lysimeter suggested a slight modification of Jensen's formulation with the expression:

$$PET = \frac{R_a (T_a + 5)}{68\lambda\rho} \tag{3}$$

Another widely used approach is the Hargreaves model (Hargeanes and Samani, 1982) that estimates the reference evapotranspiration at the monthly and daily scale by:

$$\text{PET} = 0.0023 — (T_\alpha + 17.8)\,(T_{\max} - T_{\min})^{0.5} \tag{4}$$

The method has received considerable attention because it can produce very acceptable results under diverse climates using only temperature measurements. According to several researchers (Samani, 2000;Xu and Singh 2002) the method tends fails in extreme humidity and wind conditions.

A recent research (Oudinet al., 2005) evaluated a number of evapotranspiration methods, on the basis of precipitation and streamflow data from a large sample of catchments in U.S., France and Australia. After extended analysis with the use of four hydrological models, the researchers proposed a modification of Jensen and McGuiness model:

$$PET = \frac{R_a (T_a + 5)}{100\lambda\rho} \tag{5}$$

In the four radiation-based formulas PET(mm/d) is the potential evapotranspiration, R_a (kJ $m^{-2}d^{-1}$) is the extraterrestrial shortwave radiation, T_a (°C) is the air temperature, λ latent heat of vaporization (kj/kgr) and p is the water density (kgL^{-1}).

3. Implementation of the parametric approach

3.1. The PET parametric model

Koutsoyiannis and Xanthopoulos (1999), Tegos *et al*. (2013), Tegos *et al.* (2015) examined the structure and the sensitivity of input data in Penmann-Monteith model. They concluded that there are "one to one" relationship between potential evapotranspiration, extraterrestrial radiation and temperature. In the parametric simplification of the Penman-Monteith formula, the numerator is approximated by a linear function of extraterrestrial solar radiation, Ra, while the denominator is approximated by a linear descending function of temperature.

The generalized mathematic equation of the parametric model is:

$$PET = \frac{aS_0 - b}{1 - cT_a} \tag{6}$$

where PET (mm) is the potential evapotranspiration, S_0 (kJ m^{-2}) is the extraterrestrial shortwave radiation, T_a (°C) is the air temperature, and c (°C^{-1}), a ($kgkJ^{-1}$) and b (kg m^{-2}) are parameters.

The mode parameters have physical interpretation of model parameters while:

- The dimensionless term "$a / \lambda\rho$" represents the average percentage of the energy provided by the sun (in terms of R_a) and, after reaching the Earth's terrain, is transformed to latent heat, thus driving the evapotranspiration process.
- Parameter b lumps the missing information associated with aerodynamic processes, driven by the wind and the vapour deficit in the atmosphere.
- The term "$1 - c\ T_a$" approximates "$1 + \gamma'/\Delta$"which is function of surface and aerodynamic resistance and Δ is the slope vapour pressure curve, which is function of T_a.

3.2. Study areas and processes

We used monthly meteorological data from 37 stations distributed over Greece, run by the National Meteorological Service of Greece, from 39 stations of CIMIS hydrometeological network in California, 10 from Germany and finally 4 from Spain.

The organization of the time series and the calculation of potential evapotranspiration with different methods (Penman-Monteith, Parametric, Hargreaves) were carried out using the Hydrognomon software. Finally, the other expression (Jensen, Mcguiness and Oudin) modeled through appropriate spreadsheets.

Every time series was split to two control periods (calibration and validation), where in the first developed the parametric model and in the second tested its predictive ability. At each station, the three parameters of parametric model were calibrated against the reference potential evapotranspiration timeseries. This procedure was automatically employed via a least square optimization technique, embedded in the evapotranspiration module of Hydrognomon. The optimized values of a, b and c were next embedded to the parametric model.

3.3. Evaluation of the new parametric formula in Greece

The distribution of the coefficient of efficiency (CE),introduced by Nash and Sutcliffe (1970), is presented in the Table 1. The results for the parametric model are satisfactory while CE values are greater than 95% at all locations (90% for validation). The globally used radiation-based approaches by McGuiness et al. (1972) and Oudin et al. (2005) present moderate results.

In order to provide a further parsimonious parametric formulas alternative parameterizations were also examined through optimization techniques, i.e. (a) by omitting parameter b, and (b) by omitting b and substituting c by its average value over Greece; in formulation (a) the reduction of CE was negligible.

Table 1 : Distribution of CE values of radiation-based approaches in Greece

CE	Parametric		Mcguiness		Oudin	
	Cal	Val	Cal	Val	Cal	Val
95-100	37	30	0	2	5	2
90-95	0	6	8	9	5	9
70-90	0	1	12	19	12	15
50-70	0	0	15	6	12	7
<50	0	0	2	1	3	4

3.4. Evaluation of the new parametric formula in California and in Europe

The distribution of the CE for the CIMIS stations is presented in Table 2 and for European stations in Table 3. The results for both period and in different climatic regimes are satisfactory for the parametric model, while the average CE in calibration are 94.80% (CIMIS), 96.52% (European) and in validation period are 94.34% (CIMIS) and 90.06% (European). Similar satisfactory results shown Hargreaves model especially in CIMIS network (average

CE 94.39% for the calibration period and 91.80% for the validation period) where the model has been developed, while in European stations the indexes are lower (91.80% in validation period and 87.53% in calibration period). Mcguiness model gives lower results than parametric and Hargreaves with 87.14% in calibration period and 87.76% in the validation period.

Oudin's model which is a modern improved version of radiation-based methods presents moderate results in CIMIS network (52.18% calibration and 46.82% validation period) but quite better results in European stations (89.37 % calibration and 82.82% validation period).

By combining the results with the previous study (Tegos et al., 2013) the model's performance is more acceptable in humid than in arid climatic regimes. Finally, Jensen-Haise model totally failed to produce physical results.

Table 2: Distribution of CE values of radiation-based approaches in CIMIS network

CE	Parametric		Hargreaves		Jensen-Haise		Mcguiness		Oudin	
	Cal	Val	Cal	Val	Cal	Val	Cal	Val	Cal	Val
95-100	26	26	26	23	0	7	16	15	0	0
90-95	11	5	10	7	0	2	6	7	0	0
80-90	2	8	3	9	1	2	10	10	1	0
70-80	0	0	0	0	6	3	3	3	3	5
60-70	0	0	0	0	1	6	2	3	7	4
50-60	0	0	0	0	3	4	1	1	12	6
0-50	0	0	0	0	16	9	1	0	16	24
<0	0	0	0	0	12	6	0	0	0	0

Table3 : Distribution of CE values of radiation-based approaches in European stations

CE	Parametric		Hargreaves		Jensen-Haise		Mcguiness		Oudin	
	Cal	Val	Cal	Val	Cal	Val	Cal	Val	Cal	Val
95-100	10	9	6	0	0	0	0	0	9	1
90-95	4	4	4	6	0	0	0	0	2	8
80-90	0	0	3	7	0	0	0	0	0	2
70-80	0	0	1	1	0	0	7	1	1	1
60-70	0	0	0	0	0	0	3	1	1	1
50-60	0	0	0	0	0	0	3	1	1	0
0-50	0	1	0	0	5	1	2	9	0	1
<0	0	0	0	0	9	13	1	2	0	0

4. Spatial variability of the parameters

4.1. Mapping of the parameters over Greece

Assuming the simplified parameterization, in which b is omitted, we re-calibrated the local values of a and c, and mapped them over Greece, using typical interpolation tools (e.g. Inverse Distance Weighting, Kriging etc.).

As shown in Figure 1 parameter a exhibits a systematic geographical pattern, since it increases from SE to NW Greece, following the increase of sunshine duration and wind velocity as moving from the continental to insular Greece, while parameter c is site-specific.

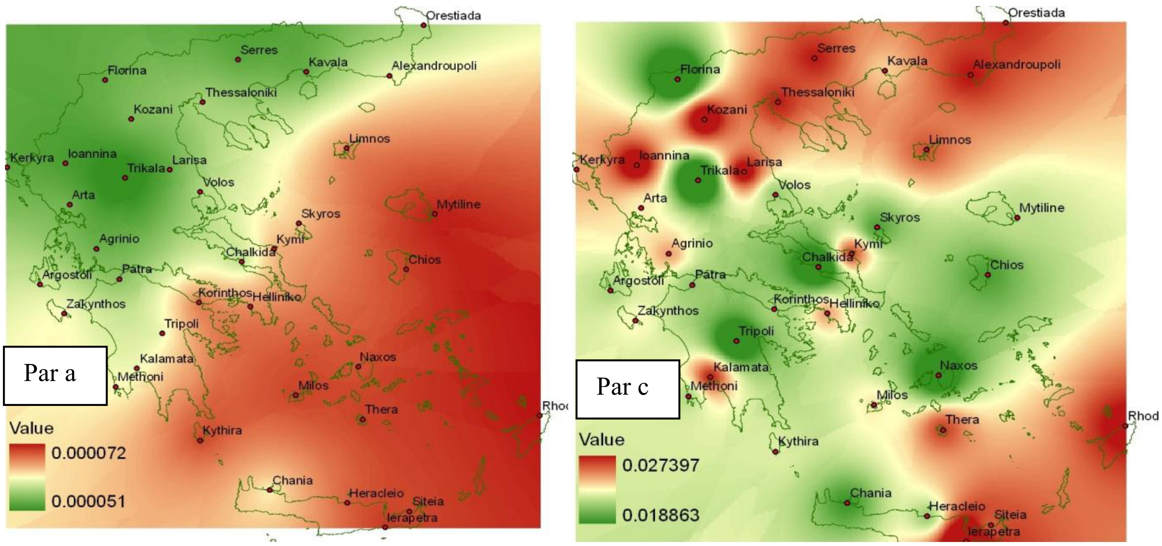

Fig. 1. Geographical distribution of parameters a and c over Greece

4.2. Spatial interpolation of models parameters over California

We implemented three well-known interpolation methods, i.e. Inverse Distance Weighting (I.D.W.), Kriging, Natural Neighbours (NaN) and a recently proposed Bilinear Surface Smoothing (Malamos and Koutsoyiannis, in press) in California territory.

After extended analysis with these alternatives interpolation techniques in a validation set of 11 stations, the Inverse Weighting Distance, i.e. the simplest of interpolation methods, provides the more accurate point estimations of model parameters.

The mapping of the three parameters over California through the I.D.W. approach is illustrated in Figure 2. Generally, we detect that the parameters a, c increase from North to SE and the opposite occurs for the parameter b.

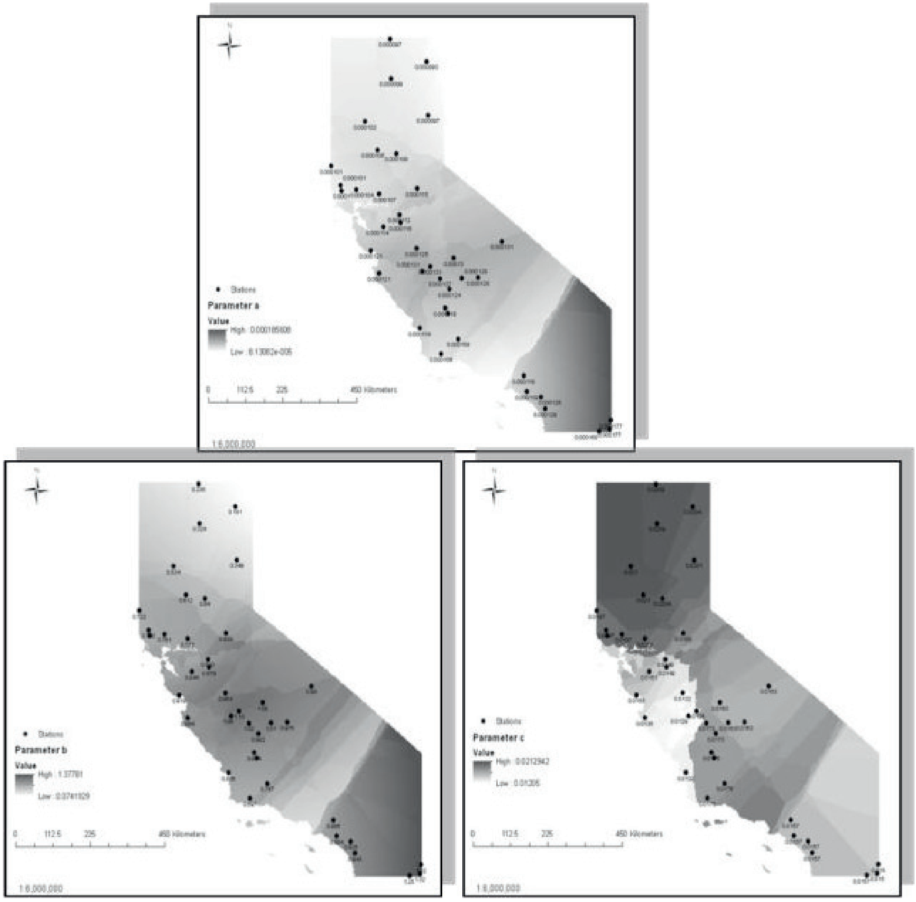

Fig. 2. Geographical distribution of the parameters over California

5. Conclusions

The proposed parametric model can be considered as simplification of the Penman-Monteith formula, in an attempt to compromise parsimony, in terms of model structure and data requirements, and physical consistency. The parameters a, b and c have some physical background, since they substitute, to some extent, the three missing meteorological variables.

The model ensures excellent predictive capacity (in terms of reproducing monthly PET estimations through the Penman-Monteith) in all examined locations in Greece and California, as well as in Germany and Spain (full results shown in Tegos et al. 2015). Additionally even simpler parameterizations in Greece through optimization (i.e. the formulation with two parameters, a and c) provide similarly good results.

The appropriateness of the method is further revealed through extensive comparisons with other radiation-based approaches, most of which exhibit poor performance.

The comparisons across different climates reveal the great advantage of parametric approaches against radiation-based ones, since calibration allows the coefficients that are involved in the mathematical formulas to be fitted to local climatic conditions.

Reliable estimations of PET, both at point basis as well as over extended areas of interest (i.e. river basins), can be obtained by interpolating the known (i.e., locally optimized) parameter values and next employing the parametric formula.

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