Comparative evaluation of 24 reference evapotranspiration equations applied on an evergreen-broadleaved forest

Athanassios Bourletsikas, Ioannis Argyrokastritis and Nikolaos Proutsos

ABSTRACT

Reference evapotranspiration (ET_0) is a major component of the hydrological cycle. Its use is essential both for the hydrological rainfall–runoff assessment models and determination of water requirements in agricultural and forest ecosystems. This study investigates the performance of 24 different methods, which produce ET_0 or potential evapotranspiration estimates above a grass-covered ground in a Mediterranean forest environment in Greece and compares the derived results with those of the presumed most accurate and scientifically acceptable Penman–Monteith method ($ET_{P\text{-}M}$). Their performance was evaluated on a daily basis for a period of 17 years, using 17 different statistical parameters of goodness of fit. The results showed that some empirical methods could serve as suitable alternatives. More specifically, Copais (ET_{COP}), Hargreaves original (ET_{HAR}), and Valiantzas2 (ET_{VA2}) methods, exhibited very good values of the model efficiency index, EF (0.934, 0.932, and 0.917, respectively) and the index of agreement, *d* (0.984, 0.982, and 0.977, respectively). Additionally, the differences of the estimated mean daily value against the respective $ET_{P\text{-}M}$ value (rt index) for all methods had a range of -27.8% (Penman – ET_{PEN}) to $+59.5\%$ (Romanenko – ET_{ROM}), while Copais (ET_{COP}), Hargreaves–Samani modified1 (ET_{HS1}), and STU (ET_{STU}) yielded the best values (-0.06%, $+0.06\%$, and 0.22%, respectively).

Key words | comparative analysis, evergreen-broadleaved forest, FAO56 Penman–Monteith, Mediterranean climate, reference evapotranspiration, western Greece

Athanassios Bourletsikas (corresponding author)
Nikolaos Proutsos
Department of Forest Ecology and Hydrology,
Institute of Mediterranean Forest Ecosystems,
Terma Alkmanos, Ilissia,
Athens,
Greece
E-mail: *mpat@fria.gr*

Ioannis Argyrokastritis
Department of Natural Resources Development and Agricultural Engineering,
Agricultural University of Athens,
Athens,
Greece

INTRODUCTION

Evapotranspiration (ET) is an important component of both the water and energy cycles. ET is used in agricultural and forest hydrometeorology and in urban planning. It is also used in many rainfall–runoff and ecosystem models (Vörösmarty *et al.* 1998; Hay & McCabe 2002; Oudin *et al.* 2005a, 2005b), even for the estimation of ecosystem productivity (Currie 1991). ET also affects significantly regional water availability and use (Zhang *et al.* 2001; Sun *et al.* 2006). In order to carry out a long-term study of hydrological, environmental, and ecological processes, reliable estimates and/or accurate measurements of ET are required (Rosenberry *et al.* 2007; Tabari *et al.* 2011).

The concept of 'reference evapotranspiration' (ET_0) was defined by Doorenbos & Pruitt (1977) as '*the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water*'. Allen *et al.* (1998) evolved an ET_0 definition based on a reference surface (a hypothetical grass and/or alfalfa reference crop) to define unique evaporation parameters for each crop and growth stage. Hence, the FAO Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements accepted the following unambiguous definition for the reference surface: '*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, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered*' (Allen *et al.* 1998). The method proposed by Allen *et al.* (1998) was the FAO56 Penman–Monteith ($ET_{P\text{-}M}$) equation, which was accepted worldwide as the best

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estimator of ET_0 in many regions and in different weather conditions (Droogers & Allen 2002; Xu & Singh 2002; Oudin *et al.* 2005a, 2005b; Alexandris *et al.* 2006; Gavilán *et al.* 2006; Tabari *et al.* 2011; Rahimikhoob *et al.* 2012; Khoshravesh *et al.* 2015; Valipour 2015a, 2015b).

As ET_0 is considered to be the most difficult component to estimate, the wealth of ET_0 methods and empirical equations proposed by many researchers have certain strong points and limitations depending on the methods' applications and assumptions (Rana & Katerji 2000; Grismer *et al.* 2002; Valipour 2014a, 2014b). Additionally, past studies at various scales proved that different ET_0 methods gave widely different values at particular locations (Federer *et al.* 1996; Vörösmarty *et al.* 1998). This means that all these methods cannot be used globally as they need calibration for regional application (Kolka & Wolf 1998; Grismer *et al.* 2002; Xu & Singh 2002; Rosenberry *et al.* 2004; Lu *et al.* 2005; Tabari *et al.* 2011; Rahimikhoob *et al.* 2012; Xu *et al.* 2013; Bogawski & Bednorz 2014; Samaras *et al.* 2014; Valipour & Eslamian 2014; Valipour 2015c). The selection of the appropriate method based on the availability of data, its cost, estimation accuracy, operational time and space scales, is challenging.

There are many methods in the literature used for the estimation of ET_0. These methods can be grouped into categories depending on the variables needed for input. The main categories reported in the literature are: mass-transfer, temperature-based, radiation-based, pan-evaporation, and combination. Many researchers reported overviews by using these methods and categories (Jensen *et al.* 1990; Xu & Singh 2002; Rosenberry *et al.* 2004, 2007; Oudin *et al.* 2005a; Alexandris *et al.* 2008; Trajkovic & Kolakovic 2009; Tabari *et al.* 2011; Xystrakis & Matzarakis 2011; Xu *et al.* 2013; Valipour 2014c) in different areas and environments.

It would be really interesting to investigate the performance of the ET_0 methods in a forested area because: (1) forests affect the climatic status variability since they influence the hydrological and carbon cycles at regional and global scale (Houghton 1991; Musselman & Fox 1991; Nepstad *et al.* 1994) and (2) it is well established that forested sites and catchments have higher ET rates than grassed catchments (Zhang *et al.* 2001). In the literature there is a lack of studies dealing with ET_0 in forests. This is due to the costly equipment requirements (lysimeters, eddy covariance towers, etc.) and to the fact that the main interest of the scientific community focuses on agriculture (Fisher *et al.* 2005; Alexandris *et al.* 2008).

Such studies have been performed mainly in coniferous species. Indicatively, McNaughton & Black (1973) measured the ET in a Douglas fir forest for 18 days and came up with a proposed estimation method. Scholl (1976) determined the ET in a Chaparral stand. Spittlehouse & Black (1980) used the Bowen ratio/energy balance method to measure the ET of a thinned Douglas fir forest. Riekerk (1985) measured the ET of a young splash pine stand (*Pinus elliottii*) with lysimeters for 2 years. Stannard (1993) evaluated three ET models in a sparsely vegetated, semi-arid rangeland. Federer *et al.* (1996) used specific coefficients to estimate the potential evapotranspiration (PET) in different forested areas. Farahani & Ahuja (1996) worked in partial canopy/residue-covered fields. Kolka & Wolf (1998) modified the Thornthwaite model in order to estimate the actual ET in 29 forested sites. Fisher *et al.* (2005) compared five models of PET in a mixed (dominant species *Pinus ponderosa*) coniferous forest. Ha *et al.* (2015) worked in semi-arid high-elevation disturbed ponderosa pine forests and compared ET between eddy covariance measurements and meteorological and remote sensing-based models.

To our knowledge, except for Gebhart *et al.* (2012) who studied some temperature-based and radiation-based methods in northern Greece, there have been no reports for comparative evaluation of the behavior of ET_0 methods in forested areas of Greece. Other studies conducted in Greece used meteorological data from the Greek National Meteorological Service (Xystrakis & Matzarakis 2011; Samaras *et al.* 2014) exclusively for urban and agricultural areas. The meteorological stations that provided the data did not always follow the protocols imposed by the FAO (Alexandris *et al.* 2013). Moreover, there has not been such a study in the Mediterranean forests containing evergreen sclerophyllous broadleaved species.

For the above reasons, the main objective of this study was to test and evaluate the accuracy of different ET_0 estimation equations, taking into account the data requirements for each model and making the assumptions that: (1) the $ET_{P\text{-}M}$ model is the best estimator for the ET_0 and (2) the environmental conditions of the site approximate the conditions for the application of the $ET_{P\text{-}M}$ model. The 24 selected equations are very common, extensively used in other studies, and represent the four main categories (mass-transfer, temperature-based, radiation-based, and combination).

The models tested in this work produce ET_0 or PET estimates above ground covered with grass in a Mediterranean forest environment in Greece. The results will be useful to other researchers for incorporating them as input into hydrological, environmental, and soil models applied on similar Mediterranean vegetative and climatic conditions.

MATERIALS AND METHODS

Site description

The study was carried out in a small experimental forest watershed (1.23 km^2) covered by evergreen sclerophyllous broadleaved vegetation (*maquis* vegetation) in Western Greece close to Varetada village (Figure 1). This is a multi-layer, dense coppice forest with canopy closure 1.2–1.3 (tree canopies overlap). The understorey is dominated by *Phillyrea latifolia, Arbutus unedo*, and *Erica arborea*. Sporadic stems of *Cercis siliquastrum* and *Erica verticilata* are also present. In the upper storey there is a number of *Quercus ilex* stems distributed almost uniformly (Baloutsos *et al.* 2009). The height of all species varies from 4 to 15 m. The terrain is hilly and the soil is a Haplic Luvisol one (FAO 1988) and its parent material is flysch.

The site receives a mean annual amount of precipitation of 1,174 mm in the form of rain which ranges from 696 to 2,230 mm, as calculated from climatic data of the period 1996–2012. The wettest months are October (161 mm) and November (130.8 mm) and the driest ones July (46 mm) and June (46.5 mm). The mean annual air temperature is 15.6 °C. The coldest month is January with a mean monthly value of 7.1 °C with August being the hottest (25.5 °C) one. The mean annual relative humidity is 67.5% with an average of 80% during December and 59% during June. The average annual wind speed is 1.9 m/s with a monthly average value of 2.4 m/s during July and 1.5 m/s during December.

The wider area is classified in the Csa climatic type according to the Köppen–Geiger updated world map (Kottek *et al.* 2006), which shows seasonal variability (warm temperate rainy climates with mild winters and very hot dry summers).

The particular site was selected for forest research purposes for two reasons: (1) the *maquis* vegetation is one of the most representative vegetations in Mediterranean forest ecosystems and (2) the watershed is a long way from urban and industrial areas, so it is not likely that it receives any kind of pollution. Additionally, the entire existing forest has not been managed by the local Forest Service for over 40 years; therefore, there has not been any land use change for the same period of time.

Meteorological data (evaluation and processing)

The meteorological data were collected from an automatic meteorological station (latitude $38^\circ\ 50'\ 35''$, longitude $21^\circ\ 18'\ 25''$, elevation 332 m a.s.l.) installed in a natural forest opening inside the watershed. The main advantage

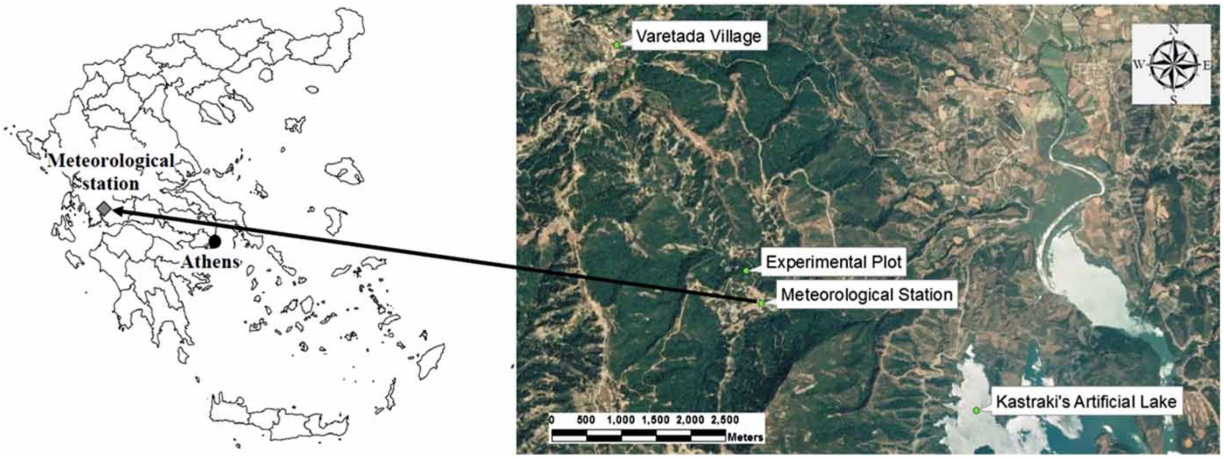

Figure 1 | The location of the forest meteorological station in Greece.

of the location and the ground vegetation of the meteorological station is that they meet the specifications imposed by the FAO to avoid (as much as possible) significant and systematic cumulative errors in determining ET_0 (from 27% up to 47% during the warm season – Alexandris *et al.* 2013). Meteorological variables, such as air temperature (T_{aver}, T_{max}, T_{min}), relative humidity (RH_{aver}, RH_{max}, RH_{min}), solar radiation (R_s), wind speed (u_2), and precipitation (PR) were continuously recorded for a time period of 17 years (1996–2012). All sensors were set at 2 m above the ground level except for the rain gauge which was at a height of 1.3 m. The sampling period for all the monitored variables was set up to 15 min and the collected data were stored in a digital datalogger connected to the sensors. The data were periodically downloaded to be summarized and provide hourly, daily, monthly, and annual averages. These values constituted the input data used for the estimation of the daily values of ET_0 in all of the equations.

For the present study, daily data covering the 87.5% of the total length of the 17-year period (5,433 days) were used. The existing gaps (12.5% or 777 daily values: 356 in winters, 114 in springs, 100 in summers, and 207 in autumns) were randomly distributed and were excluded from the statistical analysis, since any gap filling could possibly affect the reliability of the results. The gaps were due to the lack of measurements of some parameters that made the application of the $ET_{P\text{-}M}$ equation prohibitory. In some cases, some of the methods included in this study estimated a negative ET_0 daily value. These values were also excluded from the statistical analysis. A summary of the notations, definitions, and the units of the symbols used are shown in Table 1.

ET_0 estimation equations

The 24 different equations used in this study were categorized in the following groups: five mass-transfer (Albrecht,

Table 1 | Notations, definitions, and units used in all equations for the estimation of the ET_0

Notation	Definition	Unit
ET	Evapotranspiration	mm/day
Δ	Slope of vapor pressure curve	kPa/°C
λ	Latent heat of vaporization	MJ/kg
ρ	Water density	=1.0 kg/l
γ	Psychrometric constant	kPa/°C
e_s	Saturation vapor pressure	kPa
e_a	Actual vapor pressure	kPa
u_2	Wind speed at 2 m above ground surface	m/s
T_{aver}	Mean daily air temperature	°C
R_n	Net solar radiation	MJ/m^2/day
C_1 and C_2	Functions of the attributes R_s, T_{aver} and RH_{aver}	mm/day
G	Soil heat flux density	=0 MJ/m^2/day for daily computations (ASCE-EWRI 2005)
R_s	Incident shortwave solar radiation flux	MJ/m^2/day
R_a	Extraterrestrial solar radiation	MJ/m^2/day
T_{max}	Maximum daily air temperature	°C
T_{min}	Minimum daily air temperature	°C
PR	Precipitation	mm
N	Maximum possible duration	hrs
RH_{aver}	Mean daily relative humidity	%
φ	Latitude	Rad
α	Albedo	=0.23

Note: For details needed for the computation of the parameters which were not measured directly, refer to Allen *et al.* (1998).

Mahringer, Penman, Romanenko, and WMO), four combination (Copais, Solar Thermal Unit, Valiantzas (1) and (2)), ten radiation-based (Abtew, Caprio, De Bruin–Keijman, FAO24 Radiation, Jensen–Haise, Hansen, Makkink, McGuiness–Bordne, Priestley–Taylor and Turc), and five temperature-based (Hargreaves original, Hargreaves–Samani, two modified Hargreaves–Samani, and modified Thornthwaite) methods. The formulas of the equations are presented in Table 2 along with their references. The conversion of the units is in agreement with the units shown in Table 1.

Statistical analysis

There are many widely used statistical indices and coefficients to evaluate the systematic quantification of the accuracy of compared models (Willmott 1982; Berengena & Gavilán 2005; Alexandris *et al.* 2008; Valiantzas 2013). A great number of them was selected in this study aiming to facilitate further comparison of the results with those of other studies.

The computational formulas for all indices and coefficients except of mean value (MV), standard deviation (SD), coefficient of determination (R^2), and the coefficients of the linear trend line *a* (slope) and *b* (intercept) are the following:

Correlation

$$\text{Correl} = \frac{\sum_{i=1}^{n}(E_i - E_{aver})(O_i - O_{aver})}{\sqrt{\sum_{i=1}^{n}(E_i - E_{aver})^2 \sum_{i=1}^{n}(O_i - O_{aver})^2}}$$

$$\text{Mean bias error} = \text{MBE} = \frac{\sum_{i=1}^{n}(E_i - O_i)}{n}$$

$$\text{Mean absolute error} = \text{MAE} = \frac{\sum_{i=1}^{n}|E_i - O_i|}{n}$$

$$\text{Root mean square error} = \text{rMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_i - O_i)^2}$$

$$\text{Average absolute error} = \text{AAE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}|E_i - O_i|}$$

$$\text{Relative mean square error} = \text{RMSE} = \frac{\sum_{i=1}^{n}((E_i - O_i)/E_i)^2}{n}$$

$$\text{Relative mean absolute error} = \text{RMAE} = \frac{\sum_{i=1}^{n}|(E_i - O_i)/E_i|}{n}$$

Index of agreement =

$$d = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(|E_i - O_{aver}| + |O_i - O_{aver}|)^2}$$

$$\text{Weighted determination coefficient} = \text{wR}^2 = \frac{R^2}{a},$$

$$\text{where } a > 1,\ \text{wR}^2 = R^2 \times a,\ \text{where } a < 1$$

Variance of distribution of differences =

$$S_d^2 = \frac{\{\sum_{i=1}^{n}(E_i - O_i - MBE)\}^2}{n-1}$$

$$\text{Model efficiency} = \text{EF} = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{aver})^2}$$

$$\text{Long-term average ratio} = \text{rt} = \frac{\text{E}_{\text{aver}}}{\text{Long term Mean of ET}_{\text{P-M}}}$$

where E_i and E_{aver} are the predicted daily and the average of the ET_0 method values, respectively, O_i and O_{aver} are the calculated daily and the average of the $\text{ET}_{\text{P-M}}$ values, respectively, and n is the total number of data.

Specifically, Correl, R^2, *a* and *b* indices, of the least squared regression analysis, are commonly used correlation measures. The MV and SD indices provide a general view of the models' performance. For more efficient model assessment, Krause *et al.* (2005) suggest the use of the combined index wR^2. For the mean error evaluation, MBE, S_d^2, and rMSE indices were used (Fox 1981; Berengena & Gavilán 2005). For the absolute and/or relative errors' estimation, MAE, AAE, RMSE, and RMAE indices were also calculated, so as to facilitate the discussion in this work, since they are widely reported in the literature (Xystrakis & Matzarakis 2011; Gebhart *et al.* 2012; Kisi 2014; Samaras *et al.* 2014). The descriptive *d* index was used for the

Table 2 | Formulas, symbols, and references of the ET_0 equations

	Method	Symbol	Equation	References
Benchmark equation				
1	FAO56 Penman–Monteith	$ET_{P\text{-}M}$	$= \dfrac{0.408\,\Delta(R_n - G) + \gamma \dfrac{900}{T_{aver} + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$	Allen *et al.* (1998)
Mass-transfer equations				
2	Albrecht	ET_{ALB}	$= F(e_s - e_a)$, where $F = 0.4$ if $u_2 \geq 1$ m/s and $F = 0.1005 + 0.297\,u_2$ if $u_2 < 1$ m/s	Albrecht (1950) and Friesland *et al.* (1998)
3	Mahringer	ET_{MAH}	$= 0.15072\,\sqrt{3.6\,u_2}(e_s - e_a)$	Mahringer (1970) and Tabari *et al.* (2011)
4	Penman	ET_{PEN}	$= 0.35\left(1 + \dfrac{0.98}{100\,u_2}\right)(e_s - e_a)$	Penman (1948) and Tabari *et al.* (2011)[a]
5	Romanenko	ET_{ROM}	$= 4.5\left[1 + \left(\dfrac{T_{aver}}{25}\right)\right]^2\left(1 - \dfrac{e_a}{e_s}\right)$	Oudin *et al.* (2005a, 2005b) and Xystrakis & Matzarakis (2011)
6	WMO	ET_{WMO}	$= (0.1298 + 0.0934\,u_2)(e_s - e_a)$	WMO (1966) and Tabari *et al.* (2011)[b]
Combinations equations				
7	Copais	ET_{COP}	$= m_1 + m_2C_2 + m_3C_1 + m_4C_1C_2$ where $m_1 = 0.057$, $m_2 = 0.277$, $m_3 = 0.643$, $m_4 = 0.0124$	Alexandris *et al.* (2006, 2008)[c,d]
8	Solar Thermal Unit	ET_{STU}	$= 6.1\,\times 10^{-9}\,R_s\,(1.8T_{aver} + 1)$	Caprio (1974)
9	Valiantzas (1)	ET_{VA1}	$= 0.0393R_s\sqrt{T_{aver} + 9.5} - 0.19R_s^{0.6}\varphi^{0.15}\ + 0.078\,(T_{aver} + 20)\left(1 - \dfrac{RH_{aver}}{100}\right)$	Valiantzas (2013)
10	Valiantzas (2)	ET_{VA2}	$= 0.0393R_s\sqrt{T_{aver} + 9.5} - 0.19R_s^{0.6}\varphi^{0.15}\ + 0.0061\,(T_{aver} + 20)(1.12T_{aver} - T_{min} - 2)^{0.7}$	Valiantzas (2013)
Radiation-based equations				
11	Abtew	ET_{ABT}	$= \dfrac{1}{56}\dfrac{R_sT_{max}}{\lambda}$	Abtew (1996) and Samaras *et al.* (2014)
12	Caprio	ET_{CAP}	$= 1.65\,\dfrac{\Delta}{\Delta + \gamma}\left(\dfrac{R_n - G}{\lambda}\right)$	Caprio (1974) and Samaras *et al.* (2014)
13	De Bruin–Keijman	ET_{DBK}	$= \left(\dfrac{\Delta}{0.85\Delta + 0.63\gamma}\right)\left(\dfrac{R_n - G}{\lambda}\right)$	DeBruin & Keijman (1979) and Rosenberry *et al.* (2007)
14	FAO24 Radiation	ET_{F24}	$= b\left(\dfrac{\Delta}{\Delta + \gamma}R_s\right) - 0.3$	Doorenbos & Pruitt (1977) and Frevert *et al.* (1983)[e]

(*continued*)

Table 2 | continued

	Method	Symbol	Equation	References
15	Hansen	ET_{HAN}	$= 0.7\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{R_s}{\lambda}\right)$	Hansen (1984) and Xu & Singh (2002)
16	Jensen–Haise	$ET_{J\text{-}H}$	$= \left(\frac{R_s}{\lambda}\right)(0.025\,T_{aver} + 0.08)$	Rosenberg *et al.* (1983) and Xystrakis & Matzarakis (2011)
17	Makkink	ET_{MAK}	$= 0.61\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{R_s}{\lambda}\right) - 0.12$	Rosenberry *et al.* (2004) and Alexandris *et al.* (2008)
18	McGuinness–Bordne	ET_{MGB}	$= \left(\frac{R_a}{\lambda\rho}\right)\left(\frac{T_{aver}+5}{68}\right)$	McGuinness & Bordne (1972) and Oudin *et al.* (2005a, 2005b)
19	Priestley–Taylor	$ET_{P\text{-}T}$	$= a\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{R_n}{\lambda}\right)$	Priestley & Taylor (1972)[f]
20	Turc	ET_{TUR}	$= 0.013\left(\frac{T_{aver}}{T_{aver}+15}\right)(R_s+50)$, for $RH_{aver} > 50\%$	Turc (1961) and Lu *et al.* (2005)
			$= 0.013\left(\frac{T_{aver}}{T_{aver}+15}\right)(R_s+50)\left(1+\frac{50-RH_{aver}}{70}\right)$, for $RH_{aver} < 50\%$	
21	Hargreaves (original)	ET_{HAR}	$= 0.0135\ R_s\ (T_{aver} + 17.8)$	Hargreaves (1975)
22	Hargreaves–Samani	$ET_{H\text{-}S}$	$= 0.0023\ \sqrt{(T_{max} - T_{min})}(T_{aver} + 17.8)\ 0.408\ R_a$	Hargreaves & Samani (1985)
23	Hargreaves–Samani (modified 1)	ET_{HS1}	$= 0.0030\ (T_{max} - T_{min})^{0.4}(T_{aver} + 20)\ 0.408\ R_a$	Droogers & Allen (2002)
24	Hargreaves–Samani (modified 2)	ET_{HS2}	$= 0.0025\ \sqrt{(T_{max} - T_{min})}(T_{aver} + 16.8)\ 0.408\ R_a$	Droogers & Allen (2002)
25	Thornthwaite (modified)	ET_{THO}	$= 0.533\ \frac{N}{12}\left(\frac{10\ T_{aver}}{WI}\right)^{A}$, where $WI = 33.617$ and $A = 1.033$	Siegert & Schrodter (1975)

[a] e_s and e_a are in mmHg and u_2 is in miles/day.

[b] e_s and e_a are in hPa.

[c] In the original paper (Alexandris *et al.* 2006) the coefficient m_2 is 0.227 due to a misprint and should be replaced with the correct value 0.277 (Alexandris *et al.* 2008).

[d] $C_1 = 0.6416 - 0.00784\ RH_{aver} + 0.372\ R_S – 0.00264\ RH_{aver}$; $C_2 = -0.0033 + 0.00812\ T_{aver} + 0.101\ R_S + 0.00584\ R_S T_{aver}$.

[e] $b = 1.066 – 0.13 \times 10^{-2}\ (RH_{aver}) + 0.045\ (u_2) – 0.20 \times 10^{-3}\ (RH_{aver} \times u_2) – 0.135 \times 10^{-4}\ (RH_{aver})^2 – 0.11 \times 10^{-2}\ (u_2)^2$.

[f] $a = 1.26$ = Priestley–Taylor's empirically constant, dimensionless.

cross-comparison between the models, expressing the degree to which a model's predictions are error free (Willmott 1982). Finally, the EF index specifies the relationship between calculated and predicted mean deviations (Greenwood *et al.* 1985), while rt returns a long-term value of the predicted against the calculated MVs.

RESULTS AND DISCUSSION

On an annual basis, the average observed ET_0 rate calculated from the $ET_{P\text{-}M}$ for the period 1996–2012, was found to be 1,190 mm. This value is a little different from the mean annual precipitation (1,174 mm) and specifically indicates that the water requirements of a reference crop are totally sufficed. Additionally, the mean seasonal values of ET_0 showed seasonal variation, as expected for the Mediterranean climate (Csa), varying from 99 mm (winter) to 558 mm (summer) and moderate values during the transitional periods of spring and autumn (307 mm and 226 mm, respectively).

From the analysis of the annual values, the best approaches seem to give the ET_{HS2}, ET_{COP}, and ET_{STU} methods, in which the percentages of ET_0 average annual values diverge by +0.47%, −0.69%, and −2.27%, respectively. In contrast, the largest annual deviations appeared in the ET_{ROM} (+60.85%), ET_{MAK} (−26.47%), and ET_{PEN} (−26.23%) methods. These results were in line with Federer *et al.* (1996), who reported that different methods gave widely differing estimates of annual ET_0 at particular locations which sometimes were up to several hundreds of millimeters.

From the analysis of 5,433 daily values with 18 different statistical parameters and indices, the 24 tested methods were evaluated comparatively. Their performance against the $ET_{P\text{-}M}$ method is shown in Figure 2 and Table 3 and the obtained results are the following.

Mass-transfer equations

Among the five examined methods, the ET_{PEN} showed average daily ET_0 equal to 2.44 mm, a value significantly lower (−27.8%, $rt = 0.722$) compared to the corresponding $ET_{P\text{-}M}$. Simultaneously, it displayed the smallest correlation coefficient ($R^2 = 0.826$). The approaches of the average daily ET_0 of the ET_{ALB}, ET_{WMO}, and ET_{MAH} were very similar, with deviations of +9.1% ($rt = 1.091$), −9.9% ($rt = 0.901$), and +13.0% ($rt = 1.131$), respectively. However, their R^2s are not considered satisfactory (0.830, 0.855, and 0.860 respectively). Finally, the ET_{ROM} method displayed the worst statistics for almost all of the evaluation indices.

It is worth noting that this category of methods resulted in the smallest EF index ranging from −0.437 (ET_{ROM}) to 0.759 (ET_{WMO}). Overall, the statistical indices of the mass-transfer equations were not satisfactory (Table 3). Hence, these methods cannot be recommended for use without calibration, in models that need the input of ET_0 daily values. Similar results were reported by Valipour (2014b, 2015c), who examined R^2 and MBE and suggested new calibrated mass-transfer equations for the provinces of Iran which relatively improved the performance of the original models.

In our study (forest environment with warm humid Mediterranean climate), except for ETP_{PEN}, the high summer daily values (>5 mm) are overestimated with the mass-transfer equations. Although Tabari *et al.* (2011) reported that the majority of the mass-transfer empirical equations they tested, had also the worst performances but at the same time underestimated $ET_{P\text{-}M}$ in humid environments. This could be attributed to the fact that VPD ($e_s - e_a$) presents significant variations among locations, as stated by Irmak *et al.* (2006), who performed a sensitivity analysis of the Penman–Monteith method for several regions with different climate types, in the USA.

Combination equations

Combination methods, in general, showed much better statistical indices compared to the methods of all other categories (Table 3). The four methods examined here presented sufficiently strong correlations (R^2 is ranging from 0.937 in ET_{COP} to 0.958 in ET_{VA1}), compared to $ET_{P\text{-}M}$. However, the rt was significantly lower in ET_{COP} deviating only by −0.6% ($rt = 0.994$), compared to the other three methods, while ET_{VA1} presented the greatest divergence (+11.3%, $rt = 1.113$). Impressive was the finding that despite the relatively small R^2 of ET_{COP}, most of the other statistical indices outweighed the respective indices which derived from the analysis of all 24 tested methods (Table 3). Similar results for the ET_{COP}, ET_{VA1}, and ET_{VA2} equations were presented by Kisi (2014) in a Mediterranean environment in Turkey. The findings of Valipour (2015b) in Iran for the Valiantzas' equations are also in line with the results presented here.

The ET_{STU} method also gave satisfactory results ($rt = 0.978$, $R^2 = 0.955$) despite the small requirements in input data. These methods are strongly recommended for use in models which need the input of ET_0 daily values because they have a very satisfactory EF index ranging from 0.894 (ET_{STU}) to 0.934 (ET_{COP}).

Radiation-based equations

In this category ten methods were tested. The radiation-based equations overall performed better than the mass-transfer

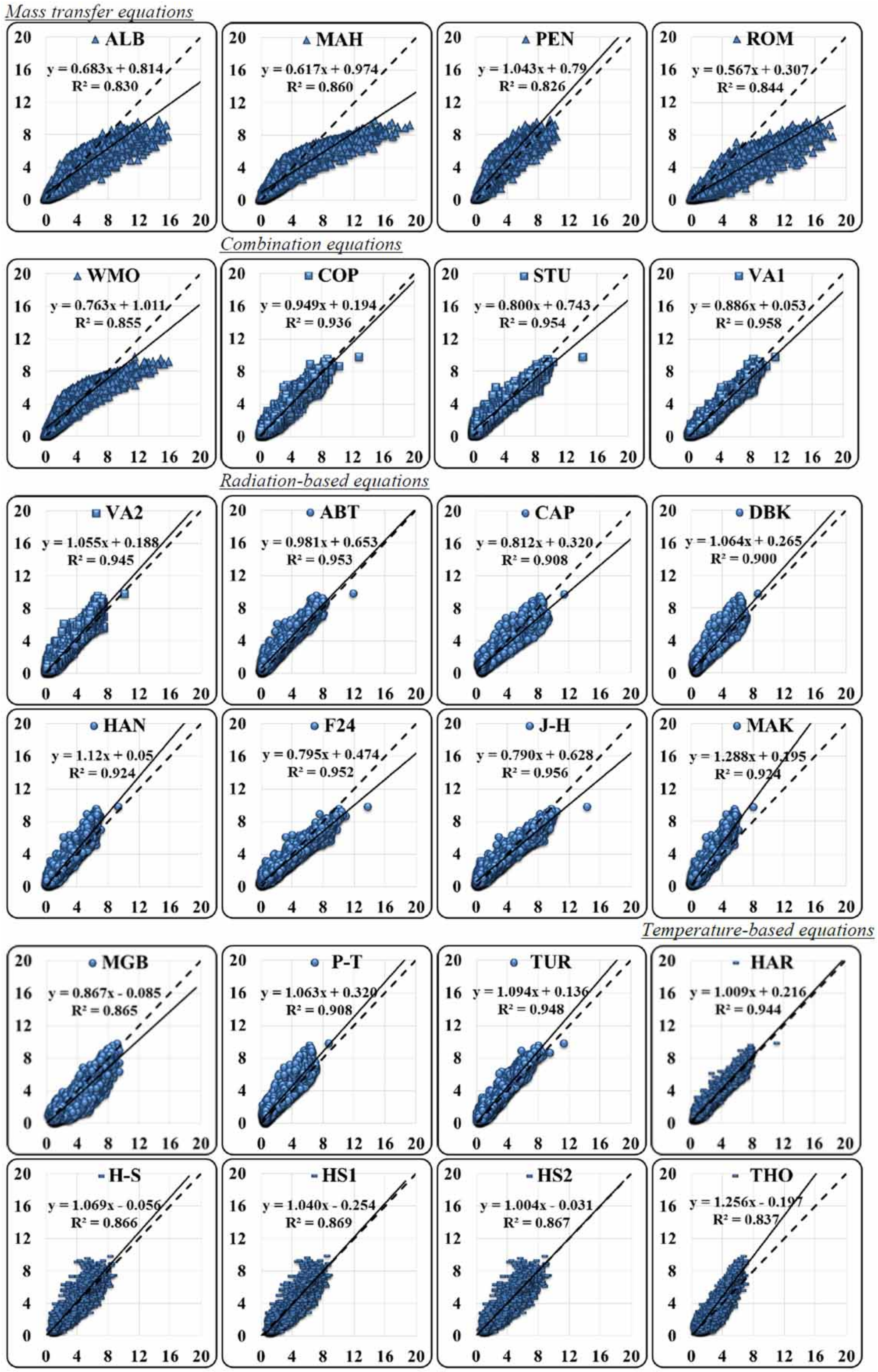

Figure 2 | R^2 coefficient, slope, and intercept of the daily values of ET_0 (in mm) estimated by various methods (x axis) vs. the standardized $ET_{P\text{-}M}$ (y axis). The continuous line in all figures indicates the trendline of the scatter and the dashed line indicates the 1:1 slope trend. The point shapes for each category differ.

Table 3 | Statistical analysis of the 24 methods versus the FAO56 PM model for estimating daily ET_0 during the study period (1996–2012)

A/A	Categories	Symbol	N	Mean (mm)	SD (mm)	rt	Correl	MBE (mm)	MAE (mm)	rMSE (mm)	rMAE (mm)	RMSE (mm)	RMAE (mm)	*d*	wR^2	S_d^2 (mm)	EF
1		$ET_{P\text{-}M}$	5,433	3.380	2.196												
2	Mass-transfer methods	ET_{ALB}	5,414	3.687	2.900	1.091	0.911	0.379	0.901	1.348	0.949	1.381	0.863	0.928	0.567	1.673	0.625
3		ET_{MAH}	5,414	3.821	3.265	1.131	0.927	0.523	0.984	1.593	0.992	1.066	1.078	0.914	0.531	2.265	0.475
4		ET_{PEN}	5,414	2.440	1.895	0.722	0.909	−0.897	0.990	1.283	0.995	0.757	0.737	0.905	0.654	0.843	0.660
5		ET_{ROM}	5,414	5.392	3.611	1.595	0.919	2.046	2.099	2.642	1.449	0.293	0.604	0.811	0.478	3.117	−0.437
6		ET_{WMO}	5,414	3.046	2.635	0.901	0.925	−0.270	0.773	1.080	0.879	2.026	1.278	0.949	0.652	1.094	0.759
7	Combination methods	ET_{COP}	5,428	**3.360**	2.241	**0.994**	0.968	**−0.022**	**0.442**	**0.564**	**0.665**	0.438	0.325	**0.984**	**0.921**	0.318	**0.934**
8		ET_{STU}	5,426	3.306	2.681	0.978	0.977	−0.079	0.569	0.715	0.755	1.940	0.704	0.978	0.764	0.513	0.894
9		ET_{VA1}	5,425	3.763	2.423	1.113	**0.978**	0.375	0.523	0.649	0.723	1.214	0.294	0.980	0.849	0.281	0.913
10		ET_{VA2}	5,367	3.051	2.023	0.903	0.972	−0.355	0.468	0.635	0.684	2.024	0.364	0.977	0.847	0.278	0.917
11	Radiation-based methods	ET_{ABT}	5,430	2.783	2.186	0.824	0.976	−0.600	0.623	0.766	0.789	1.857	0.827	0.970	**0.926**	**0.227**	0.878
12		ET_{CAP}	5,433	3.772	2.579	1.116	0.953	0.391	0.697	0.913	0.835	0.183	0.259	0.963	0.737	0.681	0.827
13		ET_{DBK}	5,433	2.930	1.959	0.867	0.949	−0.452	0.597	0.836	0.773	0.337	0.318	0.959	0.762	0.495	0.855
14		ET_{F24}	5,260	3.763	2.668	1.114	0.976	0.296	0.622	0.783	0.788	2.676	0.975	0.974	0.753	0.526	0.877
15		ET_{HAN}	5,433	2.974	1.884	0.880	0.961	−0.408	0.556	0.765	0.746	0.714	0.339	0.965	0.762	0.418	0.879
16		$ET_{J\text{-}H}$	5,431	3.488	2.719	1.032	**0.978**	0.105	0.575	0.740	0.758	1.697	0.475	0.977	0.755	0.537	0.886
17		ET_{MAK}	5,399	2.487	1.635	0.736	0.901	−0.912	0.926	1.192	0.962	2.603	0.731	0.907	0.662	0.590	0.707
18		ET_{MGB}	5,432	3.876	2.361	1.147	0.930	0.618	0.815	1.063	0.903	**0.133**	0.264	0.945	0.863	0.749	0.766
19		$ET_{P\text{-}T}$	5,433	2.881	1.969	0.852	0.953	−0.501	0.608	0.843	0.780	0.407	0.345	0.959	0.775	0.460	0.853
20		ET_{TUR}	5,419	2.970	1.956	0.879	0.974	−0.414	0.513	0.674	0.716	0.316	0.397	0.974	0.819	0.283	0.906
21	Temperature-based methods	ET_{HAR}	5,433	3.139	2.116	0.929	0.972	−0.244	**0.427**	**0.572**	**0.653**	0.780	0.321	**0.982**	0.884	**0.268**	**0.932**
22		$ET_{H\text{-}S}$	5,433	3.123	1.910	0.924	0.931	−0.167	0.603	0.832	0.777	0.171	0.248	0.958	0.701	0.664	0.856
23		ET_{HS1}	5,433	**3.400**	1.969	**1.006**	0.932	0.116	0.615	0.808	0.784	**0.111**	**0.231**	0.961	0.726	0.640	0.865
24		ET_{HS2}	5,433	3.300	2.034	0.976	0.931	**0.016**	0.590	0.802	0.768	0.154	**0.237**	0.963	0.748	0.643	0.867
25		ET_{THO}	5,423	2.777	1.608	0.822	0.915	−0.532	0.895	1.111	0.946	0.942	0.593	0.913	0.558	0.951	0.744

The two best fitted methods for each index or coefficient are in bold and underlined.

N: Sample days; **Mean**: Time series average; **SD**: Standard deviation; **rt**: long-term average ratio; **Correl**: Pearson's correlation; **MBE**: Mean bias error; **MAE**: Mean absolute error; **rMSE**: Root mean square error; **rMAE**: Root mean absolute error; **RMSE**: Relative mean square error; **RMAE**: Relative mean absolute error; ***d***: Index of agreement; **wR^2**: Weighted determination; **S_d^2**: Coefficient variance of distribution of differences; **EF**: Model efficiency.

equations, since a more important role is expected for R_s when estimating ET_0 in humid climates (Irmak *et al.* 2006) and in forest environments (Gebhart *et al.* 2012). $ET_{J\text{-}H}$ and ET_{ABT} ($R^2 = 0.956$ and 0.953, respectively) methods presented satisfactory correlations. Additionally, the $ET_{J\text{-}H}$ method showed the lowest deviation from the daily MV (+3.2%, rt = 1.032), while ET_{ABT} had the best indices, wR^2 and S_d^2, over all of the 24 tested methods. These findings for $ET_{J\text{-}H}$ are in contrast to Tabari *et al.* (2011), who worked in humid environments.

ET_{TUR} can be considered as the best performing equation in this category, in terms of its EF (0.906), rMAE (0.716), RMSE (0.674), and MAE (0.513). The best performance of the equation was also found by Lu *et al.* (2005) in forest watersheds with warm and humid climates in the southeastern USA, and by Trajkovic & Kolakovic (2009) who recommended ET_{TUR} for use under humid conditions, and by Gebhart *et al.* (2012) who suggested the use of ET_{TUR} for the southern regions of Central Macedonia in Greece.

In contrast, the ET_{MGB} and ET_{DBK} methods gave the worst correlations among all the radiation-based equations ($R^2 = 0.865$ and $R^2 = 0.901$, respectively). Under humid conditions, similar results were reported for ET_{MGB} by Tabari *et al.* (2011). The largest deviations from the daily MV were displayed by ET_{MAK} (−26.4%, rt = 0.736) and ET_{ABT} (−17.6%, rt = 0.824). The EF index ranged from 0.707 (ET_{MAK}) to 0.886 ($ET_{J\text{-}H}$). The poor performance of ET_{MAK} was also reported by Lu *et al.* (2005).

From the above, it can be concluded that some methods (ET_{TUR}, $ET_{J\text{-}H}$, and ET_{ABT}) of this category can be satisfactorily accepted for use in models needing the input of ET_0 daily values.

Temperature-based equations

In this category five methods were tested. The best correlation was exhibited by ET_{HAR} with $R^2 = 0.945$ and the worst by ET_{THO} ($R^2 = 0.837$). Concerning the deviation from the daily MV, the ET_{HS1} gave the best of all 24 tested methods (along with ET_{COP}), with rt = 1.006. These findings were similar to those of Valipour & Eslamian (2014) and Valipour (2015a) who gave specific ranges of the meteorological parameters used in 11 temperature-based equations for Iran's provinces and found a better performance of $ET_{H\text{-}S}$, ET_{HS1}, and ET_{HS2} against ET_{THO}. The results in our study indicated a slight underestimation in ET_0 daily values for all of the tested temperature-based equations (except of ET_{THO} which underestimated by 17.8%). Valipour (2015a) also found a slight underestimation in ET_0 daily values with $ET_{H\text{-}S}$ and ET_{HS1} equations, while the ET_{HS2} equation showed overestimation but not a significant one.

Contrary to these results, Trajkovic & Kolakovic (2009) and Tabari *et al.* (2011) found overestimation when using ET_{HS1}, ET_{HS2}, and $ET_{H\text{-}S}$ equations, on a monthly timestep analysis and under humid conditions. They also found very poor performance of the ET_{THO} equation. Additionally, Lu *et al.* (2005) suggested careful calibration and verification when applying the ET_{THO} equation.

The ET_{HAR} method, despite the small data requirements, exhibited in general impressive statistical indices (e.g., best MAE, rMSE, rMAE, d, S_d^2, and EF values) compared to all tested methods of all categories (Table 3). Gebhart *et al.* (2012) also proposed the ET_{HAR} equation as a good alternative for ET_0 estimations in northern regions of Central Macedonia in Greece. From the above mentioned, it can be concluded that this category of equations seems to have similar performance (with the exception of ET_{THO}) and they are recommended for use in forest environments.

CONCLUSIONS

This study attempted to investigate and evaluate the best-fit methods for the estimation of daily ET_0 in a humid Mediterranean evergreen broadleaved forest environment. Twenty-four different equations classified in four categories were tested and seventeen different statistical indices were used for the evaluation.

At the category level, the combination equations seem to have the best performance followed by temperature-based and radiation-based methods. The mass-transfer methods have the worst coefficients and overestimate ET_0, especially for the high summer daily values (>5 mm).

At the method level, the most accurate and consistent estimates of ET_0 derived from ET_{COP} and ET_{HAR}, followed by ET_{VA1} and ET_{VA2}. The methods ET_{TUR}, ET_{HS2}, ET_{STU}, and $ET_{J\text{-}H}$ are also proposed for use because their ET_0 estimations compared quite well with those of the $ET_{P\text{-}M}$ method. The latter ones can also be used for the annual estimation of the

ET_0. Concerning the rest of the tested methods, it is suggested that calibration should be made for local conditions, mainly at a seasonal time-step to obtain more reliable daily estimates. Especially, calibration is necessary for all the mass-transfer equations and the ET_{MAK} and ET_{THO} methods. There is an ongoing work by the authors, in which new coefficients will be proposed for some of these methods. The results of this study will be useful to a multidisciplinary community working on similar climates. More specifically, the best performing equations in Figure 2 could be tested further in order to optimize the ET_0 obtaining values of the empirical models in the Mediterranean. Further research is needed in order to evaluate the performance of the proposed modified equations in other areas with different climates. Finally, evaluation is needed for the performance of the models on a different time scale (monthly and seasonal).

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