Water Resour Manage (2011) 25:1581–1600
DOI 10.1007/s11269-010-9762-1

Crop Reference Evapotranspiration: A Discussion of the Concept, Analysis of the Process and Validation

Nader Katerji · Gianfranco Rana

Received: 30 November 2009 / Accepted: 6 December 2010 /
Published online: 5 January 2011

Abstract The study at first recalls the concept of "potential evapotranspiration" (PET), originally considered equal to the evaporation climatic demand; then, it reminds the steps of its progressive evolution toward the concept of "reference crop evapotranspiration" (ET_0) determined on irrigated grass. A physical analysis conducted on the evaporation process is subsequently reported to help clarifying the links between ET_0 and evaporation climatic demand. This analysis clearly demonstrates that the equivalence of ET_0 to evaporation climatic demand is not correct, although still common assumption in recent scientific literature, particularly in hydrology. The study also identifies two processes acting in opposite directions in the dynamics of ET_0: (1) the climatic variables determining the evaporation demand, and (2) the canopy resistance which slows down the response of irrigated grass to such demand. The analysis of the respective impact of these two processes on ET_0 dynamics shows that the available energy is the dominant process. This variable takes into account the 60–70% of the variation of ET_0, both at hourly and daily scales, while canopy resistance only explains 10–20% of ET_0 variation of irrigated grass. The study regards different climatic situations. Possible effects on practical applications were also discussed in the conclusions, together with comments on the correct canopy resistance modelling.

Keywords Canopy resistance · Evaporation · Tall crops · Mediterranean climate · Humid climate

N. Katerji
INRA–UMR 1091 EGC, 78850 Thiverval-Grignon, France
e-mail: katerji@bcgn.grignon.inra.fr

G. Rana (✉)
CRA–Research Unit for Agriculture in Dry Environments,
via C. Ulpiani 5, 70125 Bari, Italy
e-mail: gianfranco.rana@entecra.it

1 Introduction

The concept of "potential evapotranspiration" originated in the framework of studies performed by hydrologists, geographers, climatologists and botanists trying to define "aridity" at regional through continental to global scale (see the review by Guyot 1998). The aim was to establish criteria or indices to compare and/or classify time series of climatic variables. Historically, the first climatic indices of aridity combined different types of climatic variables: precipitation and air temperature (De Martonne 1926; Bagnouls and Gaussen 1953; Peguy 1961), precipitation and the difference between maximum and minimum temperatures (Emberger 1930), or precipitation and air vapour pressure deficit (index found by de Meyer in 1926, see the review by Guyot 1998). These indices provided synthetic descriptive variables by combining measured climatic data at large temporal scale (in general yearly means).

A fundamental improvement in the development of the concept of aridity can be ascribed to botanist and climatologist Thornthwaite (1948) who introduced crop water requirements in the calculation of the drought index, through the notions of potential (PET) and actual (AET) evapotranspiration measured at a yearly scale. PET corresponds to a loss of water by a canopy if soil never limits evapotranspiration (Thornthwaite and Wilm 1944). The term "potential" is equivalent to maximum possible level under given climatic conditions. In other words, the potential evapotranspiration is considered as equivalent to the evaporative demand of the atmosphere under given climatic conditions. When soil water depletes, the evapotranspiration will decrease: evapotranspiration also reduces from "potential" to "actual" (AET).

The concept of PET greatly enhanced our knowledge on evaporation in nature particularly by linking this variable to the characteristics of climate for the first time. When a clear definition of PET was given in an international meeting held in Wageningen, The Netherland (Anon 1956) and it was defined as the rate of water vapour loss from a short grass canopy under the following conditions: grown in a large surface, during an active growth stage, completely covering the soil, of homogeneous height, in optimal water and nutritional status. Thus, this ideal crop was rapidly established as the most suitable crop for the comparison and/or the calibration of PET values (Penman 1948; Makking 1957; Stanhill 1961; Turc 1961; Damagnez et al. 1962; McIlroy and Angus 1964; Pruitt 1964; Van Bavel 1966; Sarraf 1973; Riou 1975), with technological advances of weighing lysimeters enabling measurements of PET in larger surfaces and for shorter time scales (see the review by Aboukhaled et al. 1982).

In climatology, and above all in hydrology, the use of the concept of PET has been very useful. The comparison between the values of PET and precipitation (P), expressed in the same units, allows quantification of climatic water deficit and to analyse the aridity of a given environment in more details (Donohue et al. 2007). During a specific year, it is possible to distinguish a humid period (when P > PET) which corresponds to a storage of water in the soil, and a dry period (when PET > P) which corresponds to a climatic deficit (Guyot 1998). The cumulated value of the P-PET difference enables hydrologists to evaluate water balance at different space and time scales (plot, watershed, catchment, region) and to define the water reservoir available in a given area for different water uses (Margat 1992).

The use of PET in agronomy to determine crop water requirements has caused some criticism to this concept, as Blaney and Criddle (1950) noticed that, for most crops, AET > PET during the active growth stage. For more details see the review by Doorenbos and Pruitt (1976). This (i.e., AET > PET) contradicts the meaning of the word "potential" supposing to translate the maximal possible evaporation, i.e. the evaporative atmospheric demand. Thus, crop water requirements specialists suggested abandoning the concept of "potential evapotranspiration, PET" to replace it with the concept of "reference crop evapotranspiration ET_0" (Doorenbos and Pruitt 1976; Perrier 1984) while preserving almost the same definition first provided by Anon (1956). However, new specifications concerning the height of grass (between 8 and 15 cm) were introduced following studies by Doorenbos and Pruitt (1976) as well as suggestions on the precautions to follow to avoid the effects of advection on the measurement (Perrier 1984). Note that this concept is more generic than Allen's et al. (1998) FAO-56 reference crop evapotranspiration which in this paper always explicitly has the symbol "FAO-56 ET_0".

The concept of reference crop evapotranspiration was definitively adopted by the scientific community following the recommendations issued by the International Irrigation and Drainage Commission, during the conference held in Paris in 1984, because of inconsistent use and definition of PET (Perrier 1984). Nowadays, this concept is practically disappeared from international literature, except in hydrology where it is considered as a robust input parameter (Douglas et al. 2009) to model at catchment scale. Recent papers (Lu et al. 2005; Oudin et al. 2005; Weiss and Menzel 2008; Verstraeten et al. 2008; Douglas et al. 2009; Trajkovic and Kolakovic 2009; Hazrat Ali and Yeang Shui 2009; Donohoue et al. 2010) still continue to debate and analyse differences among methods adopted in the calculation of PET.

Despite the changes in nomenclature, doubts still persist regarding both concepts of PET and reference crop evapotranspiration ET_0. These doubts may be formulated through three groups of questions:

1. (1) How to define the evaporation climatic demand or PET? (2) What is the link between this and the ET_0?
2. (3) What are the climatic and biological variables governing ET_0? (4) And what is the relative weight of each?
3. (5) Do these relative weights change in function of the climate type? (6) In which range? (7) And what are the consequences on the determination or modelling of the ET_0?

We have structured this study in order to answer to the ensemble of the above seven questions and to give some conclusions about the correct use of the different definition of "evapotranspiration".

Our theoretical knowledge on evapotranspiration has certainly improved over the last years and, since measurement techniques, mainly micrometeorological practices, nowadays allow the determination of reference crop evapotranspiration with high accuracy (see the review by Katerji and Rana 2008), it is now also possible to add useful elements in the definition of these concepts by trying to answer the above questions.

2 Analysis of Reference Evapotranspiration

2.1 Meaning and Identification of the Process

The theoretical works developed chronologically by Penman (1948, 1956), Monteith (1963, 1965), Thom (1972, 1975), Perrier (1975) first allowed the identification of the physical laws and afterword the biological variables acting in the process of the evapotranspiration. Since the analysis of the evapotranspiration concept in the first decades of the last century was based on an intuitive understanding, all these papers permitted the comprehension of the phenomenon on analytical base. The Table 1 summarizes these main concepts as well as their chronological evolution following the different authors.

To separate the climatic variables from the crop ones (e.g., architecture, the properties of the evaporative surface, the resistances to the diffusion of water vapour) Perrier (1975) proposed a scheme (see Fig. 1) allowing three types of evaporative surfaces to be distinguished:

1. Potential evaporation PE*: i.e., evaporation from a surface saturated in water (free water at the surface, or 100% of humidity on the crop) with the aim of preventing loss of water, either due to biological control (stomatal closure) or to control exerted by the vegetation structure (architecture). This variable is only theoretical, except in the very improbable case in which the plant leaves represent a very thin layer at the top of the stem (Fig. 1). This definition includes large surfaces of water (such as lakes, seas, oceans), or saturated soils. PE* values can be calculated using the Penman equation (Penman 1948):

$$PE^* = \frac{1}{\lambda}\frac{\Delta A + \rho c_p D/r_a}{\Delta + \gamma} \tag{1}$$

where λ is the latent heat of vaporisation for water (2.46 MJ kg^{-1}), Δ is the slope of the saturation vapour pressure function vs. temperature (Pa °C^{-1}), γ is the psychrometric constant (Pa °C^{-1}), ρ is the density of the air (kg m^{-3}), c_p is the specific heat at constant pressure (J kg^{-1} °C^{-1}), A is the available energy (W m^{-2}) calculated as difference between net radiation and soil heat flux and r_a is the aerodynamic resistance (s m^{-1}). The aerodynamic resistance r_a is the only resistance term in PE*. It translates the obstacles encountered by the water vapour between the evaporative surface and the reference height z. This resistance, dependent on the surface roughness (z_0) and crop height (h_c), can be obtained by the following relationship (Perrier 1975):

$$r_a = \frac{\ln\frac{z-d}{z_0}\ln\frac{z-d}{h_c-d}}{k^2 u\left(z\right)} \tag{2}$$

Where d is the zero plane displacement height (m), k the von Kármán constant and u is the wind speed (m s^{-1}). In the particular case of grass, its surface characteristics (height, roughness) have very low impact on the calculation of r_a (Perrier 1975; Rana and Katerji 1998). In fact, in a very large range of wind speed measured at the height z, the heat exchange coefficient of air (h, in ms^{-1}, the inverse of the resistance r_a) calculated on a grass crop and on a bare soil are very close (Fig. 2).

Table 1 Summary of the main expressions found in the literature and used in text for defining the evapotranspiration (adapted by Perrier 1984)

Symbol	Definition	Meaning	Year and author
PET	Potential evapotranspiration	This expression has been used as: (1) the evaporative demand of the atmosphere; (2) the amount of water evaporated by a short grass crop, completely shading the ground of uniform height and'never short of water. These definition are no longer recommended because of inconsistent usage and definition	1948 Thornthwaite 1956 Anon
PE*	Potential evaporation	The evaporation from a given surface when all surface-atmospheric interfaces are wet (saturated), so that there is no restriction due to either biological control or soil water content on the water vapour loss from the surface area. This definition includes large surfaces of water (such as lakes, seas, oceans) or very moisten soils. PE* values can be calculated using the Eq. 1	1948 Penman
PE	Crop potential evaporation	The evaporation from a given soil and crop when all surface-atmospheric interfaces are wet (saturated), so that there is no restriction due to stomatal conductance or soil water content on the water vapour loss from the surface area. The only possible restriction is due to the resistance r_0 which translate the opposition of the crop architecture to the diffusion of the water vapour. PE can be observed in nature during a relatively short period (evaporation of free water from leaves) just after a rain, a strong dew or an irrigation by aspersion. PE values can be calculated using the Eq. 3	1975 Perrier
ET	Crop evapotranspiration	The total water vapour loss by evaporation from soil and transpiration from a vegetated surface. ET values can be calculated using the Eq. 4	1963–1965 Monteith 1972–1975 Thom 1975 Perrier
ET_0	Reference crop evapotranspiration	The evapotranspiration from crop selected for comparative purposes under given weather conditions (it is often grass) and with adequate fetch (sufficient to make edge effects relatively unimportant) and for standardized watering regime appropriate for this crop and the region concerned. ET_0 values can be calculated using the Eq. 7	1976 Doorenbos and Pruitt 1984 Perrier
FAO-56 ET_0	FAO reference crop evapotranspiration	The evapotranspiration from hypothetical crop having 0.12 m in height, an albedo of 0.23 and fixed canopy resistance of 70 s m^{-1}. This resistance is supposed not to be sensitive to the environment and to maintain the same value under different climates without reference to the site	1998 Allen et al.

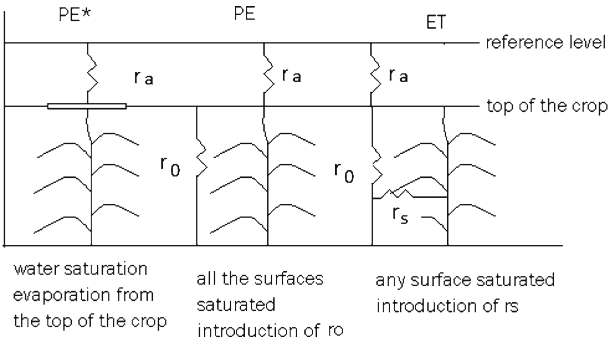

Fig. 1 Schematic representation of the resistances appeared in the potential evaporation PE*, crop potential evaporation PE and crop evapotranspiration ET (after Perrier 1975; see Table 1 for detailed definitions); r_a is the aerodynamic resistance, r_0 the crop structure resistance and r_s the crop stomatal resistance

The concept of potential evaporation PE* allows the determination of the evaporation demand of the atmosphere for all evaporative surfaces, including crop surfaces when all the hypothesis are met (see Fig. 1). However, crop surfaces have different physical characteristics influencing the evaporation PE*: the factor regulating solar radiation reflectivity (albedo) and the canopy architecture influencing the available energy R_n-G (R_n is the net radiation and G is the soil heat flux), even if these factors have secondary importance. Crop height and roughness take part to the calculation of r_a. For the same wind speed u, at a reference level, the taller the crop, the higher the aerodynamic resistance (see Eq. 2). Therefore, for the same climatic conditions (same R_n-G, D and u) the taller the crop, the higher the values of PE* (Table 2).

2. Potential crop evaporation PE: i.e., evaporation of a crop having all evaporative surfaces (leaves, stems, soil) saturated or covered in water. Thus, no biological control is exerted for the water losses (the crop stomatal resistance, r_s, is zero). Yet, the crop itself shows resistance to water vapour transfer, r_0, due to its structure (Perrier 1975). Therefore, if r_a is the same, it is:

$$\text{PE}^* \geq \text{PE}$$

where:

$$PE = \frac{PE^*}{1 + \frac{\gamma}{\gamma + \Delta} \frac{r_0}{r_a}} \tag{3}$$

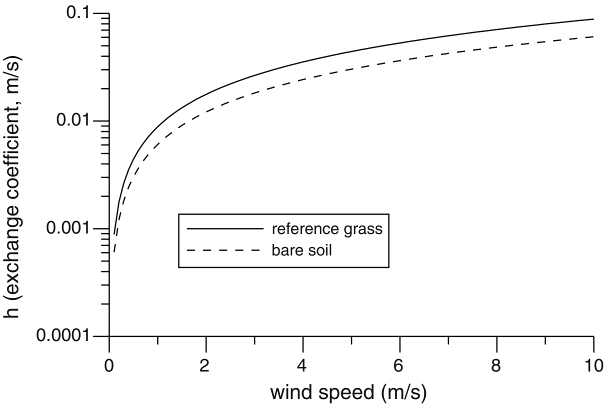

Fig. 2 Evolution of the exchange coefficient h (the inverse of the aerodynamic resistance r_a) for heat and mass in function of the wind speed measured at 2 m above the surface, for reference crop evapotranspiration ET_0 (irrigated grass) and bare soil

Table 2 Mean values of potential evaporation PE* in W m^{-2} for different type of crop of different heights (after Perrier 1975)

	Maize 2.2 m	Maize 0.6 m	Bean	Grass
PE*(W m^{-2})	800	550	500	450

Thus, this variable corresponds to a theoretical concept, although it can only be found in nature during a relatively short period (evaporation of free water from leaves) just after a rain, a strong dew or an irrigation by aspersion. Therefore only under these particular conditions it is possible to determine the resistance r_0. Table 3 shows the values of r_0 for different crop surfaces. It must be noted that the more important the vertical structure of the crop, the higher the values of r_0. Nevertheless, there is a particular case where $PE^* \sim PE$: it's the case of a grass saturated at the surface, because the resistance r_0 for this canopy can be considered as negligible (see Table 3).

3. Crop evapotranspiration ET: i.e., when no saturation can be found on all the evaporative surfaces. Since crop canopy resistance is $r_c = r_s + r_0$ with r_s crop stomatal resistance. The crop canopy resistance r_c varies between a minimum value observed in a well watered crop and the maximal value observed in a completely dry crop. Thus:

$$PE^* \geq PE \geq ET$$

Crop evapotranspiration can be written as follows:

$$ET = \frac{PE^*}{1 + \frac{\gamma}{\gamma + \Delta} \frac{r_c}{r_a}} \tag{4}$$

By applying the above analysis to a well-watered grass we can then clarify the links between the climatic demand PE*, calculated for a grass surface, and ET_0 measured in a well-watered grass. Actually, this last variable corresponds to ET for grass, which is different from its PE* (since r_0 is null) mainly because the stomatal resistance of the irrigated grass is minimal but not equal to zero.

The equivalence of ET_0 to the climatic demand of the atmosphere is a hypothesis usually accepted in scientific literature, also in very recent works (Guyot 1998;

Table 3 Mean values of the structural resistance r_0 for some crops of different height and in different climatic conditions (after Perrier 1975 and Katerji 1977)

Crop	Height (m)	Climatic conditions	r_0 (s m^{-1})
Grass	0.1	Normal	0–5
Bean	0.4	Normal	5–10
Maize	0.6	Normal	10–15
Maize	2.2	Normal	20–30
Wheat	0.2	Weak demand	0
Wheat	0.4	Weak demand	6
Wheat	0.6	Weak demand	10
Wheat	0.2	Normal	5
Wheat	0.4	Normal	10
Wheat	0.6	Normal	20

De Parcevaux and Huber 2007; Douglas et al. 2009; Zhang et al. 2010). Actually, this equivalence is the same as to admit to the following equality:

$$PE^{*} = PE = ET_0 \quad (5)$$

This hypothesis can only be verified if the crop resistance for the well-watered grass r_c is negligible with respect to the aerodynamic resistance r_a (see Eq. 4). This hypothesis has long been explicitly accepted by the scientific community, following publications by Thornthwaite and Penman. Indeed, these authors considered grass as a wick with roots plunged in the water reservoir of the soil and leaves subject to solar radiation and wind. The role of grass in this system is only passive and it consists in making the water in the soil available to the atmosphere without any opposition.

Nowadays, the use of microclimatic techniques in ET_0 accurate measuring and r_c calculation by inversion of Eq. 4, allows for accurate estimations of canopy resistance at hourly and daily scales. The values found for r_c on irrigated grass ranged between 30 and 70 s m^{-1} (Allen et al. 1989; Smith et al. 1991; Ventura et al. 1999; Lecina et al. 2003; Wright et al. 2002; Katerji and Rana 2006). When grass evapotranspiration is positive during the day (between 5:00 am and 6:00 pm), the values of r_c and r_a are close, as shown in Fig. 3. Therefore, the hypothesis that r_c is negligible with respect to r_a is incorrect.

Here we have ended the discussion about the three of the fundamental forms of evaporation as defined by Perrier (1975) and we can make some observations about the recent use of reference crop evapotranspiration and the evaluation of the canopy resistance.

The main consequences resulting from the above analysis can be summarized as follows:

1. The concept of potential evapotranspiration or climatic evaporative demand PET is not an universal concept representing a given climate. Actually, it depends on the characteristics (albedo, vegetation height,…) and on the type of the evaporative surface (bare soil, vegetative surface, water surface, forest,…).
2. The ET_0 must not be systematically equated to the climatic demand PE^{*} calculated for the grass surface. In practice, this hypothesis can be close to reality for

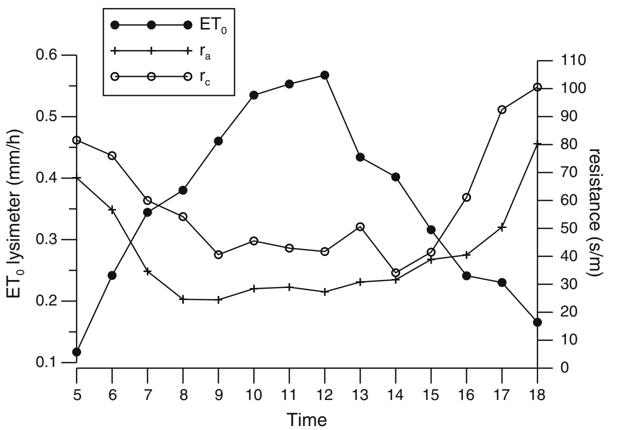

Fig. 3 Hourly path of reference crop evapotranspiration by weighing lysimeter (ET_0), the grass canopy (r_c) and the aerodynamic (r_a) resistances during a sunny day (30 August 1990) at Rutigliano (South Italy)

a grass surface just after a rain or irrigation, while, it can be very far from reality if the space is covered in forests.

3. Two processes may affect the dynamics of ET_0 in opposite ways: A) the climatic parameters (A, D and r_a) determining PE* and making the evaporative demand; B) the canopy resistance r_c which adapts its response to this demand.

At this point the respective impact of climatic (A, D, r_a,) and biological (r_c) variables on ET_0 should be determined.

2.2 Relative Impact of the Different Processes Taking Part to the Evapotranspiration Process: The Case of ET_0

In general, the analysis of the relative impact of climatic (A, D, r_a) and biological (r_c) variables on function ET aims at establishing what variable(s) cause(s) the most relevant variation of ET in the different situations.

The analysis here presents results from Rana and Katerji (1998), who obtained, within the Mediterranean region, hourly experimental data, from three irrigated crops having different height: grass (0.1 m), grain sorghum (1 m) and sweet sorghum (3 m). In the next we focused the attention on the ET_0.

Following McCuen (1974) and Beven (1979), Rana and Katerji (1998) calculated the non-dimensional relative sensitivity coefficients:

$$S_i = \frac{\partial (ET)}{\partial p_i} \frac{p_i}{ET} \tag{6}$$

for i = 1, 2, 3, 4, they represent that fraction of the change in each variable p_i ($p_1 = A$, $p_2 = D$, $p_3 = r_a$, $p_4 = r_c$) that is transmitted to change ET. A similar approach has been recently presented by Donohoue et al. (2010) for analysing the dynamics of the evaporative demand.

The main results of this study can be summarized as follows:

1. Under irrigated crop conditions ET showed to be very sensitive to any variations in the value of A in the case of grass. For, this variable (see Fig. 4) explained 60–70% of ET hourly variations; in fact the sensitivity coefficient for this variable $S(A)$ is always close to 0.6–0.7 for the grass. Furthermore, the variations in the value of D explained 50% of the ET hourly variations in the case of grain sorghum and 60–70% in the case of sweet sorghum (sensitivity coefficient $S(D)$ around 0.5 and 0.6–0.7 for grain and sweet sorghums respectively). Finally, ET proved less sensitive to r_a variations in all three crops studied, $S(r_a)$ being close to 0 for all cases.
2. The sensitivity coefficient for resistance $S(r_c)$ explained 10–20% of the ET variations in the case of grass against 40–50% in the case of both grain and sweet sorghums.

Following the above analysis it can be argued that for irrigated grass:

A. The available energy A is the main force in the dynamics of ET_0.
B. If compared with the crops having greater heights, the biological resistance (r_c) is less central of ET_0 dynamics than the climatic variables. So, the choice of irrigated grass as reference is fully justified.

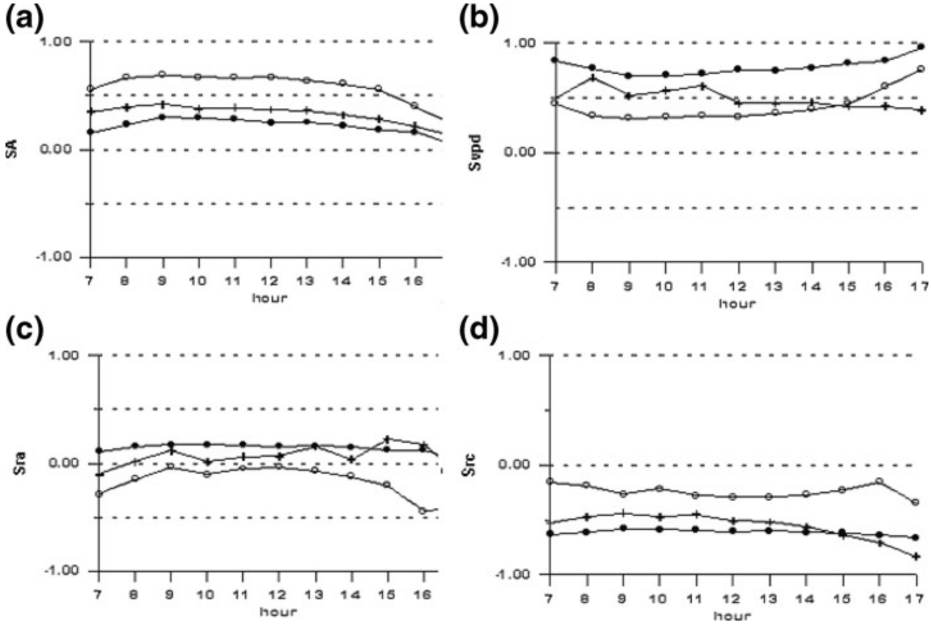

Fig. 4 Sensitivity coefficients for the hourly AET ($S_i = \left[\partial\left(AET\right)/AET\right]/\left[\partial i/i\right]$) for: **a** available energy A, **b** vapour pressure deficit D, **c** aerodynamic resistance r_a, **d** canopy resistance r_c, found in grass, grain sorghum and sweet sorghum crops cultivated in well-watered conditions (*open circle* grass; *plus sign* grain sorghum; *close circle* sweet sorghum). (After Rana and Katerji 1998)

2.3 Validation

The analysis above identified two processes in ET_0: the climatic demand PE^* and the canopy resistance. Among the climatic variables included in PE^*, in the determination of ET_0 the main role is played by the available energy, while the role of the canopy resistance is much less important.

In the context of the present work, at this point, we analyse these conclusions starting from measurements of ET_0 carried out under different climates and summarize the consequences on the measurements or on the estimation of ET_0, from a practical point of view.

2.3.1 The Role of Available Energy A

According to the analysis presented in the Section 2.1, ET_0 for the reference grass can be written as:

$$ET_0 = \frac{PE^*}{1 + \dfrac{\gamma}{\gamma + \Delta}\dfrac{r_c}{r_a}} \tag{7}$$

by differentiating the previous expression with respect to the aerodynamic resistance r_a, in order to evaluate the way ET_0 varies with the wind speed, it is possible to highlight a particular value of r_c, called "critical resistance" for which the value of ET is independent on r_a (Daudet and Perrier 1968), i.e:

$$\frac{\partial ET_0}{\partial r_a} = \frac{1}{\lambda}\frac{\Delta\gamma A r_c - \rho c_p D\left(\Delta+\gamma\right)}{\left[r_a\left(\Delta+\gamma\right)+r_c\gamma\right]^2} \tag{8}$$

this expression is null for the following value of r_c:

$$\frac{\partial ET_0}{\partial r_a} = 0 \Rightarrow r_c = \frac{\Delta+\gamma}{\Delta\gamma}\rho c_p \frac{D}{A} = r^* \tag{9}$$

Thus, the expression (7) can be written as follows:

$$ET_0 = \frac{1}{\lambda}\frac{\Delta}{\Delta+\gamma}A\frac{1+\dfrac{\gamma}{\gamma+\Delta}\dfrac{r^*}{r_a}}{1+\dfrac{\gamma}{\gamma+\Delta}\dfrac{r_c}{r_a}} \tag{10}$$

By putting $C = \frac{1+\frac{\gamma}{\gamma+\Delta}\frac{r^*}{r_a}}{1+\frac{\gamma}{\gamma+\Delta}\frac{r_c}{r_a}}$, the expression for ET_0 becomes

$$ET_0 = \frac{1}{\lambda}C\frac{\Delta}{\Delta+\gamma}A \tag{11}$$

The coefficient C was considered as a real crop coefficient by Katerji and Perrier (1983). Equation 11 allows the estimation of ET_0 from few weather variables, centred around the available energy.

The approach above described, which relates ET_0 to A through a coefficient, was followed for 40 years in the last century by many authors for the determination of PET:

It is the case of Makking (1957) who proposed the following relation:

$$PET = \frac{1}{\lambda}C_1 R_n \tag{12}$$

Also Priestley and Taylor (1972) suggested an expression of PET adapted to large well-watered surfaces, including vegetated surfaces and large water bodies (lakes and oceans) i.e.:

$$PET = \frac{1}{\lambda}C_2\frac{\Delta}{\Delta+\gamma}R_n \tag{13}$$

where C_2 varies between 1.08 ± 0.01 and 1.34 ± 0.05 with average of 1.26 according to these authors.

Therefore, the Eqs. 12 and 13 are empirical formulations belonging to the same family of expressions which underlines the role of A in ET_0 as a driver, fully in accordance with our conclusions in Section 2.2. On the other hands, several authors illustrated the influence of aerodynamic terms on the evaporative process, as determined from open water (Roderick et al. 2007, 2009; Johnson and Sharma 2010).

To find the relations among coefficients C, C_1 and C_2, a simple consideration is needed:

1. For well-watered wheat, the value of the G at hourly scale is around 5% of R_n (Gosse 1976). At daily scale, the balance of G is close to zero. Thus, C and C2 can be considered as very close at this time scale.
2. $\Delta/(\Delta+\gamma)$ varies from 0.55 at 10°C to 0.74 at 25°C. Which means that $\Delta/(\Delta+\gamma) \approx 0.65$.

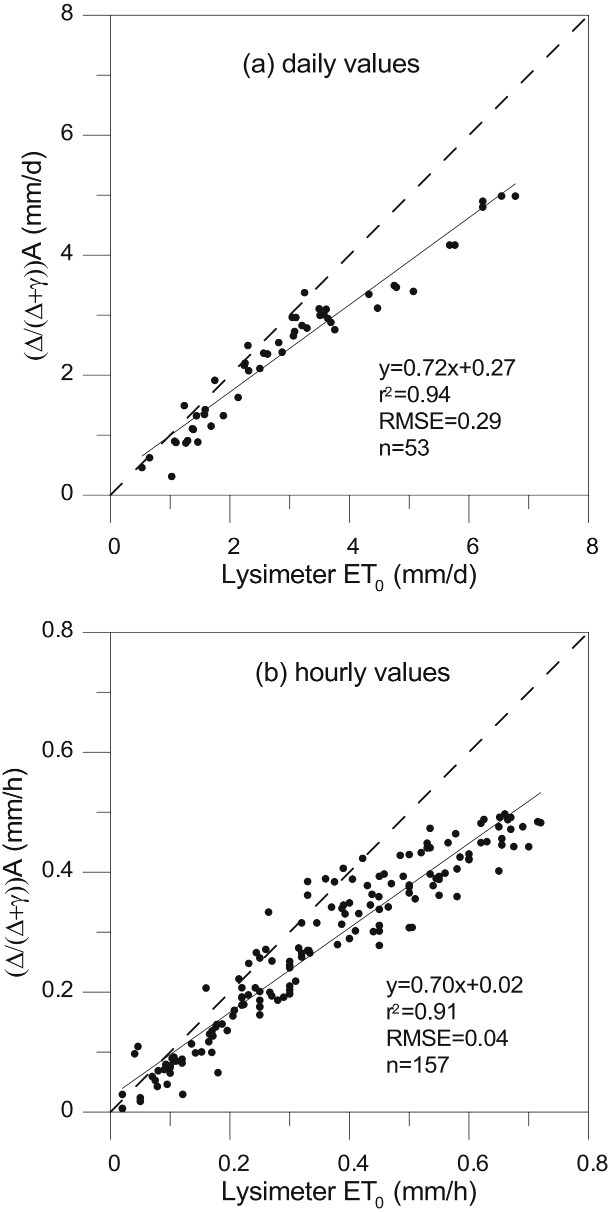

Fig. 5 Relationships between **a** daily and **b** hourly values of the term $(\Delta/(\Delta+\gamma))\,A$ and reference crop evapotranspiration measured by weighing lysimeter (ET_0; Rutigliano, Bari region, after Katerji et al. 1990)

At this point in this study we analysed the effects of different climate regimes on coefficients C and C1 under different climate conditions (Mediterranean climates characterised by a dry season, humid and equatorial climates).

Figure 5 shows one of the relations observed, that between $\Delta/(\Delta+\gamma)A$ and ET_0 measured at Rutigliano, a site in the Mediterranean region, at hourly and daily scales. From this figure, it can be argued that the relation between these two variables is linear, mainly at daily scale. In Table 4 the values of coefficient C obtained at daily scale from the same site in Southern Italy are compared with the following variables:

3. The values of coefficients C_1 and C_2 observed at another site in the Mediterranean region (Caesarea, Israel) and at a non-Mediterranean site subject to a Mediterranean-type climate (California, USA);
4. The values of coefficient C_2 observed at a site in Northern Europe subject to humid climate (the area of Paris, France);
5. The values of coefficients C_1 and C_2 observed in the tropical humid regions of Ivory Coast, Central Africa and Brazil.

By looking at the values of coefficients C and C_1 in Table 4 it is clear that these values showed a strong stability going from semi-arid to humid climates. On the other hand, we already observed by discussing the sensitivity analysis of the ET calculation, that the A was the main driving force of ET_0 at all the sites observed. Its impact estimated from coefficients C or C_1 was strongly stable despite the difference in climates. Finally, it can be underlined that the values of coefficient C (~0.75) experimentally calculated at daily scale were in full accordance with the relative impact attributed to the available energy (60–70%) in the hourly ET_0 following the analysis reported in Section 2.2.

The data shown in the Table 4 were obtained according to the definition of ET_0 (see Table 1), without advective transport of energy. When important advective fluxes occur, Katerji and Perrier (1983) demonstrated that the coefficients C and C_1 can increase up to 100% of their original value. Advection widely occurs, above all when the land use is not uniform and in irrigated areas as in the Mediterranean region. So studies (Flint and Childs 1991; Castelvì et al. 2001; Pereira 2004) were developed to take into account it in the crop water loss determined using a Priestley-Taylor approach.

2.3.2 The Role of Canopy Resistance r_c

Since the early 1990's a large range of literature has been devoted to the experimental determination of the canopy resistance of reference grass, r_c, following its

Table 4 Values of the coefficients C, C1 and C2 observed on the irrigated grass for different sites characterised by different climate

Site (country)	C	C_1	C_2	Time scale	Authors
Rutigliano (Bari, south Italy)	0.88		1.2	Daily	Katerji et al. (1990)
Versailles (Paris region, France)			1.27	Daily	Grebet (1982)
Davis (California, USA)			1.27	Daily	Pereira (2005)
Caesarea (Israel)		0.76		Monthly	Rosenberg et al. (1983)
Piraciaba (Brazil)			1.2	Daily	Pereira (2005)
Bangui-Brazzaville (Central Africa)		0.77		Daily	Riou (1975)
Adiopodaumé (Ivory Coast)		0.77		Daily	Gosse (1976)

introduction in Eq. 4 for the estimation of ET_0. Theoretically, from a physical point of view, this equation is valid under permanent regime, i.e. only at hourly scale. Several adaptations of this equation for the estimation of ET_0 at daily scale have been discussed and adopted by many authors (Penman 1956, 1963; Allen et al. 1989, 1998; Rana et al. 1994; Katerji and Rana 2006).

The first works (Allen et al. 1989) adopted a simple solution, previously proposed by Monteith et al. (1965) for barley crop, to characterise the resistance r_c of a well-irrigated grass. It was supposed to be constant during the day, related to leaf area, and equal to 70 s m^{-1} for grass having 0.12 m in height. Furthermore, this resistance was supposed not to be sensitive to the environment and to maintain the same value under different climates. These hypotheses, of course, made the practical determination of ET_0 easier and therefore they were later maintained in the formula for the calculation of FAO-56 ET_0 proposed by FAO bulletin no. 56 (Allen et al. 1998). The latter is a handbook providing advice for practical calculation of crop water requirements.

Steduto et al. (1996) compared the values of FAO-56 ET_0 calculated according and those measured by weighing lysimeters at 6 sites within the Mediterranean region: in Italy, Tunisia, Morocco, Spain and Turkey. The results of this test (see Fig. 6) showed that the FAO-56 ET_0 formula underestimated the measured ET_0 of

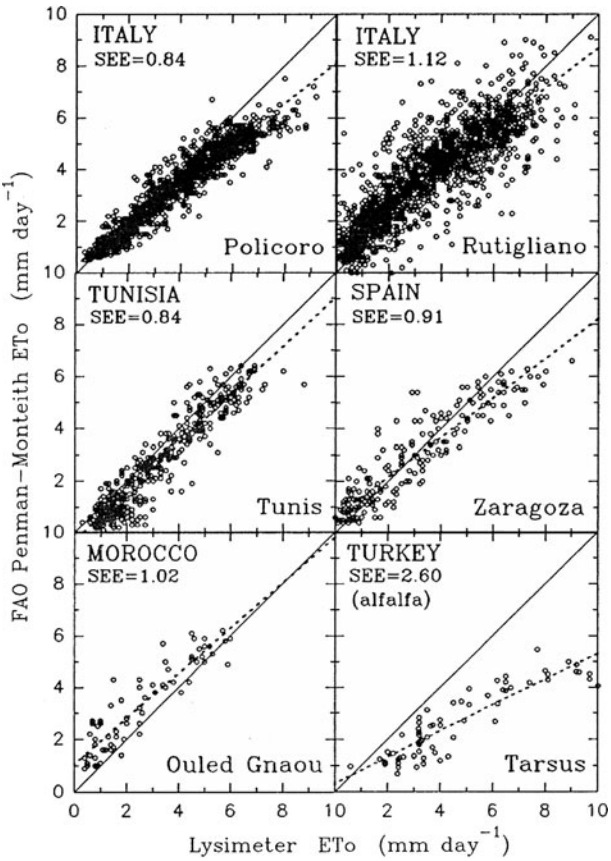

Fig. 6 Comparison between the values of ET_0 estimated by the FAO Penman-Monteith ET_0 (i.e. the FAO-56 ET_0) and crop reference ET_0 measured by lysimeter at six locations in the Mediterranean region. SEE indicates the standard error of estimate ET_0 (after Steduto et al. 1996)

about 2 to 18% at all sites except in Morocco, where it tended to overestimate the measured values. However, it must be underlined that the number of days considered for the test in Morocco was lower than that considered for the other countries, and that in Morocco the values of ET_0 were lower than 6 mm d^{-1}, against 8–9 mm d^{-1} recorded at the other sites. On the other hand, there is also a tendency to clearly underestimate ET_0 when its values are greater than 4–5 mm d^{-1} (Steduto et al. 1996).

The difference found between the measured and calculated values in the previous test was due to the not realistic hypotheses assumed by Allen et al. (1989), as follows:

1. The first concerns the stability of the canopy resistance r_c during the day. In fact, many studies clearly show that this resistance is not constant during the day; it varies in function of radiation, vapour pressure deficit and the interval between two successive irrigations (see the review by Rana et al. 1994). Models to calculate ET_0, taking into account the daily variation of r_c, have been proposed by several authors (Rana et al. 1994; Todorovic 1999; Lecina et al. 2003). They generally provided a better estimation of ET_0.
2. The second concerns the insensitivity of r_c to the environment. The mean daily values of r_c experimentally found at different sites varied between 30 and 70 s m^{-1} (Smith et al. 1991; Wright et al. 2002; Ventura et al. 1999; Lecina et al. 2003; Katerji and Rana 2006). Figure 7 shows an example of r_c determined as daily mean at the site of Rutigliano (Bari, Southern Italy). The values locally found (50 s m^{-1}) were 40% lower than that (70 s m^{-1}) adopted by Allen et al. (1989). The overestimation of the r_c values in the FAO-56 ET_0, with respect to the locally calibrated site values explains the underestimation of ET_0 observed at this site through this formula (see Fig. 6).

Katerji and Rana (2006) analysed the errors in the ET_0 calculation only due to the determination of r_c at the Mediterranean site of Rutigliano. The authors noticed that:

1. When the hypothesis of hourly variable r_c is considered valid, the slope of the linear regression between simulated and measured values is close to 1 (Fig. 8a).
2. When the hypothesis of daily constant r_c locally calibrated is considered valid ($r_c = 50$ s m^{-1}) the slope decreases from 1 to 0.85 (Fig. 8b).

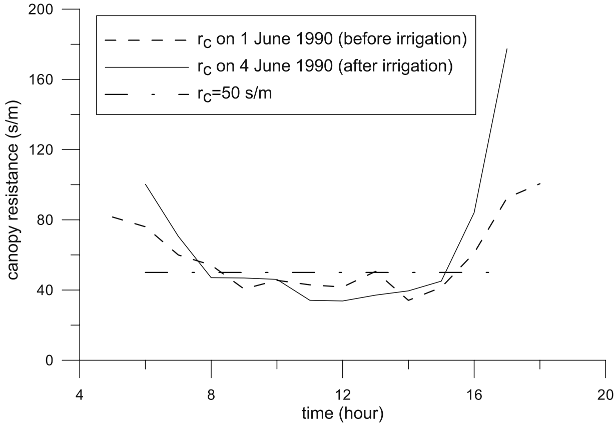

Fig. 7 Hourly evolution of the canopy resistance measured before and after irrigation (20 mm) in a reference crop evapotranspiration in Rutigliano (south Italy), together with the canopy resistance considered constant at 50 s/m (after Katerji and Rana 2006)

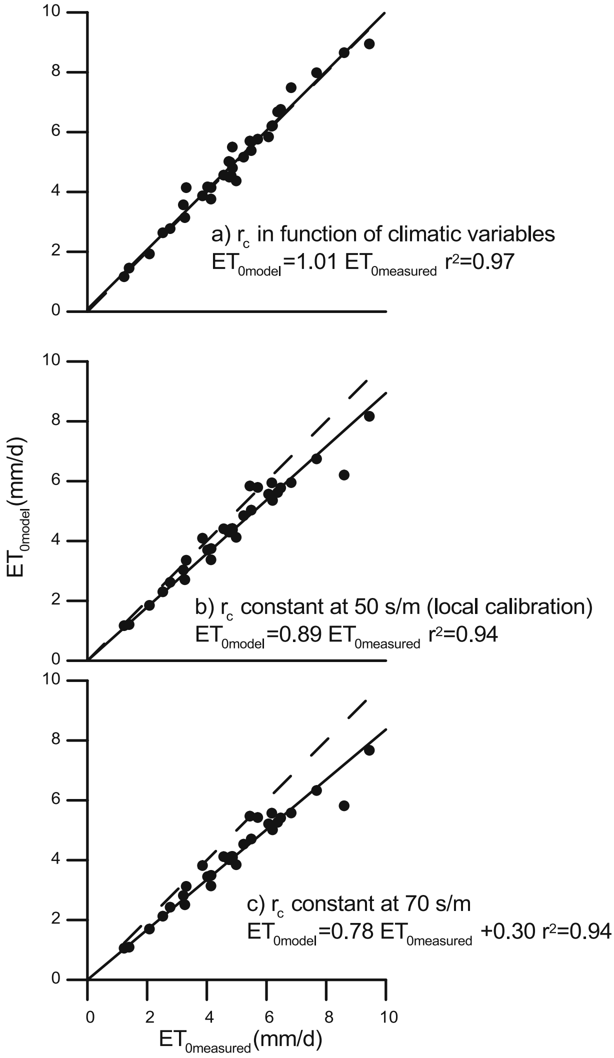

Fig. 8 Comparison between reference crop evapotranspiration ET_0 measured by lysimeter in a southern Italian site (Rutigliano, Bari) and ET_0 modelled by three different approaches: **a** with r_c calculated as function of climatic variables, **b** with a constant r_c of 50 s m^{-1}, **c** with the FAO-56 ET_0 formulation and r_c constant at 70 s m^{-1}; (after Katerji and Rana 2006)

3. Finally, when the FAO-56 ET_0 hypothesis is considered valid ($r_c = 70$ s m^{-1}), the ET_0 is strongly underestimated and the slope decreases from 1 to 0.78 (Fig. 8c).

Therefore, the different ways to determine r_c have important consequences on estimated ET_0 values. However, it is possible to notice that a 40% overestimation on daily mean values of r_c (70 s m^{-1} instead of 50 s m^{-1}) corresponds to an underestimation of about 12% of ET_0. Thus, the error on the determination of r_c is not proportional to the error on the determination of ET_0, because of the small impact of the variable r_c on calculated ET_0, already underlined in Section 2.2. So, an acceptable estimation of ET_0, close to ±10%, can not be interpreted as an evidence of an appropriate estimation of r_c of the grass.

On the contrary, for tall crops (height > 1 m) the error in the determination of r_c has a large influence (40–50%) on the accuracy of the determination of ET values (see the review by Katerji and Rana 2006). For such crops an acceptable estimation of ET needs a preliminary accurate evaluation of r_c.

3 Conclusions

The concept of potential evapotranspiration PET introduced by Thornthwaite, and adopted by the scientific community over the last six decades, aimed at defining the maximum evaporation demand for a given climate. This concept has been proven to be inappropriate because the evaporation climatic demand is not only linked to the climate, but also to the kind of evaporative surface (e.g., bare soil, water surface, crop), and particularly to the physical characteristics of these surfaces, influencing the evaporation (e.g., albedo, surface roughness length, crop height, stomatal regulation). Nevertheless, the concept of reference grass evapotranspiration is interesting as the values of evapotranspiration measured under different climates or in order to estimate crop water requirements.

The analysis of the physical and biological mechanisms intervening in the determination of reference grass ET_0 clearly underlines that this last has not been equated to the climatic demand PE^* calculated for the grass surface, in contrast with a hypothesis still very wide spread in scientific literature. Actually, two processes act in opposite directions in the dynamics of ET_0: on one side, the evaporation demand PE^* and, on the other side, the canopy resistance r_c which reduces the response to this demand. However, it was demonstrated that the impact of the variable r_c on ET_0, although not negligible, is less important than the climatic variables determining PE^*. The available energy plays a major role among these variables.

The well-demonstrated previous conclusions were analysed and discussed in the framework of studies on ET_0 modelling. Firstly, the available energy seemed to be the main climatic engine of ET_0. Then, the relationship linking these two variables (A and ET_0) seemed to be very stable both under Mediterranean and equatorial humid climates.

Furthermore, the different hypotheses found in the existing literature to determine the value of r_c of irrigated grass were tested under Mediterranean climate. The accuracy of the estimated ET_0 values varied according to the approach used to determine r_c (constant, variable, locally calibrated). Nevertheless, the impact of the differently determined r_c had very less importance on grass than on crops typically higher than 1 m.

As to ET_0 modelling, research efforts over the last decades have mainly been focused on determining and modelling $r_{c.}$ Contrarily, the present study illustrates the need to correctly determine available energy, whose accuracy is essential, given its greater importance on the determination of ET_0. In scientific literature, formulas linking ET_0 to the available energy (e.g. Makking and Prestley-Taylor formulas), using simple climatic variables, have been proposed. In fact, in situations characterised by lack of climatic data needed for the calculation of ET_0, these formulas may be a suitable and very useful method for its determination. Recently Douglas et al. (2009) come to the same conclusions.

Acknowledgements We wish to express thanks to the Editor and to the anonymous reviewers for some very important suggestions which improved a lot this work. The work was supported by the Agricultural Research Council "Collezioni e a-or" project through funds by The Italian Ministry of Agriculture.

References

Aboukhaled A, Alfaro A, Smith M (1982) Lysimeters. FAO Irrigation and Drainage Paper 39, p 68
Allen RG, Jensen ME, Wright JL, Burman RD (1989) Operational estimate of reference evapotranspiration. Agron J 81:650–662
Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. FAO, Rome, p 300
Anon J (1956) Proceeding of the informal meeting on physics in agriculture. Neth J Agric Sci 4:162
Bagnouls F, Gaussen H (1953) Saison sèche et indice Xérothermique. Documents pour les cartes de production végétales. Série généralités Toulouse, p 48 (In French)
Beven K (1979) A sensitivity analysis of the Penman–Monteith actual evapotranspiration estimates. J Hydrol 44:169–190
Blaney HF, Criddle WD (1950) Determining water requirements in irrigated areas from climatological and irrigation data. Soil Conservation Service, Washington DC, p 48
Castelvì S, Stockle CO, Perez PJ, Ibanez M (2001) Comparison of methods for applying the Priestley-Taylor equation at regional scale. Hydrol Process 15:1609–1620
Damagnez J, Riou C, De Villele O, Ammami S (1962) Problèmes d'évapotranspiration potentielle en Tunisie. Ann INRA Tunisie 35:161–184 (In French)
Daudet FA, Perrier A (1968) Etude de l'évapotranspiration ou de la condensation à la surface d'un corps à partir du bilan énergetique. Rev Gén Therm 76:353–364 (In French)
De Martonne E (1926) Une nouvelle fonction climatologique: l'indice d'aridité. La météorologie, Octobre, pp 449–459 (In French)
De Parcevaux S, Huber L (2007) Bioclimatologie. Concepts et applications. Editions Quae, p 336
Donohue RJ, Roderick ML, McVicar TR (2007) On the importance of including vegetation dynamics in Budyko's hydrological model. Hydrol Earth Syst Sci 11:983–999
Donohoue RJ, McVicar TR, Roderick ML (2010) Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand with a changing climate. J Hydrol 386:186–197
Doorenbos J, Pruitt WO (1976) Guidelines for predicting crop water requirements. FAO ONU, Rome, Irr. And Drain. Paper no. 24 (revision), p 144
Douglas EM, Beltràn-Przekurat A, Niyogi D, Pielke RA, Vorosmarty CJ (2009) The impact of agricultural intensification and irrigation on land–atmosphere interactions and Indian monsoon precipitation—a mesoscal modeling perspective. Glob Planet Change 67(1–2):117–128
Emberger L (1930) La végétation de la région méditerranéenne. Essai d'une classification des groupements végétaux. Rev Gen Bot 42:705–721 (In French)
Flint AL, Childs SW (1991) Use of the Priestley-Taylor evaporation equation for soil water limited conditions in a small forest clearcut. Agric For Meteorol 56(3–4):247–260
Gosse G (1976) Evapotranspiration et caractéristiques d'un gazon en climat équatoriale humide. Ann Agric 27:141–163 (In French)
Grebet P (1982) Evapotranspiration Mesure et calcul. Thèse Doc Ing. Université de Paris VI, p 272 (In French)
Guyot G (1998) Physics of the environment and climate. John Wiley, Chichester, USA, p 632
Hazrat Ali M, Yeang Shui L (2009) Potential evapotranspiration model for Muda irrigation project, Malaysia. Water Resour Manage 23(1):57–69
Johnson F, Sharma A (2010) A comparison of Australian open water body evaporation trends for current and future climates estimated from Class A evaporation pans and general circulation models. J Hydrometeorol 11:105–121
Katerji N (1977) Contribution à l'étude de l'évapotranspiration réelle du blé tendre d'hiver. Application à la résistance du couvert en relation avec certains facteurs du milieu. Thése Doc. Ing. Université de Paris VII, p 120 (In French)
Katerji N, Rana G (2006) Modelling evapotranspiration of six irrigated crops under Mediterranean climate conditions. Agric For Meteorol 138:142–155

Katerji N, Rana G (2008) Crop evapotranspiration measurements and estimation in the Mediterranean region. INRA–CRA. ISBN 978-8-89015-241-2, p 173
Katerji N, Perrier A (1983) Modélisation de l'évapotranspiration réelle d'une parcelle de luzerne: rôle d'un coefficient cultural. Agronomie 3(6):513–521 (In French)
Katerji N, Ferreira I, Mastrorilli M, Losavio N (1990) A simple equation to calculate crop evapotranspiration: results of several years of experimentation. Acta Orthod 278:477–489
Lecina S, Martinez-Cob A, Pérez PJ, Villalobos FG, Baselga JJ (2003) Fixed versus bulk canopy resistance for reference evapotranspiration estimation using the Penman-Monteith equation under semiarid conditions. Agric Water Manage 60:181–198
Lu J, Sun G, McNulty SG, Amatya DM (2005) A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. J Am Water Resour Assoc 41: 621–633
Makking GF (1957) Testing the Penman formula by means of lysimeters. J Inst Water Eng 11(3):277–288
Margat J (1992) L'eau dans le bassin méditerranéen: situation et prospective. Les fascicules du plan bleu n° 6. Edition Economica, p 198 (In French)
McCuen RH (1974) A sensitivity and error analysis of procedures used for estimating evaporation. Water Resour Bull 10(3):486–498
McIlroy IC, Angus DE (1964) Grass, water and soil evaporation at Aspendale. Agric Meteorol 1:201–224
Meyer A (1926) Uber einige Zusammenhänge zwischen Klima und Boden in Europa. Chem Erde 2:209–347
Monteith JL (1963) Gas exchange in plant communities. In: Evans (ed) Environmental control of plant growth. Academic Press, New York, pp 95–112
Monteith JL (1965) Evaporation and environment. In: Fogg (ed) The state and movement of water in living organism. Soc Exp Biol Symp 19:205–234
Monteith JL, Szeicz G, Waggoner PE (1965) The measurement and control of stomatal resistance in the field. J Appl Ecol 2(2):345–355
Oudin L, Michel C, Anctil F (2005) Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 1—can rainfall–runoff models effectively handle detailed potential evapotranspiration inputs? J Hydrol 303(1–4):275–289
Peguy C (1961) Précis de bioclimatologie. In: Masson (ed), p 347 (In French)
Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc R Soc A 193:120–146
Penman HL (1956) Estimating evaporation. Trans Amer Geoph Uninon 37:43–50
Penman HL (1963) Vegetation and hydrology. Technical com. 53, Commonwealth bureau of soils. Harpenden, UK, p 124
Pereira AR (2004) The Priestley-Taylor parameter and the decoupling factor for estimating refernce evapotranspiration. Agric For Meteorol 125:305–313
Pereira AR (2005) The Priestley–Taylor parameter and the decoupling factor for estimating reference evapotranspiration. Agric For Meteorol 125:305–313
Perrier A (1975) Etude physique de l'évapotranspiration dans les conditions naturelles. I. Evaporation et bilan d'énergie des surface naturelles. Ann Agron 26:1–18 (In French). II. Expression et paramètres donnant l'évapotranspiration réelle d'une surface mince. Ann Agron 26:105–123 (In French). III. Evapotranspiration réelle et potentielle des couverts végétaux. Ann Agron 26:229–243 (In French)
Perrier A (1984) Updated evapotranspiration and crop water requirement definitions. In: Perrier, Riou (eds) Les besoins en eau des cultures. Conférence internationale de Paris, pp 885–887
Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large scale parameters. Mon Weather Rev 100:81–92
Pruitt WO (1964) Evapotranspiration: a guide to irrigation. Calif Turfgrass Cult 14:27–32
Rana G, Katerji N (1998) A measurement based sensitivity analysis of Penman–Monteith actual evapotranspiration model for crops of different height and in contrasting water status. Theor Appl Climatol 60:141–149
Rana G, Katerji N, Mastrorilli M, El Moujabber M (1994) Evapotranspiration and canopy resistance of grass in a Mediterranean region. Theor Appl Climatol 50(1–2):61–71
Riou C (1975) La détermination pratique de l'évaporation. Application à l'Afrique centrale. Mémoire ORSTOM °N 80, p 236 (In French)
Roderick ML, Rotstayn LD, Farquhar GD, Hobbins MT (2007) On the attribution of changing pan evaporation. Geophys Res Lett 34:L17403. doi:10.1029/2007GL031166

Roderick ML, Hobbins MT, Farquhar GD (2009) Pan evaporation trends and terrestrial water balance. II. Energy balance and interpretation. Geogr Compass 3:761–780
Rosenberg NJ, Blad L, Verma B (1983) Microclimate: the biological environment, 3rd edn. Wiley, New York, p 315
Sarraf S (1973) Estimation de l'évapotranspiration potentielle et consommation en eau des cultures en région semi-aride (Liban). Thèse Doc Ing. Université de Montpellier, p 114 (In French)
Smith M, Allen RG, Monteith JL, Perrier A, Pereira LS, Segeren A (1991) Report on the expert consultation on revision of FAO methodologies for crop water requirements. FAO Land and Water Development Division, FAO, Rome, p 129
Stanhill G (1961) A comparison of methods of calculating potential evapotranspiration from climatic data. Isr J Agric Res 11:159–171
Steduto P, Caliandro A, Rubino P, Ben Mechlia N, Masmoudi M, Martinez-Cob A, Jose Faci M, Rana G, Mastrorilli M, El Mourid M, Karrou M, Kanber R, Kirda C, El-Quosi D, El-Askari K, Ait Ali M, Zareb D, Snyder RL (1996) Penman-Monteith reference evapotranspiration estimates in the Mediterranean region. In: Proceedings of international conference on evapotranspiration and irrigation scheduling, San Antonio, Texas, 3–6 November 1996, pp 357–363
Thom AS (1972) Momentum, mass and heat exchange of vegetation. Q J R Meteorol Soc 98:124–134
Thom AS (1975) Momentum, mass and heat exchange of plant communities. In: Monteith (Td.) Vegetation and atmosphere, Principles, vol I. Academic Press, London, pp 57–109
Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev NY 38:55–94
Thornthwaite CW, Wilm HG (1944) Report of the committee on evapotranspiration and transpiration, 1943–1944. Washington, D.C., Transactions of the American Geophysical Union, pp 686–693
Todorovic M (1999) A model to estimate hourly and daily evapotranspiration using variable canopy resistance. PhD thesis, Univ. of Sassari (Italy), p 204
Trajkovic S, Kolakovic S (2009) Evolution of reference equations under humid conditions. Water Resour Manage 23(14). doi:10.1007/s11269-009-9423-4
Turc L (1961) Evaluation des besoins en eau d'irrigation. Evapotranspiration potentielle. Ann Agric 12:13–49 (In French)
Van Bavel CHM (1966) Potential evapotranspiration: the combination concept and its experimental verification. Water Resour Res 2:455–467
Ventura F, Spano D, Duce P, Snyder RL (1999) An evaluation of common evapotranspiration equations. Irrig Sci 18:163–170
Verstraeten WW, Veroustraete F, Feyen J (2008) Assessment of evapotranspiration and soil moisture content across different scales of observation. Sensors 8:70–117
Weiss M, Menzel L (2008) A global comparison of four potential evapotranspiration equations and their relevance to stream flow modelling in semi-arid environments. Adv Geosci 18:15–23
Wright JL, Allen RG, Howell TA (2002) Conversion between evapotranspiration references and methods. In: Proc., 4th decennial national irrigation symposium, Phoenix, AZ, ASAE, St. Josef, MI, pp 251–259
Zhang Q, Xu C-Y, Chen X (2010) Reference evapotranspiration changes in China: natural processes or human influences? Theor Appl Climatol. doi:10.1007/s00704-010-0315-6