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An operational direct model to accurately determine crop evapotranspiration of crops cultivated in the Mediterranean region

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Abstract. Two methods can be considered as able to determine E for well irrigated crops. The first method is indirect (the “crop coefficient approach”). It is based on the knowledge of a crop coefficient, K_c , and an estimation of the reference evapotranspiration of grass E_0 . The second method directly calculates the E of a crop, without a step through a reference surface. It similarly applies a Penman-Monteith type formula. However, in this method the canopy resistance, r_c , is specific for each species, it is not constant but variable as a function of climatic characteristics of the atmosphere below the top of the boundary layer above the crop. This study proposes to explore and to test a more operational version of the direct model. In this version, the canopy resistance r_c will be considered as constant but specific for each crop. The performances of this method are evaluated with respect to the above cited direct and indirect methods, by means of experimental validation carried out on 3 crops having contrasted height. The best performance was given by the original version of the direct model, both at daily and hourly scales. The operational version of the direct model gave acceptable results only for grass. The indirect model gave the worst results both at daily and hourly scales. The practical use of this new version is discussed in the conclusions.

Keywords. Canopy resistance – Height crop – Penman-Monteith formulation – Vapour pressure deficit – Aerodynamic resistance.

Un modèle opérationnel direct pour déterminer correctement l'évapotranspiration des cultures en Région méditerranéenne

Résumé. Il existe deux méthodes pour déterminer correctement l' E des cultures irriguées. La première méthode est indirecte (l'« approche coefficient cultural »). Elle repose sur la connaissance d'un coefficient cultural, K_c , et sur l'évaluation de l'évapotranspiration de référence du gazon E_0 . La seconde méthode calcule directement l' E d'une culture, sans considérer la surface de référence. Elle applique la formule du type Penman-Monteith. Cependant, dans cette méthode, la résistance du feuillage, r_c , est spécifique pour chaque espèce ; elle n'est pas constante mais varie en fonction des caractéristiques climatiques de l'atmosphère sous la partie supérieure de la couche limite au-dessus de la culture. Le but de la présente étude est d'explorer et de tester une version plus opérationnelle du modèle direct. Dans cette version, la résistance du feuillage, r_c , est considérée comme constante, mais spécifique pour chaque culture. La performance de cette méthode est évaluée par rapport aux méthodes directe et indirecte qu'on vient de citer, à travers la validation expérimentale sur trois cultures ayant une différente hauteur. La meilleure performance est obtenue par la version originale du modèle directe à l'échelle journalière et horaire. La version opérationnelle du modèle direct a donné des résultats acceptables seulement pour le gazon. Le modèle indirect a donné les résultats les plus mauvais à l'échelle journalière et horaire. Enfin, l'application pratique de cette nouvelle version est illustrée dans les conclusions.

Mots-clés. Résistance du feuillage – Hauteur de la culture – Formule de Penman-Monteith – Déficit de pression de vapeur – Résistance aérodynamique.

I – Introduction

The evapotranspiration (E) of an irrigated crop can be calculated directly by using the Penman-Monteith formula with a specific value of the crop resistance and the meteorological variables

measured above the canopy. In practice, the use of this formulation needs, for each species, specific modelling of the canopy resistance (r_c) in relation to the environmental variables (Katerji and Perrier, 1983; Katerji and Rana, 2008). The direct calculation of E , compared to micrometeorological methods and weighing lysimeter, is considered the best way to estimate correctly the actual E (see the review by Katerji and Rana, 2008). Nevertheless, this way to calculate E has been considered too complex to be used in practice, since it needs the modelling of the canopy resistance r_c specific for each cropped surface. At the moment, this constraint, together with the need of determining the climatic variables above the given crop, leads to consider this direct method as not much operational.

From the application point of view, the calculation of the crop E is usually made by the formulation by Allen *et al.* (1998). It is an indirect calculation; in fact E is determined by the following relationship:

$$E = K_c E_0 \quad (1)$$

In this formulation, E_0 is the reference evapotranspiration and K_c is the crop coefficient.

Following a critical revision, the more recent FAO no. 56 paper (Allen *et al.*, 1998) redefined the concept of E_0 and adopted the Penman-Monteith equation adapted to a grass crop. Anyway, the authors simplified the procedure to calculate the resistance r_c for the grass. In fact, this was considered constant in all climatic conditions and takes a fixed value in the Penman-Monteith formula. The accuracy of the E values determined by the Eq. (1) depends on two factors. Firstly, on the accuracy of the determination of E_0 as carried out by the users in different geographical sites; then, on the accuracy of the K_c values. These values were given by Allen *et al.* (1998) for three stages of crop growth cycle (initial, middle and end) for the main cultivated crops.

The hypothesis of a constant resistance r_c in the determination of E_0 for the grass could be a possible source of error. However, some studies showed that this hypothesis gave acceptable estimation of E_0 in different regions of the world (Allen *et al.*, 1994a, 1994b). Other studies, mainly carried out in semi-arid and arid regions, showed opposite results, i.e. that the previously mentioned hypothesis underestimated, except for a few exceptions the values of E_0 as measured by lysimeters (see the results obtained by Steduto *et al.* 1996 in Morocco). The under-estimation ranged between 2 and 18% (Rana *et al.*, 1994; Steduto *et al.*, 1996; Ventura *et al.*, 1999; Lecina *et al.*, 2003; Pereira, 2005). Moreover, in humid regions, de Medeiros *et al.*, (2006) observed that the hypothesis of a constant r_c leads to a 13.4% over-estimation of the E_0 measured by lysimeter. Anyway, since the experimental error of the direct measurement of E_0 by the lysimeter is about 15% (Katerji and Rana, 2008), the performance of this method seems to be reasonable. Therefore, the approach proposed by Allen *et al.* (1998) merits the attention of researchers.

The second source of possible error concerns the values of K_c . Actually, these values showed more or less important differences with respect to the experimentally determined values of the E/E_0 relationship. Many papers can be found on this subject in the scientific literature. If we consider only the more recent literature (Testi *et al.*, 2004; Parkes *et al.*, 2005; Rana *et al.*, 2005; Lovelli *et al.*, 2005; Amayreh and Al-Abed, 2005; Kar and Verma, 2005; Vu *et al.*, 2005; de Medeiros *et al.* 2006), it is possible to find differences of $\pm 40\%$ between the K_c values reported by Allen *et al.* (1998) and the values experimentally obtained, especially during the middle growth cycle. These big differences are mainly due to the complexity of the coefficient K_c , which actually integrates several functions (Testi *et al.*, 2004): aerodynamic factors linked to the height of the crop, biological factors linked to the growth and senescence of the leaves, physical factors linked to the evaporation from the soil, physiological factors linked to the response of the stomata to the air vapour pressure deficit and agronomical factors linked to the crop management (distance between rows, using mulch, irrigation system, etc.). For this reason, Allen *et al.*, (1998) recommended that the evaluation of K_c values in local climatic conditions by observed data using lysimeters is necessary. Nevertheless, the simple local determination of K_c is not enough if general values of

K_c are required. Therefore, it is necessary to search for the relationships between K_c and more or less complex parameters, such as the surface area of the leaves, the humidity of the soil surface and the 3D energy balance (Testi *et al.*, 2004; Orgaz *et al.*, 2005; Lovelli *et al.*, 2005; Kar and Verma, 2005; Luquel *et al.*, 2005).

Following such a review of the indirect calculation of E , some researchers underlined (Testi *et al.*, 2004) or experimentally demonstrated (Rana *et al.*, 2005) the interest in the direct evaluation of E . This evaluation used the one-step approach as opposed to the two-step approach of the Eq. (1). Since it is based on a lower number of computation steps and on a lower number of error sources, the one-step approach can provide a more accurate estimation of E .

In the present paper, the original model proposed by Katerji and Perrier (1983), based on the hypothesis of a variable canopy resistance, will be recalled. In the following, we propose a second more operational version of the model, in which the hypothesis of a constant r_c was adopted for well watered crops, according to the approach proposed by Allen *et al.* (1998). To our knowledge, this is the first attempt to make the direct model for calculation the actual evapotranspiration more operational. This new version, in contrast with the original one, does not need the modelling of the canopy resistance. The comparison between measured and simulated E values with the above mentioned model will be carried out in a semi-arid region, at two time scales (hour and day), for 3 irrigated crops having contrasted height. This comparison will be evaluated with respect to another one, for the same crops at daily scale, between measured and calculated E using the standard FAO 56 method. In the following, we demonstrate that the studied crops showed a higher or lower sensitivity to the vapour pressure deficit of the air, which strongly characterised the climate of the semi-arid regions (Rana and Katerji, 1998).

In conclusion, a proposal for simplifying the direct model is given for application in the Mediterranean region.

II – Materials and methods

1. The direct model

The analysis of the crop actual evapotranspiration was made on the basis of the Penman-Monteith model. In this model, which is applicable to the hourly time scale, E is written as:

$$E = \frac{1}{\lambda} \frac{\Delta A + \rho c_p D / r_a}{\Delta + \gamma (1 + r_c / r_a)} \quad (2)$$

where $A=Rn-G$ is the available energy ($W m^{-2}$), ρ is the air density ($kg m^{-3}$), Δ is the slope of the saturation pressure deficit versus temperature function ($kPa C^{-1}$), γ is the psychrometric constant ($kPa C^{-1}$), c_p is the specific heat of moist air ($J kg^{-1} C^{-1}$), D the vapour pressure deficit of the air (kPa), r_c is the bulk canopy resistance ($s m^{-1}$) and r_a is the aerodynamic resistance ($s m^{-1}$), λ is the latent heat of evaporation ($J kg^{-1}$). The resistance r_a was calculated between the top of the crop and a reference point z sited in the boundary layer above the canopy, following Perrier (1975), as:

$$r_a = \frac{\ln \frac{z-d}{z_0} \ln \frac{z-d}{h_c-d}}{k^2 u_z} \quad (3)$$

where d (m), the zero plane displacement, is estimated by $d=0.67 hc$, with hc mean height of the crop (m); k is the von Kármán constant, u_z is the wind speed (m s⁻¹) at the reference point z above the canopy, z_0 (m) the roughness length estimated by $z_0=0.1hc$.

The hourly variation of r_c can be simulated starting from a relationship, which takes into account the associated effects of solar radiation, air vapour pressure deficit and wind speed. Katerji and Perrier (1983) proposed to simulate the resistance r_c by the following relation:

$$\frac{r_c}{r_a} = a \frac{r^*}{r_a} + b \quad (4)$$

where a and b are empirical calibration coefficients which require experimental determination. r^* (s m⁻¹) is written as:

$$r^* = \frac{\Delta + \gamma}{\Delta \gamma} \frac{\rho c_p D}{A} \quad (5)$$

It can be considered as a “climatic” resistance, because it depends only on weather variables.

This model has been used to calculate E for different species: (see review in Katerji and Rana, 2008) Therefore, from the above analysis, two models of direct E calculation are tested in this work: in the first version (model 1), by adopting the hypothesis of a variable r_c during the day by combination of Eqs. (2) and (4). It can be written as:

$$E = \frac{1}{\lambda} \frac{\Delta A + \rho c_p D / r_a}{\Delta + \gamma \left(a \frac{r^*}{r_a} + b \right)} \quad (6)$$

In the second more operational version (model 2), by adopting the hypothesis of r_c constant during the day. In this case, the hourly E can be written as:

$$E = \frac{1}{\lambda} \frac{\Delta A + \rho c_p D / r_a}{\Delta + \gamma \left(1 + \frac{r_c}{r_a} \right)} \quad (7)$$

The sensitivity analysis of the Penman-Monteith model is the analysis, at hourly scale, of the weight of each input variable A , D , r_c and r_a on the output variable E . Following the studies of the sensitivity made in the last decades, the weight of the resistance r_c depends on two factors:

the height of the crops in the formulation of the aerodynamic resistance r_a (Beven, 1979). This decreases when the height of the crop increases (see Eq. (3));

the soil water conditions of the crops (Rana and Katerji, 1998) which determines the values of r_c , for a given micrometeorological condition.

Starting from a sensitivity analysis carried out on three crops (grass, grain sorghum, sweet sorghum) with different increasing heights of 0.1, 1 and 3 m respectively, Rana and Katerji (1998) gave the weight of each input variable on the calculated E . In fact, from this paper it can be

argued that, in the case of well watered crops, r_c is responsible of 10-20% (case of grass) and 40-50% (case of grain and sweet sorghum) of the E variation. In the case of water stress conditions, the variable r_c is a dominant parameter in the variation of E, since it explains from 70% (grain sorghum) to 90% (sweet sorghum) of the E variation. In well watered conditions, the sensitivity of E to the input variables A and D varies also as a function of the crop height. The variable A explains 60-70% of the hourly E in the grass crop. Furthermore, the variable D explains 50% (grain sorghum) and 65% (sweet sorghum) of the hourly E. This analysis underlines a very important fact: in the case of well-watered crops the same error in the determination of r_c can give errors in the estimation of E which increases as the height of the crop increases. Therefore, the different models for the estimation of E have to be validated on a large range of crops with variable height in order to define their suitability.

The two versions of the direct model can be applied both at hourly and daily scales.

2. The indirect model

In this case, the actual evapotranspiration was estimated by the Eq. (1). The reference evapotranspiration E_0 was estimated by the following equation, as recommended by Allen *et al.*, (1998):

$$E_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 D}{\Delta + \gamma(1 + 0.34u_2)} \quad (7)$$

Where the energetic terms R_n , G and E_0 are in (MJ m⁻² day⁻¹); the other variables T (°C) and u_2 (m s⁻¹) are the air temperature and the wind speed measured at 2 m, respectively. The net radiation R_n and the soil heat flux G in this case were measured.

The coefficient K_c , for each crop, was taken for 4 growth periods from the same paper, following the "single crop coefficient" approach. The calculation of E using the standard FAO 56 method can be made only at daily time scale.

3. The site and the crops

This study was carried at a site of Southern Italy (Rutigliano, Bari, 41°0' N, 17°54' E, 122 m a.s.l.). The climate in Rutigliano is characterised by hot dry summers, with maximum air temperature sometimes higher than 40 °C and minimum relative air humidity often less than 20%. Mean annual rainfall is 500 mm, almost exclusively concentrated in spring and autumn.

The experiments were carried out on 3 well watered crops: grass, grain and sweet sorghum. These are annual crops (except grass) cultivated during the summer. These crops are different in height in the range of 0.1 – 3 m. For grain sorghum, the experimental period concerned only the phase when the crop completely covers the soil ($LAI > 2$); for sweet sorghum the experimental period also included the installation phase ($LAI \leq 2$). Therefore, the problem of partially covering crops is taken into account in this study.

For grass, measurements were taken in a field of grass (*Lolium perenne* L., var. Barvestra); it completely covered the soil and was from 0.07 to 0.15 m high. The meadow was well irrigated so that the soil water content was always near field capacity. Measurements were taken in 1994 and 1995. Actual E was measured by weighing lysimeter. Details of the experiment can be found in Rana *et al.* (1994).

The grain sorghum (*Sorghum bicolor* L. Moench, cv. Aralba) was sown on 2 May 1991, with a plant density at harvest of 20 plants/m², in a plot of 2 ha (200 x 100 m), the distance between rows

being 0.5 m. By means of drip irrigation, water was uniformly distributed all over the field. The actual E was measured by energy balance/Bowen ratio method. Details of the experiment can be found in Rana *et al.* (1997a).

The sweet sorghum (*Sorghum vulgare* L., cv. Saccharatum) field has a surface of about 4 ha, with a density of about 12 plants m⁻², the distance between adjacent rows was 0.6 m and the mean distance between the plants on a row was 0.12 m; the fetch from the field edge to the micrometeorological instrumentation was about 200 m in the direction of the predominant wind (NNW). The crop was maintained under well watered conditions. The actual E was measured by energy balance/Bowen ratio method. Details about the experiment can be found in Rana *et al.* (2001).

III – Results and discussion

1. Calibration of the models

The calibration of the models was carried out using the hourly data of r_c , determined during two clear days casually chosen during the experiment period. The calculation of r_c was carried out by introducing the hourly data of the measured E in the Eq. (2). Figure 1 shows the hourly values of r_c for the 3 crops. In general, the resistance r_c showed a standard evolution during the day. It decreased from sunrise with increasing solar radiation, to reach the minimum value around 8 – 9:00 a.m.. When the solar radiation decreased again in the afternoon around 3-4:00 p.m. then the r_c values increased again. Between 9:00 a.m. and 3:00 p.m., the canopy resistance varied very little in the grass crop, which is a low crop having a very high aerodynamic resistance r_a . On the other hand, r_c in the sweet sorghum crop, characterised by a great height and a small r_a , varied significantly from 12:00 to 3:00 p.m. This was interpreted as the response of the stomata to the air vapour pressure deficit (Ferreira and Katerji, 1992). The grain sorghum showed an intermediate situation between the grass and the sweet sorghum.

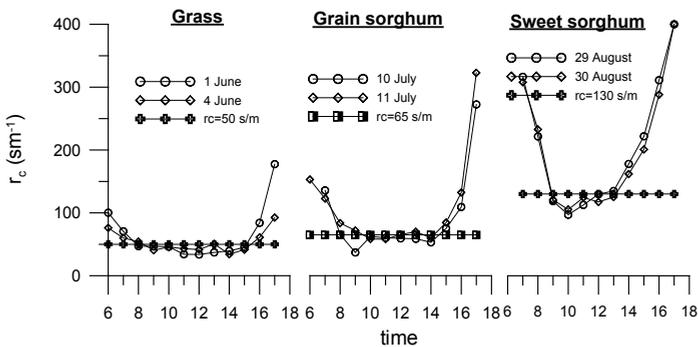


Figure 1. The measured crop resistance r_c for two clear days, for the three studied crops, together with mean daily values.

The calibration of the direct model needs the determination, for each species and during the two days casually chosen for the calibration, the relation r_c/r_a as a function of r^*/r_a . Figure 2 presents, as an example, the relation found for grass. Table 1 also presents all the relations for the 3 studied crops. The mean values of the hourly r_c found in the present study for the grass is about 50 s m⁻¹ and it is in the range of values found in the literature for this species. These values ranged between 30 and 70 s m⁻¹ (Wright *et al.*, 2002; Ventura *et al.*, 1999; Lecina *et al.*, 2003). The hypothesis followed by Allen *et al.* 1998 that r_c should be constant in the different climatic

conditions is not verified in practice. In the case of the other annual crops, the mean values found in the present study (between 65 and 130 s m⁻¹) are generally greater than those found in the literature. From the current analysis it is suggested that the air vapour pressure deficit must play a major role in the environments of the region where this work was carried out, particularly for tall crops, like the sweet sorghum, compared to grass.

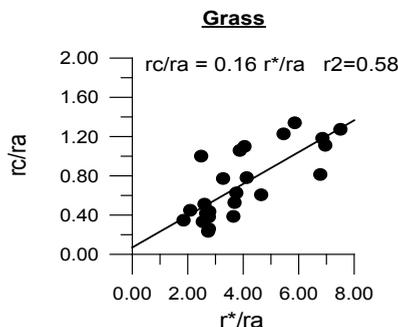


Figure 2. Relationship between the ratio rc/ra and r^*/ra , at hourly scale, for the grass.

Table 1. Summary of the crop characteristics and values of coefficient a et b(see eq. 4) obtained by calibration for each studied crop.

Crop	Experimental Period	Height (m)	LAI	E measurement Method	a	B	R2
Grass	1/06 – 21/09	0.07-0.15	2 – 2.5	Weighing lysimeter	0.16	0	0.58
Grain sorghum	9/07 – 27/08	1	3.8 - 4.2	Bowen ratio	0.54	0.61	0.43
Sweet sorghum	20/04 – 18/10	1.5 – 2.8	1 – 6.4	Bowen ratio	0.845	1	0.88

Validation of the models

Figure 3 presents the comparison between hourly values of E simulated by model 1 and measured E, for the 3 studied crops. Here, as for in the other linear regressions, the intercept is fixed to 0 if it is not significantly different from 0.

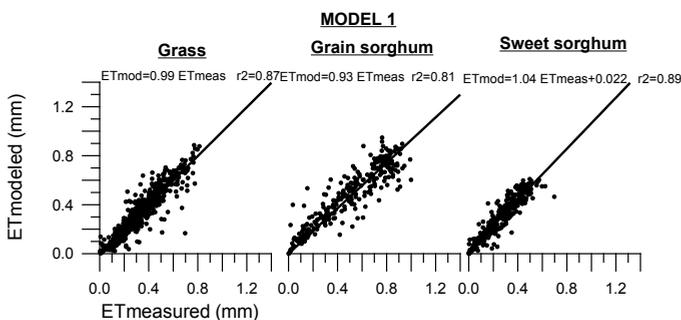


Figure 3. Comparison between measured and calculated evapotranspiration by the model 1 at hourly scale, for the three studied crops.

In all the cases, model 1 works pretty well. Therefore, the hypothesis of a variable resistance rc taken into account in the model 1 satisfactorily agrees with the hourly E measured in all the studied situations. Figure 4 shows, for the same crops, the comparison between hourly values of E simulated by model 2 and measured E. In the grass crop, the observed correlation is good, but

the slope of the linear regression is around 0.85 instead of 0.99 for the case of model 1. For the other 2 studied crops, model 2 generally overestimates the actual E: furthermore, the slopes and the correlation coefficients are not satisfactory. Since the experimental error in the determination of the hourly E is about 15% (Katerji and Rana, 2008), the hypothesis in model 2 of a constant canopy resistance, locally determined, can be considered acceptable only in the case of the grass crop.

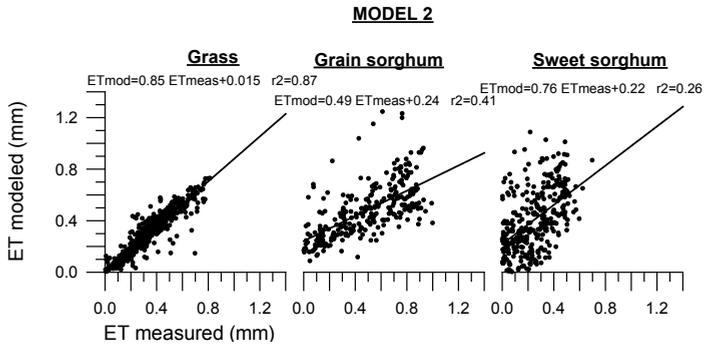


Figure 4. Comparison between measured and calculated evapotranspiration by model 2 at hourly scale, for the three studied crops.

Daily scale

The daily values E estimated by models 1 and 2 have been calculated by the sum of the hourly values simulated by the same models, from 8:00 a.m. to 6:00 p.m., for each day.

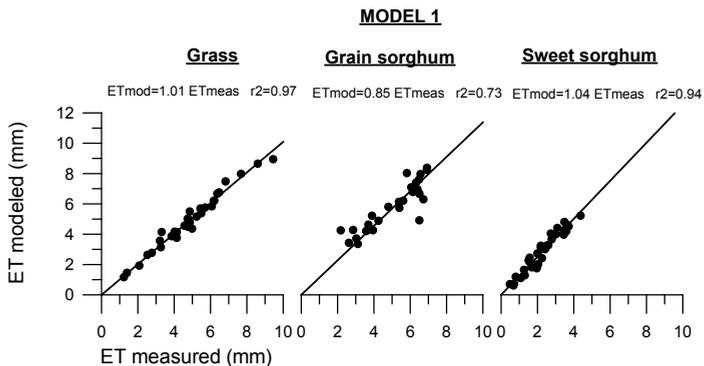


Figure 5. Comparison between measured and calculated evapotranspiration by model 1 at daily scale, for the three studies crops.

Figure 5 presents the comparison between E daily values simulated by model 1 and measured in the same period, for the studied crops. In summary, the calculation of the daily E made by model 1 gave acceptable results. Figure 6 shows the comparison between daily E measured and simulated by model 2. In this case the daily simulation of E is satisfactory only for grass. For the other studied species, the calculation is not acceptable. Figure 7 shows the comparison between daily E measured and calculated by the standard FAO 56 method. In the grass crop, the observed correlation is good, but the slope of the linear regression is around 0.78 instead of 0.99 for the case of model 1. In the case of sweet sorghum, the slope of the regression is correct, but the coefficients of correlation are low ($R^2=0.53$). For the other crop, the slopes and the correlation coefficients are not satisfactory.

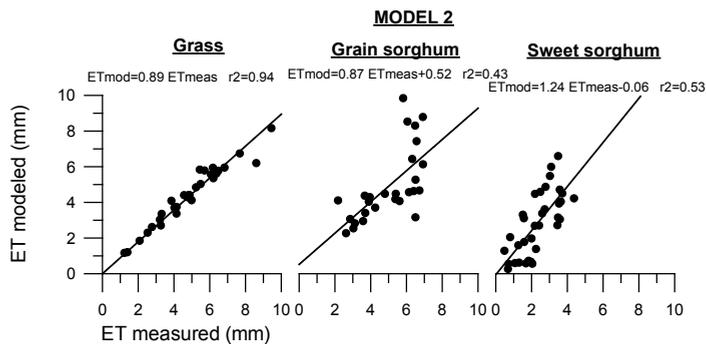


Figure 6. Comparison between measured and calculated evapotranspiration by model 2 at daily scale, for the three studied crops.

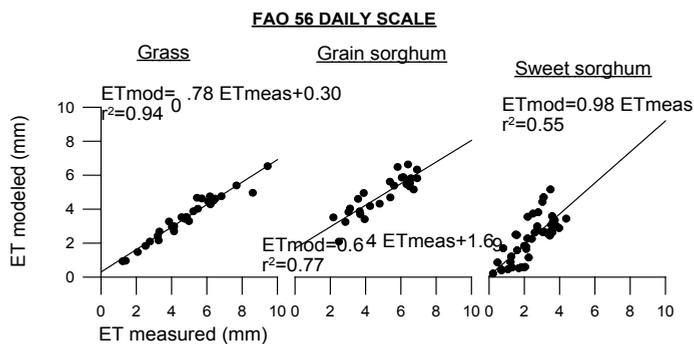


Figure 7. Comparison between measured and calculated evapotranspiration by the FAO 56 using the standard single crop coefficient approach at daily scale, for the three studied crops.

IV – Conclusions

From many works in the scientific literature, the calculation of the crop evapotranspiration by direct models seems to be more accurate than the indirect models in the calculation of the crop water requirements. The intermediate calculations of E_0 and K_c needed for the indirect calculations generates significant errors, as shown in the bibliographic review presented in the introduction of this paper and the results presented in Figure 6.

Two approaches, here presented, are possible for calculating directly the E :

In the first one (model 1) the canopy resistance has been modelled as a function of three climatic variables. We checked the performances of this model for 3 crops grown in a semi-arid region, where the sensitivity of the crops to the air vapour pressure deficit is greater than in the case of humid and semi-humid environments. The results are satisfactory both at hourly and daily scales for all the studied crops. Another important advantage of the direct model 1 is the possibility to extend the modelling of E to other sites and places (Rana *et al.*, 1997b; 2001). The only difficulty of this approach is due to the necessity of modelling of the canopy resistance r_c .

The second more operational approach (model 2) is based on the assumption that the canopy resistance of every crop in well-watered conditions can be considered constant. The experimental verification showed that the E is much less accurate than using model 1. The model 2 particularly failed in certain days, when the canopy resistance, r_c , varied significantly during the day, mainly

in the case of tall crops. Nevertheless, it gave acceptable results in the case of low crops: i.e. the grass (at hourly and daily sales). This can be due to two main reasons:

low crops have a large aerodynamic resistance r_a . So these have a weak stomatal response to the variations of the air vapour pressure deficit. In this case, local calibration of the mean daily resistance r_c represents an acceptable value of the single hourly resistance.

In general, for low crops, the weight of the canopy resistance r_c is low in the calculation of E . Therefore, a large error in the determination of r_c has a small impact in the calculation of E .

Nevertheless, the necessity of the local determination of r_c deprives this approach of its main advantage. So we think that it is more interesting to model the resistance r_c as for model 1. Moreover, this modelling does not need the determination of supplementary parameters or input variables. On the contrary, it increases the accuracy of the calculated E also in the case of tall crops. However, the direct models need the measurement of weather variables above the crop, not easily feasible in routine. Thus, it is surely interesting to study another further version of the model which needs the determination of the weather variables collected in a standard agro-meteorological station. This last path of research, permitting to obtain an analogous more operational version of the direct model, has been recently studied by Rana and Katerji (2009). Actually, these authors showed that it is possible to determine E with high accuracy, at least at daily scale, on a large range of crops, simply using climatic variables collected in a standard agro-meteorological station.

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