Soil Water balance correction due to light rainfall, dew and fog in Ebro river basin (Spain)

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Highlights

- We evaluate the methodology used to estimate the contribution of fog, dew or light rainfall to crop water use.
- The method is based on the time of day when dew deposition, fog interception, or rainfall initial abstraction mostly dries from the plant foliage.
- This study uses data from the Ebro River Basin to further evaluate the method proposed by Moratiel et al. (2013) for California to see if the method can be universally applied or if it only works in California.
- We found that the California model also works in the Ebro River Basin in Spain

- Accuracy of the method depends mainly on the estimation of the time when the canopy dries

Abstract

Accumulated daily crop evapotranspiration (ET_c) generally provides good estimates of cumulative soil water depletion between irrigation of well drained soils. If the canopy is wet due to fog, dew, or light rainfall, however, energy contribution to surface evaporation will reduce transpiration and hence soil water losses. When surface evaporation occurs, the ET_c overestimates the soil water depletion by an amount approximately equal to the surface water evaporation. Moratiel et al. (2013) proposed a method to estimate the contribution of surface water to ET_c based on the time of canopy drying. The first method assessment was done with California data, and this evaluation was conducted in the Ebro basin, Spain, to appraise the method in a higher latitude in area with a somewhat different climate. Differences between the California and Spain corrected models were less than 10% and depended mainly on the time of canopy drying. The comparison showed that the model is robust and useful to estimate the fraction (F) of ET_c coming from the soil under dew, light rainfall, and fog conditions.

INTRODUCTION

Three main mechanisms, which are often neglected, that provide water for evapotranspiration are fog interception, dew formation, and light rainfall. Fog occurs when water vapor (in the atmosphere) reaches saturation and condenses on aerosols regardless of the surface conditions. Dew occurs when the surface temperature reaches the dew point temperature, and the water vapor from the air in contact with the cold surface condenses to form dew. Light rainfall is often insufficient in magnitude to cause tipping bucket raingauges to tip and it is difficult to measure in standard rain gages. All three of these sources of water will wet a crop canopy, and contribute to evapotranspiration, so it is important to consider the contributions in water balance calculations. There are few studies dealing with the contribution of fog and dew to the soil water balance of crops. Dew deposition provides a relatively small contribution to crop evapotranspiration (ET_c), it depends on microclimate at night, and it varies to a great extent even within the same region (Moro et al. 2007). In coastal regions, fog can provide a considerable fraction of the annual water (Dawson, 1998). The majority of studies dealing with the fog contribution were developed for natural ecosystems (Kidron, 1999; Moro et al., 2007; Prada et al., 2009; Mildenberger et al., 2009; Kataka et al. 2010), while only a few studies investigated the contribution of dew and fog to the water balance of crops (Cosh et al., 2009; Kabela et al. 2009). In this paper, the model developed using California data to estimate the reduction in soil water losses due to the evaporation of fog, dew, and light rainfall interception by crop canopies is further tested in Spain at higher latitude than California. Quantification of dew, fog, and light rainfall contribution to ET_c is important for efficient water usage in irrigated agriculture.

In regions with high evaporative demand, the contribution of fog, dew, or light rainfall is relatively small, however, in locations and times when ET_c rates are small, the surface water contribution becomes important. For irrigation scheduling based on the soil water balance, the goal is to calculate the soil water depletion (S_D) using ET_c, deep percolation, and runoff of precipitation and irrigation applications, water table contributions, and surface water supplied by fog, dew, and light rainfall. For well-drained soils and well-managed irrigation systems, there is no water table contribution to ET_c and the sum of deep percolation and runoff are relatively easy to estimate. Estimating the contribution of surface water, however, is more difficult. When the plant foliage is wet, surface evaporation reduces transpiration losses because the energy that would contribute to transpiration is used to vaporize water from the leaf surfaces. Thus, surface vaporization (V_S) causes a reduction in soil water losses to ET_c roughly equal to the V_S contribution.

Proper irrigation scheduling requires information on the soil water depletion (S_D) within the crop root zone, application uniformity and efficiency, and application rate. The soil water depletion (S_D) is the difference between the volumetric water content at field capacity and the soil volumetric water content, where field capacity is the soil water content reached after drainage of the gravitational water. For well-drained soils, the two main methods to determine $\mathrm{S_D}$ are based on (1) gravimetric water content sampling and (2) cumulative crop evapotranspiration (CET_c) estimate. Assuming the other gains and losses of soil water are small, most of the soil water loss is due to ET_c.

The crop coefficient method is commonly used to estimate ET_c from the standardized reference evapotranspiration for short canopies (ET_0), where $ET_c = ET_0 \times K_c$. Crop coefficient (K_c) values are determined by calculating the ratio of measured ET_c to the ET_0, which is calculated using data from an agrometeorological station and equations described by Allen et al. (1998) and Allen et al. (2005). For a well-watered crop, the ET_c mainly depends on the energy available for vaporizing water on the plant surfaces, from the soil (evaporation), and from water vaporized inside the plant leaves (transpiration). Clearly, if the plant surfaces are wet, then some of the ET_c comes from surface vaporization rather than from transpiration.

There are few studies regarding the contribution of water from dew, fog, and light rainfall to the crop. Recently, Moratiel et al. (2013) reported a method to separate ET_c into S_D and V_S contributions for 30 California weather stations. The aim of this study was to evaluate the method under the semiarid conditions of the Ebro river basin (Spain), which is at higher latitude than California, to develop appropriate monthly models for this area, and to use the information to improve water balance calculations under dew, fog, and light rainfall conditions.

MATERIAL AND METHODS

Study area: Ebro basin

The Ebro basin is located in Spain between meridians 4ºW and 2ºE and the parallels 40º and 43ºN (Fig. 1). The basin surface area is 85,362 km^2 and it is located mostly in Spain (98.9%) with small areas in Andorra and France. The ring of mountains that surround the basin formed a depression in the central zone where most of the irrigated area is located. The Ebro basin originated during the Tertiary period. The central sector of the Ebro Tertiary Basin is characterized by Oligo-Miocene sediments deposited in evaporite and carbonate shallow lakes in a continental environment, disconnected from the sea (Gutiérrez Elorza and Gutiérrez Santolalla 1998). The bedrock mainly consists of sub-horizontal evaporites of the Oligo-Miocene Zaragoza Gypsum Formation with laminated and nodular gypsum alternating with marls and lutites (sedimentary rocks, which are composed of silt-size sediment, clay-size sediment, or a mixture of both).

Consequently, in the middle of the Ebro River Basin, the soils and surface water, which is the main source of irrigation water in the area, have the potential to contribute to salinity. Most of the soils in the irrigated areas are classified as Xerosol Gypsic and Xerosol Calcic, while the soils near the river are classified as Fluvisol Eutric (Salvador et al., 2011). The predominant climate is Mediterranean Continental. The average precipitation in the basin is 622 mm per year, concentrated in autumn and spring, but the average precipitation in irrigated areas is usually between 300 and 500 mm per year (Martínez- Cob and García-Vera, 2004). In the central part of the basin, the climate is semiarid or arid with annual ET_o in the range of 840-1500 mm, with an average value of 1150 mm (Salvador et al. 2011).

The Ebro Basin has 783,948 ha of irrigated land. The irrigation systems used in the basin are surface (69%), sprinkler (19%), and drip (12%). Surface water comprises 91% of the water use in the basin (CHE, 2012). The main field crops are: alfalfa (*Medicago sativa* L.), 121,499 ha, about 56% of the national alfalfa crop area; grain corn (*Zea mays* L.), 105,694 ha; barley (*Hordeum vulgare* L.), 83,550 ha; wheat (*Triticum aestivum* L.), 69,026 ha; peach orchard (*Prunus persica* (L.) Batsch.), 31,089 ha; vineyards (*Vitis vinifera* L.), 30,605 ha; rice (*Oryza sativa* L.), 30,515 ha; pear tree (*Pyrus communis* L.), 23,397 ha; olive tree (*Olea europaea* L.), 19,393 ha; and apple orchard (*Malus domestica* Borkh.), 16.179 ha.

Climate data

Half-hourly climate data were collected from 49 stations (Fig. 1B) from the agrometeorological network SIAR (Information System for Irrigation Districts), which is managed by the Spanish Ministry of Agriculture, Food and Environment (MAGRAMA, 2012). Characteristics of the agrometeorological stations were described by Moratiel et al. (2011). Each station included global solar radiation, air temperature, relative humidity, wind speed and direction, and precipitation. Climate data from 2004 to 2010 were used to calculate hourly standardized reference evapotranspiration for short canopies (ET_{0i}) in mm d^{-1} following Allen et al. (1998, 2005, 2006):

$$ET_{0i} = \frac{0.408\Delta\left(R_{ni} - G_i\right) + \left(\frac{37\gamma}{T_i + 273}\right)u_{2i}\left(e_{si} - e_{di}\right)}{\Delta + \gamma\left(1 + 0.24U_{2i}\right)} \qquad for\ R_n > 0$$

$$ET_{0i} = \frac{0.408\,\Delta\left(R_{ni} - G_i\right) + \left(\frac{37\gamma}{T_i + 273}\right)u_{2i}\left(e_{si} - e_{di}\right)}{\Delta + \gamma\left(1 + 0.96U_{2i}\right)} \qquad for\ R_n \le 0 \qquad (1)$$

where the hourly variables included: R_{ni} (MJ $m^{-2}h^{-1}$) the net radiation, G_i (MJ m^{-2} h^{-1}) the soil heat flux density, T_i (ºC) the mean hourly temperature; Δ (kPa $^{o}C^{-1}$) the slope of the saturation vapor pressure curve at T_i, γ (kPa ^{o}C-^{1}) the psychrometric constant, e_{si} (kPa) the saturation vapor pressure at temperature T_i, e_{di} (kPa) the actual vapor pressure, and u_{2i} (m s^{-1}) the mean wind speed.

Methodology

The original model, which is called the Soil Water Balance-Corrected California (C_{CA}) was described by Moratiel et al. (2013). The daily total evapotranspiration (ET_{od}) was calculated as the sum of the 24 hourly ET_{oi} values (Eq. 2):

$$ET_{od} = \sum_{i=1}^{24} ET_{0i} \qquad (2)$$

The hourly cumulative evapotranspiration was computed and normalized relative to ET_{od}. Thus, the cumulative hourly normalized evapotranspiration (NET_{oh}) was computed as:

$$NET_{oh} = \frac{\sum_{i=1}^{h} ET_{oi}}{ET_{od}} \tag{3}$$

Monthly means of NET_{oh} for h=1-24 were determined for each station as the mean over years (2004-2010). Only months having fewer than five missing data points were included in the mean NET_{oh} calculations.

In the model, it was assumed that the relationship between normalized hourly ET_o and time of the day is similar to the relationship between normalized hourly ET_c and time of the day. According to Moratiel et al (2013), NET_{oh} is a sigmoidal function of the hour of the day, the time (a) when NET_{oh} attains half of its maximum value, and a parameter (b) which determines curvature of the sigmoidal function. The NET_{oh} is calculated as:

$$NET_{oh} = 1 - F = 1 - \frac{1}{1 + e^{\left(\frac{t-a}{b}\right)}} \tag{4}$$

where t is the local mean time (Greenwich Mean Time, “GMT” in Spain) in hours when the surface water dries from a wet canopy; F is the fraction of ET_c that is the soil water depletion at the end of hour t.

Four models based on Eq. 4 were used in this analysis to estimate NET_{oh} as a function of hour of the day. At any time (t) during the day, the corresponding NET_{oh} is the fraction of the daily ET_o that occurs between the previous midnight and time t. Therefore, if a crop canopy dries off at time t, then the corresponding NET_{oh} is the fraction of the daily ET_o coming from dew, fog, or light rainfall (Vs). The models are variations of the model developed and presented by Moratiel et al. (2013) using data from California.

1) The C_{CA} model used a mean value of a = 12.5 and b was determined by month and location using Ebro Basin stations.
2) The model C_{EB} was developed in a similar manner as C_{CA} but the parameters a and b were obtained by month using Ebro Basin data.
3) The C_{EBa} model uses the annual mean parameter values a = 12.7 and b = 1.72 from the Ebro Basin for all months and locations.
4) The C_{CAa} model is the same as C_{CA} except it uses the annual means a = 12.5 and b = 1.73 for all months and stations rather than the mean b = 1.70 from California.

In this study, maps of ET_{od} were generated using the Surfer®8 program applying the Kriging method for spatial interpolation of the estimates at the stations. The curves for F were adjusted using equation 4 to obtain a and b with the curve Expert 1.4 program. The values a and b were optimized by reducing the chi-square value as much as possible. Typically, this optimization required 7 and 11 iterations starting with a and b equal to 1.0. Values for a and b from the Ebro Basin were analyzed and compared with the values obtained by Moratiel et al. (2013).

RESULTS AND DISCUSSION

Annual ET_o for the stations of the Ebro Basin ranged between 900 and 1470 mm with a large variability between stations and years. The overall mean for all stations over the seven years was 1204 mm, which was similar value to that reported by Salvador et al. (2011).

Figure 2 presents the monthly mean values for ET_{od} during 2004-2010. The ordinary kriging method was used for spatial interpolation (Martinez Cob, 1996 ; Kamali et al., 2015), it represented the general spatial distribution of mean ET_{od} (mm d^{-1}) in the basin. Other geostatistical interpolation methods, such as cokriging, could be used to obtain more precise interpolation estimates of ET_{od} (Martínez-Cob, 1996), but it is unnecessary for this study. The highest ET_{od} values were observed in the southeast. The overall mean ET_{od} was 3.4 mm d^{-1} for the basin. The months with the lowest and highest mean daily ET_o were December (0.9 mm d^{-1}) and July (6.6 mm d^{-1}).

As an example, a plot of the mean NET_{oh} versus local time (GMT) for Montañana station is shown in Figure 3. The experimental values of NET_{oh} were fit to the sigmoidal curve (Eq. 4). For Montañana and CEB model, values for b were 1.51, 1.74, 2.05 and 1.74 and values for a were 12.13, 12.90, 12.95 and 12.71 for January, March, July and September, respectively. The parameter a corresponds to the time when NET_{oh} = 0.5, while the parameter b corresponds to the time when the curve is not adjacent to the horizontal asymptote 0 and 1. Due to changes in the duration of the day over a year, the winter months show a values slightly lower than those for the summer months (Fig. 4 a). The b variable identifies the curvilinear shape (Fig. 4 b). The b values were lower in winter than in summer because of the shorter day length.

Table 1 lists the monthly values of parameter b for the C_{CA} model (Moratiel et al., 2013) under Ebro Basin conditions, as well as the parameters a and b for the Ebro

Basin model (C_{EB} model). For the C_{EB}, parameter b values were slightly lower than those for the C_{CA} model for all months except October and November. The slightly low b values are likely related to the Ebro Basin having a higher latitude than most stations in the California study; leading to a difference in daylength and different values of parameter a calibrated by month for CEB model.

Figure 5 shows the monthly average values of F for both C_{CA} and C_{EB} models computed for a time of 10:30 local standard time. Values of F for the model C_{CA} were slightly lower except for January, February, November, and December, when similar values were observed for both models. Again, the difference is probably related to longer day length at higher latitude in Spain. The difference between models (Fig. 5) was less than 8% (< 0.6 mm day^{-1}). For July with 7.5 mm day^{-1}, the C_{EB} estimated F =0.78, this implies 0.78x7.5=5.9 mm d^{-1}, while the C_{CA} estimated 5.4 mm d^{-1}. Moratiel et al. (2013) obtained a b = 1.7 as the mean over 12 months for 30 stations in California. In this research, b = 1.73 was obtained (Table 1). The average a value was 12.7 for C_{EB} compared to 12.5 for C_{CA}. The values a and b were optimized with R^2>0.98 and standard error less than 0.03. The C_{CA} model (which uses a fixed value of parameter a=12.5) resulted in a 7% difference for t = 11 used in Eq. 4 when applied to the Ebro Basin. As the error in estimating the time of drying is likely to be considerably greater than 7%, the a=12.5 is acceptable.

The biggest uncertainty to adjust the C_{CA} model for Spain is to obtain the b parameter. Figure 6 shows the graph of estimated b values for model C_{CA} versus monthly mean ET_{od} (mm d^{-1}). The coefficient of determination was near 80%, the standard error was 0.109, and the regression was significant at 95% level. For a confidence level 0.95, the slope varied between 0.106 and 0.115 and the intercept varied between 1.34 and 1.37. Thus, the graph offers a method to adjust the model for different evaporation conditions.

Figure 7 shows the graphs for a and b using the C_{EB} model. For parameter a, the $R^2 = 0.66$, which suggests that 34% of the variability is not explained by the regression. Moratiel et al. (2013) reported the value $a = 12.5$ for C_{CA}, and the error resulting from use of a variable range (as in model C_{EB}) or a fixed value (as in model C_{CA}) is about 8% of F. During the summer with high b values, the error in parameter a was about 6%, while 11% error was observed for the winter months (with low b). The parameter b shows the same trend as the parameter b in the C_{EB} model, with an $R^2 = 80\%$. The values for b were always within 0.03 for the two models with C_{EB} slightly lower than C_{CA}.

Moratiel et al. (2013) recommended the use of annual mean values for a and b to estimate F in the C_{CA} model instead of monthly values because the errors were less than 5%. Table 2 shows differences between the models C_{CA}, C_{EB}, C_{CAa}, and C_{EBa} when applied to the Ebro Basin data. C_{CAa} and C_{EBa} were the same as C_{CA} and C_{EB} except they use the annual mean values rather than monthly values for parameters a and b. Differences between the models increase with time from t=8 to t=11, but mean differences are never more than 3% and the maximum and minimum differences approach 10 %. The difference between models is within the range of error found in direct measurement of crop evapotranspiration with lysimeters (Allen et al., 2011), so the errors should be considered as reasonable. For conditions of the Ebro Basin, plants rarely stay wet from fog or dew later than t = 10:00 h and the model differences are small in the morning. The results indicate that using monthly or annual parameters results in minimal differences in NET_{oh}, so using the annual parameters seems adequate for making the water balance corrections for dew, fog, and light rainfall in the Ebro Basin. More research is needed to identify a method to objectively determine when a plant canopy dries. This will further standardize the C_{CA} model, and then research to quantify dew, fog, and light rainfall contributions to ETc in various regions.

CONCLUSIONS

The differences in estimates of soil water losses between monthly and annual models are within the range of possible evapotranspiration errors (5-15%) from high precision lysimeters, and errors in estimating the time of drying for surface water are also likely to be bigger than differences in the models reported in this study. The results suggest that the C_{CAa} model is easier to apply because it requires only the computation of an annual b parameter without the need for monthly computation of F. The annual C_{CAa} parameter $b = 1.7$ reported by Moratiel et al. (2013) for California was similar to the C_{EBa} value $b = 1.73$ observed in the the Ebro Basin. This implies that the C_{CA} model is robust and it provides a good method to estimate the fraction of ET_c coming from the soil (F) when crop canopies are exposed to dew, fog, and light rainfall events in the Ebro Valley of Spain, which is at higher latitude than most stations in California. Accuracy of the method depends somewhat on the estimation of when the canopy dries, which is subjective at this time. Generally, if about 90% of the exposed foliage at the canopy top visually appears dry, we assume that the canopy is dry. Research to objectively measure canopy dryness is needed.

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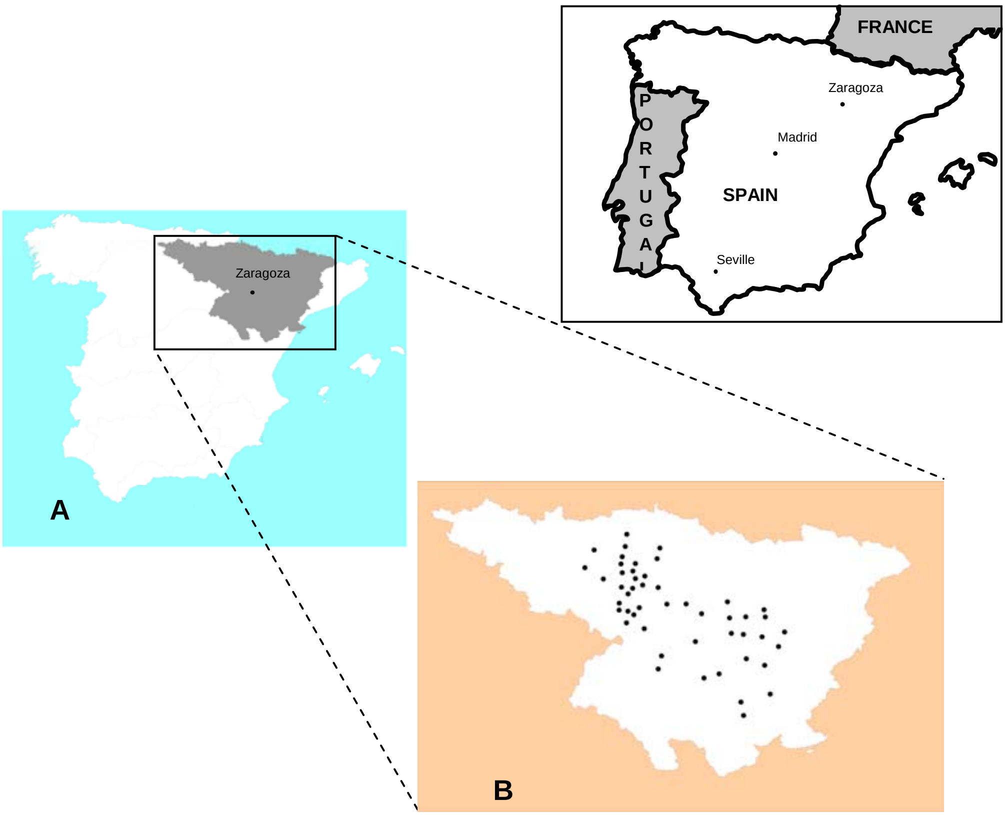

Fig.1. (**A**). Location of the Ebro basin. (**B**). Location of the agrometeorological stations of the Ebro basin.

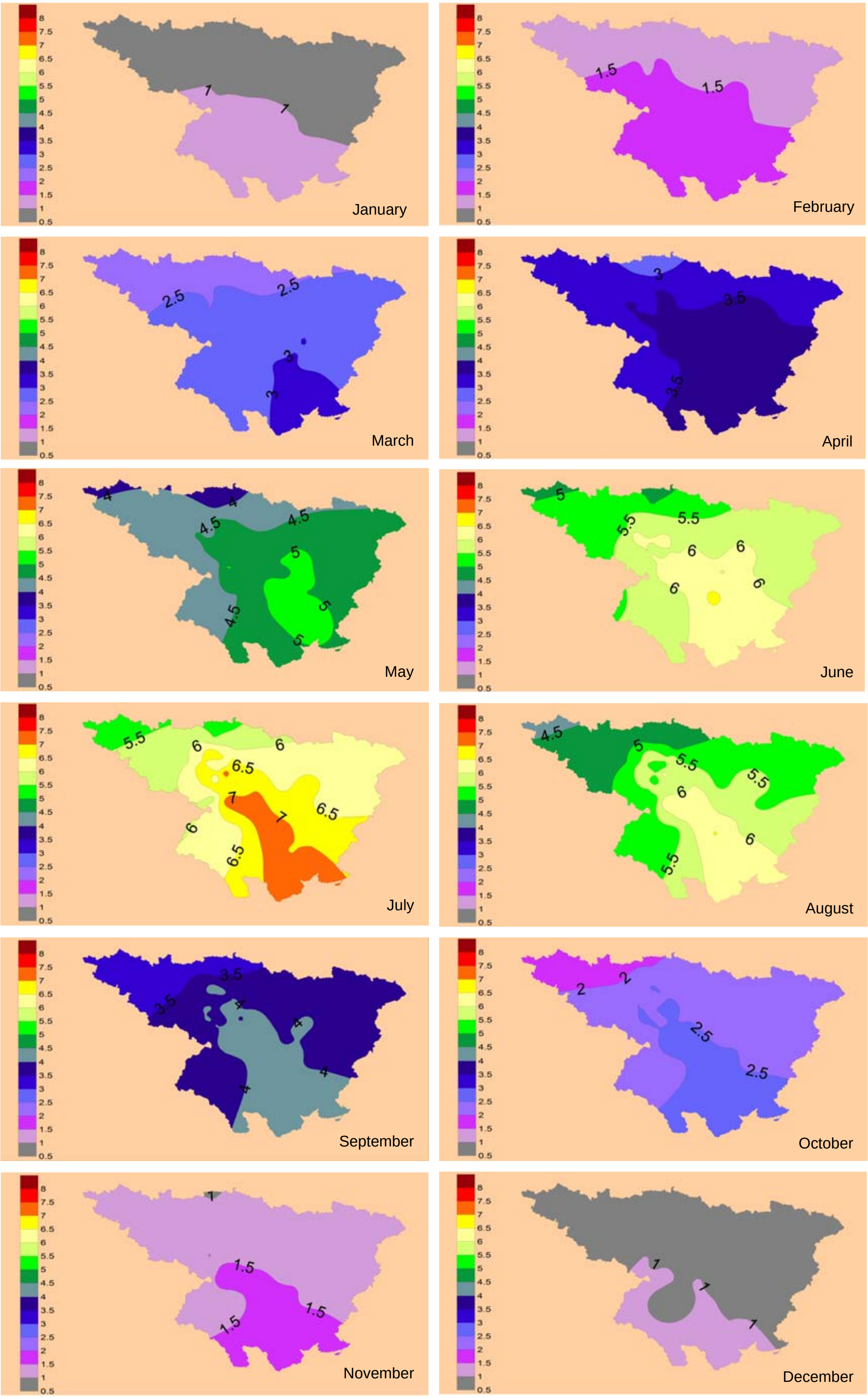
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Fig.2. Monthly averages of daily reference evapotranspiration (*ET_{od}*, mm d^{-1}) during the period 2004-2010.

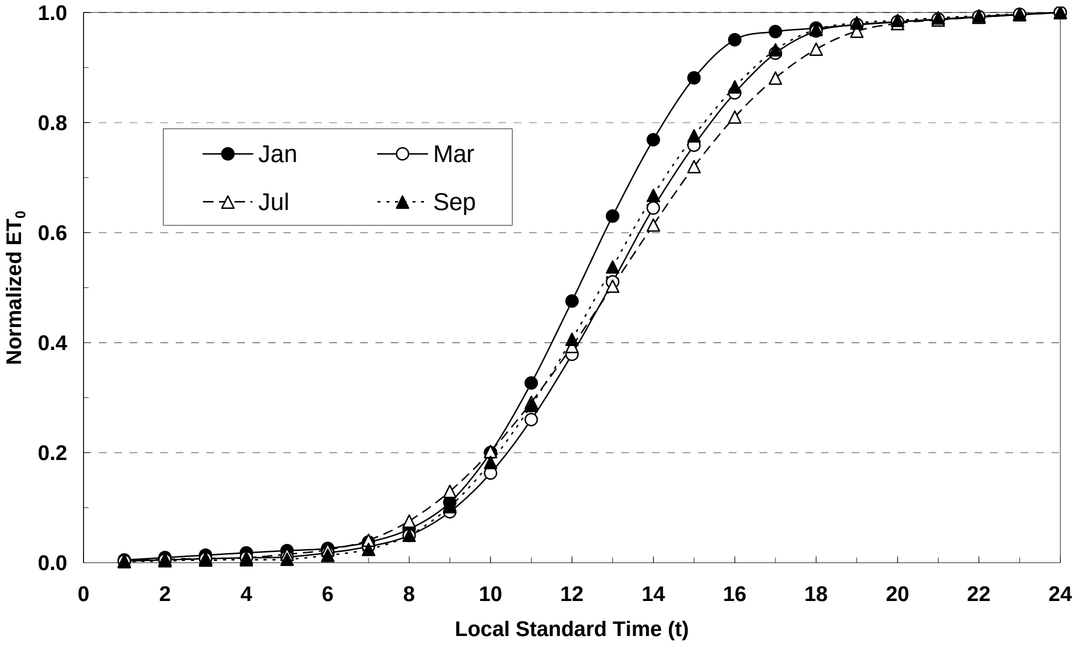

Fig. 3. Plot of the mean normalized hourly *NET_{oh}* versus local standard time (GMT in Spain) for January, March, July and September at Montañana, Zaragoza (Spain). Data were means for the period 2004 to 2010.

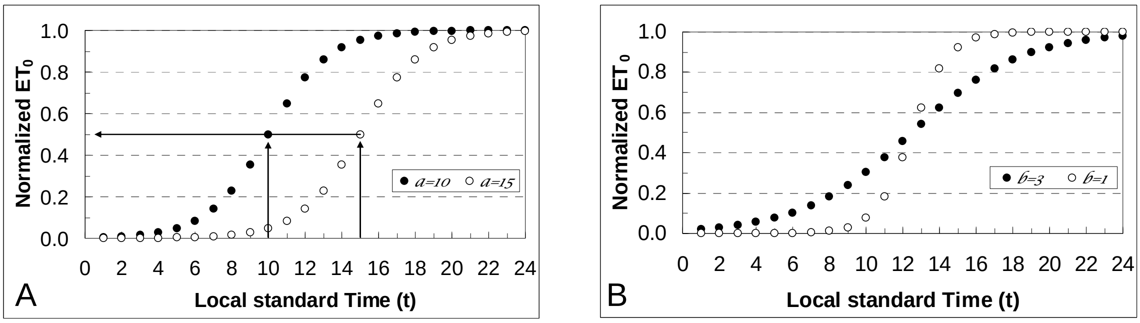

Fig. 4. Graphical depiction of the effect of parameters ***a*** and ***b*** on the curves of the normalized hourly NET_{oh} versus local standard time using Eq. 4. The plot (A) is for parameter ***a***, ***b*** is constant with 1.7 and plot (B) is for parameter ***b***, ***a*** is constant with 12.5.

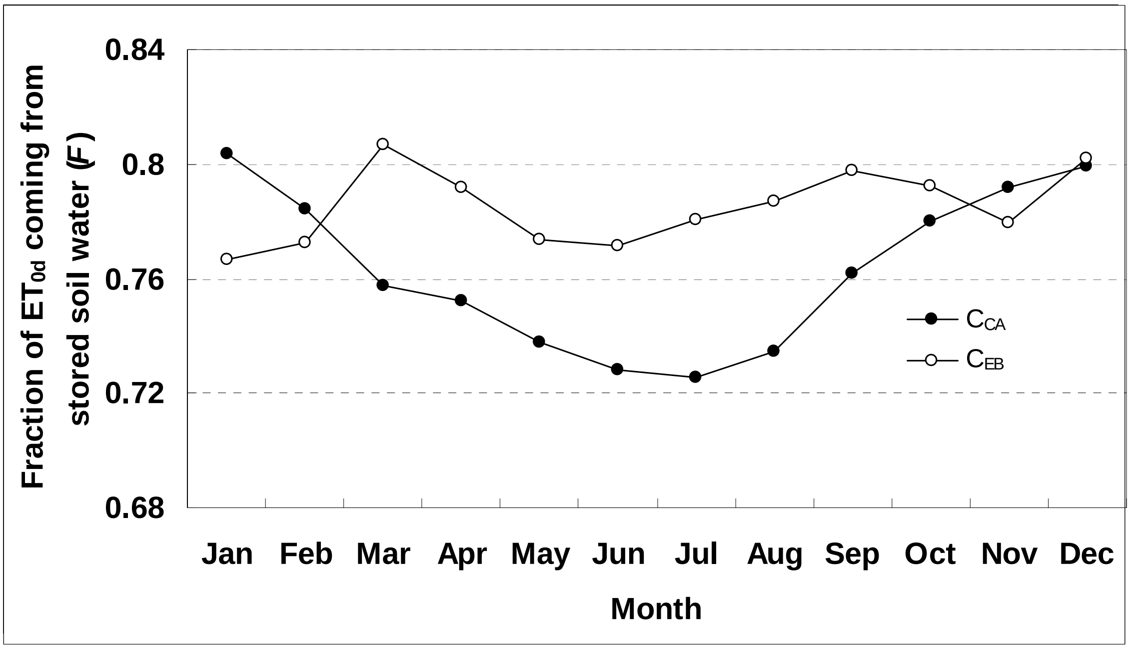

Fig. 5. Fraction (*F*) of ET_0 coming from stored soil water for different months and the models C_{CA} and C_{EB} assuming the plant surface water dries at t = 10:30 local standard time. Monthly mean values for 49 stations of Ebro basin.

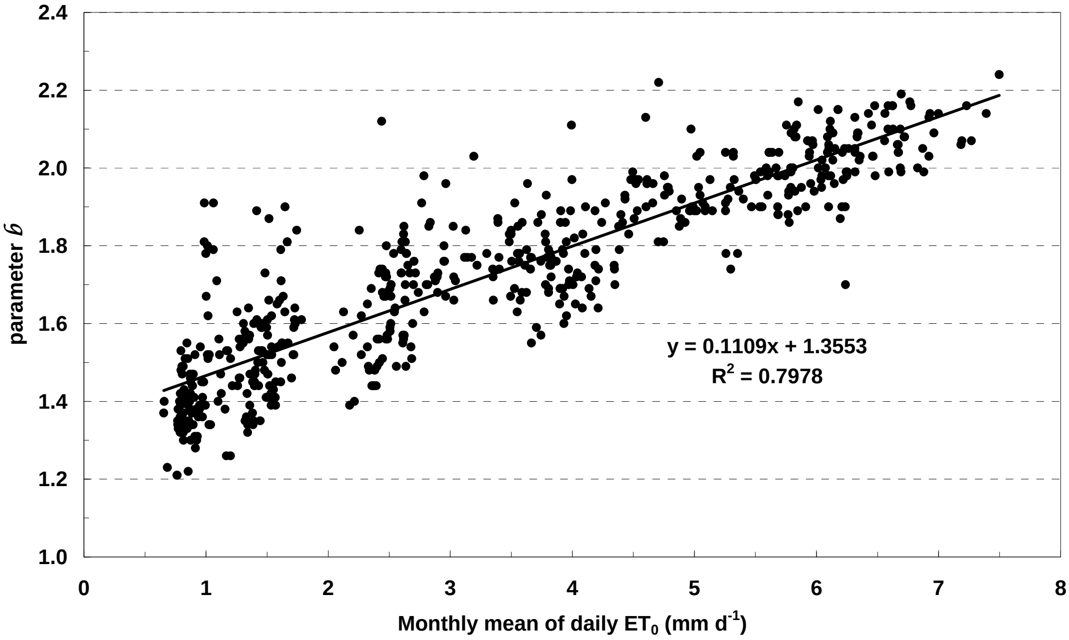

Fig. 6. A plot and regression of parameter ***b*** for model C_{CA} versus monthly mean of daily ET_0 (mm d^{-1}) for 49 stations of Ebro basin.

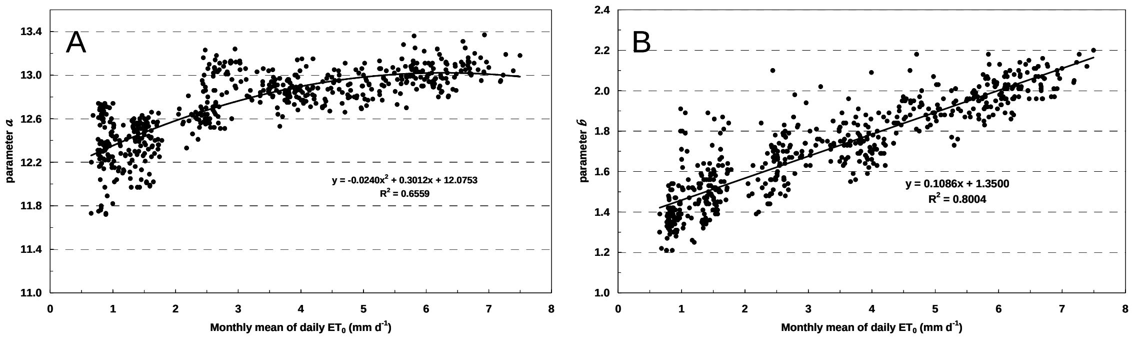

Fig. 7. Plots of model parameters for the model C_{EB} versus monthly mean ET_{od} (mm d^{-1}) for 49 stations of Ebro Basin for (A) parameter a and (B) parameter b.

Table 1. Mean monthly values for parameter ***b*** using the model C_{CA} and *a* = 12.5 and for the parameters ***a*** and ***b*** obtained for the model C_{EB}. SD = standard deviation and CV = coefficient of variation.

Model		Paremeter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	SD	CV (%)
C_{CA}	$F=\frac{1}{1+e^{\left(\frac{t-12{,}5}{b}\right)}}$	b	1.42	1.55	1.76	1.80	1.93	2.03	2.06	1.96	1.72	1.58	1.50	1.45	1.73	0.23	13.3
C_{EB}	$F=\frac{1}{1+e^{\left(\frac{t-a}{b}\right)}}$	a	12.17	12.39	12.97	12.89	12.86	12.95	13.08	13.03	12.84	12.62	12.39	12.52	12.73	0.30	2.4
		b	1.40	1.54	1.73	1.78	1.92	2.02	2.03	1.94	1.70	1.58	1.50	1.44	1.72	0.23	13.1

Table 2. Percentage differences in *F* between models C_{CA}-C_{EB}, C_{CA}-C_{CAa}, C_{EB}-C_{EBa}, and C_{CAa}-C_{EBa} for *t* = 8, 9, 10, and 11 am local standard time. The parameters used in C_{CAa} and C_{EBa} are the means over 12 months and 49 stations.

		C_{CA}-C_{EB}	C_{CA}-C_{CAa}	C_{EB}-C_{EBa}	C_{CAa}-C_{EBa}
t=8	Mean	-0.96	-0.04	0.02	-0.90
	Max	2.28	4.54	3.81	-0.90
	Min	-4.28	-4.92	-4.54	-0.90
t=9	Mean	-1.39	0.09	0.07	-1.42
	Max	3.99	6.43	5.41	-1.42
	Min	-5.76	-5.65	-6.42	-1.42
t=10	Mean	-1.91	0.25	0.07	-2.10
	Max	7.19	7.83	6.60	-2.10
	Min	-7.24	-5.60	-8.67	-2.10
t=11	Mean	-2.41	0.31	-0.08	-2.81
	Max	11.25	7.14	6.13	-2.81
	Min	-9.23	-4.27	-11.46	-2.81

C_{CA}: $F=\frac{1}{1+e^{\left(\frac{t-12{,}5}{b}\right)}}$ where parameter $b = 12.5$ is the same for each month and station (and parameter b is different each month and station)

C_{EB}: $F = \dfrac{1}{1+e^{\left(\frac{t-a}{b}\right)}}$ where parameters a and b are different for each month and station based on data from the Ebro Basin

C_{CAa}: $F = \dfrac{1}{1+e^{\left(\frac{t-12,5}{b}\right)}}$ where parameter b (1.73) is the mean of all months and stations

C_{EBa}: $F = \dfrac{1}{1+e^{\left(\frac{t-a}{b}\right)}}$ where parameters a (12.73) and b (1.72) are the mean values for all months and stations