A WIND-BASED QUALITATIVE CALIBRATION OF THE HARGREAVES ET_0
ESTIMATION EQUATION IN SEMIARID REGIONS

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9 SUMMARY

10 This study evaluates the Hargreaves equation for estimation of monthly ET_0
11 under the semiarid conditions of the middle Ebro River Valley (NE Spain). First, the
12 Hargreaves equation was compared against measured lysimeter ET_0 values at
13 Zaragoza for the period May 1997 to October 2000. The average of estimated values
14 was only 5.6 % above the average of measured values. Later, the Hargreaves
15 equation was compared against the FAO Penman-Monteith equation for monthly ET_0
16 estimation at 9 locations. These locations can be grouped as non-windy (Alcañiz,
17 Daroca and Tamarite) and windy (Almudévar, Ejea, Gallocanta, Monflorite, Sariñena
18 and Zaragoza). Simple linear regression and error analysis statistics suggest that
19 agreement between the two estimation methods was quite good for the windy
20 locations. Average errors ranged between 2-5 % for Almudévar, Ejea, Sariñena and
21 Zaragoza, and between 7-10 % for Gallocanta and Monflorite where some
22 underestimation was observed. However, the agreement between the Hargreaves
23 and FAO Penman-Monteith equations was lower for the non-windy locations. In this
24 case, the Hargreaves equation overestimated ET_0 and average errors varied
25 between 14-20 %. According to these results, it is proposed that, under the semiarid
26 conditions of this study, no local calibration would be required for windy locations
27 (those where monthly average windspeeds above 2.0 m s^{-1} are frequent), while a
28 value of 0.0020 instead of the original 0.0023 should be used in the Hargreaves
29 equation for non-windy locations. Further research should be undertaken to evaluate
30 whether these results can be extended to other semiarid regions of the World.

KEYWORDS

Evapotranspiration, Hargreaves, Semiarid climate, Calibration

1. INTRODUCTION

In semiarid regions, water use in irrigated agriculture is a paramount issue for different aspects of water resources management, such as planning and design of new irrigation districts and systems, and water distribution among existing districts. Accurate knowledge of crop water requirements is required to deal with these issues. Irrigation engineering widely uses reference evapotranspiration (ET_0) estimates to predict crop water requirements.

Many methods exist for ET_0 estimation. Recently, the *FAO-56* version of the Penman-Monteith equation (*FPM*) has been established as the new standard definition of ET_0 (Allen et al., 1998). The *FPM* equation has a sound physical background and has proven to accurately estimate measured ET_0 worldwide (Jensen et al., 1990; Allen et al., 1994, 1998). Nevertheless, an important constraint to application of the *FPM* equation is that requires measurements of air temperature and relative humidity, solar radiation and wind speed. While air temperature is available at most of weather stations worldwide, the remaining variables are only collected at relatively very few locations and those recordings are not always very reliable (Droogers and Allen, 2002).

This lack of reliable weather data lead to the development of simpler ET_0 estimation equations. Allen et al. (1998) proposed the use of the Hargreaves (*HARG*) equation (Hargreaves and Samani, 1985) as an alternative ET_0 estimation equation when only air temperature data is available at weather stations. Several studies have

shown this equation may provide accurate ET_0 estimates for 10-days or longer time steps (Jensen et al., 1990; Choisnel et al., 1992; Hargreaves, 1994; Henggeler et al., 1996; Droogers and Allen, 2002). Nevertheless, the *HARG* equation tends to overestimate ET_0 in humid regions and to underestimate it in very dry regions (Saeed, 1986; Jensen et al., 1990; Amatya, 1995; Droogers and Allen, 2002; Xu and Singh, 2002). It has also been shown that the *HARG* equation tends to overestimate ET_0 at low ET rates and to underestimate it at high ET rates (Droogers and Allen, 2002; Xu and Singh, 2002). Therefore, the *HARG* equation requires local calibration before applying it for monthly ET_0 estimation at a given region (Jensen et al., 1997; Vanderlinden et al., 1999; Xu and Singh, 2002).

There have been previous attempts to use a wind function to adjust the *HARG* equation at semiarid regions (Allen, 1993; Jensen et al., 1997). Different wind functions have been computed for different locations because of interactions of wind, aridity, temperature and instrumentation biases leading to different wind effects on ET at different climates (Jensen et al., 1997). This circumstance and the lack of reliable wind data at many weather stations (Droogers and Allen, 2002) discourage the development of wind functions for adjusting the *HARG* equation.

However, it would be assumed that the behavior of the *HARG* equation would be alike at locations of semiarid regions with similar wind characteristics, as well as other climatic factors. In this paper, the *HARG* equation has been evaluated at nine weather stations located at the middle Ebro River Valley, in the region of Aragón, NE Spain (Figure 1). Wind speed recordings at those weather stations were analyzed in order to group those stations in two or more wind categories. The goal was to investigate whether the behavior and the tentative calibration of the *HARG* equation

at locations of the same group are alike. Then, the use of the *HARG* equation at a given location within semiarid regions would only require to know, as additional information, the wind category into which that location would be classified in order to choose the appropriate calibration factor. In fact, a preliminary study performed with three weather stations suggested that calibration of the *HARG* equation would only be required at non-windy locations of semiarid regions (Martínez-Cob and Tejero-Juste, 2002).

2. MATERIAL AND METHODS

Meteorological data were collected at 8 automatic and one manual weather stations of Aragón (Table 1). Those weather stations belonging to the authors' Institution (Ejea, Gallocanta, Tamarite and Zaragoza) recorded 30-min averages of precipitation, air temperature and relative humidity, wind speed and global solar radiation. Air temperature and relative humidity were measured at 1.5 m (Tamarite and Zaragoza) and at 2.0 m (Ejea and Gallocanta) above soil surface. Wind speed was measured at 2.0 m in the four weather stations. Data was recorded using Campbell Scientific CR10X dataloggers. The remaining weather stations (Alcañiz, Almudévar, Daroca, Monflorite and Sariñena) belong to the Spanish National Meteorological Institute (INM) and all of them but Almudévar recorded 10-min averages of precipitation, air temperature and relative humidity, and wind speed. Measurement heights were 1.5 m (air temperature and relative humidity) and 10.0 m (wind speed) above soil surface. Wind speeds at 2.0 m height were obtained from those at 10.0 m height using the log-wind profile equation (ASCE, 1996). Data was recorded using SEAC dataloggers. In all automatic weather stations, platinum

resistors and capacitive sensors were used for measuring air temperature and relative humidity values. Wind speed was measured using cup anemometers. Daily maxima and minima of air temperature and relative humidity, and daily averages of wind speed and solar radiation were derived from the 10 or 30-min recordings. On the other hand, Almudévar is a manual weather station where daily values of precipitation, maximum and minimum air temperature and relative humidity, and wind run were collected. Measurement heights were the same than the INM automatic weather stations. Daily bright sunshine values were manually recorded at the five INM weather stations using a Campbell-Stokes sunshine recorder.

The daily values of the meteorological variables were used to compute reference evapotranspiration (ET_0) using the *FPM* and *HARG* equations (Allen et al., 1998). The following equation was applied for the *FPM* equation:

$$ET_{PM} = \frac{0.0864}{\lambda} \frac{\Delta (R_n - G) + c_p \rho_a DPV / r_a}{\Delta + \gamma (1 + r_c / r_a)} \quad (1)$$

where: ET_{PM} , computed ET_0 estimate using the *FPM* equation (mm d^{-1}); λ , latent heat of vaporization (MJ kg^{-1}); Δ , slope of the vapor pressure vs. temperature curve ($\text{kPa } ^\circ\text{C}^{-1}$); γ , psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$); R_n , net radiation (W m^{-2}); G , soil heat flux (W m^{-2}); c_p , specific heat of air ($1013 \text{ J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$); ρ_a , atmospheric density (kg m^{-3}); DPV , vapor pressure deficit (kPa); r_a , aerodynamic resistance (s m^{-1}); r_c , bulk canopy resistance (s m^{-1}); the ratio $0.0864/\lambda$ was used to transform W m^{-2} to mm d^{-1} . All variables included in equation (1) were computed as described in Allen et al. (1998), taking care of appropriate measurement heights.

The following equation was applied for the *HARG* equation:

$$ET_H = f_c \frac{0.0864 R_a}{\lambda} (T_x - T_n)^{0.5} (T_m + 17.8) \quad (2)$$

where: ET_H , computed ET_0 estimate using the *HARG* equation (mm d^{-1}); f_c , the original calibration factor (0.0023) of the Hargreaves equation as described by Allen et al. (1998); R_a , extraterrestrial radiation (W m^{-2}) computed as described by Allen et al. (1998); T_x , T_n and T_m , daily maximum, minimum and mean air temperature ($^{\circ}\text{C}$), respectively; T_m was computed as the average of T_x and T_n ; the ratio $0.0864/\lambda$ was also used to transform W m^{-2} to mm d^{-1} . Computed daily estimates of ET_0 (ET_{PM} and ET_H) were averaged to obtain monthly estimates of ET_0 .

Additionally, daily ET_0 values were measured with a weighing lysimeter (6.3 m^2 effective surface, 1.7 m depth), installed at the center of the field plot where the Zaragoza weather station is located (Martínez-Cob, 2001; Lecina et al., 2003). Daily, weekly and monthly ET_H estimates were first compared against lysimeter ET_0 (ET_{lys}) values at Zaragoza. This comparison was performed for the period May 1997 to October 2000 for which lysimeter data were available. Later, monthly ET_H estimates were compared at the 9 weather stations against monthly ET_{PM} estimates. ET_H and ET_{PM} estimates are not completely independent each other as both methods use the same air temperature values for calculations. Since these viewpoint, it would have been preferable to compare ET_H estimates at the nine locations against ET_0 values measured either by lysimeters or by micrometeorological methods. However, these instruments are expensive and have intensive highly-qualified labor requirements for proper maintenance and operation. They are only available at research stations and they are generally operated within specific research projects so only short-term records are available. Then, the evaluation of ET_0 estimation equations at a regional

or local level, as in this case, can only be made against such a method as the Penman-Monteith equation, currently widely used, which is considered the standard approach to define and compute reference evapotranspiration, and to calibrate other ET_0 equations (Allen et al., 1994, 1998; Walter et al., 2000).

All comparisons were performed by simple linear regression $y = b_0 + b_1 x$, where y is the dependent variable (ET_{lys} or ET_{PM}), x is the independent variable (ET_H), b_0 is the intercept and b_1 is the slope. Likewise, for each location data set, the mean square error (MEE), the root mean square error ($RMSE$) and the relative error (RE) were computed using the following expressions (Willmott, 1982):

$$MEE = \frac{\sum_{i=1}^n (y_i - x_i)}{n_o} \quad (4)$$

$$RMSE = \left[\frac{\sum_{i=1}^n (y_i - x_i)^2}{n_o} \right]^{0.5} \quad (5)$$

$$RE = \frac{RMSE}{\bar{y}} 100 \quad (5)$$

where: y_i , estimated ET_{PM} value for month i ; x_i , estimated ET_H value for month i ; n_o , sample size; $\bar{y}$, average of ET_{PM} estimates for a given location.

3. RESULTS AND DISCUSSION

Table 2 lists the statistics of the comparison between the ET_H estimates and the ET_{lys} measured values at the Zaragoza site. The agreement between estimated and measured ET_0 increased from daily to monthly time steps. For this later time step

the performance of the Hargreaves equation was quite good with a relative error (RE) of 13.7 %. The averages of ET_H and ET_{lys} values were 3.8 and 3.6 mm d⁻¹, respectively; i.e. average ET_H was 5.5 % greater than average ET_{lys} . This uncertainty was quite similar to that obtained when comparing daily ET_{PM} estimates against ET_{lys} measured values at the same location (Lecina et al., 2003). The results shown were also similar to those reported by Choisnel et al. (1992) and Hargreaves (1994) when comparing the Hargreaves equation to lysimeter measurements at different semiarid and semihumid locations. Therefore, these results suggested that the Hargreaves equation could be considered at a first glance as a relatively accurate method to estimate monthly ET_0 under the semiarid conditions of the middle Ebro River Valley in those locations where only air temperature has been recorded. However, these results must be evaluated in other locations within the region with somewhat different climatic conditions and so a further evaluation of the Hargreaves equation was performed at nine locations.

Table 3 lists the annual average values of several meteorological variables at the study sites for the available recording period. Average annual precipitation was less than 400 mm at six locations and it was less than 475 mm at the other three sites. Average annual air temperature ranged from 13.1 to 14.5 °C, except for Gallocanta, the coldest site, where that figure was 11.6 °C. The coldest sites, Daroca and Gallocanta are located at the mountainous areas surrounding the middle Ebro River Valley (Figure 1, Table 1). Average annual air relative humidity was relatively similar in all locations ranging from 65 to 76 %.

The main difference between locations was the average annual windspeed which ranged from 1.1 m s⁻¹ (Daroca) to 3.1 m s⁻¹ (Gallocanta) (Table 3). Average

annual windspeeds of Daroca, Tamarite and Alcañiz were not significantly different than each other but they were significantly different ($\alpha = 0.95$) than those of the remaining six locations (Table 3) according to the Bonferroni procedure of multiple comparison of more than two population means (Devore and Peck, 1986). However, statistical difference between the average annual windspeeds of these other six locations was not so distinct (Table 3). The Bonferroni test suggest that there were three non-windy sites, Daroca, Tamarite and Alcañiz, and six windy sites, the remaining ones, although this category perhaps could also be divided in two groups, the moderate-wind (Sariñena, Almudévar and Zaragoza) and the strong-wind sites (Monflorite, Ejea and Gallocanta).

Table 4 lists the statistics of the comparison between the monthly ET_H and ET_{PM} estimates at the 9 studied locations. All coefficients of determination were high, above 96 %. However, the different statistics suggest that the performance of the Hargreaves equation was different for the three non-windy sites (Alcañiz, Daroca and Tamarite) and the other six locations. At the three non-windy locations, the Hargreaves equation overestimated ET_0 as shown in Figure 2 and indicated by the MEE values, lower than -0.45 mm d^{-1} . The regression slopes were statistically different than 1 ($\alpha = 0.95$). According to the ratios of average ET_{PM} to average ET_H , and the medians of the ratios of monthly ET_{PM} to monthly ET_H estimates, the Hargreaves overestimation varied between 14 to 20 % (Table 5). For the three non-windy locations, the $RMSE$ values were relatively high, about 0.6 mm d^{-1} , and the RE values were subsequently relatively high, above 21 %.

On the other hand, the agreement between ET_H and ET_{PM} estimates was higher at the six windy locations (Almudévar, Ejea, Gallocanta, Monflorite, Sariñena

and Zaragoza). In this case, the regression slopes were not significantly different than 1 ($\alpha = 0.95$) but that of Gallocanta (Table 4). The *MEE* values suggest that there was neither overestimation nor underestimation at Ejea, Sariñena and Zaragoza sites, while there was some underestimation at the other three sites, Almudévar, Gallocanta and Monflorite (Figure 2). The ratios of average ET_{PM} to average ET_H , and the medians of the ratios of monthly ET_{PM} to monthly ET_H estimates, suggest that average error was less than 2 % at Ejea, Sariñena and Zaragoza, and between 5 to 10 % at Almudévar, Gallocanta and Monflorite (Table 5). *RMSE* values were within 0.2-0.4 mm d⁻¹, i.e. the *RE* values varied between 7 to 12 % (Table 4). These uncertainties are similar to those considered as adequate for accurate, well operated and maintained micrometeorological evapotranspiration methods such as Bowen ratio and eddy covariance (ASCE, 1996). These uncertainties are also similar to those reported by Jensen et al. (1997) for an evaluation of the Hargreaves equation against the FAO Penman-Monteith equation at several semiarid locations of mid-western and western United States.

Wind mixes up the top and bottom layers of the atmosphere and, in turn, reduces the difference between T_x and T_n by decreasing T_x during daytime and by increasing T_n during nighttime (Temesgen et al., 1999). This would explain at some extent the different behavior of the Hargreaves equation at the non-windy and windy locations.

Figure 3 represents the ratios of monthly ET_{PM} to monthly ET_H estimates versus the monthly average windspeed for the 9 studied locations. As wind speed increases those ratios also increase. Thus, for low wind speed values ET_{PM} are lower than ET_H estimates but for high wind speeds the opposite occurs. Figure 3 also

shows the corresponding fits that could be seen as possible wind functions to correct the Hargreaves equation for each location. However, the use of these wind functions is not recommended as they differ from one location to other and wind speed recordings are only available at few weather stations (Allen, 1993; Jensen et al., 1997; Droogers and Allen, 2002). Figure 3 shows that most or all recorded monthly wind speeds averages were lower than 2.0 m s^{-1} at Alcañiz, Daroca and Tamarite and most or all ratios of monthly ET_{PM} to monthly ET_H estimates were lower than 1.0, i.e. Hargreaves equation overestimated ET_0 for most cases. At Gallocanta and Monflorite, most recorded average monthly windspeeds were above 2.0 m s^{-1} and most ratios of monthly ET_{PM} to monthly ET_H estimates were higher than 1.0, i.e. Hargreaves equation underestimated ET_0 for most months, although this underestimation was on average less important than the overestimation seen at Alcañiz, Daroca and Tamarite (Tables 4 and 5). Results for Almudévar, Ejea, Sariñena and Zaragoza were intermediate to those mentioned above.

The uncertainties of the measurement instruments, operation and maintenance of weather stations, the effect of surroundings (ground cover under the measurement instruments, topography, etc.) on the measurements, and the interactions between the different meteorological variables at each particular location could explain the differences of the results obtained in these different sites (Jensen et al., 1997; Droogers and Allen, 2002). Nevertheless, results of Tables 4 and 5, and Figures 2 and 3 strongly suggest that, under the conditions of this study, there was a significantly different behavior of the Hargreaves equation at the windy (Almudévar, Ejea, Gallocanta, Monflorite, Sariñena and Zaragoza) and non-windy (Alcañiz, Daroca and Tamarite) locations. For non-windy locations, where average monthly

windspeeds above 2.0 m s^{-1} were quite uncommon, the Hargreaves equation overestimated ET_0 and a local calibration would be required. For windy locations, where average monthly windspeeds above 2.0 m s^{-1} were frequent, the Hargreaves equation can provide accurate monthly ET_0 estimates and no local calibration would be needed. It is possible that for strong-wind locations, the Hargreaves equation could underestimate ET_0 and require a local calibration (Figure 3), although the results shown on Tables 4 and 5 for Monflorite and Gallocanta do not support that.

If the regression lines are forced through the origin, the regression slopes multiplied by the f_c value of 0.0023 (equation 1) would provide the local calibration coefficient of the Hargreaves formula for each location. Table 6 lists these new computed calibrated f_c values. For Alcañiz, Daroca and Tamarite, these new f_c values were practically the same and they were about 14-16 % lower than the original value of 0.0023. In the case of the windy locations, the computed f_c values were also similar for Almudévar, Ejea, Sariñena and Zaragoza and were within 1 % of the original value of 0.0023 (4 % at Almudévar). For Monflorite and Gallocanta the computed f_c values were slightly different and they were about 7 % higher than the original value of 0.0023 (equation 1). As stated before, it is possible that local calibration for strong-wind locations could be different than that for moderate-wind locations. However, statistics of the error analysis (Tables 4 and 5) do not support that conclusion as these errors are within the accuracy of the measurement instruments, the errors associated with the operation and maintenance of the stations and the effect of surroundings on the quality of measured meteorological variables. Then, under the conditions of this study and the available information, it is concluded that only local calibration would be required for non-windy locations. The lack of more

weather stations in the middle Ebro River Valley with long-term records of wind speed did not allow a deeper analysis of the possible underestimation of the Hargreaves equation at strong-wind locations. Further research should be carried out in other semiarid strong-wind locations when available. If a simple regression analysis (forced through the origin) between ET_H and ET_{PM} is computed combining together monthly estimates of Alcañiz, Daroca and Tamarite, then the proposed new f_c value for equation 1 for non-windy locations under semiarid conditions would be 0.0020 instead of the original value of 0.0023.

On average, certain months of the year are windier than others. It would be possible that the calibration for a site be changed depending on the month being considered in addition to the overall classification of windy versus non-windy. However, under the conditions of this study and the available information, differences among monthly windspeed averages at a given site were generally smaller than those between sites. Then, changes of the calibration factor between months for a given site are not expected be relevant. However, further research should be performed to answer this question.

The results shown in this paper suggest that a qualitative calibration of the Hargreaves equation, based on a qualitative knowledge of wind speed at the site of interest, can be performed at semiarid regions. However, an important concern raises as wind speed recordings are not frequent and then it would be difficult to determine whether a specific site is windy or not windy if wind measurements are not available. Nevertheless, the windiness of a site would only require a qualitative knowledge of wind and continuous long-term wind measurements would not be required. For instance, in the middle Ebro River Valley, in the recent years, there has

been an increase of wind measurements promoted by the wind power industry. In general, they are short-term measurements, only for limited periods of time (1 to 2 years) and no other meteorological measurements have been taken in those sites. The wind power industry has used these recordings to look for appropriate locations for installation of wind mills. Then, it could be followed the thumb rule that a specific site is windy if there are wind mills installed nearby and it is not windy in the opposite case. In general, in the middle Ebro River Valley, these wind mills are installed in the surroundings of valleys and uplands that are oriented from northwest to southeast. In fact, the main winds in Aragón, “cierzo” and “bochorno” blow from northwest and from southeast, respectively.

Further research is required to evaluate this wind-based qualitative calibration of the Hargreaves equation in other semiarid regions. Because of the empirical nature of the Hargreaves equation, a single, universal calibration of this equation would be difficult to achieve. Droogers and Allen (2002) proposed such a calibration by including precipitation values in the equation. However, the *RMSE* and *R*² values of the comparison between the FAO Penman-Monteith and the precipitation-calibrated Hargreaves equations were about 0.67 mm d⁻¹ and 0.93, respectively, clearly worse than those obtained in this study (Table 4), suggesting that depending on the accuracy required for *ET*₀ estimation, a local calibration would still be required at a specific region.

4. CONCLUSIONS

The Hargreaves equation can provide relatively accurate estimates of monthly *ET*₀ at weather stations with only air temperature available, under the semiarid

conditions of the middle Ebro River Valley (NE Spain) as indicated by simple linear regression and error analyses results obtained when comparing ET_H estimates with measured lysimeter values at the Zaragoza location.

However, the accuracy of the Hargreaves equation would vary depending on the meteorological conditions of a particular location. Thus, the Hargreaves equation was compared against the FAO Penman-Monteith equation for monthly time steps at 9 locations within the middle Ebro River Valley. Results suggest that accuracy of the Hargreaves equation is quite high for windy locations, where monthly averages of windspeed above 2.0 m s^{-1} are quite frequent. Averages errors of 2-5 % for moderate-wind locations and 7-10 % for strong-wind locations were obtained. Some underestimation was observed at the strong-wind locations. However, for non-windy locations, the Hargreaves equation overestimated ET_0 . In this case, average errors varied between 14 to 20 %.

It is proposed that, under the semiarid conditions of this study, no local calibration would be required for windy locations. But, for non-windy locations, it is proposed that a new f_c value of 0.0020 in equation 1 be used instead of the original value of 0.0023. For application of the Hargreaves equation at other locations within the study area, it must be decided whether that location can be classified as windy or non-windy in order to apply the appropriate local calibration. The limit between these two categories is somewhat subjective and a location could be defined as non-windy if monthly average windspeeds above 2.0 m s^{-1} are quite uncommon. The likely windiness of a specific site should rely on some indirect assessment of wind based on such characteristics as for instance topography of the area and the presence of

wind mills for production of wind power energy besides any short-term wind measurement if available.

Further research is required to evaluate the wind-based qualitative calibration of the Hargreaves equation proposed in this study in other semiarid regions. Because of the empirical nature of the Hargreaves equation, a single, universal calibration of this equation would be difficult to achieve. However, the approach outlined in this paper could likely be applied in other semiarid regions to obtain appropriate local calibrations of the Hargreaves equation.

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Table 1. Weather stations used in the study. Geographical coordinates, elevation at sea level, period of record, surface over which the station is located, and owner. All of them but Almodévar are automatic weather stations.

Station	Latitude (degrees)	Longitude (degrees) ^a	Elevation (m)	Record period	Surface	Owner ^f
Alcañiz	41.0581 N	0.1378 W	320	1992-2001	Bare soil ^b	INM
Almodévar	42.0297 N	0.5892 W	390	1988-1999	Bare soil ^b	INM
Daroca	41.1147 N	1.4108 W	779	1992-2001	Bare soil ^b	INM
Ejea	42.1703 N	1.2139 W	380	1999-2002	Grass ^c	EEAD
Gallocanta	40.9858 N	1.5047 W	1000	2000-2002	Bare soil ^b	EEAD
Monflorite	42.0833 N	0.3264 W	541	1990-1998	Bare soil ^b	INM
Sariñena	41.7914 N	0.1553 W	275	1990-2001	Bare soil ^b	INM
Tamarite	41.7800 N	0.3733 E	218	1997-2002	Grass ^d	EEAD
Zaragoza	41.7192 N	0.8197 W	225	1995-2002	Grass ^e	EEAD

^a W, west of Greenwich Meridian; E, east of Greenwich Meridian.

^b Some short-canopy natural vegetation may be present.

^c 10 m x 10 m field plot.

^d 86 m x 105 m field plot.

^e 120 m x 100 m field plot.

^f EEAD, the authors' Institution; INM, Spanish National Meteorological Institute.

Table 2. Comparison between lysimeter measured ET_0 values (dependent variable, y) and estimated ones using the Hargreaves equation (independent variable, x) at Zaragoza weather station for three time scales (May 1997 to October 2000). n_o , sample size; R^2 , coefficient of determination of the simple linear regression $y=b_0+b_1x$; b_0 , intercept; b_1 , regression slope; MEE , mean estimation error; $RMSE$, root mean square error; RE , relative error.

Time scale	n_o	R^2 %	b_0 mm d ⁻¹	b_1	MEE mm d ⁻¹	$RMSE$ mm d ⁻¹	RE %
Daily	656	73.9	0.023 ^a	0.934 ^d	-0.22	1.15	33.4
Weekly	123	89.1	-0.289 ^b	1.018 ^c	-0.22	0.71	19.9
Monthly	35	95.0	-0.399 ^b	1.054 ^c	-0.20	0.49	13.7

^a no significantly different than 0 ($\alpha = 0.95$).

^b significantly different than 0 ($\alpha = 0.95$).

^c no significantly different than 1 ($\alpha = 0.95$).

^d significantly different than 1 ($\alpha = 0.95$).

Table 3. Annual mean values of several meteorological variables at the different studied weather stations. *Precip*, precipitation; *Tmax*, maximum air temperature; *Tmin*, minimum air temperature; *Tmean*, mean air temperature; *RelH*, mean air relative humidity; *Wind*, wind speed at 2.0 m height; *SignWind*, significance of the difference ($\alpha = 0.95$) among wind speed values; same letter indicates average annual wind speeds no significantly different each other.

Station	<i>Precip</i> mm	<i>Tmax</i> °C	<i>Tmin</i> °C	<i>Tmean</i> °C	<i>RelH</i> %	<i>Wind</i> m s ⁻¹	<i>SignWind</i>
Alcañiz	340.5	20.7	8.7	14.5	69.1	1.46	a
Almudévar	450.6	19.8	7.9	13.9	65.7	2.26	bc
Daroca	363.7	20.0	6.9	13.1	66.5	1.08	a
Ejea	448.3	20.4	6.5	14.0	76.3	2.77	de
Gallocanta	361.0	19.1	4.3	11.6	67.5	3.10	e
Monflorite	474.3	19.2	8.4	13.3	65.1	2.65	cd
Sariñena	356.7	20.0	8.6	14.0	66.3	2.17	b
Tamarite	374.7	20.8	7.0	13.5	76.0	1.17	a
Zaragoza	352.9	21.4	8.3	14.5	73.7	2.43	bcd

Table 4. Comparison between FAO Penman-Monteith (dependent variable, y) and Hargreaves (independent variable, x) monthly ET_0 estimates at the different studied weather stations. n_o , sample size; R^2 , coefficient of determination of the simple linear regression $y=b_0+b_1x$; b_0 , intercept; b_1 , regression slope; MEE , mean estimation error; $RMSE$, root mean square error; RE , relative error.

Station	n_o	R^2 %	b_0 mm d ⁻¹	b_1	MEE mm d ⁻¹	$RMSE$ mm d ⁻¹	RE %
Alcañiz	86	97.6	0.010 ^a	0.854 ^d	-0.455	0.582	21.4
Almudévar	134	96.4	0.119 ^a	1.009 ^c	0.147	0.387	12.1
Daroca	100	99.0	-0.203 ^b	0.893 ^d	-0.542	0.598	22.7
Ejea	39	96.3	-0.016 ^a	1.011 ^c	0.020	0.358	11.0
Gallocanta	30	98.2	0.057 ^a	1.056 ^d	0.248	0.382	10.4
Monflorite	65	98.2	0.314 ^b	1.000 ^c	0.314	0.397	11.8
Sariñena	65	98.3	0.056 ^a	0.995 ^c	0.039	0.238	7.1
Tamarite	56	99.1	-0.363 ^b	0.930 ^d	-0.597	0.636	23.2
Zaragoza	86	97.1	-0.012 ^a	0.990 ^c	-0.045	0.323	9.8

^a no significantly different than 0 ($\alpha = 0.95$).

^b significantly different than 0 ($\alpha = 0.95$).

^c no significantly different than 1 ($\alpha = 0.95$).

^d significantly different than 1 ($\alpha = 0.95$).

39 Table 5. Averages of ET_H ($\overline{ET_H}$) and ET_{PM} ($\overline{ET_{PM}}$) estimates obtained at the
40 different studied weather stations; ratios of $\overline{ET_{PM}}$ to $\overline{ET_H}$; and medians of the
41 ratios of FAO Penman-Monteith to Hargreaves monthly ET_0 estimates (PM/H_{50}).

Station	$\overline{ET_H}$ (mm d ⁻¹)	$\overline{ET_{PM}}$ (mm d ⁻¹)	$\overline{ET_{PM}} / \overline{ET_H}$	PM/H_{50}
Alcañiz	3.17	2.72	0.857	0.857
Almudévar	3.06	3.21	1.048	1.045
Daroca	3.18	2.64	0.830	0.833
Ejea	3.23	3.25	1.006	0.997
Gallocanta	3.41	3.66	1.073	1.072
Monflorite	3.06	3.38	1.103	1.111
Sariñena	3.31	3.35	1.012	1.000
Tamarite	3.34	2.75	0.821	0.797
Zaragoza	3.33	3.28	0.987	0.980

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Table 6. Slopes of simple linear regressions $y = c x$ between monthly ET_{PM} (dependent variable, y) and ET_H (independent variable, x) estimates, and new computed f_c coefficient at the different studied locations. R^2 , coefficient of determination.

Station	R^2 %	c	f_c	$(f_c / 0.0023) \times 100$
Alcañiz	96.5	0.856 ^b	0.00197	-14.3
Almudévar	95.5	1.038 ^b	0.00239	3.9
Daroca	97.6	0.845 ^b	0.00194	-15.7
Ejea	93.7	1.007 ^a	0.00232	0.9
Gallocanta	94.8	1.069 ^b	0.00246	7.0
Monflorite	95.9	1.076 ^b	0.00247	7.4
Sariñena	96.7	1.008 ^a	0.00232	0.9
Tamarite	96.3	0.848 ^b	0.00195	15.2
Zaragoza	96.0	0.987 ^a	0.00227	-1.3

^a no significantly different than 1 ($\alpha = 0.95$).

^b significantly different than 1 ($\alpha = 0.95$).

Figure 1. Study area and location of the weather stations.

Figure 2. Hargreaves versus FAO Penman-Monteith monthly ET_0 estimates at the different studied weather stations.

Figure 3. Ratios of FAO Penman-Monteith to Hargreaves monthly ET_0 estimates versus monthly average windspeed at the different studied weather stations.