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ESTIMATION OF REFERENCE EVAPOTRANSPIRATION IN A MOUNTAINOUS MEDITERRANEAN SITE USING THE PENMAN-MONTEITH EQUATION WITH LIMITED METEOROLOGICAL DATA

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ABSTRACT.– In recent decades many authors have adopted the Penman-Monteith formula as the standard way to estimate reference evapotranspiration from climate data. The main drawback associated with the Penman-Monteith method is the relatively high data demand: temperature, solar radiation, relative humidity and wind speed are the minimum inputs required by the formula. In the Spanish Pyrenees historical databases usually consist of temperature and rainfall only, although an improvement in data acquisition is expected in terms of parameters monitored. Under situations of data scarcity, some authors recommend the use of less data intensive methods, such as the empirical Hargreaves equation. Other authors suggest that it is better to estimate the missing parameters and to apply the Penman-Monteith equation. This paper presents a study on the accuracy of the Penman-Monteith method for a situation where some parameters have to be estimated from available temperature, and wind speed data must be replaced by a constant value. The results have been compared with the information available for a location in the central Spanish Pyrenees (period 1999-2003) where parameters required by the Penman-Monteith method have been monitored. A comparison is then made with the Hargreaves model in order to assess the most appropriate method for calculation of the reference evapotranspiration. The results indicate that the use of the Penman-Monteith formula results in errors in reference evapotranspiration ET_o estimation of different magnitude and sign throughout the year. However, in general, it offers a more accurate estimation of reference evapotranspiration than the Hargreaves formula.

Keywords: Reference evapotranspiration, Penman-Monteith, Hargreaves, data scarcity, parameter estimation, Spanish Pyrenees.

RESUMEN.– En los últimos años, diferentes autores han adoptado el método de Penman-Monteith para estimar la evapotranspiración potencial mediante datos climáticos. El principal inconveniente de este método es que precisa de un gran número de variables para ser calculado: temperatura, radiación solar, humedad relativa y velocidad del viento. En el Pirineo español las bases de datos climáticas a menudo solamente muestran disponibilidad de datos térmicos y pluviométricos. Bajo estas carencias, algunos autores recomiendan el uso de métodos que precisan de menos datos, como es el caso de la ecuación empírica de Hargreaves. Otros autores sugieren que resulta preferible estimar los datos no disponibles necesarios para aplicar la ecuación de Penman –Monteith a partir de los datos disponibles de temperatura y velocidad del viento. Los resultados de ambos procedimientos han sido comparados con la información disponible en una estación del Pirineo central español (1999-2003) donde están disponibles los parámetros para aplicar la ecuación de Penman-Monteith. Se han comparado los resultados con el modelo de Hargreaves para valorar el método más apropiado de cálculo. Los resultados muestran errores estacionales muy diferentes mediante la fórmula de Penman-Monteith, sin embargo, este procedimiento muestra una aproximación mejor para obtener la evapotranspiración potencial que aplicando la fórmula de Hargreaves.

Palabras clave: Evapotranspiración potencial, Penman-Monteith, Hargreaves, carencia de registros, estimación de parámetros, Pirineo Español.

1. Introduction

Evapotranspiration is the sum of the volume of water used by vegetation (transpiration) and that evaporated from the soil and intercepted precipitation. Water entering the evaporation phase of the hydrological cycle becomes unavailable for generation of runoff or replenishment of groundwater. As a global average, 57% of annual precipitation returns to the atmosphere due to evapotranspiration, and this value may reach 90-100% in arid or desert areas (SANCHEZ-TORIBIO, 1992). Seasonal evapotranspiration mainly depends on the characteristics of the weather and plant cover (structure, density, vegetative cycle). These factors vary with time due to both climate fluctuations and land use/land cover changes. Since evapotranspiration is a very important part of the water cycle, any change in climate or plant cover can affect the availability of water resources.

Mountain areas are the main runoff sources in Mediterranean environments. For this reason a number of studies have been focussed on the recent evolution of stream flow in relation to possible changes in climate and/or land cover, especially in the Pyrenees (GALLART & LLORENS, 2004; GARCÍA-RUIZ *et al*., 2001; BEGUERÍA *et al*., 2003). In the Spanish Pyrenees no generalized precipitation or temperature trend has been observed for the period since the middle of the 20th century, although important fluctuations have been identified at a decadal scale. During the same period the enlargement of shrub areas and forests occurred after the generalised abandonment of cultivated fields on the hill slopes located under 1600 m a.s.l. Likewise, the sub-alpine grasslands have increased in density and are affected by a natural colonization of trees. BEGUERÍA *et al*. (2003) attribute the statistically significant decrease in stream flow of the Pyrenean rivers to these land use/ land cover changes. The study of evapotranspiration would help in this case to understand and parameterise the changes that occur at the scale of the hydrological cycle and the consequences for water resources. The concept of a reference evapotranspiration (ET_o) can be used to estimate the climatic effect on evapotranspiration and represents the evapotranspiration from a hypothetical, reference surface (ALLEN *et al*., 1994).

Many equations are used to estimate ET_o. They can be divided into two main groups, i) those that are empirical and have lower data requirements, and ii) those that are physically-based and require proportionately more data. In a scenario of climate and land use change, a physically or process-based approach offers more flexibility and does not depend on relationships which may be changing over time. The International Commission for Irrigation (ICID), the Food and Agriculture Organization of the United Nations (FAO) and the American Society of Civil Engineers (ASCE) have adopted the Penman-Monteith (PM) method (ALLEN *et al*., 1998) as the standard way to compute ET_o from climate data. PM is widely used because:

a) it is a predominantly physically-based approach and so it can be used globally,
b) it has been widely tested using lysimeter data from a wide range of climate conditions (ALLEN *et al.*, 1994; ITENFISU *et al*., 2000).

The main drawback of using the PM method is the relatively high data demand, requiring solar radiation, temperature, wind speed and relative humidity data. In the Pyrenees, as in the majority of mountain areas, the scarcity of meteorological data is a frequent problem. As a result, there are few continuous time periods or sites with all the parameters required for the PM method. In the literature it is possible to find two different suggestions for ET_o estimation with scarce data: i) to estimate indirectly the absent parameters from the available data in order to use PM equation (ALLEN *et al*., 1998); or ii) to calculate ET_o using a less data intensive formula. For this, second route, the empirical Hargreaves (HG) equation is considered to be a good option (XU & SINGH, 2001; DROOGERS & ALLEN, 2002; MARTINEZ-COB, 2002).

This paper provides an evaluation of the possible errors resulting from the use of the PM approach for the Central Pyrenees, where many of the input data must be estimated from other available information. Specifically, the objectives of this work are:

a) to estimate the relative humidity and solar radiation from maximum and minimum temperature data using different methods
b) to assess the error in ET_o due to the estimation of both solar radiation and relative humidity,
c) to assess the error in ET_o due to the absence of wind speed as an input to the PM equation,
d) to assess the resultant combined error in ET_o due to the use of estimated parameters instead of monitored data, and
e) to compare the results from the PM equation using estimated parameters with the less data intensive HG equation.

2. Study site and used data

The Pyrenees is a mountainous area located in the north-east of the Iberian Peninsula. Precipitation increases towards the north along the altitudinal gradient, and to the west because of the Atlantic influence. The average annual precipitation in the northernmost sector of the range reaches values above 2000 mm, with around 600-800 mm in the lowest areas. Most of the precipitation falls in autumn and spring (GARCÍA-RUIZ *et al*., 2001). The summer is relatively dry (with occasional rainstorms), when long anticyclonic periods are frequent.

The mean annual temperature decreases from north to south and it is mainly controlled by the altitude. Above 1000 m a.s.l. the average annual temperature is lower than 10 ºC. At 2000 m the mean annual temperature is around 5 ºC. The thermic gradient varies, according to different authors, between 0.49 ºC and 0.6 ºC (GARCÍA-RUIZ *et al*., 1985; DEL BARRIO *et al*., 1990).

Throughout the Spanish Pyrenees the meteorological data collected at most monitoring sites consists of daily mean, maximum and minimum temperature, and daily precipitation. However, some sites have other data for short periods, and a new network of monitoring stations is currently being installed. Thus, although precipitation and temperature data are found at all sites, many locations have some coverage of other data types, particularly cloud cover at 08:00 hours.

The meteorological station of Yesa (515 m a.s.l.; Lat. 42-37-92, Long. 01-11-24W) is located on the south west edge of the Pyrenean range and has supplied a continuous data set of the required parameters for the PM equation from February 1999 to December 2003. The station is managed by the Govern of Navarra region (http://meteo.navarra.es/estaciones/estacion_detalle.cfm?IDestacion=10). Figure 1 shows the daily series of temperature, precipitation, wind speed, relative humidity and solar radiation recorded during the available period. Series have been previously checked to detect potential anomalous values, no gaps were found for any variable in the whole studied period. Mean annual temperature at Yesa station is 13.7 ºC, and oscillates between 22.38ºC in August and 5.03ºC in January. The annual evolution of solar radiation is very similar to temperature although the maximum and minimum annual values occur in June and December respectively. Mean annual precipitation is 810 mm with most rain falling in the autumn and winter seasons. Relative humidity tends to increase from summer to winter, but the daily series show a high variability. Finally wind speed tends to remain constant throughout the year around 2ms^{-1}, although a slight variability is found, as well as isolated events which exceed 5ms^{-1}, more details about the characteristics of wind speed in Yesa will be discussed in results.

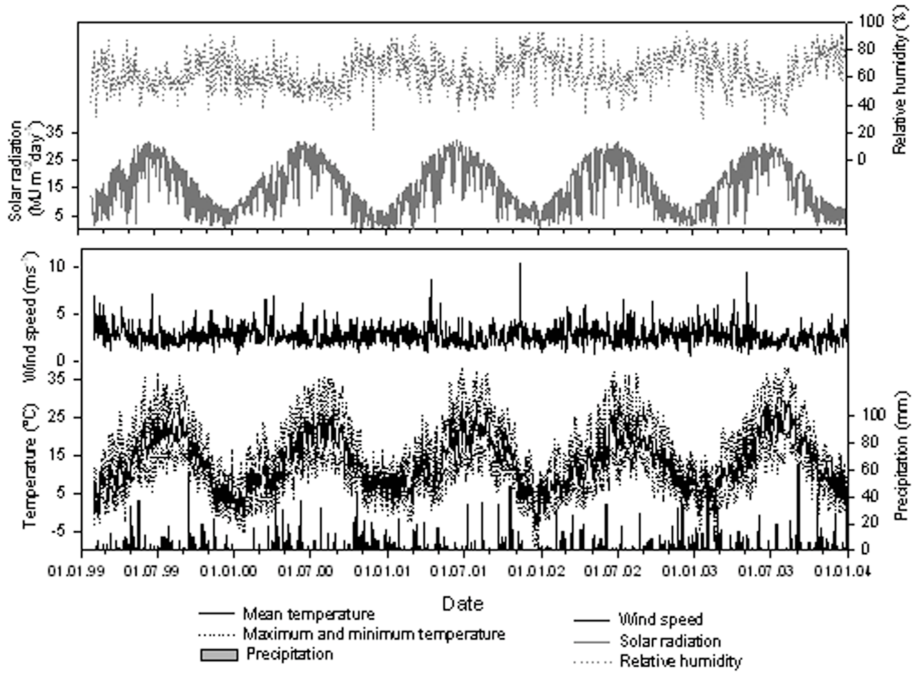

Figure 1. Daily series of the available climatic parameters.
Figura 1. Series diarias de los parámetros climáticos disponibles.

3. Estimation of the reference evapotranspiration

Two approaches were used to estimate reference evapotranspiration, (i) the Penman-Monteith (PM) equation with missing parameters estimated from the available data, and (ii), the HARGREAVES (HG) (1985) equation based on temperature alone.

3.1. Estimation of parameters for Penman-Monteith

The PM equation can be expressed as the sum of a radiation component and an aerodynamic component,

$$ET_{rad} = \frac{\Delta}{\Delta + \gamma^*} \frac{(R_n - G)}{\lambda} \qquad (1)$$

where
Δ slope of vapour pressure curve, kPa °C^{-1}
γ^* modified psychrometric constant, kPa °C^{-1}
R_n net radiation, MJ m^{-2} d^{-1}
G Soil heat flux, MJ m^{-2} d^{-1}
λ latent heat of vaporisation, MJ kg^{-1}

$$ET_{aero} = \frac{86.4}{\lambda} \frac{1}{\Delta + \gamma^*} \frac{\rho cp}{ra} (ea - ed) \qquad (2)$$

where
γ psychrometric constant, kPa °C^{-1}
ρ atmospheric density kg m^{-3}
cp specific heat of moist air, 1.013 kJ kg^{-1} °C^{-1}
ra aerodynamic resistance, s m^{-1}
ea mean saturation vapour pressure, kPa
ed actual vapour pressure, kPa
Then,

$$ET_o = ET_{rad} + ET_{areo} \qquad (3)$$

where
ET_o reference evapotranspiration, mm d^{-1}

The net radiation, R_n, can be estimated from solar radiation, temperature, humidity, date and latitude. Soil heat flux, G, can be estimated from the change in mean air temperature between two days. The humidity terms, *ea* and *ed*, can be determined from maximum and minimum air temperature and relative humidity respectively, whilst *ra* and γ^* are both functions of the mean daily wind speed. The parameters Δ, γ and λ are all dependant on mean air temperature. Hence, ET_o can be derived from daily observations of maximum and minimum temperature, relative humidity, solar radiation and wind speed (see ALLEN et al., 1998 for a full description of the equations used).

In this study, ET_o has been calculated using an evapotranspiration modelling package called WaSimET (HESS, 2000) that follows the methods of ALLEN *et al.* (1998). Although maximum and minimum air temperature data are commonly available, relative humidity, solar radiation and wind speed are often missing. This study focuses on the estimation of these parameters, and the resultant errors in ET_o.

3.1.1. Solar Radiation

Where no radiation data are available, they are best estimated from sunshine duration. In this case, the only data related to sunshine are the observations of cloud cover. Two equations have been tested in order to obtain the shortwave radiation from the available data:

a) HARGREAVES *et al.* (1985) showed that the relative solar radiation (i.e. global radiation at the surface, R_s, as a proportion of extraterrestrial radiation, R_a) could be estimated from the maximum and minimum temperature by,

$$R_s = aR_a\sqrt{T_{\max} - T_{\min}} + b \quad (4)$$

Where

R_s *is* the global radiation at the surface, MJ m^{-2}
R_a is the extraterrestrial radiation, MJ m^{-2} and is determined from latitude and date using the methods detailed in ALLEN *et al.*, 1998.
T_{max} and T_{min} are the maximum and minimum air temperature, °C
a,b are coefficients.

This method for the solar radiation estimation has been successfully tested in other locations of the Iberian Peninsula (CASTELLVI, 2001).

b) Supit and van KAPPEL (1998) extended the Hargreaves equation by introducing a term based on cloud cover:

$$R_s = R_a\left(a\sqrt{T_{\max} - T_{\min}} + b\sqrt{1 - {C_w}/{8}}\right) + c \quad (5)$$

Where:
C_w is the mean daytime cloud cover in octaves and
a, b, c are empirical coefficients that have been calibrated for a number of stations in Europe (SUPIT & VAN KAPPEL, 1998).

3.1.2. Relative Humidity

The mean daily vapour pressure deficit (*ea – ed*) in the P-M equation is usually determined from air temperature and relative humidity.

The mean saturation vapour pressure, *ea*, is estimated from

$$ea = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2} \tag{6}$$

where $e^o(T)$ is the saturation vapour pressure at temperature, *T*, and is estimated from

$$e^o(T) = 0.6018 e^{\left(\frac{17.27T}{T+237.7}\right)} \tag{7}$$

The mean daily vapour pressure, *ed*, is estimated from

$$ed = \frac{h_r}{100} ea \tag{8}$$

where h_r is the mean daily relative humidity.

The mean daily vapour pressure, *ed*, can also be taken to be the saturation vapour pressure at mean daily dew-point temperature, T_d. T_d is usually relatively constant during the day, and night-time minimum temperature, T_{min}, tends to come into equilibrium with T_d. Thus, *ed* can be approximated from

$$ed \approx e^o(T_{\min}) \tag{9}$$

This assumption has been shown to work well in a range of climates except in arid and semiarid areas (KIMBALL *et al*., 1997).

3.1.3. Wind Speed

Wind speed is an important variable required by the PM equation, but it is irregularly measured in the Pyrenean stations. The extrapolation from nearby stations is not recommended because large differences in wind speed are recorded even over short distances due to the topographic heterogeneity of mountain areas.

In order to assess the effect of the lack of this variable in the estimation of $ET_{o,}$ it has been necessary to assume that wind speed presents similar values throughout the study area, although this is probably an under-estimate for high mountain areas. For this study a constant wind speed of 2 ms^{-1} has been assumed. This is justified as:

a) In the absence of any information on wind speed, ALLEN *et al*. (1998) recommend use of 2 ms^{-1} as an average of global wind speed measurements, and
b) mean wind speed at Yesa (1999-2003) was 2.07 ms^{-1}.

3.2. Estimation of the reference evapotranspiration using the Hargreaves method

HARGREAVES *et al.* (1985) combined the relationship between temperature range and solar radiation used above, with an empirical relationship between solar radiation, temperature and reference evapotranspiration. Thus, the Hargreaves equation can be used to estimate ET_o from maximum and minimum temperature alone (HARGREAVES & ALLEN, 2003):

$$ET_0 = 0.023R_a + (T_{med} + 17.8)\sqrt{T_{\max} - T_{\min}} \qquad (10)$$

where T is the mean air temperature, °C, and other symbols are as defined above. R_a is the extraterrestrial radiation expressed as an equivalent evaporation depth.

3.3. Error estimation

To assess the accuracy of the estimated values of relative humidity and solar radiation, as well as the deviation of the constant value of wind speed in relation to the measured speed, these have been compared with observed data from the Yesa automatic weather station. Also, ET_o obtained from PM using monitored values of R_s, H_r and wind speed have been compared with i) ET_o obtained with estimated parameters, and ii) using the Hargreaves equation. Differences between observed and estimated data series have been measured by means of different error estimators: mean bias error, MBE (eq. 11), standardized mean bias error, SMBE (eq. 12), mean absolute error, MAE (eq. 13) and standard mean absolute error, SMAE (eq.14), defined as follows:

$$MBE = N^{-1}\sum_{i=1}^{N}\left(P_i - O_i\right) \qquad (11)$$

$$SMBE = \frac{N^{-1}\sum_{i=1}^{N}(P_i - O_i)}{\bar{O}} \tag{12}$$

$$MAE = N^{-1}\sum_{i=1}^{N}|P_i - O_i| \tag{13}$$

$$SMAE = \frac{N^{-1}\sum_{i=1}^{N}|P_i - O_i|}{\bar{O}} \tag{14}$$

Where:
N = number of observations
O = Observed value
$\bar{O}$ mean of observed values
P = predicted value
i = counter for individual observed and predicted values

The purpose of the work is to know the expected error in parameters and ET_o estimations, including the events that can be considered as outliers. Thus, error estimators or efficiency model indices which reduce the effect of the outliers, such as RSME, Efficiency model or Willmott´s D (WILLMOTT, 1982) have not been considered.

The described error estimators supply different information. MBE indicates the expected average and the sign (over-estimation or sub-estimation) of the error for a given period. MAE indicates the observed average error for each observation in absolute terms. The standardized errors (SMBE and SMAE) consider the magnitude of the error in relation to observed values in a given period, so it is possible to compare the error of different periods of calculation.

4. Results

4.1. Calculation and validation of the required parameters

4.1.1. Solar radiation

The empirical coefficients *a* and *b* have been estimated from the correlation between observed R_s and $R_a\sqrt{T_{\max} - T_{\min}}$ (see equation 4) where *a* is the slope and *b* is the constant of the regression equation. Observed R_s data comes from the automatic weather station at Yesa for the period 1999-2003. The coefficients were obtained using the Rs values observed during 1999, and the observations from 2000 to 2003 were used to validate. The obtained coefficients (a=0.17; b=0.76) agree with the values given by SUPIT & VAN DER GOOT (2003) for the surrounding locations in the Iberian Peninsula. The station is installed on a plot of irrigated grass so the condition for R_s data acquisition is adequate (LLASAT & SNYDER, 1998).

Figure 2 shows the correlation between observed and estimated Rs values with (Fig. 2a) and without (Fig. 2b) cloud cover data. The error of the estimation is high for the extended HG approach including cloud cover: MBE = -0.18 and MAE = 6.2. The non-extended equation gives lower errors: MBE = -0.21 and MAE = 3.3. The noticeable increase in accuracy of the estimation without cloud cover is probably due to the subjective manner in which cloud cover data is acquired, with the accuracy of the data depending on the ability of the observer. In addition, cloud cover data are usually only recorded in the morning and the variability through the day is not taken into account. At Jaca, 50 km eastward, cloud cover data have been collected at 07:00, 13:00 and 18:00 h from 1970-1988. These data show considerable variability during the day and the difference of the average of the three observations compared with values collected at 7 a.m. is 1.65 octas, a difference of 20.2%. These results suggest that the use of such data are not recommended when only one daily observation is available, and when the quality of the observations cannot be veri-

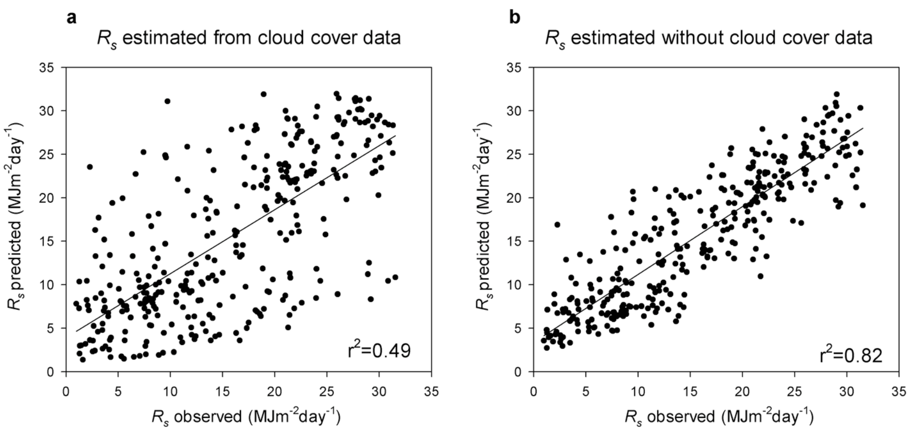

Figure 2. Correlation between observed and predicted R_s values for Yesa station, using (a) extended Hargreaves equation (eq.5) and (b) non extended Hargreaves equation (eq. 6).
Figura 2. Correlación entre los valores observados y predichos de R_s para la estación de Yesa, utilizando (a) la ecuación extendida de Hargreaves (eq. 5) y (b) la ecuación no extendida (eq. 6).

fied. Errors in cloud cover can lead to large errors in the estimation of R_s, so, in this study the non-extended HG equation (eq. 6) has been used. This method of solar radiation estimation has been successfully tested in other locations of the Iberian Peninsula (CASTELLVI, 2001).

Table 1 shows the monthly average errors obtained in the estimation of R_s from temperature data. MBE and SMBE present low values throughout the year, indicating that the daily sign of the error does not show any seasonal pattern. MAE oscillates between 1.55 and 4.28 MJ m^{-2} d^{-1} in December and April respectively. MAE is bigger in the months with higher solar radiation, but SMAE suggests that the maximum relative error is from the middle of autumn to the middle of spring, when the error exceeds 30% of the observed R_s. The error estimators shown in Table 1 suggest a high ability of equation 6 to predict Rs from temperature data.

Table 1. Observed error in Rs estimation from temperature data.
Tabla 1. Errores observados en la estimación de Rs a partir de datos de temperatura.

Month	*Observed Rs*	*Estimated Rs*	*MBE*	*SMBE*	*MAE*	*SMAE*
January	6.13	5.95	-0.18	-0.03	2.07	0.34
February	9.81	8.89	-0.92	-0.09	2.71	0.28
March	13.72	13.94	0.24	0.02	2.98	0.22
April	17.74	17.28	-0.47	-0.03	4.28	0.24
May	22.15	22.16	0.02	0.00	3.98	0.18
June	26.13	25.46	-0.68	-0.03	3.50	0.13
July	25.12	24.68	-0.43	-0.02	3.44	0.14
August	21.34	21.75	0.39	0.02	2.96	0.14
September	16.64	16.20	-0.45	-0.03	3.03	0.18
October	9.90	10.18	0.28	0.03	2.48	0.25
November	6.83	6.46	-0.38	-0.06	1.93	0.28
December	4.97	4.96	-0.01	0.00	1.55	0.31
Annual	15.04	14.82	-0.21	-0.01	2.91	0.22

4.1.2. Relative humidity

Table 2 shows the results from comparing the measured relative humidity at Yesa and the estimated H_r values from eq.8. MAE shows similar values throughout the year, oscillating between 9.12 and 12.72 %, but it tends to increase from winter to summer when it is considered as a relative value with regard to the monthly H_r (SMAE). MBE and SMBE indicate the major importance of the error during the warm season, when the results stress a clear underestimation of H_r. During the cold and wet period the sign of the error occurs randomly, so the MBE is close to 0. The climate characteristics of Yesa explain the seasonal distribution of the error. The moderate summer dryness conditions observed in summer lead to a difference between minimum temperature and dew point temperature that implies an underestimation of Hr. The disappearance of water stress conditions in winter leads to an increase of the accuracy of Hr estimation as a consequence of the equilibrium between T_{min} and T_d.

Table 2. Observed error in Hr estimation from temperature data.
Tabla 2. Errores observados en Hr a partir de datos de temperatura.

Month	*Observed H_r*	*Estimated H_r*	*MBE*	*SMBE*	*MAE*	*SMAE*
January	73.67	72.84	-0.83	-0.01	10.17	0.14
February	66.33	68.21	1.87	0.03	12.78	0.16
March	64.28	60.85	-3.37	-0.05	10.19	0.16
April	61.63	61.65	0.02	0.00	9.44	0.15
May	61.69	55.24	-6.42	-0.10	10.34	0.17
June	55.17	48.49	-6.68	-0.12	10.09	0.18
July	56.08	47.87	-8.22	-0.15	11.04	0.20
August	54.52	47.51	-6.97	-0.13	9.12	0.17
September	61.01	53.10	-7.91	-0.13	10.08	0.17
October	70.31	62.19	-8.16	-0.12	11.18	0.16
November	71.95	70.53	-1.42	-0.02	11.12	0.15
December	74.56	73.57	-0.99	-0.01	10.60	0.14
Annual	64.27	60.17	-4.09	-0.06	10.51	0.16

4.1.3. Wind speed

Table 3 shows the observed error when the wind speed (*Ws)* data are replaced by a constant value of 2 ms^{-1}. In Yesa mean *Ws* is very close to the proposed constant value during May, June, September and October. However, wind speed is underestimated in July, August and October; and overestimated from November to April. Thus, MBE shows a period around summer with positive signs, reaching values of 0.2 ms^{-1} (SMBE=0.11). In contrast, the sign of the MBE is negative in winter with a maximum amount of 18% of the observed wind speed in February. MAE has two periods of high values (over-estimation and under-estimation) separated by months of spring and autumn when the absolute error declines. The absolute expected error for a day can exceed 0.3 ms^{-1} in February, April and August, which gives values of SMAE of 0.16, 0.14 and 0.18 respectively.

Table 3. Observed error in wind speed applying a constant value of 2 ms^{-1}.
Tabla 3. Errores observados en la velocidad del viento aplicando un valor constante de 2 ms^{-1}.

Month	*Observed Ws*	*Estimated Ws*	*MBE*	*SMBE*	*MAE*	*SMAE*
January	2.11	2.00	-0.11	-0.05	0.21	0.10
February	2.45	2.00	-0.45	-0.18	0.40	0.16
March	2.22	2.00	-0.22	-0.10	0.28	0.13
April	2.31	2.00	-0.31	-0.13	0.32	0.14
May	2.00	2.00	0.01	0.00	0.01	0.00
June	1.92	2.00	0.08	0.04	0.14	0.07
July	1.83	2.00	0.17	0.09	0.26	0.14
August	1.80	2.00	0.20	0.11	0.32	0.18
September	2.01	2.00	-0.01	0.00	0.02	0.01
October	1.93	2.00	0.06	0.03	0.14	0.07
November	2.22	2.00	-0.22	-0.10	0.26	0.12
December	2.10	2.00	-0.10	-0.05	0.21	0.10
Annual	2.07	2.00	-0.07	-0.04	0.21	0.10

4.2. Impact of the replacement of measured parameters by indirectly estimated parameters on ET_o calculation

4.2.1. Solar radiation

Figure 3 shows the estimated error in ET_o calculation when it is necessary to replace the instrumental R_s data by the estimated values from temperature (eq.4). MBE shows a low error throughout the year, with values close to 0. Thus, the error does not exceed 1% of the mean monthly ET_o in any case. The annual evolution of MAE is very similar to the evolution of the absolute error in R_s estimation (Table 1), suggesting that the effect of error in R_s calculation has a direct effect on the PM equation. The expected absolute error in a given day is below 0.42 mm throughout the year. Standardized mean absolute error never exceeds 10% of the monthly ET_o. These results suggest that solar radiation may be replaced by an estimate obtained from the daily range of temperature, without serious implications for calculation of ET_o. Thus, on a monthly basis the expected error is almost zero, whilst the expected average daily error is below 10% of the monthly ET_o.

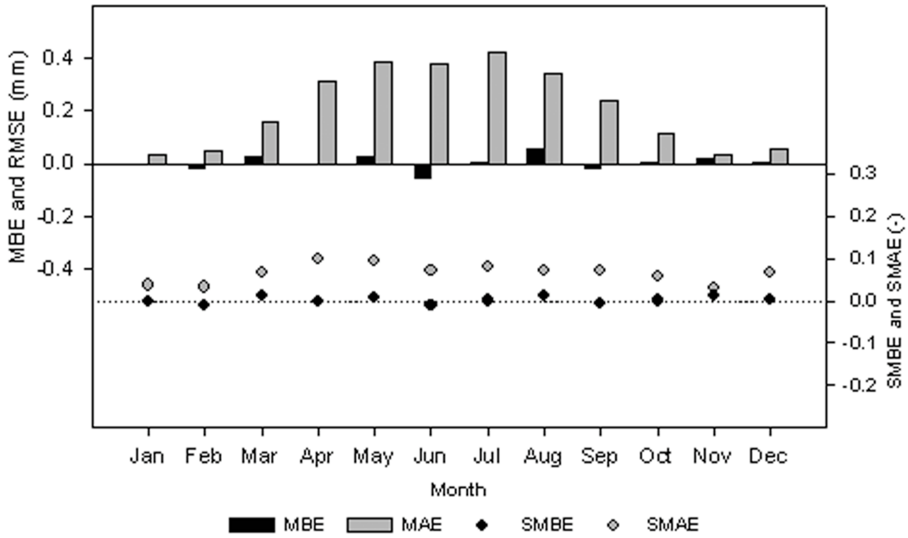

Figure 3. Observed error in ET_o estimation as consequence of the absence of solar radiation.
Figura 3. Error observado en la estimación de ET_o a consecuencia de la ausencia de datos de radiación.

4.2.2. Relative humidity

Figure 4 shows the effect of the replacement of H_r monitored by H_r estimated on the PM equation by means of eq. 8. MBE indicates that for the months when H_r was underestimated (Table 2), ET_o is overestimated. As relative values (SMBE), the error may exceed 5% of the monthly average ET_o, reaching 11% in October. Mean absolute error indicates high errors in winter, whilst the lower daily error is observed in summer. It is interesting to note that the months with the lowest absolute error in H_r estimation provide the highest values of absolute error in ET_o estimation, and *vice-versa*. This fact is explained by the variability of the response of the PM equation to H_r throughout the year. To support this conclusion, ET_o was calculated using H_r data with errors of different magnitude. The relationship between the monthly errors in H_r and ET_o estimations was expressed linearly (Fig.5), and the slope of the regression lines is different according to the sensitivity of the PM equation to H_r variation in each month. Thus, the sensitivity of PM is very high from November to September, when H_r is successfully estimated. For the months when the Hr estimation shows less accuracy, the sensitivity of the ET_o response is lower. Thus SMAE during summer is lower than 0.1, whilst during the months with high sensitivity it can exceed 0.3.

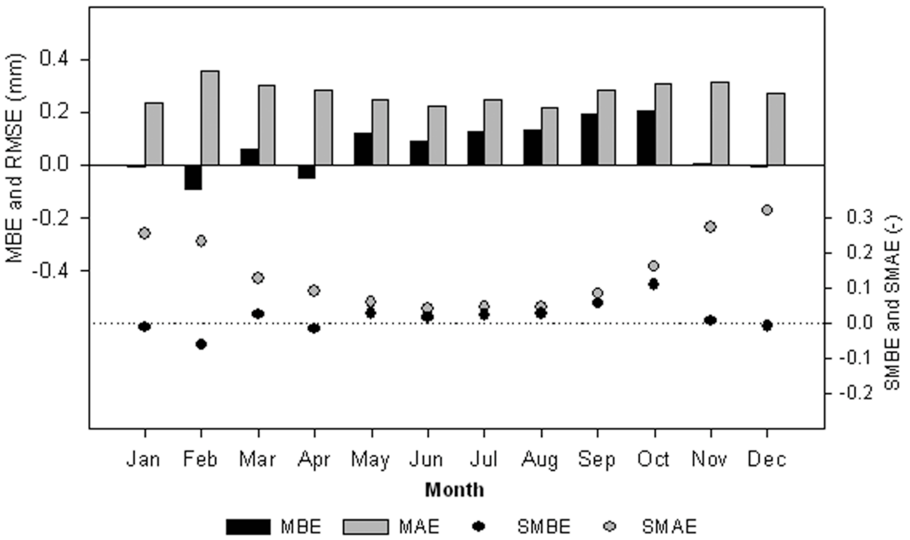

Figure 4. Observed error in ET_o estimation as consequence of the absence of relative humidity.
Figura 4. Error observado en la estimación de ET_o a consecuencia de la falta de datos de humedad relativa.

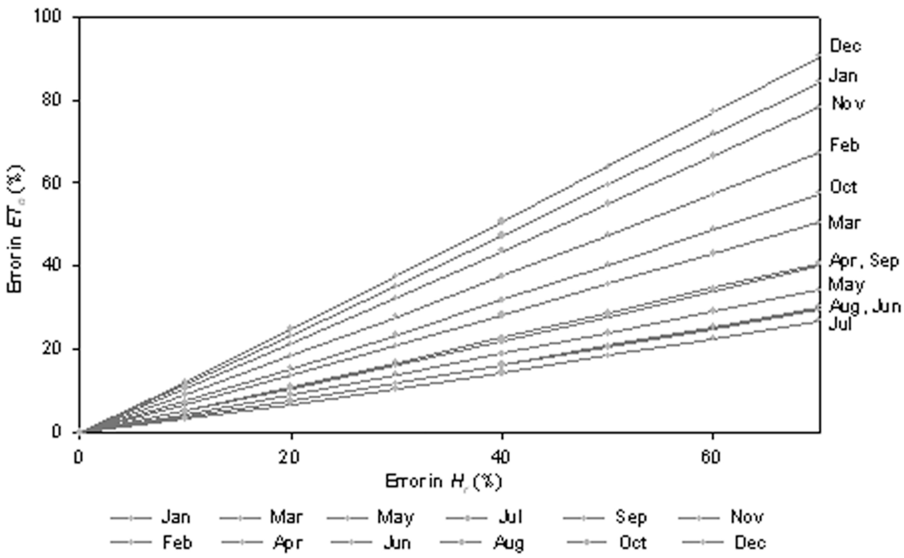

Figure 5. Error in ETo estimation for different inaccuracy levels of H_r estimation.
Figura 5. Error en la estimación de ET_o a consecuencia de diferentes niveles de inexactitud en la estimación de H_r.

4.2.3. Wind speed

In section *4.1.3* it has been shown that the use of a constant value of wind speed may lead to noticeable deviations in comparison to the real wind speed. The effect of the error in wind speed leads to an MBE that oscillates between -0.06 mm in February and 0.06 in August. This means that SMBE is between -0.08 when wind speed is underestimated, and 0.03 when the wind speed is overestimated. Figure 6 shows that the monthly estimation of ET_o is only affected by the absence of wind speed information in some months of the cold season, never exceeding 8 % of the monthly ET_o. The highest values of MAE are observed during summer when the daily estimation of ET_o falls around 0.25 mm. The high evapotranspiration during this period explains the low values of SMAE. Thus the maximum values of SMAE are observed in February and November with 0.14 in both cases.

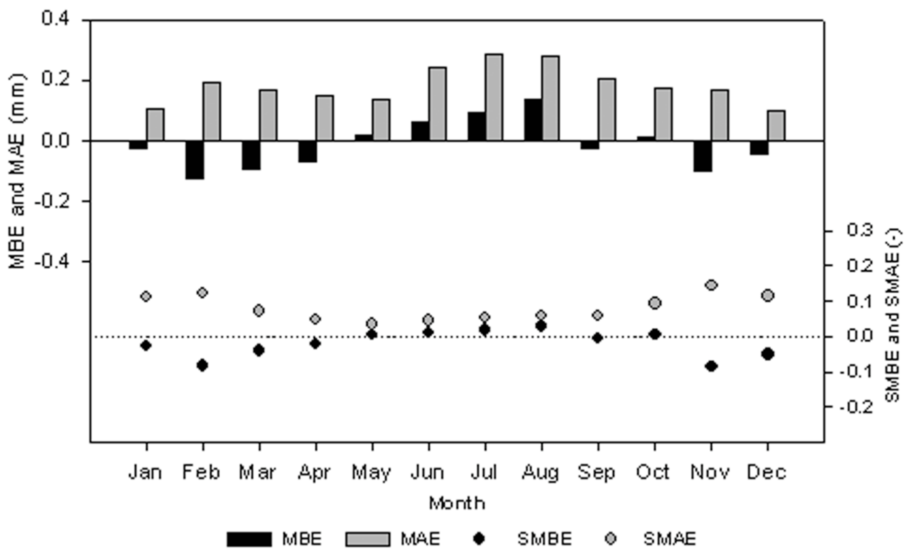

Figure 6. Observed error in ET_o estimation as consequence of the absence of relative wind speed.
Figura 6. Errores observados en la estimación de ET_o a consecuencia de la ausencia de datos de velocidad de viento.

4.2.4. Combining the errors

The resulting error in the calculation of ET_o due to the use of R_s and H_r estimated from temperature information and use of a constant value of wind speed shows noticeable variations in magnitude and timing relating both to the parameter replaced and the season. The variability of the error due to the parameter replaced depends on the error in the estimation of the parameter (4.1) and the weight of each variable in the PM equation. The seasonal variability that each parameter causes in ET_o estimation depends on (i) the pattern of error in parameter estimation throughout the year (as a consequence of the aridity, seasonal patterns of wind sped, etc.), and (ii) the different monthly sensitivity of the PM equation to possible errors in the estimation of the required parameters. Thus, Figure 7 represents the error caused by the absence of each parameter calculated in sections *4.2.1*, *4.2.2* and *4.2.3* and the combined error when all three parameters are replaced. It is necessary to consider that on a given day the errors caused by each parameter can be in different directions. Thus, in the absence of more than one of the required parameters, the resulting error may be the sum of several deviations of the same sign, or errors of different sign may counteract one another. The largest SMBE observed is due to the absence of wind speed data with negative values in November, December and February. The two former months show low error due to the absence of Rs and H_r, so the total error due to the absence of all three parameters is -0.13 and -0.14 % respectively. Otherwise, in February a large and negative SMBE is also observed due to the absence of H_r, so this is the month when the largest total error occurs with an underestimation of ET_o of -0.19 %. The important overestimation caused by the absence of H_r in September and October is counteracted by the errors in the other two parameters, so the total error is very close to 0. In January, although the SMBE of the three parameters is low, the coincidence of negative values of H_r and wind speed leads to a total error of -0.14 %, so this is the month with the second largest error of the year. The relationship between the observed partial SMBEs during the rest of the year leads to low values of the combined SMBE.

The absence of relative humidity data is the main source of error shown by SMAE from September to March. The use of a constant value of wind speed is the second highest cause of SMAE error from October to March. During spring and summer the highest values of absolute error in ET_o are caused by the absence of solar radiation. The lowest standard mean absolute error is observed during summer (around 0.1) and it tends to increase continuously later. The largest combined SMAE occurs from November to February with values close to or exceeding 30% of the observed ET_o. During some months the monthly combined error is the sum of the errors obtained in the three absent parameters, whilst in other months the combined error is less than that obtained by the absence of only one parameter, as a consequence of the counteracting of the deviations within the PM equation.

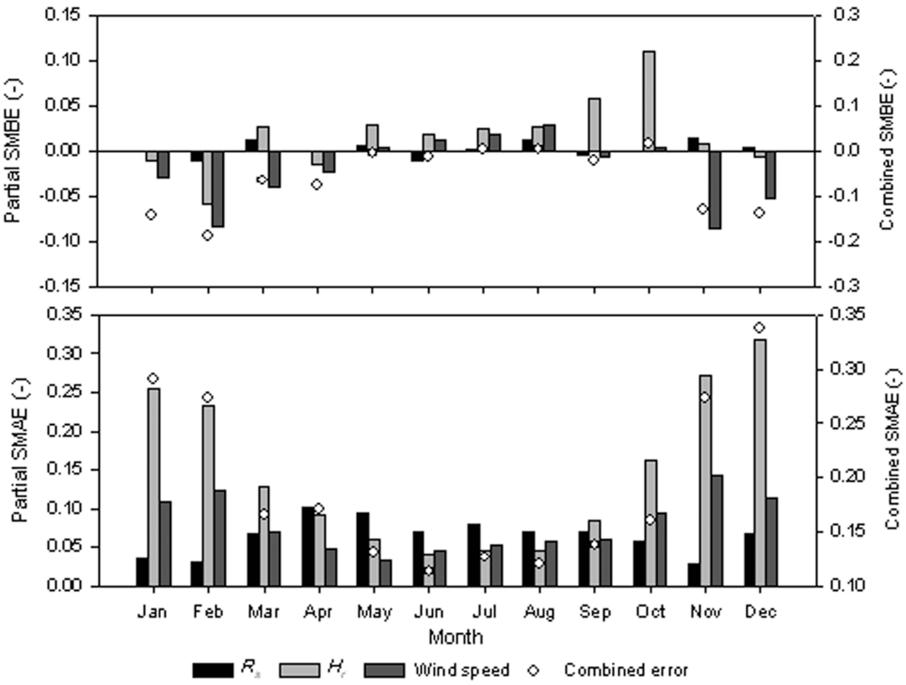

Figure 7. Observed error in ET_o estimation as consequence of the absence of solar radiation, relative humidity and wind speed.

Figura 7. Errores observados en la estimación de ET_o a consecuencia de la ausencia de radiación solar, humedad relativa y velocidad de viento.

4.3. Comparison between Penman-Monteith and Hargreaves equations

Figure 8 shows the SMBE and SMAE obtained in the calculation of ET_o using the PM equation with the parameters indirectly estimated compared with ET_o calculated by means of the HG equation. On a monthly basis, SMBE indicates a better performance of the PM method. Thus, PM gives insignificant errors from March to October, whilst HG tends to overestimate ET_o noticeably from May to August. The rest of the year the differences are less marked, although the PM method out-performs the HG estimation during

November, December, and January. The Hargreaves equation shows better estimations during the mild periods (March- April and September-October). In fact HG is slightly more accurate than PM in February, March, April, September and October. Figure 8 suggests that the comparison of methods using annual values, may lead to masking of significant deficiencies in the ET_o calculation. Thus, in Yesa, the HG equation would provide a very low value of error on an annual basis, as a result of the counteracting effects of the sign of the error for different months.

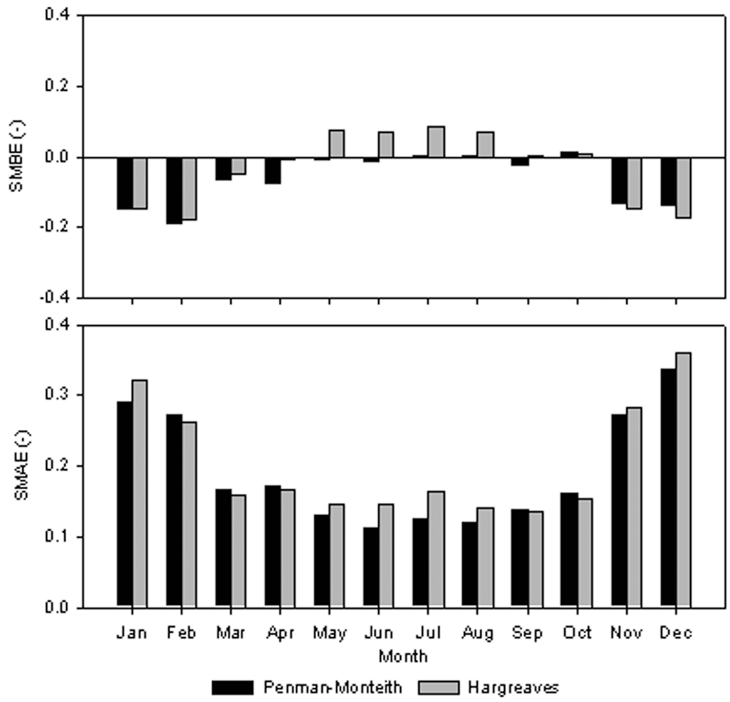

Figure 8. Comparison of error in ET_o using Penman Monteith and Hargreaves equations.
Figura 8. Comparación de los errores de ET_o *utilizando las ecuaciones de Penman Monteith y Hargreaves.*

SMAE indicates that the higher errors in ET_o estimation are expected using HG in most of the months for a given day. PM is clearly more accurate from May to August and from November to January. HG only shows better results in October and February. In March, April and September significant differences are rarely found.

5. Discussion and conclusions

Many authors consider that the PM formula is the most accurate method for estimation of reference evapotranspiration (JENSEN *et al*., 1990; ALLEN *et al*. 1994; 1998; XU & SINGH, 1998; DROOGERS & ALLEN, 2002). This is the reason for adopting the PM method as the standard way to compute reference evapotranspiration by the International Commission of Irrigation (ICID), the Food and Agriculture Organization (FAO) and the American Society of Civil Engineers (ASCE).

The high data demand of PM, as for most of the physically-based approaches, is the major problem to its application in areas where complex weather stations are not available. When one or more of the required parameters are unavailable there are two possibilities: a) to use this equation with indirectly estimated parameters; b) to use less demanding formulae, such as the HG equation, based on empirical relationships between temperature, radiation and ET_o.

DROOGERS & ALLEN (2002) suggested that under scarce climatic data availability, the HG equation can be considered as a good alternative for ET_o estimation, in its original formulation (HARGREAVES & SAMANI, 1985) or including precedent precipitation as a predictor variable. Recently, MARTINEZ-COB (2002) suggested an adequate fit between HG and PM in the Ebro Depression Valley, NE Spain. Later, MARTINEZ-COB & TEJERO (2004) proposed calibration of the HG equation in those stations where wind speed is lower than 2 ms^{-1}, in the same study area. XU & SINGH (2001) obtained satisfactory results when comparing HG with other temperature-based methods, using the PM formula as reference method to compute ET_o. In spite of the good results obtained for HG, these authors indicate several disadvantages. Thus, HG tends to overestimate ET_o in low ET_o areas and to underestimate it in sectors with high ET_o. (DROOGER & ALLEN, 2002; XU & SINGH, 2002). Also, the necessity to calibrate the equation according to the annual rainfall has been assessed, because HG overestimates in humid regions whilst it underestimates in arid areas (JENSEN *et al*., 1990; AMATYA *et al*., 1995; DROOGERS & ALLEN, 2002; HARGREAVES & ALLEN, 2003). STÖCKLE *et al*. (2004) concluded that HG without calibration provide poor agreement with PM ET_o results for either daily or weekly periods. Another drawback related to HG is the associated error when it is applied for short time periods. Thus, HARGREAVES & ALLEN (2003) do not recommend the use of the HG equation for periods shorter than five days. Other authors consider inadequate the use of HG for intervals shorter than a week (JENSEN *et al*., 1990; CHOISINEL *et al*., 1992; DROOGERS & ALLEN, 2002). Such a restriction hinders the study of runoff generation and transport of sediment and nutrients, since ultimately, changes in water balance at a daily level are usually required. The difficulty to apply the HG equation worldwide without calibration and the limitation of the time scale applicability leads some authors to prefer the PM equation with a reduced data set, through the indirect estimation of the absent parameters. Thus, CHRISTIANSEN & WORLTON (1998) did not find significant errors using the FAO-PM with only temperature and solar radiation. ALLEN *et al*. (1998) concluded that, in areas of low data availability, PM provides more accurate ET_o estimations than Hargreaves, in spite of the indirect estimation of R_s, H_r and wind speed. Recently, STÖCKLE *et al.* (2004) considered PM equation using estimated parameters as a suitable method for calculating weekly ET_o.

In this paper, the information provided by the automatic weather station at Yesa has been used to i) assess the accuracy of the estimation of relative humidity and solar radiation from temperature data and the error obtained when wind speed is replaced by a constant value; and ii) to measure the error in ET_o estimation as a consequence of the replacement of the monitored parameters by indirectly estimated H_r, R_s and wind speed. In addition, the estimated ET_o values obtained by means of the PM formula with estimated parameters, and by means of the Hargreaves equation have been compared. The error obtained in parameter estimation varies in magnitude, sign and seasonal distribution along the year. The influence of the error observed in each estimated parameter on ET_o estimation also shows high variability. This variability depends on (i) the accuracy of the parameter estimation and (ii) the sensitivity of the PM equation to changes in a given variable. Both factors vary throughout the year, so the distribution of the error amount and sign explains the seasonal variations seen. The combined error due to the absence of R_s, H_r and wind speed is the result of the sum, or the counteracting, of the individual errors. The SMBE suggests that using PM the error obtained in ET_o estimation at monthly level is low, except from November to February when ET_o is significantly underestimated. The absolute errors show higher values than mean errors. Thus, from November to February MAE exceeds 25% of the monthly reference evapotranspiration. From March to October the magnitude of the error decreases with values below 15%.

This paper suggests that it is preferable to estimate ET_o by means of the PM equation even though some of the required parameters must be indirectly estimated. This conclusion is supported by the better results obtained with PM than with the HG equation. The improvement of ET_o estimation is especially noticeable during summer, coinciding with the season when the highest water stress occurs (more ET_o and less precipitation). During this season higher accuracy in the estimation of the water losses is required for the assessment of water resource availability and irrigation planning. In addition, PM is a much more flexible method than HG, which will permit incorporation of new monitored data as they become available. The accuracy of the method should improve noticeably with reliable information to correct the errors that show seasonal patterns, such as wind speed and relative humidity.

Acknowledgments

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