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Parameterization of the Hargreaves equation in the northern oasis of Mendoza, Argentina

Parametrización de la ecuación de Hargreaves en el oasis norte de Mendoza, Argentina

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Abstract

In view of the water scarcity that affects the province of Mendoza, Argentina, information on reference crop evapotranspiration (ET_0) is crucial for irrigation scheduling. Data that are not generally available is required for the determination of ET_0, with the Penman-Monteith FAO56 equation (PM). The Hargreaves equation (HG), which only requires air temperature data, represents an alternative to calculate ET_0, after its local or regional calibration with PM. In this paper, the Hargreaves equation was calibrated locally by means of annual (C_a) and monthly ($C_{m,j}$) adjustment coefficients for the northern oasis of Mendoza. Also, a regionalisation of the C_a was performed considering environmental variables. The local adjustment with both coefficients made it possible to correct the positive bias that indicated an overestimation of HG with respect to PM in 12 meteorological stations. The mean value of the root mean square error decreased from 0.80 mm day^{-1} to 0.57 mm day^{-1} with the C_a adjustment coefficient, and to 0.55 mm day^{-1} with the $C_{m,j}$ adjustment coefficient, while the absolute error decreased from 0.63 to 0.42 and 0.39, respectively. Wind speed was the variable that best explained the regional variability of the C_a ($R^2 = 0.64$).

Keywords
reference evapotranspiration • irrigation programming • Hargreaves equation • water scarcity • adjustment coefficient

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RESUMEN

Ante la escasez hídrica atravesada por Mendoza, Argentina, es importante conocer la evapotranspiración referencia (ET_0) de los cultivos para programar el riego. Su cálculo, a partir de la ecuación de Penman-Monteith FAO56 (PM), requiere contar con datos no disponibles en general. La ecuación de Hargreaves (HG), que solo requiere datos de temperaturas del aire, representa una alternativa para calcular ET_0, luego de su calibración local o regional con PM. En este trabajo se calibró localmente la ecuación de Hargreaves por medio de coeficientes de ajuste anuales (C_a) y mensuales ($C_{m,j}$) para el oasis norte de Mendoza. También, se llevó a cabo una regionalización del C_a considerando las variables ambientales. El ajuste local con ambos coeficientes logró eliminar el sesgo positivo que indicaba una sobrestimación de HG con respecto a PM en las 12 estaciones meteorológicas consideradas. El valor promedio del error cuadrático medio disminuyó de 0,80 mm día^{-1} a 0,57 mm día^{-1} con el ajuste con C_a y a 0,55 mm día^{-1} con el uso de $C_{m,j}$, mientras que el error absoluto disminuyó de 0,63 a 0,42 y 0,39 respectivamente. La velocidad del viento fue la variable que mejor explicó la variabilidad regional del C_a ($R^2 = 0,64$).

Palabras claves
evapotranspiración de referencia • programación de riegos • ecuación de Hargreaves • escasez hídrica • coeficientes de ajuste

INTRODUCTION

Evapotranspiration from agricultural lands constitutes the greatest consumptive water use globally (7). Nearly 70% of the land in Argentina is arid (25) and the province of Mendoza, located in the central-western part of the country (32° and 37° 35' S, 66° 30' and 70° 35' W), is one of the most desertified provinces with a mean annual rainfall of 200 mm. The rivers, which are fed by snowmelt from the Andes mountain range, and groundwater use have given rise to the so called "oasis" and a particular settlement pattern (11). The oasis, where 98% of the population is concentrated, occupies only 3% of the total land area. The available surface water resources are estimated at 6000 hm^3 per year (12) and groundwater withdrawals are about 250 and 600 hm^3, depending on surface water availability (16). The northern oasis of the province of Mendoza, irrigated by the Mendoza and Lower Tunuyán rivers, is the second largest irrigated area in Argentina (8). Climate change scenarios for the region (6) anticipate changes in climate as well as in local water availability. For the Andes mountain range, between 32° to 36° S parallels, the models developed by the Centro de Investigaciones del Mar y la Atmósfera (CIMA), based on scenario A2 (Scenario where effective mitigation measures or technological developments to reduce CO_2 emissions are not expected (IPCC, Synthesis Report 2001), predict a mean temperature increase of 1.25 to 1.5°C and a mean precipitation decrease of 100 mm for the period 2020-2030. A mean elevation of the 0°C isotherm of 150 to 130 metres with respect to the current situation is also expected. Under this scenario, a decline in the winter snowpack and a progressive reduction of the ice cover are likely to occur. These changes will reduce water availability in the rivers running from the Andes mountain range and will consequently affect the irrigable lands. In this sense, since 2009 the province has been under a state of water emergency because the volume of water in the rivers of Mendoza is below the historical mean, principally due to little snowfall in the mountain range.

The water balance of the oasis shows a deficit of nearly 80 hm^3 $year^{-1}$ for the Mendoza River (1,041.46 hm^3 $year^{-1}$ while water demand is 1,121.05 hm^3 $year^{-1}$) and a notably increasing water deficit (422 hm^3 $year^{-1}$) for the Lower Tunuyán River (12) (822 hm^3 $year^{-1}$ while water demand is 1,244 hm^3 $year^{-1}$). Water scarcity affects mainly the agricultural sector since it uses 92% of the water from the Mendoza and Tunuyán rivers.

In this sense, it is crucial to estimate crop water requirements accurately in order to: (i) plan irrigation management and ensure efficient water use, (ii) increase productivity and efficiency in water use, and (iii) reduce water and carbon footprints (22). Irrigation water requirements can be estimated on the basis of the reference evapotranspiration (ET_0) (2). Among the existing methods, the Food and Agriculture Organization of the United Nations (FAO) recommends to use the Penman-Monteith equation (FAO56-PM) as the standard method for estimating ET_0 (2).

The equation calls for information on temperature, relative humidity, solar radiation and wind speed, which is not always available. Other equations, such as the one proposed by Hargreaves (HG) and its modifications (13, 14, 15), basically require data on air temperature that is available in most meteorological stations.

The HG equation has received considerable attention for its accurate ET_0 estimates in different climatic regions (2). However, it should be evaluated and calibrated to improve its application accuracy in each area (10, 24). For example, when the HG equation is applied in coastal regions, the ET_0 is usually underestimated while in interior regions it is overestimated (4, 10, 24). Moreover, when there is intense sensible heat advection on the surface, the HG tends to underestimate daily ET_0 values by 25% (5). Previous research has shown that the results obtained with the HG equation are very local and depend specifically on the location of each study (17). Therefore, it is often recommended to perform a local calibration of the HG equation (18) by adjusting the daily or monthly ET_0 values obtained with FAO56-PM (10, 18, 20, 24). The HG equation has been calibrated at international level in different locations with satisfactory results. In southeast China, Feng *et al.* (9) improved the adjustment of the HG equation with a relative root-mean-square error (RRMSE) and mean-absolute error (MAE) of 0.284 and 0.433 mm day^{-1} for local calibration against 0.567 (RRMSE) and 0.959 (MAE) mm day^{-1} corresponding to the original HG model. In the semi-arid region of southeast Spain some authors have differentiated the adjustment of the equation for windy and non-windy zones (19) and between coastal and interior zones (10, 24). In this regard, Maestre-Valero *et al.* (2013) recommended a regionally calibrated HG equation for the calculation of long series of monthly ET_0 when they lacked complete data on temperature and air humidity, radiation or wind speed. In Argentina, Almorox *et al.* (2012) reported that they had no meteorological data for calculating the ET_0 FAO56-PM in Coronel Dorrego (Buenos Aires) but since data on temperature was available, they recommended the HG method to estimate the ET_0. Moreover, they concluded that the HG method, parameterized by means of a local coefficient calibration, is more in line with the FAO56-PM results, with an RMSE of 0.89 mm day^{-1} and an MBE of 0.27 mm day^{-1}.

Irrigators in the northern oasis of Mendoza are concerned about inaccurate meteorological information and the need for a service to estimate crop water requirements (1). In this context, in regions with scarce information on climate it is crucial to develop locally or regionally calibrated equations for accurate ET_0 estimates. Therefore, the objective of this work is to calibrate and validate the HG equation on a daily scale for the northern oasis of Mendoza in order to provide irrigators with a tool to estimate crop water requirements and contribute to the sustainability of the region's agricultural sector.

MATERIALS AND METHODS

Study area and climate data

This work was carried out in the northern oasis of Mendoza which lies between latitudes 32°28' and 33°23' S and longitudes 69°03' and 67°31' W. Daily meteorological information from 12 weather stations was used for the period 2008-2014 (2008-2011 for calibration and 2012-2014 for validation).

The principal characteristics of these stations are presented in table 1 and their location in the northern oasis is shown in figure 1 (page 221). Three of the stations belong to the *S*ervicio Meteorológico Nacional (SMN) and the rest to the network of automatic meteorological stations of the provincial Dirección de Agricultura y Contingencias Climáticas (DACC). All stations provide hourly or tri-diurnal data on meteorological variables which the SMN and the DACC use to calculate daily values.

Table 1. Meteorological stations in the study area, location (latitude and longitude) and altitude.

Tabla1. Estaciones meteorológicas del área de estudio, localización (latitud y longitud) y altitud.

Station (nomenclature)	Institution	Location	Altitude (m a. s. l.)
Chacras de Coria (Cha)	SMN	32°59' S 68°50' O	921
Mendoza Aero (MAero)	SMN	32°50' S 68°48' O	704
Mendoza Observatorio (MObs)	SMN	32°54' S 68°52' O	823
Jocolí (Joc)	DACC	32°35' S 68°35' O	590
Las Violetas (LasVio)	DACC	32°48' S 68°36' O	625
Tres Porteñas (3P)	DACC	32°54' S 68°23' O	627
Junín -(Jun)	DACC	33°07' S 68°29' O	667
Los Campamentos (LosCam)	DACC	33°15' S 68°27' O	661
El Marcado (ElMar)	DACC	33°05' S 68°13' O	622
Las Catitas (LasCat)	DACC	33°15' S 68°03' O	595
Russell (Rus)	DACC	33°01' S 68°45' O	790
Perdriel (Per)	DACC	33°07' S 68°54' O	981

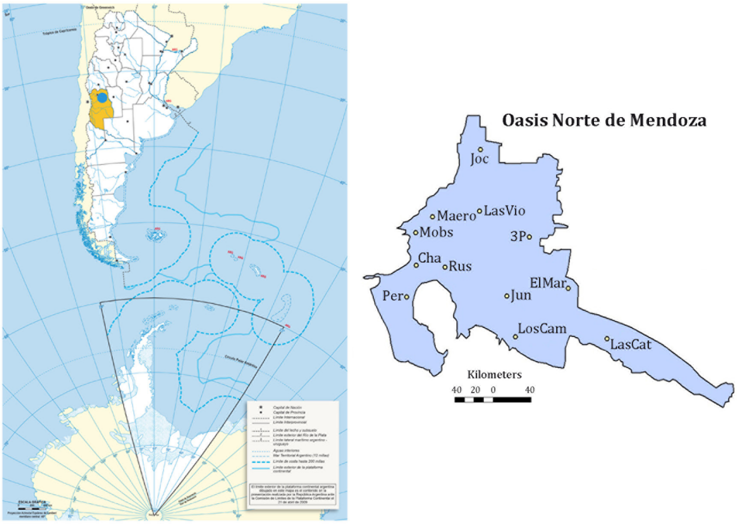

Figure 1. Location of the meteorological stations in the northern oasis of Mendoza, Argentina. The names of the stations are shown in table 1 (page 220).

Figura 1. Localización de las estaciones meteorológicas en el oasis norte de Mendoza, Argentina. Los nombres de las estaciones se pueden ver en la tabla 1 (pág. 220).

FAO-56 Penman-Monteith Equation

Due to the lack of direct measurements of real evapotranspiration, either by lysimeter or by soil water balance, the reference value of ET_0 is the one recommended in FAO-56 (2) (ET_0PM):

$$ET_0PM = \frac{0.408(R_n - G) + \gamma\left[\frac{900}{(T_{med} + 273)}\right] V_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34V_2)} \quad (1)$$

where:

ET_0PM = reference evapotranspiration (mm day^{-1})

R_n = net radiation on crop surface (MJ m^{-2} day^{-1})

G = ground heat flux (MJ m^{-2} day^{-1})

T = mean air temperature at a height of 2 m (°C)

V_2 = wind speed at a height of 2 m (m s^{-1})

e_s = equilibrium vapour pressure or saturated vapour pressure at air temperature (kPa)

e_a = real air vapour pressure (kPa)

$e_s - e_a$ = air vapour pressure deficit (kPa)

Δ = slope of the equilibrium vapour pressure curve (kPa $°C^{-1}$)

Υ = psychrometric constant (kPa $°C^{-1}$).

These variables and physical parameters were determined following the method outlined in FAO-56, which provided daily estimates of reference evapotranspiration in the 12 stations (ET_0PM). They were used to calibrate (period 2008-2011) and validate (period 2012-2014) the different adjustment coefficients proposed for the Hargreaves equation.

Hargreaves Equation

The Hargreaves-Samani equation (1985) was used to determine ET_0 (ET_0HG) as a function of the extraterrestrial radiation (R_a; mm day^{-1}), and the mean (T_{med}; °C), minimum (T_{min}; °C) and maximum (T_{max}; °C) air temperature.

$$ET_0HG = C\ R_a(T_{med} + 17.78)(T_{\max} + T_{\min})^{0.5} \tag{2}$$

where:

C = 0.0023, represents the Hargreaves coefficient.

Local calibration of the Hargreaves equation

Calibration by means of the annual adjustment coefficient

A calibration of the HG method was carried out using the C_a annual adjustment coefficient for each station.

The adjustment was carried out by calculating forced-origin linear regressions from the daily calculated values of ET_0PM and ET_0HG/0.0023 in the period 2008-2011. The values of C_a substituted 0.0023 in (2), thus the HG equation calibrated with an annual coefficient (ET_0HG_a) was obtained.

Calibration by means of monthly adjustment coefficients

The calibration was also performed by means of monthly $C_{m,j}$ adjustment coefficients for each station obtained by forced-origin linear regressions from daily calculated values of ET_0PMm,j and ET_0HGm,j/0.0023 in the period 2008-2011, where ET_0PMm,j and ET_0HGm,j are the daily ET_0 values for the month j by PM and HG, respectively.

Adjustment validation of the Hargreaves equation

The equations calibrated with the C_a and $C_{m,j}$ adjustment coefficients were validated using the 2012-2014 data series for each of the stations (table 1, page 220) that were not previously used for the calibration. The results obtained with the original HG equation (ET_0HG) were statistically compared between their annual (ET_0HG_a) and monthly ($ET_0HG_{m,j}$) calibrations -expected values- and those calculated from the ET_0PM -observed values- by, (i) the determination coefficient, R^2; (ii) the mean bias error, MBE; (iii) the root-mean-square error, RMSE, and (iv) the absolute error, AE:

$$R^2 = \frac{\sigma^2 xy}{\sigma^2 x \sigma^2 y} \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}} \tag{4}$$

$$MBE = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \tag{5}$$

$$AE = \frac{\sum_{i=1}^{n}\left|y_i - x_i\right|}{n} \tag{6}$$

where:

n = number of data

y = the expected value of ET_0 (ET_0HG, ET_0HG_a or $ET_0HG_{m,j}$)

x = the observed value of ET_0 (ET_0PM)

σ_{xy} = the covariance of x and y

σ_x = the typical deviation of x

σ_y = the typical deviation of y

Regional calibration of the Hargreaves coefficient

In order to determine one or more variables that explain the variability of C_a among the stations, a sensitivity analysis was carried out for different environmental variables using linear regressions. The mean annual variables that were analyzed were: latitude, altitude -station's altitude-, T_{max}, T_{min}, T_{med}, P (atmospheric pressure), V_2, R_a, R_n, HR (relative humidity), ΔT (T_{max}-T_{min}) and $\Delta T/T_{med}$. For each station, a matrix of correlations among these variables and C_a was calculated to determine which variables exert the greatest impact to explain the variance at a 99% confidence level.

RESULTS AND DISCUSSION

Application of the original Hargreaves equation

The results of the statistical comparison between ET_0PM and ET_0HG are shown in table 2.

The determination coefficient R^2 was higher than 0.80 for all the stations, with a mean of 0.91. The statistical analyzes (RMSE, MBE and AE) showed significant errors. Considering all stations, the RMSE varied between 1.034 and 0.49 mm day^{-1}, with a mean of 0.80±0.18 mm day^{-1}, the MBE varied between 0.698 and 0.077 mm day^{-1} with a mean of 0.41±0.23 mm day^{-1} and the AE varied between 0.802 and 0.375 mm day^{-1} with a mean of 0.63±0.14 mm day^{-1}.

The mean values of the MBE indicated that ET_0HG overestimated ET_0PM in all stations. These results are similar to those that Gavilán *et al.* (2006) obtained for interior zones in southern Spain, where the climate is semi-arid and local calibrations of the HG equation are required.

Local calibration using annual adjustment coefficients (C_a)

According to other similar studies performed in arid and semi-arid regions (10, 18, 22), annual coefficients for all stations were lower than the original HG coefficient (0.0023).

Table 2. Statistical results among daily ET_0 values with the Penman-Monteith (ET_0PM) and original Hargreaves (ET_0HG) equations.

Tabla 2. Resultados estadísticos entre valores diarios de ET_0 con Penman-Monteith (ET_0PM) y Hargreaves original (ET_0HG).

Station	R²	RMSE	MBE	AE
Chacras de Coria	0.88	1.034	0.686	0.802
Mendoza Aero	0.97	0.738	0.619	0.633
Mendoza Observatorio	0.80	0.998	0.173	0.716
Jocolí	0.88	0.898	0.460	0.656
Las Violetas	0.98	0.830	0.698	0.712
Tres Porteñas	0.96	0.494	0.189	0.375
Junín	0.98	0.811	0.686	0.704
Los Campamentos	0.84	0.903	0.130	0.695
El Marcado	0.91	0.698	0.411	0.570
Las Catitas	0.94	0.485	0.077	0.376
Russell	0.94	0.706	0.427	0.536
Perdriel	0.83	0.980	0.379	0.801
Mean	0.91 ± 0.06	0.80 ± 0.18	0.41 ± 0.23	0.63 ± 0.14

C_a presented a rather stable value ranging between 0.0019 (Cha, LosCam, LasCat) and 0.0022 (Joc, LasVio, Maero, Per, 3P) and a mean value of 0.0021. Figure 2, shows the spatial variation of C_a in the Northern oasis of Mendoza, although no clear spatial behavioural pattern or possible relationship with other geographic variables such as altitude or latitude can be identified.

The results obtained agree with those presented by Martinez Cob *et al.* (2004) for non-windy semi-arid regions in Spain, where they proposed a coefficient of 0.0020, or with those obtained by Vanderlinden *et al.* (2004) in interior areas of southern Spain where the annual mean of the adjustment coefficient was 0.0022.

Validation of the use of an annual coefficient

The determination coefficient (R^2) between ET_0HG_a and ET_0PM was practically identical to that obtained with the original HG, with no appreciable differences in any of the stations (table 3, page 225).

The RMSE improved considerably, ranging between 0.96 and 0.26, with a mean of 0.57 ± 0.24 mm day^{-1}. The adjustment bias was almost completely eliminated, with the MBE ranging between 0.17 and -0.03, with a mean of 0.04 ± 0.07 mm day^{-1}.

Finally, the AE also improved considerably when compared to that obtained with the original HG, showing values between 0.69 and 0.21, with a mean of 0.42 ± 0.18 mm day^{-1}.

The MBE values, close to zero, demonstrated that the use of an equation calibrated with an annual coefficient eliminated the systematic overestimation produced by the original HG in calculating the daily ET_0.

Local calibration by means of monthly adjustment coefficients ($C_{m,j}$)

Monthly coefficients showed a similar pattern throughout the 12 stations (figure 3, page 225-226), with slight decreases in value during the autumn months and slight increases at the end of winter and early spring.

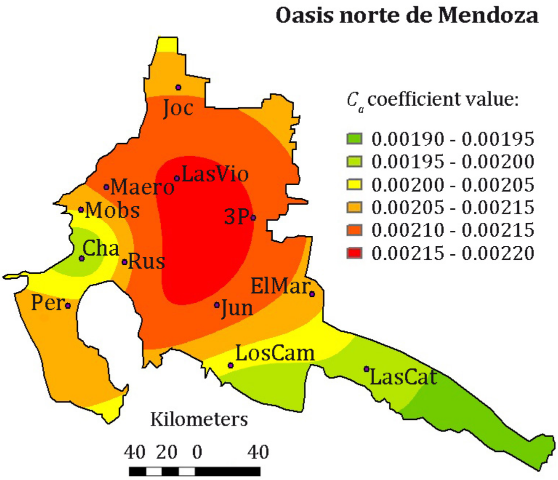

Figure 2. Map of annual coefficient values in the northern oasis of Mendoza.

Figura 2. Mapa de valores de coeficiente anual en el oasis norte de Mendoza.

Table 3. Statistical results among daily ET_0values with Penman-Monteith (ET_0PM) and Hargreaves calibrated with an annual coefficient (ET_0HG_a).

Tabla 3. Resultados estadísticos entre valores diarios de ET_0 con Penman-Monteith (ET_0PM) y Hargreaves calibrada con coeficiente anual (ET_0HG_a).

ET_0HGa	R^2	RMSE	MBE	AE
Chacras de Coria	0.88	0.624	0.024	0.448
Mendoza Aero	0.97	0.314	-0.030	0.247
Mendoza Observatorio	0.80	0.959	0.011	0.673
Jocolí	0.88	0.720	0.166	0.512
Las Violetas	0.98	0.300	0.019	0.229
Tres Porteñas	0.96	0.448	-0.024	0.310
Junín	0.98	0.260	0.032	0.206
Los Campamentos	0.84	0.895	-0.015	0.662
El Marcado	0.91	0.497	-0.004	0.369
Las Catitas	0.94	0.469	-0.007	0.353
Russell	0.94	0.501	0.126	0.358
Perdriel	0.83	0.885	0.143	0.688
Mean	0.91 ± 0.06	0.57 ± 0.24	0.04 ± 0.07	0.42 ± 0.18

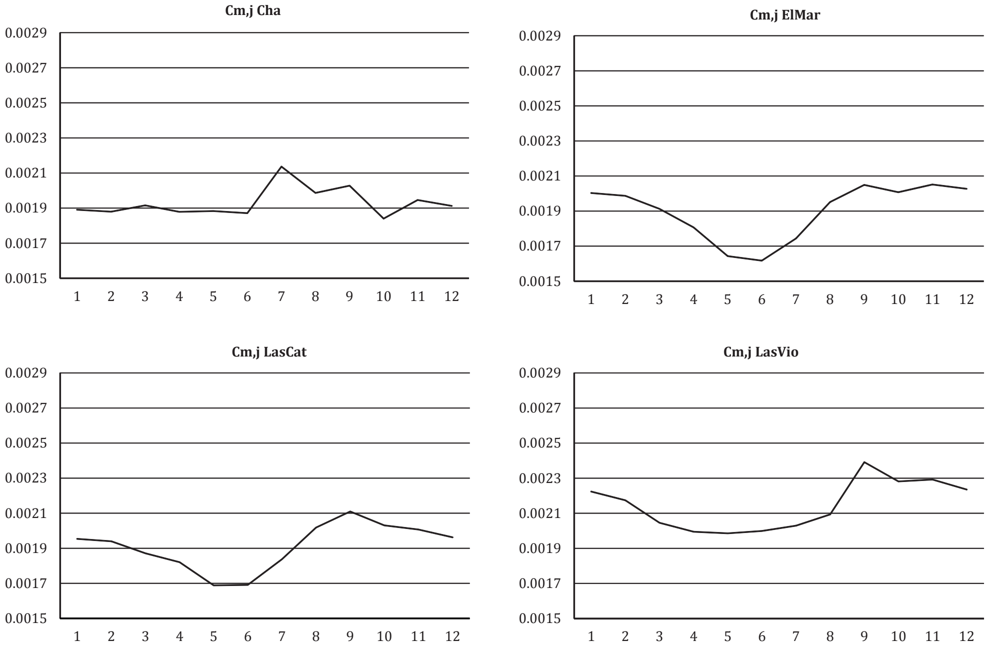

Figure 3. Evolution of monthly coefficients ($C_{m,j}$).

Figura 3. Evolución de coeficientes mensuales ($C_{m,j}$).

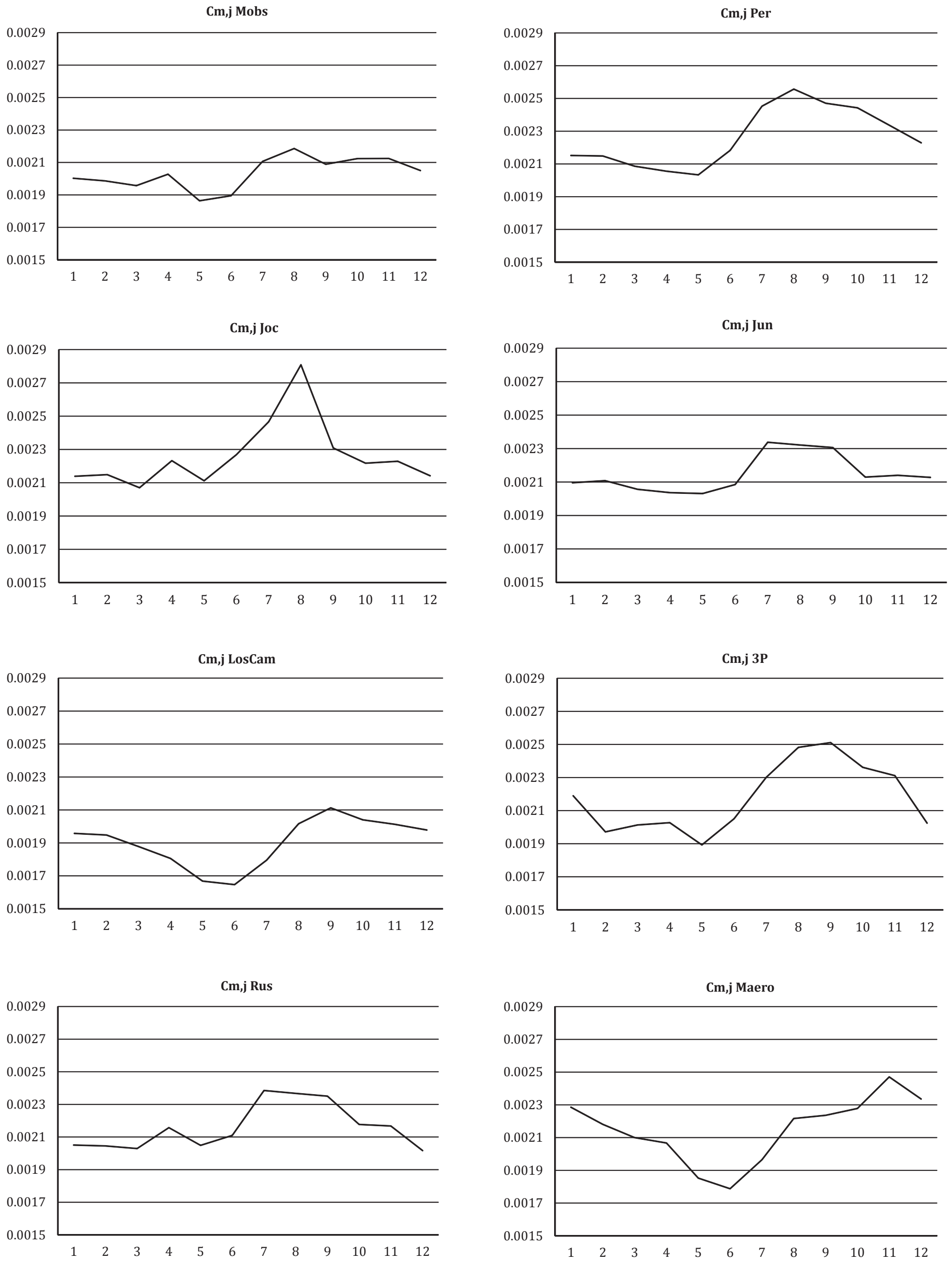
Cm,j Mobs
Cm,j Per
Cm,j Joc
Cm,j Jun
Cm,j LosCam
Cm,j 3P
Cm,j Rus
Cm,j Maero

Figure 3 (cont.). Evolution of monthly coefficients ($C_{m,j}$).

Figura 3 (cont.). Evolución de coeficientes mensuales ($C_{m,j}$).

This variation was similar to the intensity of the Zonda wind (21), whose variability throughout the year presents the same behaviour.

In general, the $C_{m,j}$ were also lower than the original HG value (0.0023), with the exceptions of the Joc, Per and 3P stations where it was exceeded by the end of winter when the Zonda wind reaches its maximum intensity.

Validation of the use of monthly coefficients

Calibration by means of monthly coefficients virtually reduced the adjustment bias (mean of the MBE of 0.04 ± 0.07) eliminating the systematic overestimation produced by the original HG. Additionally, the values of RMSE and AE decreased slightly with respect to the calibration with the annual coefficient (table 4).

The improvement in RMSE and AE is most significant in those stations with greater monthly $C_{m,j}$ variability, as is the case of the *El Marcado* and *Perdriel* stations.

Regional calibration by means of annual coefficients

An assessment of the correlation performed among the different environmental variables and the annual adjustment coefficient (C_a) showed that wind speed is the variable that best explains the higher percentage of adjustment variance (R^2 = 0.64; figure 4, page 228). Other authors also found a good relationship between wind speed and the HG coefficient. For a semi-arid region in southern Spain Martínez-Cob and Tejero (2004) used annual mean wind speed as the parameter defining calibration groups of the HG equation and recommended not to perform a calibration when the wind speed was over 2 m s^{-1} due to the good performance of HG with respect to PM. Moreover, they suggested using a coefficient of 0.0020 rather than 0.0023 for non-windy locations, where ET_0HG overestimated ET_0PM with a mean error of 14 to 20%.

Table 4. Statistical results of daily ET_0 values with Penman-Monteith (ET_0PM) and Hargreaves calibrated with monthly coefficients ($ET_0HG_{m,j}$).

Tabla 4. Resultados estadísticos entre valores diarios de ET_0 con Penman-Monteith (ET_0PM) y Hargreaves calibrada con coeficientes mensuales ($ET_0HG_{m,j}$).

Station	R^2	RMSE	MBE	AE
Chacras de Coria	0.87	0.622	0.026	0.447
Mendoza	0.98	0.274	-0.023	0.186
Mendoza Observatorio	0.80	0.942	0.022	0.646
Jocolí	0.88	0.700	0.168	0.495
Las Violetas	0.98	0.267	0.025	0.187
Tres Porteñas	0.96	0.408	-0.023	0.268
Junín	0.98	0.255	0.033	0.189
Los Campamentos	0.85	0.882	-0.007	0.635
El Marcado	0.92	0.483	-0.003	0.355
Las Catitas	0.95	0.442	-0.004	0.316
Russell	0.94	0.470	0.126	0.326
Perdriel	0.83	0.882	0.141	0.677
Mean	0.91 ± 0.06	0.55 ± 0.25	0.04 ± 0.07	0.39 ± 0.18

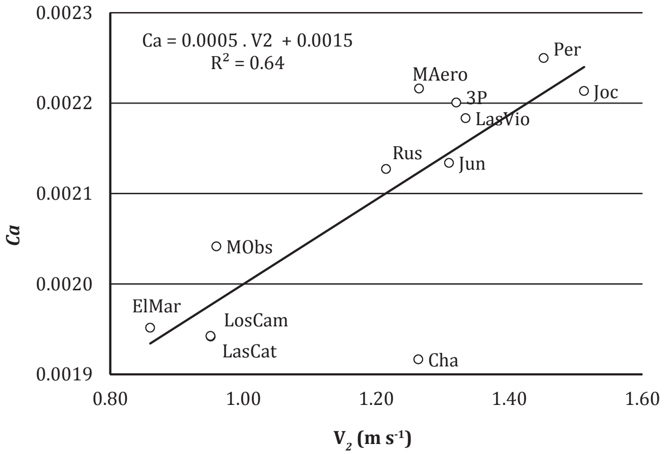

Figure 4. Dispersion between V_2 (m s^{-1}), and *Ca* (dimensionless) values of the ET_0HG_a equation.

Figura 4. Dispersión entre valores de V_2 (m s^{-1}), y C_a (adimensional) de la ecuación de ET_0HG_a.

For the Oasis of Mendoza the mean annual wind speed at 2 m is low in all stations (less than 1.5 m s^{-1}) and ET_0HG performed better in those stations with higher wind strengths (near 1.5 m s^{-1}).

The mean value of the annual HG adjustment coefficient for locations with weak winds was 0.0020 for the Oasis (figure 2, page 224). Gavilán *et al.* (2006) found overestimations of ET_0HG over ET_0PM in interior areas of Spain. They concluded that V_2 and ΔT exerted a significant influence on the precision of the HG equation and classified overestimated and underestimated areas through a combination of these two variables.

The regions with V_2 below 1.5 m s^{-1} and with ΔT above 12 °C overestimated the daily ET_0 value that was calculated with ET_0HG; a coefficient of 0.0021 must be used to improve the estimates. This example explains the results obtained in the northern oasis of Mendoza, where the annual thermal amplitude is even greater (ΔT>15°C) in all locations due to desert and continentality conditions.

Finally, Shahidian *et al.* (2013) analysed different environmental variables to perform the calibration of ET_0HG by testing different models under different climate scenarios. They concluded that wind speed was the most important parameter to improve ET_0HG estimates. However, in the northern oasis of Mendoza wind speed values are not usually available when the ET_0HG equation can be useful. So, from a practical point of view, regional calibration of the HG equation is less interesting than local calibration.

Conclusions

On the basis of its original formulation, the Hargreaves equation is not suitable for irrigation scheduling because it offers systematic and considerable overestimates for ET_0 calculation in the northern oasis of Mendoza on a daily scale. Nevertheless, the accuracy of the equation for calculating ET_0 on a daily scale improves with the use of an annual adjustment coefficient and monthly calibration coefficients in all stations included in this study. The differences between the annual adjustment coefficient and monthly calibration coefficients are negligible, though a slight decrease in errors was detected in all stations when monthly calibration coefficients are used. Since the information required for both is the same, it is recommended to use the monthly calibration coefficient, although both methodologies can be considered equally valid.

With regard to the regionalisation of the Hargreaves equation in the northern oasis of Mendoza, the variability of environmental patterns given the great continentality and desert conditions are scant. This prevented to explain the spatial variability of the annual adjustment coefficient C_a as a function of variables that are readily available in the zone.

The main explanatory variable has been wind speed ($R^2 = 0.64$), which is of little use given that this information is not available in most of the stations of the northern oasis of Mendoza (which is why alternative methods to the Penman-Monteith are necessary, as proposed here).

Therefore, it can be concluded that when only air temperature data are available either of the two methods for local calibration of the HG equation presented in this study is suitable for estimating crop water requirements on a daily scale in the northern oasis of Mendoza.

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