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A Simple Procedure to Estimate Reference Evapotranspiration during the Irrigation Season in a Hot-Summer Mediterranean Climate

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Abstract: The Food and Agricultural Organization of the United Nations (FAO) Penman–Monteith (PM) method is widely regarded as the most effective reference evapotranspiration (ET_o) estimator; however, it requires a wide range of data that may be scarce in some rural regions. When feasible relative humidity, solar radiation and wind speed data are unavailable, a temperature-based method may be useful to estimate ET_o and provide suitable data to support irrigation management. This study has evaluated the accuracy of two ET_o estimations methods: (1) a locally and monthly adjusted Hargreaves–Samani (HS) equation; (2) a simple procedure that only uses maximum temperature and a temperature adjustment coefficient (MaxTET). Results show that, if a monthly adjusted radiation adjustment coefficient (k_{R_s}) is calibrated for each site, acceptable ET_o estimations (RMSE and R² equal to 0.79 for the entire region) can be achieved. Results also show that a procedure to estimate ET_o based only on maximum temperature performs acceptably, when compared with ET_o estimation using PM equation (RMSE = 0.83 mm day⁻¹ and R² = 0.77 for Alentejo). When comparing these results with the ones attained when adopting a monthly adjusted HS method, the MaxTET procedure proves to be an accurate ET_o estimator. Results also show that both methods can be used to estimate ET_o when weather data are scarce.

Keywords: reference evapotranspiration; FAO Penman–Monteith; Hargreaves–Samani; maximum temperature procedure; irrigation; hot-summer Mediterranean climate



Citation: Rodrigues, G.C.; Braga, R.P. A Simple Procedure to Estimate Reference Evapotranspiration during the Irrigation Season in a Hot-Summer Mediterranean Climate. *Sustainability* **2021**, *13*, 349. <https://doi.org/10.3390/su13010349>

Received: 25 November 2020

Accepted: 29 December 2020

Published: 2 January 2021

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1. Introduction

The Food and Agricultural Organization of the United Nations (FAO) Penman–Monteith (PM) reference evapotranspiration (ET_o) equation [1], despite being regarded as the most accurate method to estimate ET_o, is not always viable since data quality needs to be assured and representative of well-watered conditions [2]. Despite its wide adoption in many regions and climates [3,4], the data required may not be easily available in some rural areas where full weather stations may not exist or, if available, the data collected may be of poor quality. The PM calculation requires air temperature, windspeed, relative humidity and solar radiation. While maximum (T_{max}) and minimum (T_{min}) temperature data are commonly observed at most weather stations, windspeed (u_2), relative humidity (RH) and solar radiation (R_s) are not frequently available, and, if recorded, the data quality may not be adequate. To overcome this constraint, [1] proposed a set of methods that allow for the estimation of these missing variables. When RH data are missing, [1] recommended the estimation of actual vapor pressure based on the assumption that minimum temperature could be an acceptable estimator of dew point temperature. For estimation of R_s , [1] proposed the adoption of the Hargreaves–Samani method [5], which expresses R_s as a linear function expressed as:

$$R_s = k_{R_s} \times R_a \times (T_{\max} - T_{\min})^{0.5} \quad (1)$$

where k_{R_s} is an empirical radiation adjustment coefficient ($^{\circ}\text{C}^{-0.5}$) and R_a is the extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$). Allen et al. [1] also proposed the use of the world average wind speed value $u_2 = 2 \text{ m s}^{-1}$ as the default estimator when wind speed data are missing. However, this estimation may lead to some accuracy error [6,7].

Droogers and Allen [8] concluded that if accurate weather data collection can be expected, the PM equation is advisable but, otherwise, a modified Hargreaves–Samani equation should be considered. The latter focuses only on maximum and minimum temperatures and, if locally calibrated, can lead to accurate ETo estimations [9]. Given its simplicity, this model can be applied, as it depends only on temperature, and most weather stations collect these data [8]. Other temperature-based methods to estimate ETo are available in the literature [8,10–13]. Rodrigues and Braga [14] compared nine different temperature-based methods in order to determine the best model based on the weather conditions of fourteen locations in Alentejo, Southern Portugal. They have shown that, after calibrating the k_{R_s} for a specific location, the Hargreaves–Samani (HS) method showed its appropriateness for the most of part for the locations, leading to acceptable ETo estimations ($\text{RMSE} = 0.84 \text{ mm day}^{-1}$). However, it would benefit from further calibration, where a monthly k_{R_s} could be obtained. Nonetheless, the calculation of extra-terrestrial radiation can be a limitation for some users, and the complexity of calculation of both PM and HS methods requires a computerized approach to ease ETo estimation.

State and federal agency personnel, as well as farmers, as the final and main beneficiaries of direct methods, and their advisors would take advantage of a simpler method in terms of required data and calculation. Moreover, if we consider using meteorological forecast data rather than using historical data. An early attempt was made by [15] where potential evapotranspiration from areas of natural vegetation was determined from average temperature records alone. Despite the apparent simplicity, the method requires a complex mathematical computation to estimate ETo. A more recent approach, developed by [16] in Ethiopia, aimed to develop a simpler method. The advantage of this method is that it uses only maximum temperature to estimate ETo for a specific location. However, the method requires the calibration of a site-specific factor, dependent on average temperature. Still, when assessing its accuracy for the Alentejo region, [14] concluded that this method lacks a scaling capability since it led to an RMSE varying from 2.22 to 4.00 mm day^{-1} when estimating ETo for fourteen locations across the region.

The main objective of this study was to develop and validate a new simple temperature-based procedure that uses only maximum temperature for areas where other climatic parameters may not be available during the irrigation season and where its use is expeditious. This will allow the end users, due to the procedure's simplicity, to easily estimate ETo not only from historical data, but also to forecast ETo based on estimated maximum temperature. The main purpose is to not to create a new standard equation, but a procedure that allows the establishment of a strict relation between maximum temperature and ETo. Simultaneously, the radiation adjustment coefficient (k_{R_s}) will be calibrated for each location in order to assess if it leads to improved ETo estimations. Finally, the performance of the new simple temperature-based procedure, in comparison with the PM or HS method, will be assessed.

2. Materials and Methods

2.1. Study Area

This study was conducted in the Alentejo region, Southern Portugal. Meteorological data were collected by the weather stations network (SAGRA—<http://www.cotr.pt/servicos/sagranet.php>) installed at 14 locations managed by the Irrigation Operation and Technology Center (COTR). Each station collects data on maximum and minimum air temperatures, relative humidity, wind speed, rainfall and solar radiation. All data are validated daily by a team of experienced technicians, assuring quality and feasibility.

Figure 1 and Table 1 present, respectively, the geographical position of the locations evaluated, and their coordinates, period of data and mean and standard deviation for maximum and minimum temperatures, PM reference evapotranspiration and rainfall during the irrigation season. The region, according to Köppen–Geiger classification, has a *Csa* climate, and is characterized by a semiarid Mediterranean climate of hot and dry season in the summer and mild temperature associated with annual rainfall in winter. A more comprehensive characterization of the study is presented by [14]. This study was conducted from April to October, the period that covers the growing season of the main crops in Alentejo, where irrigation is essential to maintain crop yields and profitability.

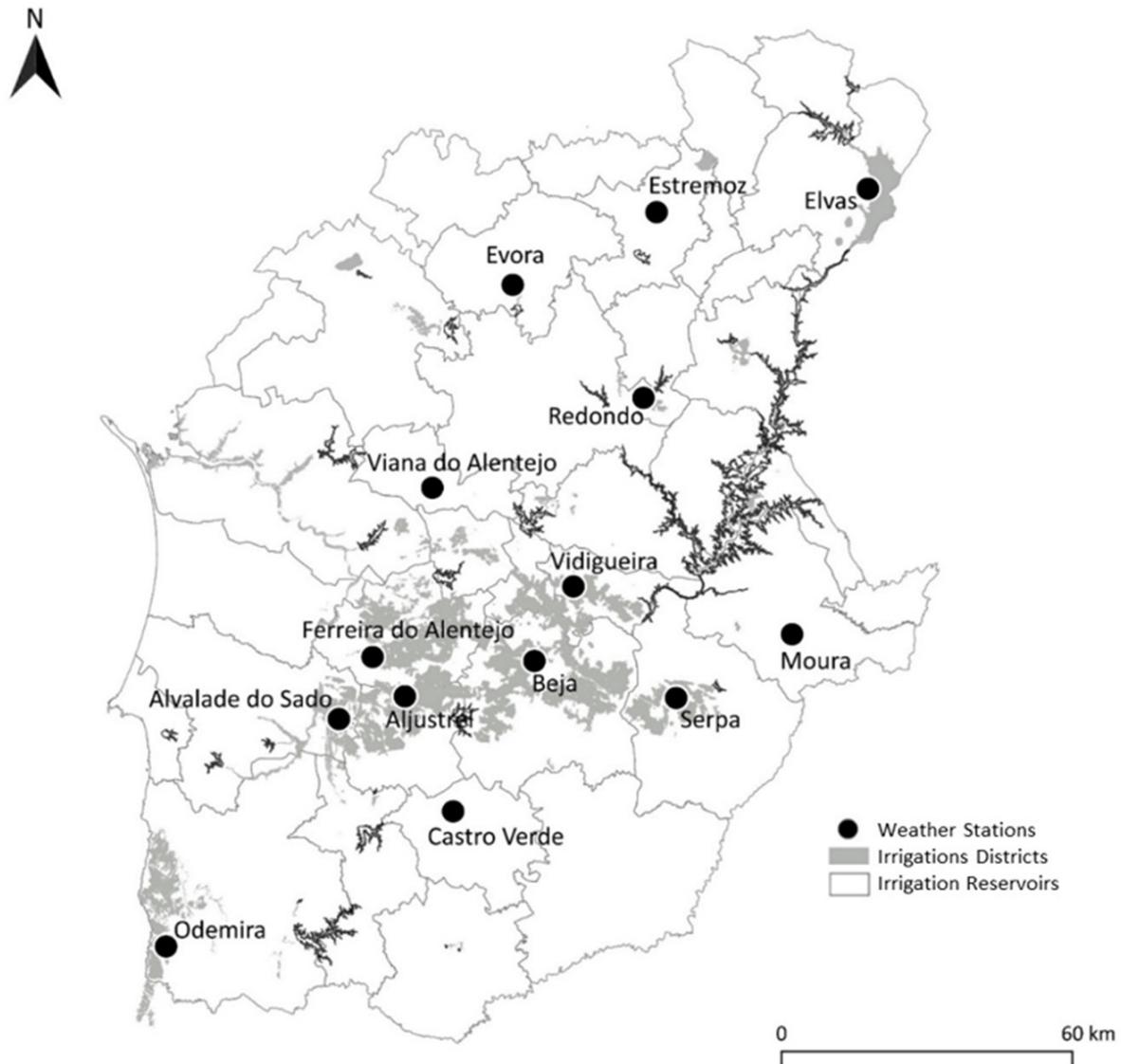


Figure 1. Weather station locations, Alentejo, Southern Portugal.

Table 1. Weather stations characterization, data range of the weather data series and annual means and standard deviations of maximum (T_{\max}) and minimum (T_{\min}) temperatures, reference evapotranspiration (ET_o) and mean annual rainfall.

Weather Station	Code	Latitude (N)	Longitude (W)	Elevation (m)	Distance to the Sea (km)	Period	T_{\max} (°C)	T_{\min} (°C)	ET _o (mm day ⁻¹)	Rainfall (mm year ⁻¹)
Aljustrel	Alj	37°58'17"	08°11'25"	104	55	2001–2019	29.1 (±5.9)	12.9 (±3.5)	4.7 (±1.7)	204
Alvalade do Sado	Alv	37°55'44"	08°20'45"	79	40	2001–2019	29.2 (±5.9)	13.3 (±3.3)	4.8 (±1.7)	183
Beja	Bej	38°02'15"	07°53'06"	206	79	2001–2019	28.8 (±6.1)	13.2 (±3.5)	5.0 (±1.8)	216
Castro Verde	CV	37°45'20.5"	08°04'35.4"	200	64	2001–2019	29.0 (±6.1)	12.8 (±3.5)	5.3 (±2.0)	151
Elvas	Elv	38°54'56"	07°05'56"	202	160	2001–2019	29.9 (±6.5)	13.0 (±4.0)	4.9 (±1.8)	218
Estremoz	Est	38°52'20"	07°35'49"	404	120	2006–2019	27.5 (±6.4)	12.2 (±3.7)	4.2 (±1.5)	256
Évora	Evo	38°44'16"	07°56'10"	246	85	2002–2019	28.6 (±6.2)	12.0 (±3.6)	4.5 (±1.6)	245
Ferreira do Alentejo	FdA	38°02'42"	08°15'59"	74	47	2001–2019	29.3 (±5.8)	12.8 (±3.5)	4.5 (±1.6)	210
Moura	Mou	38°05'15"	07°16'39"	172	100	2001–2019	30.2 (±6.4)	12.0 (±4.3)	4.4 (±1.6)	204
Odemira	Ode	37°30'06"	08°45'12"	92	4	2002–2019	23.9 (±4.2)	13.3 (±2.8)	3.8 (±1.1)	213
Redondo	Red	38°31'41"	07°37'40"	236	105	2001–2019	29.3 (±6.4)	13.6 (±3.7)	5.1 (±1.9)	210
Serpa	Ser	37°58'06"	07°33'03"	190	90	2004–2019	30.3 (±6.4)	13.6 (±3.6)	4.8 (±1.7)	197
Viana do Alentejo	Via	38°21'39"	08°07'32"	138	57	2006–2019	28.4 (±6.1)	12.6 (±3.4)	4.8 (±1.7)	247
Vidigueira	Vid	38°10'36.8"	07°47'35.1"	155	86	2007–2019	29.9 (±6.3)	13.2 (±3.6)	4.8 (±1.7)	178

2.2. Evapotranspiration Estimation Methods

For this research, three different methods were adopted to estimate reference evapotranspiration.

(a) FAO-56 Penman–Monteith (PM):

The method, as proposed by [1], is expressed by:

$$ET_{PM} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET_{PM} is the grass reference evapotranspiration (mm day⁻¹); R_n is the net radiation (MJ m⁻² day⁻¹); G is the soil heat flux density (MJ m⁻² day⁻¹), considered as null for daily estimates; T is the daily mean air temperature (°C) at 2 m, based on the average of maximum and minimum temperatures; u_2 is the average wind speed at 2 m height (m s⁻¹); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); $(e_s - e_a)$ is the saturation vapor pressure deficit (Δe , kPa) at temperature T ; Δ is the slope of the saturated vapor pressure curve (kPa °C⁻¹); γ is the psychrometric constant (0.0677 kPa °C⁻¹). As for this study, the computation of all data required for calculating ET_o were performed following [1].

(b) Hargreaves–Samani (HS):

The Hargreaves–Samani method [5] estimates ETo using only the observed maximum and minimum temperatures and the estimation of the extraterrestrial radiation base, and is expressed by:

$$ET_{HS} = 0.0135 \times k_{RS} \times 0.408R_a \times (T_{avg} + 17.8) \times (T_{max} - T_{min})^{0.5} \quad (3)$$

where ET_{HS} is the grass reference evapotranspiration (mm day^{-1}); R_a is the extraterrestrial radiation ($\text{MJ m}^{-2} \text{day}^{-1}$), 0.0135 is a factor for conversion from American to the International system of units; T_{avg} is the average air temperature ($^{\circ}\text{C}$); T_{max} is the maximum air temperature ($^{\circ}\text{C}$); T_{min} is the minimum air temperature ($^{\circ}\text{C}$) and k_{RS} is the radiation adjustment coefficient ($^{\circ}\text{C}^{-0.5}$). The empirical coefficient k_{RS} was originally considered [5] as $0.17 \text{ }^{\circ}\text{C}^{-0.5}$. For this study, a monthly k_{RS} was locally calibrated.

(c) Single temperature procedure (MaxTET):

In this study, the PM method was used as the standard method for the development of a new simple temperature method that uses only maximum temperature for the estimation of ET_o . A standard equation is hereby proposed as a maximum temperature-based evapotranspiration (MaxTET) procedure to estimate ETo:

$$ET_{Tmax} = k_{Tmax} \times T_{max} \quad (4)$$

where ET_{Tmax} is the reference crop evapotranspiration (mm day^{-1}), k_{Tmax} is the temperature adjustment coefficient ($\text{mm }^{\circ}\text{C}^{-1}$) and T_{max} is the maximum air temperature ($^{\circ}\text{C}$). For this purpose, a monthly k_{Tmax} was locally calibrated.

2.3. Evaluation Criteria

The accuracy of the ETo estimations was assessed through the indicators listed below, where ET_{PMi} and ET_{TBi} ($i = 1, 2, \dots, n$) represent pairs of values of ET_o estimated using the PM method and another temperature-based model, respectively, for a given variable and $\overline{ET_{PM}}$ and $\overline{ET_{TB}}$ are the respective mean values:

- The coefficients of regression and determination relating observed and simulated data, b and R^2 , respectively, are defined as:

$$b = \frac{\sum_{i=1}^n ET_{PMi} ET_{TBi}}{\sum_{i=1}^n ET_{PMi}^2} \quad (5)$$

$$R^2 = \left\{ \frac{\sum_{i=1}^n (ET_{PMi} - \overline{ET_{PM}}) (ET_{TBi} - \overline{ET_{TB}})}{\left[\sum_{i=1}^n (ET_{PMi} - \overline{ET_{PM}})^2 \right]^{0.5} \left[\sum_{i=1}^n (ET_{TBi} - \overline{ET_{TB}})^2 \right]^{0.5}} \right\}^2 \quad (6)$$

- The root mean square error, $RMSE$, which characterizes the variance of the estimation error:

$$RMSE = \left[\frac{\sum_{i=1}^n (ET_{TBi} - ET_{PMi})^2}{n} \right]^{0.5} \quad (7)$$

In order to improve the accuracy of ETo estimations, these indicators were used to determine both k_{RS} and k_{Tmax} . The calibration of these coefficients was performed using a trial and error procedure for each month and location, was calibrated using 50% of the years, randomly chosen from the dataset, and validated for the remainder of the years. Results for both HS and MaxTET approaches were compared with the PM method to test its accuracy.

3. Results

3.1. Estimating a Monthly Adjusted Radiation Adjustment Coefficient for Each Location

Table 2 shows the validated k_{RS} for each month and location, as well as the irrigation season calibrated factor as suggested by [14]. Results show that, for most locations, the monthly calibrated k_{RS} differ, both locally and monthly, from the seasonal coefficient as proposed by [14]. Locations with the same seasonal coefficient, such as Beja, Castro Verde, Odemira and Redondo (seasonal $k_{RS} = 0.17$), tend to have different validated monthly k_{RS} throughout the irrigation season. k_{RS} for Beja varies from 0.16 to 0.18, while for Castro Verde and Redondo the empirical coefficient varies from 0.16 to 0.19. Additionally, when comparing the validated k_{RS} between those locations for the same month, different values may be found. For the month of July, the empirical radiation coefficient equals 0.17, 0.18, 0.16 and 0.17 for Beja, Castro Verde, Odemira and Redondo, respectively; but, for the month of October, a k_{RS} of 0.18, 0.19, 0.17 and 0.19 was obtained the same locations. For the entire Alentejo region, the coefficient ranges 0.15–0.16. Results also show that there is no regularity in the variation of k_{RS} values throughout the season.

Table 2. Validated Hargreaves–Samani radiation adjustment coefficient (k_{RS}) values for each month and location.

Station	Month							Irrigation Season ¹
	April	May	June	July	August	September	October	
Aljustrel	0.15	0.15	0.15	0.16	0.16	0.15	0.16	0.16
Alvalade do Sado	0.15	0.16	0.16	0.16	0.16	0.15	0.16	0.16
Beja	0.16	0.17	0.17	0.17	0.17	0.17	0.18	0.17
Castro Verde	0.16	0.17	0.17	0.18	0.18	0.17	0.19	0.17
Elvas	0.15	0.15	0.15	0.16	0.16	0.15	0.16	0.16
Estremoz	0.15	0.15	0.14	0.15	0.14	0.14	0.15	0.14
Évora	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Ferreira do Alentejo	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Moura	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14
Odemira	0.17	0.17	0.16	0.16	0.16	0.17	0.17	0.17
Redondo	0.16	0.16	0.16	0.17	0.17	0.17	0.19	0.17
Serpa	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Viana do Alentejo	0.15	0.15	0.15	0.16	0.16	0.16	0.18	0.16
Vidigueira	0.15	0.16	0.15	0.15	0.15	0.14	0.16	0.15
Alentejo	0.15	0.16	0.15	0.16	0.16	0.16	0.16	0.16

¹—as proposed by [14].

Figure 2 reports the effect of the distance to the sea over k_{RS} . Results demonstrate that, contrarily to what is proposed by [1], the k_{RS} does not decrease with further distance to the sea. From the analysis in Figure 2, it can be concluded that “coastal” locations (such as Odemira and Alvalade do Sado) tend to reveal a lower k_{RS} than some more “interior” sites. However, there is no clear trend; locations with similar distances to the sea (e.g., Moura and Redondo) show quite different values. For Moura, the k_{RS} ranges from 0.13 to 0.14, while for Redondo the adjustment coefficient varies from 0.17 to 0.19. Indeed, the validated values for the latter are even higher than the ones obtained for more “coastal” locations, contradicting the standard trend as proposed by [1]. These results show there is no clear relation with the distance to sea, suggesting that other factors such as latitude, altitude and closeness to irrigated fields may have a direct impact on the radiation adjustment coefficient.

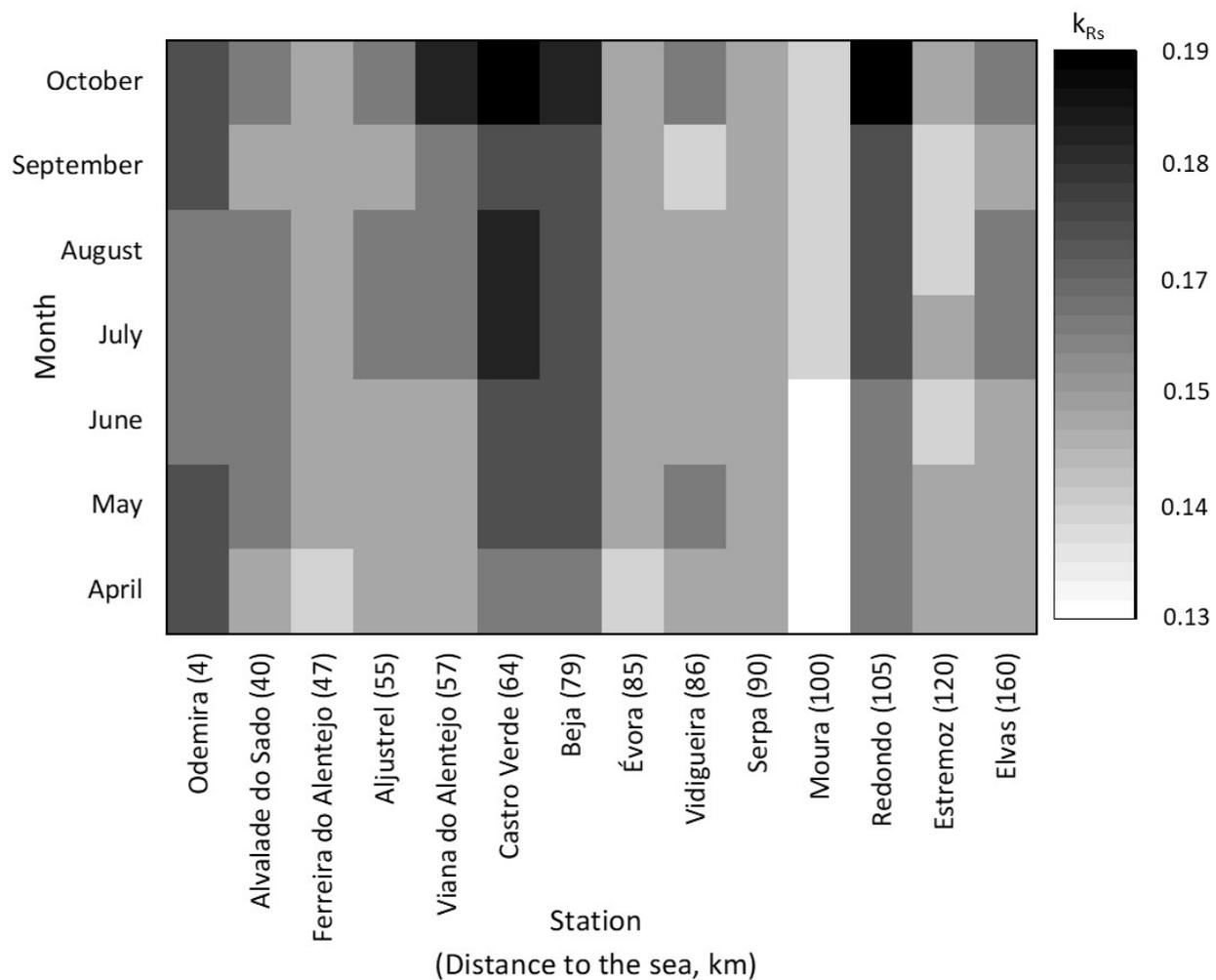


Figure 2. Validated Hargreaves–Samani radiation adjustment coefficient (k_{Rs}) values for each month and location ordered according to the distance to the sea (km).

Table 3 shows the statistical summary (b , R^2 , RMSE) of ETo estimates for each location, which resulted from adopting the monthly adjusted HS method for calibration, validation and all years. As a comparison, Table 3 also presents the accuracy of the ETo estimations when using a seasonal calibrated k_{Rs} for each site, as proposed by [14]. Results show that, after monthly calibrating the k_{Rs} factor, ETo estimations by the HS equation tend to improve the method's accuracy. For 10 locations (Aljustrel, Beja, Castro Verde, Elvas, Estremoz, Ferreira do Alentejo, Moura, Odemira, Redondo and Viana do Alentejo) the RMSE decreased, on average, from 0.77 to 0.74 mm day^{-1} , while the R^2 increased from 0.79 to 0.80 . As for the remaining four locations (Alvalade do Sado, Évora, Serpa and Vidigueira), the statistical results remain similar. For the entire Alentejo region, results also demonstrate an improvement, with the RMSE decreasing from 0.84 to 0.79 mm day^{-1} and the coefficient of determination increasing from 0.77 to 0.79 , proving that a monthly calibrated coefficient leads to improved ETo estimations. This trend come into agreement with the results found by [17], where the accuracy of ETo estimations when moving from an annual to seasonal calibration tends to improve significantly (especially from spring and summer).

Table 3. Accuracy of ETo estimations using the Hargreaves–Samani (HS) method after a monthly radiation adjustment coefficient (k_{RS}) factor calibration/validation.

Station	Monthly Adjusted HS Method									Seasonal Adjusted HS Method		
	Calibration			Validation			All			b	R ²	RMSE
	b	R ²	RMSE	b	R ²	RMSE	b	R ²	RMSE			
Aljustrel	0.99	0.80	0.74	0.97	0.80	0.76	0.98	0.80	0.75	1.01	0.80	0.78
Alvalade do Sado	0.99	0.81	0.73	0.98	0.84	0.68	0.98	0.82	0.71	0.99	0.82	0.71
Beja	1.00	0.82	0.78	1.02	0.85	0.73	1.01	0.83	0.76	1.01	0.83	0.77
Castro Verde	0.99	0.84	0.80	0.98	0.86	0.75	0.99	0.85	0.78	0.96	0.83	0.82
Elvas	0.99	0.79	0.80	0.97	0.78	0.85	0.98	0.79	0.83	1.01	0.78	0.86
Estremoz	1.00	0.81	0.64	0.99	0.78	0.73	0.99	0.79	0.69	0.96	0.79	0.70
Évora	0.98	0.78	0.79	0.98	0.75	0.82	0.98	0.76	0.80	0.99	0.76	0.80
Ferreira do Alentejo	1.01	0.79	0.74	1.00	0.81	0.69	1.00	0.80	0.71	1.01	0.80	0.72
Moura	1.00	0.80	0.68	0.97	0.81	0.70	0.98	0.81	0.69	1.01	0.81	0.71
Odemira	0.99	0.64	0.66	0.97	0.72	0.59	0.98	0.68	0.63	1.01	0.69	0.64
Redondo	0.98	0.80	0.84	0.98	0.79	0.88	0.98	0.79	0.86	1.00	0.79	0.88
Serpa	1.00	0.78	0.79	0.96	0.79	0.79	0.98	0.78	0.79	0.98	0.78	0.79
Viana do Alentejo	0.98	0.83	0.69	0.96	0.82	0.76	0.97	0.83	0.73	0.99	0.81	0.77
Vidigueira	0.99	0.80	0.74	0.97	0.79	0.78	0.98	0.80	0.75	0.97	0.80	0.75
Alentejo	0.99	0.79	0.79	0.98	0.79	0.79	0.98	0.79	0.79	1.01	0.77	0.84

3.2. Validation of a Maximum Temperature-Based ETo Estimation Procedure

The proposed approach (Equation (4)) to develop maximum temperature-based ETo estimation procedure (MaxTET) requires the determination of a temperature conversion coefficient (k_{Tmax}). Table 4 presents the validated k_{Tmax} for each month and location.

Table 4. Validated temperature adjustment coefficient (k_{Tmax}) values for each month and location.

Station	Month						
	April	May	June	July	August	September	October
Aljustrel	0.160	0.185	0.190	0.195	0.170	0.140	0.110
Alvalade do Sado	0.165	0.190	0.195	0.195	0.175	0.140	0.115
Beja	0.175	0.200	0.205	0.210	0.185	0.150	0.125
Castro Verde	0.175	0.205	0.215	0.220	0.195	0.160	0.135
Elvas	0.160	0.185	0.190	0.195	0.170	0.140	0.110
Estremoz	0.160	0.175	0.175	0.180	0.155	0.125	0.105
Évora	0.160	0.180	0.185	0.190	0.170	0.140	0.110
Ferreira do Alentejo	0.155	0.180	0.180	0.180	0.160	0.130	0.110
Moura	0.145	0.165	0.170	0.170	0.150	0.125	0.105
Odemira	0.170	0.185	0.185	0.180	0.160	0.140	0.115
Redondo	0.175	0.200	0.200	0.210	0.185	0.150	0.125
Serpa	0.155	0.180	0.185	0.185	0.160	0.130	0.105
Viana	0.160	0.185	0.185	0.195	0.180	0.145	0.130
Vidigueira	0.160	0.185	0.185	0.190	0.165	0.130	0.110
Alentejo	0.160	0.185	0.190	0.195	0.170	0.140	0.115

Table 5 presents the statistical summary (b, R², RMSE) of ETo estimates for each location, which resulted from adopting the MaxTET procedure, for calibration, validation and all years. Results show that this method predict ETo with acceptable accuracy, with R² higher than 0.75 for most locations; only Odemira shows a slightly lower coefficient of determination (R² = 0.65). Additionally, this method led to an RMSE lower than 0.91 mm day⁻¹ (as low as 0.65 mm day⁻¹ for Odemira), averaging 0.80 mm day⁻¹, with slight to no under- or overestimation of the ETo for all locations (b varied from 0.98 to 1.01). These results agree with the ones found by [8] when estimating ETo from a modified HS equation, leading to an RMSE = 0.72 mm day⁻¹. Even when upscaling the approach for the entire Alentejo region,

the MaxTET method proved to be accurate for ETo estimations, with a slope of 0.98, an R^2 equal to 0.77 and an RMSE of 0.83 mm day^{-1} . Results for calibration and validation datasets tend to be similar, with low variations for both R^2 and RMSE indicators.

Table 5. Accuracy of ETo estimations using the maximum temperature-based evapotranspiration (MaxTET) procedure after temperature adjustment coefficient ($k_{T_{\text{MAX}}}$) calibration/validation.

Station	Monthly Adjusted $k_{T_{\text{MAX}}}$								
	Calibration			Validation			All		
	b	R^2	RMSE	b	R^2	RMSE	b	R^2	RMSE
Aljustrel	1.00	0.78	0.79	0.98	0.78	0.81	0.99	0.78	0.80
Alvalade do Sado	1.00	0.78	0.78	0.99	0.81	0.74	0.99	0.80	0.76
Beja	1.00	0.79	0.85	1.02	0.82	0.80	1.01	0.81	0.82
Castro Verde	1.00	0.80	0.92	0.99	0.82	0.84	0.99	0.81	0.88
Elvas	1.00	0.78	0.84	0.98	0.76	0.88	0.99	0.77	0.86
Estremoz	1.00	0.78	0.68	0.99	0.76	0.77	0.99	0.77	0.73
Évora	1.00	0.76	0.82	1.00	0.73	0.85	1.00	0.75	0.84
Ferreira do Alentejo	0.99	0.77	0.77	0.98	0.79	0.74	0.99	0.78	0.75
Moura	1.00	0.79	0.69	0.97	0.80	0.72	0.98	0.79	0.71
Odemira	1.00	0.63	0.67	0.97	0.68	0.63	0.99	0.65	0.65
Redondo	1.00	0.78	0.89	0.99	0.77	0.93	1.00	0.78	0.91
Serpa	1.00	0.76	0.82	0.96	0.77	0.84	0.98	0.76	0.83
Viana	1.00	0.79	0.80	0.97	0.78	0.85	0.98	0.79	0.82
Vidigueira	1.00	0.78	0.79	0.98	0.78	0.83	0.99	0.78	0.81
Alentejo	0.99	0.77	0.83	0.97	0.77	0.83	0.98	0.77	0.83

3.3. Comparing the Accuracy of MaxTET and Monthly Adjusted Hargreaves–Samani Methods

To better assess the accuracy of relationships, $ET_{\text{HS}}/ET_{T_{\text{MAX}}}$ and ET_{PM} regression lines were used (Figure 3). Generally, both methods performed well in the study area. Results demonstrate that, for all locations, both Hargreaves–Samani and MaxTET tend to overestimate low ETo values, while for high ETo values both methods tend to underestimate reference evapotranspiration. For Aljustrel, Castro Verde, Évora, Redondo and Vidigueira, both methods led to similar results for high ETo values. Globally, both methods seem to accurately estimate the ETo for all 14 locations and for the Alentejo region as a whole.

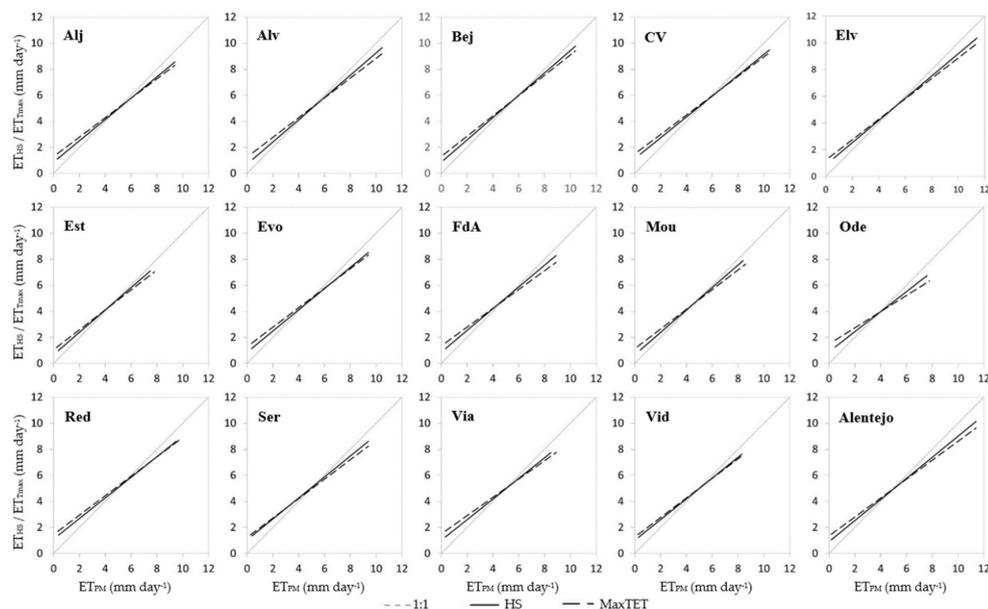


Figure 3. Comparison of monthly adjusted Hargreaves–Samani (HS) method and maximum temperature-based evapotranspiration (MaxTET) procedure with Penman–Monteith (PM) for all locations.

Figure 4 presents a comparison of the accuracy when estimating ETo, for each location, using the MaxTET, and the monthly and seasonally adjusted HS methods. Results show that for, for all 14 locations, the RMSEs for the three methods are similar. Despite of leading to a higher RMSE, in comparison with the monthly adjusted HS method, the MaxTET procedure led to differences that varied from 0.02 (for Moura and Odemira) to 0.10 mm day⁻¹ (for Castro Verde), averaging an RMSE equal to 0.05 mm day⁻¹. Similarly, when comparing to the seasonally adjusted HS method, the MaxTET procedure led to a higher RMSE by, on average, 0.03 mm day⁻¹. Contrarily, for the entire Alentejo region, the MaxTET procedure proved to be more accurate than the seasonally adjusted HS method, resulting in a lower RMSE (0.83 and 0.84 mm day⁻¹, respectively).

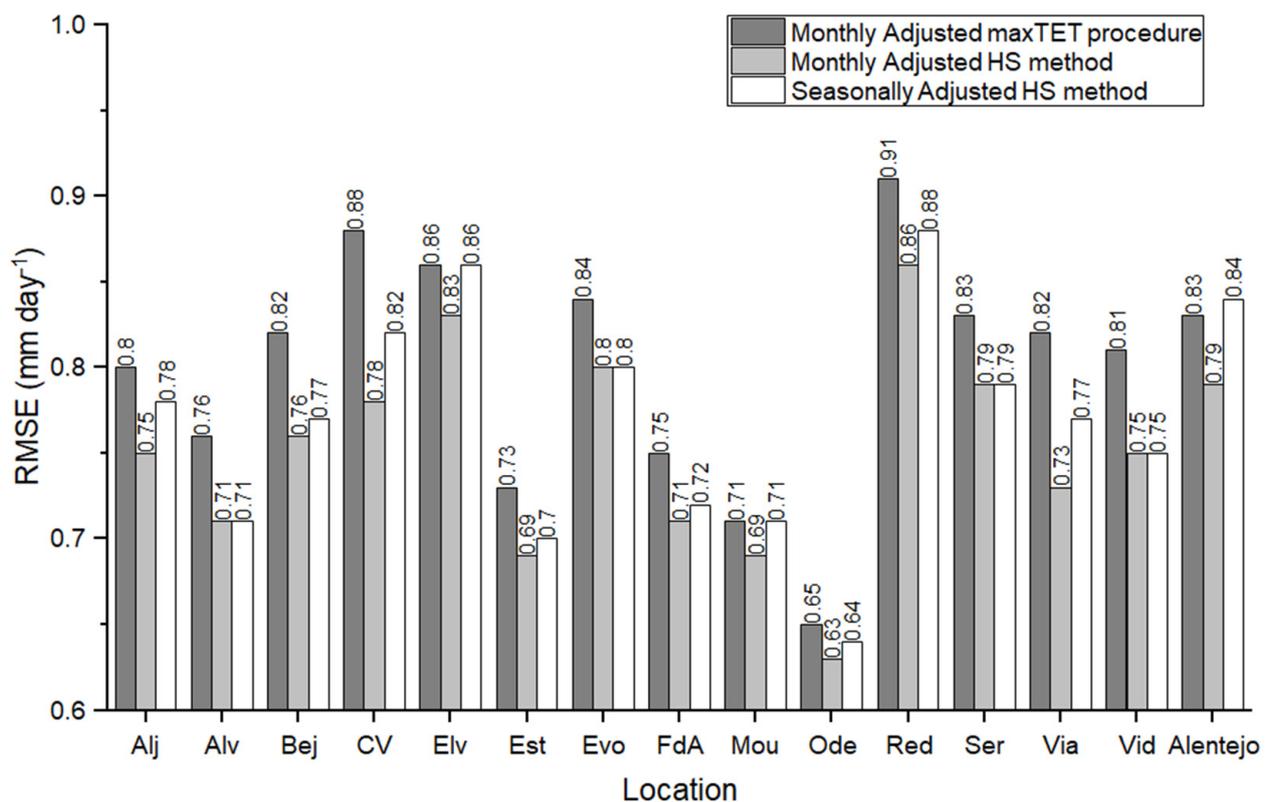


Figure 4. RMSE (mm day⁻¹) of ETo estimations using the maximum temperature-based evapotranspiration (MaxTET) procedure, and monthly and seasonally adjusted Hargreaves–Samani (HS) methods.

Figure 5 shows the spatial distribution of RMSE of ETo estimations using the MaxTET and monthly adjusted HS methods showing a trend for lower values on “coastal” locations and higher values for more “interior” sites. Estremoz, Odemira and Moura tended to show a lower RMSE for both methods. These locations also tend to have lower ETo values (Table 1), thus lower RMSEs would be expected. Contrarily, Castro Verde, Elvas and Redondo, locations where ETo tends to be high (>5 mm day⁻¹), present higher RMSE values. Globally, for all locations, the RMSE represents around 17% and 16% of the average ETo for MaxTET and monthly adjusted HS methods, respectively. One can conclude that both models perform similarly across the region.

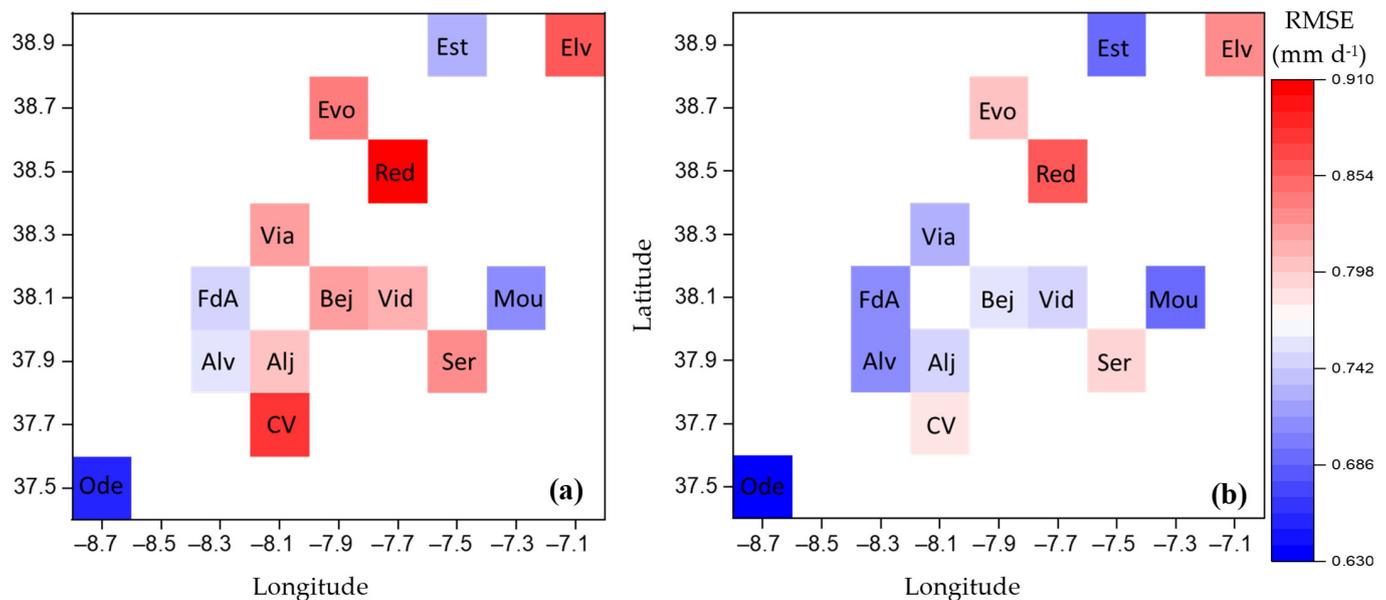


Figure 5. Spatial distribution of RMSE (mm day^{-1}) of ETo estimations using (a) the maximum temperature-based evapotranspiration (MaxTET) procedure and (b) monthly adjusted Hargreaves–Samani (HS) method for all 14 locations.

4. Discussion

According to [1], the empirical coefficient k_{RS} ranges from 0.16 to 0.19 $^{\circ}\text{C}^{-0.5}$, respectively, for “interior” or “coastal” regions, diverging from the original coefficient proposed by [5], with $k_{RS} = 0.17 ^{\circ}\text{C}^{-0.5}$. Nevertheless, k_{RS} is supposed to vary with altitude, reflecting the air pressure changes as for the volumetric heat capacity of the atmosphere [18], and should vary spatially, internalizing the effects of the site elevation and distance to sea [1]. Allen [18] also found that, for some specific locations, k_{RS} may vary seasonally. Thus, one can suggest that not only a local calibration but also a monthly adjustment should be performed to reflect the volumetric heat capacity of the atmosphere.

Results presented in Table 3 show that using just one k_{RS} per location may lead to less accurate ETo estimations. Results also show that a trend can be found across the irrigation season. For some locations, such as for Redondo and Viana do Alentejo, the radiation adjustment coefficient tended to increase during the irrigation season. Contrarily, some regions, such as Évora and Ferreira do Alentejo, remain mostly the same during the same period. Results (Figure 2) also demonstrate that, contrarily to what is proposed by Allen et al. (1998), the k_{RS} does not decrease with further distance to the sea. For summer months, “interior” and “coastal” locations illustrate the same radiation adjustment coefficient, reinforcing the statement that one should not assume the standard values of 0.16 and 0.19 $^{\circ}\text{C}^{-0.5}$, respectively, for “interior” or “coastal” regions. This can be due to the fact that, during these peak months, most cropped fields are being irrigated, influencing the air moisture and impacting the volumetric heat capacity of the atmosphere. It can be concluded that a monthly calibration/validation is advisable since k_{RS} can vary, not only depending on the distance to the sea, but also according to the month for which ETo is being estimated.

Based on the fact that to improve ETo estimation a local calibration of adjustment factors is strongly recommended, one could ask: can a simpler equation be developed to provide farmers with a method with low need of calculations and data, while still maintaining an accurate estimation of ETo? To answer this question, the MaxTET was tested. The procedure proved to be accurate for ETo estimations, with an R^2 equal to 0.77 and an RMSE of 0.83 mm day^{-1} for the entire Alentejo region. Enku and Melesse [16] aimed to develop a temperature-based evapotranspiration method for Ethiopia and, although more complex than the one proposed here, led to similar accuracy results, with an average R^2

equal to 0.65 and an RMSE averaging 0.59 mm day^{-1} . However, and according to [14], the accuracy of this method, when estimating ETo for Alentejo, does not support its adoption since it led to an RMSE higher than 2.20 m day^{-1} ; one can conclude that the MaxTET procedure outperforms the previous established method proposed by [16] since it led to more accurate estimation results.

Accuracy results (Figure 4) indicated the appropriateness of using both the MaxTET and monthly adjusted Hargreaves–Samani methods for all the locations, since they led to acceptable ETo estimations when only temperature data were available. Additionally, and based on these results, due to its simplicity (using a maximum temperature adjustment factor), the MaxTET procedure proved to be an alternative estimator of ETo to HS for all 14 locations, providing very similar results.

5. Conclusions

In some rural areas, weather data availability may be scarce. Despite being regarded as most effective reference evapotranspiration (ETo) estimator, the FAO Penman–Monteith (PM) method requires a wide range of data that may be not be available or even feasible. For these cases, a temperature-based method may be useful to estimate ETo and provide suitable data to support irrigation management. Farmers would benefit from simpler methods in terms of required data and calculation, since time and data are scarce in their daily activities. This study has evaluated the accuracy of two ETo estimations methods: (1) a locally and monthly adjusted Hargreaves–Samani (HS) equation; (2) a simple procedure that only that uses maximum temperature and a temperature adjustment coefficient.

Results show that, instead of using only one calibrated radiation adjustment coefficient (k_{Rs}) per location, if a monthly adjusted k_{Rs} is calibrated for each site, it leads to improved ETo estimations. Results also showed that there is no clear effect of the distance to the sea over k_{Rs} , reinforcing the statement that one should not assume the standard values available in the literature. Additionally, results show that a monthly calibration/validation is advisable since k_{Rs} can vary not only depending on the distance to the sea, but also according to the month for which ETo is being estimated.

Results also show that a procedure to estimate ETo based only on maximum temperature (MaxTET) performs acceptably, compared with an ETo estimation using a PM equation, with similar results for both calibration and validation datasets. When comparing these results with the ones achieved when adopting a monthly adjusted HS method, and despite leading to a slightly lower accuracy, the MaxTET procedure proved to be an accurate ETo estimator indicating the appropriateness of using this simple approach.

In conclusion, this simpler procedure to estimate could be used for the estimation of ETo where data are insufficient or of poor quality.

Author Contributions: Conceptualization, G.C.R. and R.P.B.; methodology, G.C.R. and R.P.B.; Data analysis, G.C.R.; writing—original draft preparation, G.C.R.; writing—review and editing, G.C.R. and R.P.B. Both author have read and agreed to the published version of the manuscript.

Funding: This research was funded by FCT through the research unit LEAF (UID/AGR/04129/2020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Weather data was obtained from COTR and are available at <http://www.cotr.pt/servicos/sagranet.php> with the permission of COTR.

Acknowledgments: Authors thanks COTR—Irrigation Operation and Technology Center for the data provided for this study.

Conflicts of Interest: The authors declare no conflict of interest.

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