# Regional analysis and calibration for the South of Portugal of a simple evapotranspiration model for use in an autonomous landscape irrigation controller

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*Abstract:* - This work is part of the development of an automatic and autonomous landscape irrigation controller which uses a simpler method for computing $ET_o$ than the FAO Penman-Monteith method (FAO-PM) in order to reduce the number of sensors required and lower the system cost. It is also intended to select a simple equation, since one of the requirements of this controller is that it should use an $ET_o$ formula with a reduced number of programming instructions due to its limited capacity. The controller to be developed should be autonomous and inexpensive, enabling it to be installed in small green areas such as small parks and gardens, having as main users the municipalities. Thus a regional analysis was made about the suitability of 6 methods for computing reference evapotranspiration (Hargreaves, Hargreaves-Samani, Jensen-Haise, Makkink, Priestley-Taylor and Turc) based only on the weather parameters temperature and solar radiation in the Alentejo. For this analysis a network of automatic weather stations was used, providing the meteorological data with a daily time-step for the period from 2003 to 2007. Results show that after the calibration, for each station, these methods present a good correlation with the $ET_o$ values calculated by the FAO-PM method. The best results were obtained by the Jensen-Haise method, and the worst results were computed by the Priestley-Taylor, Makkink, and Hargreaves-Samani methods. A considerable variation exists in the adjustment parameters from one weather station to another, so one can not use a single set of medium parameters to calibrate these functions for the entire region. Thus, it can be concluded that the Jensen-Haise is the best method for the Alentejo conditions, and it should be calibrated for each meteorological station. The results obtained by the Hargreaves-Samani method, based only on temperatures, are similar to other 5 methods and is the only one that does not need calibration, which indicates that this method can be considered for the elimination of the radiation sensor.

*Key-Words:* Evapotranspiration, Landscape irrigation, Water management, Hargreaves, Hargreaves-Samani, Jensen-Haise, Makkink, Priestley-Taylor, Turc.

## 1 Introduction

The analysis presented here compares the accuracy of the Reference Evapotranspiration ($ET_o$) estimated by different methods using only values of temperature and solar radiation.

This work is a central part of a project to develop a family of irrigation controllers with automatic adjustment of the irrigation depth to the local daily evapotranspiration. It is intended that the system should have the simplicity and economy of the popular irrigation controllers, and the water saving associated with the irrigation control systems based on meteorological stations.

The controllers should be simple and inexpensive, using only one or two climatic parameters to compute ETo. Thus, it is necessary to estimate $ET_o$ based only in the measurement of two weather parameters: temperature and solar radiation, in order to reduce the cost of the system through the use of a small number of sensors, and the adoption of a simpler $ET_o$ calculation procedure to minimize the number of programming lines in order to enable de adoption of a controller hardware with minimum memory requirements, lowering the system price.

The simplicity and low cost of this controller is one of the main development requirements, since cost is a very important issue in the irrigation of small green spaces, with particularly relevance for municipal councils that have limited budgets to invest in irrigation equipment but due to the significant amounts of water consumed in the irrigation have the need to save water. In fact, the automated irrigation control systems are a particularly effective tool to reduce the waste of water in lawns and landscape irrigation [22]. So, a comparative analysis, selection and calibration of the following $ET_o$ calculating methods was performed: Hargreaves [6], Hargreaves-Samani [7, 8], Jensen-Haise [9], Makkink [12], Priestley-Taylor [14] and Turc [18]. The results are compared with those of the Penman-Monteith (FAO-PM) method [1], which will serve as reference values, as proposed by Amatya *et al.,* [3].

Wu [21] compared several methods with the pan evaporation values, based on a regression analysis using ETo values obtained with moving averages. This author concluded, for one station in Hawaii, that the Hargreaves method [6] was equivalent to the Penman equation.

Xu and Singh [22] also compared several methods of $ET_o$ estimation with the pan evaporation values using data from one station located at Switzerland, and concluded that the Makkink [12] and Priestley-Taylor [14] were the best methods.

Wang *et al.*, [19] studied several temperature methods to compute $ET_o$ for conditions of limited data in Burkina Faso. This study was carried out trough the comparison of the Blaney-Cridle and Hargreaves methods with the FAO Penman-Monteith that was used as the standard method. These authors proposed for Burkina Faso the use of the mean equation (Blaney-Cridle + Hargreaves)/2 when there is only temperature data available.

Later Wang *et al.*, [20] used an artificial neural network (ANN) to estimate $ET_o$ with limited climatic data, using only maximum and minimum air temperature. They concluded that the use of ANN (in Burkina Faso) produces more accurate $ET_o$ estimates than the temperature based methods.

The methodology proposed in this paper also uses linear regression to obtain the calibration parameters of the different equations, introducing a validation process using different data sets in order to select the best method. As referred by Amatya *et al.,* [3] a regional analysis was also performed, for the Alqueva region, South Portugal, using the weather stations of the SAGRA network [4].

# 2 Material and methods

## 2.1 Study region and climatic data

For the analysis refered above was used data from the SAGRA (*Sistema Agrometeorológico para a Gestão da Rega no Alentejo*) automatic weather stations network. SAGRA is owned and operated by COTR (*Centro Operativo de Tecnologias do Regadio*), and the data is made available through its Webpage [4]. This network covers great part of the Alentejo and its spatial distribution is shown in Fig.1 [11]. The weather stations used were: Ferreira, Moura, Elvas, Redondo, Aljustrel, Alvalade, Beja, Évora, Odemira and Serpa. These stations record the data with a daily time step, and the period of time considered in this study for each station is presented in Table 1, along with the general characteristics of the stations.

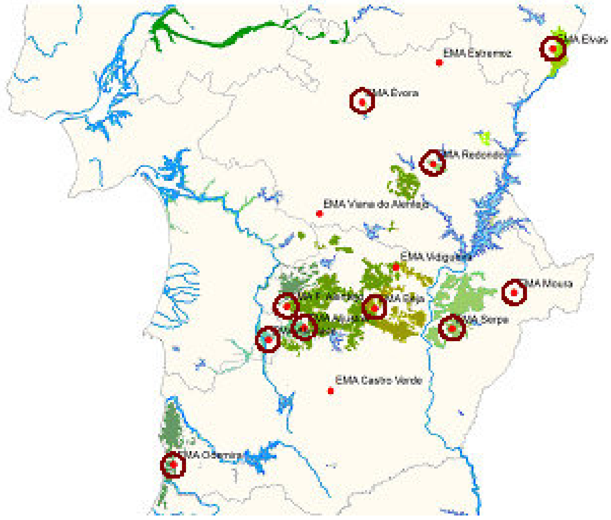


Fig.1 – Geographical distribution of the automatic weather stations of the SAGRA network (adapted from Maia [11]).

## 2.2 Brief presentation of the $ET_o$ methods

The term reference evapotranspiration ($ET_o$) was defined by Doorenbos and Pruitt [5] as “the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water”.

Later Allen *et al.*, [1] updated the term reference evapotranspiration ($ET_o$) to “the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s $m^{-1}$ and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water”.

When is not possible to measure $ET_o$ it should be computed from ET (evapotranspiration) models using climatic parameters.

There are several models to compute $ET_o$, from the more complex energy equations requiring many climate parameters as the Penman-Monteith [1, 2] to the more simpler equations that need only few parameters. Actually, the most important parameters for the calculation of $ET_o$ are temperature and solar radiation [16]. According to Jensen [10], at lest 80% of the $ET_o$ value can be explained by temperature and solar radiation.

Table 1 – Characteristics of the SAGRA network weather stations (COTR [4])

| Station | Long.(º) | Lat. (º) | Altit. (m) | Alt. anem. (m) | Series Beginning | Series end |
|---|---|---|---|---|---|---|
| Ferreira | 8.27 | 38.05 | 74 | 2 | 01-01-2003 | 23-07-2007 |
| Moura | 7.28 | 38.09 | 172 | 2 | 01-01-2003 | 23-07-2007 |
| Elvas | 7.1 | 38.92 | 202 | 2 | 01-01-2003 | 23-07-2007 |
| Redondo | 7.63 | 38.53 | 235.6 | 2 | 01-01-2003 | 23-07-2007 |
| Aljustrel | 8.19 | 37.97 | 104 | 2 | 01-01-2003 | 23-07-2007 |
| Alvalade | 8.35 | 37.93 | 78.5 | 2 | 01-01-2003 | 23-07-2007 |
| Beja | 7.89 | 38.04 | 206 | 2 | 01-01-2003 | 23-07-2007 |
| Évora | 7.94 | 38.74 | 246 | 2 | 01-01-2003 | 23-07-2007 |
| Odemira | 8.75 | 37.5 | 91.5 | 2 | 01-01-2003 | 23-07-2007 |
| Serpa* | 7.05 | 37.1 | 190 | 2 | 01-09-2006 | 23-07-2007 |

*Serpa will not be considered in the validation (section 3.2) due to the reduced size of the data series.

The $ET_o$ models can be divided in three basic types: a) temperature, b) radiation and c) combination of both. The simplest models are those that need only records of air temperature to calculate $ET_o$ [5, 10]. The radiation models [18, 5, 7] use a component of the energy balance that usually requires the existence of radiation measurements. Finally, the combination models use both the elements of the energy balance and of the mass transfer to produce accurate results [13, 5, 10, 2]. In this work 6 different models will be studied - 5 radiation models and 1 temperature model - and the results will be compared with those of the FAO Penman-Monteith.

## 2.3 Selected ETo computation methods

The reference evapotranspiration computation methods analyzed in this work based only on the climatic variable temperature and solar radiation are: Hargreaves [6], Hargreaves-Samani [7, 8], Jensen-Haise [9, 10], Makkink [12], Priestley-Taylor [14] and Turc [18]. It was decided to consider also the Hargreaves-Samani method, based only on temperatures, to understand the relevance of the parameter solar radiation ($R_s$) to enhance the estimates of the $ET_o$ values.

To evaluate these methods the $ET_o$ was calculated by the Penman-Monteith method (FAO-PM) [1], which will serve as the reference method with which all the others are compared to assess their degree of accuracy, assuming that the $ET_o$ calculated according to this method is that closest to the "real" value. Since the FAO-PM method is widely accepted as a reliable and accurate method [3, 1, 2]. The missing data FAO-PM methodology [1] was not used due to the extension of written code requirements.

The following climatic parameters were used to compute $ET_o$ by the FAO-PM method: maximum and minimum air temperature ($T_{max}$ and $T_{min}$), maximum and minimum relative humidity ($RH_{max}$ and $RH_{min}$), wind speed ($u_2$) and solar radiation ($R_s$) [1, 2]. In order to perform the $ET_o$ calculation with the other methods solar radiation ($R_s$) and maximum, minimum and average air temperature ($T_{max}$, $T_{min}$ and $T$) were used. In the following sections these models are presented with more detail.

**Penman-Monteith (FAO-PM) model**

The most common "combination" model is the FAO Penman-Monteith [1, 2]. Over the last few years this method has demonstrated its adaptability and robustness and is now accepted as providing a very accurate calculation of $ET_o$, and thus will be used as the reference method for the calibration of the other methods.

The model can be expressed as:

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

Where:

$ET_o$ – reference evapotranspiration [mm $day^{-1}$],

$R_n$ – net radiation at crop surface [MJ $m^{-2}$ $day^{-1}$],

G – soil heat flux density [MJ $m^{-2}$ $day^{-1}$],

T – air temperature at 2 m height [ºC],

$u_2$ – wind speed at 2 m height [m $s^{-1}$],

$e_s$ – saturation vapour pressure [kPa],

$e_a$ – actual vapour pressure [kPa],

$e_s$-$e_a$ – saturation vapour pressure deficit [kPa],

Δ – slope of vapour pressure curve [kPa $ºC^{-1}$],

γ – psychrometric constant [kPa $ºC^{-1}$],

The computation of the several parameters mentioned above is performed by FAO-PM own methodology which allows their determination in the absence of one or more parameters.

**Priestley-Taylor model**
The Priestley-Taylor method [14] is a simplified $ET_o$ formula requiring only the radiation and temperature for the calculation of $ET_o$. This simplification is based on the fact that evapotranspiration is more dependent on the radiation than on the relative humidity or wind speed. In fact, it has been found that [14] the radiation component is responsible for about 2/3 of ETo. Thus, it was proposed to compute the $ET_o$ component resulting directly from radiation, and increasing it by a coefficient, α, which can be calibrated in accordance with local conditions (usually values 1.12 or 1.26 are used).

$$ET_O = \alpha \frac{\Delta (R_n - G)}{\Delta + \gamma} + \beta \quad (2)$$

Where α and β are the calibration coefficients. Xu and Singh [22] calibrated the model to the Switzerland climatic conditions and obtained the values of 0.98 and 0.94 for α and β, respectively

**Makkink model**
The Makkink method [12] can be considered as a simplified form of the Priestley-Taylor, also requiring radiation and temperature for the $ET_o$ computation. The difference consists in the fact that instead of net radiation ($R_n$) and temperature the Makkink method uses solar radiation ($R_s$) and temperature. This is possible because there is a relationship between net radiation ($R_n$) and the short-wave radiation ($R_s \approx 2 R_n$).
Makkink developed in 1957 [12] this method to estimate $ET_o$ for the weather conditions of Netherlands:

$$ET_O = \alpha \frac{\Delta}{\Delta + \gamma} \frac{R_S}{2.45} + \beta \quad (3)$$

Where α is normally 0.61 and β is -0.012. Xu and Singh [22] recalibrated the model for the conditions of Switzerland and obtained the values α = 0.77 and β = 0.2.

**Hargreaves model**
The ETo computation by the "Hargreaves" method can be performed using the parameters temperature and net radiation $R_n$ adopting the Hargreaves method [6] or only temperature using the Hargreaves-Samani method [7, 8]. In the latter case, instead of the $R_n$ measured values, an equation is used to estimate $R_a$ (extraterrestrial radiation) as explained in the next section.
The original Hargreaves model is given by:

$$ET_O = \alpha (T + 17.78) R_S \quad (4)$$

Where:
$R_s$ – solar radiation [mm/day];
α = 0.0135.

Solar radiation can be expressed in $MJ/m^2$, and Equation 4 assumes the following form:

$$ET_O = \alpha (T + 17.78) R_S \left( \frac{238.8}{595.5 - 0.55T} \right) \quad (5)$$

With α = 0.0135 and $R_s$ expressed in $MJ/m^2/day$

**Hargreaves-Samani model**
Hargreaves and Samani proposed in 1982 [7] and later in 1985 [8] several improvements to the original 1975 equation [6]. The Hargreaves-Samani model is expressed by the following equation:

$$ET_O = \alpha (T + 17.78)(T_{\max} - T_{\min})^{0.5} R_a \quad (6)$$

Where:
$T_{max}$ - maximum air temperature [ºC];
$T_{min}$ - minimum air temperature [ºC];
α = 0.0023.

**Turc model**
Another method using only two parameters is the model proposed by Turc [18], which was specially designed for the humid climates of the Western Europe (France). This method is based on the values of solar radiation and temperature and is expressed as:

$$ET_O = \alpha ((23.9001 R_S) + 50) \left( \frac{T}{T + 15} \right) \quad (7)$$

With: α = 0.01333 and $R_s$ expressed in $MJ/m^2/day$

**Jensen-Haise model**
A similar model is the Jensen-Haise [9] which was determined for the more arid states of USA.

$$ET_O = \alpha \frac{T R_S}{2.450} + \beta \quad (8)$$

With α = 0.025 and β = 0.08.

Table 2 summarizes the equations and climate variables of the $ET_o$ methods presented above, and the equation coefficients adopted in this study.

## 2.4 Data analysis methodology

### 2.4.1 Exploratory analysis

The first step in this work was the execution of one exploratory analysis through a linear regression analysis to identify which are, globally, the best methods, and to select which are the best data series

to be used in the calibration and validation of the models: - the original $ET_o$ data or the moving averages.
To perform the $ET_o$ daily calculation for the 7 methods a software tool was developed using *Visual Basic 2005*. Two sets of $ET_o$ data were obtained, for each one of the stations considered, one relating to the $ET_o$ itself and the other resulting from the application of five day moving averages. Through the moving averages methodology it is possible to eliminate the variation inherent in daily weather events increasing the degree of correlation of the various methods with the reference method.
A linear regression was used to verify the correlation between the $ET_o$ calculated by the 6 methods under analysis with the values of the FAO-PM method. Thus, for each station the regression line slope (a), the intersect (b) and the coefficient of determination ($r^2$) were calculated. This procedure was performed for both series, with and without moving averages. The results obtained are the regression line parameters for each method and station, for the entire data series. These results can be used additionally as calibration parameters for the method selected from the validation (see next section).

### 2.4.2 Method calibration and validation

After the conclusion of the exploratory analysis, the $ET_o$ methods were calibrated and validated in order to assess the quality of the calculated $ET_o$ values.
To carry out this analysis the data series were split in two time series (2003-2004) and (2005-2007). A new linear regression was made for the first two years (2003, 2004) of the data series for each weather station, in order to obtain the **calibration parameters** to be used in the validation. The parameters adopted were the ones produced by the moving average since it was found that this procedure increase the coefficient of determination between the various methods and the FAO-PM. These calibration coefficients were incorporated in the software for the calculation of $ET_o$ for the remaining data series (2005-2007).
The calibration parameters were **validated** using a residuals analysis with the determination of the average error, the absolute error and relative error for the 2005-2007 period, in order to assess the degree of accuracy of the selected methods.
The average error $\bar{E}$ is defined as the arithmetic average of the residuals $e_i$ according to the following expression:

$$\bar{E} = \frac{\sum_{i=1}^{n} e_i}{n} \qquad (9)$$

where, $n$ is the size of the sample under analysis and $e_i$ is obtained according to the following equation:

$$e_i = y_i - \hat{y}_i \qquad (10)$$

where, $y_i$ is the reference value and $\hat{y}_i$ is the estimated value.
Absolute error $|\bar{E}|$ is defined as the arithmetic average of the absolute residuals $|e_i|$ being given by the following equation:

$$\left|\bar{E}\right| = \frac{\sum_{i=1}^{n} \left|e_i\right|}{n} \qquad (11)$$

The last statistics indicator used in this study was the relative error $\bar{E}_r$ which is defined as:

$$\bar{E}_r = \frac{\sum_{i=1}^{n} \frac{\left|e_i\right|}{y_i}}{n} \qquad (12)$$

Table 2 – Methods, equations, climate variables and the coefficients adopted.

| Method name | Equation | coefficients | Variables |
|---|---|---|---|
| FAO Penman-Monteith [1] | $ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$ | | $ET_o$ – reference evapotranspiration [mm day$^{-1}$], $R_n$ – net radiation at crop surface [MJ m$^{-2}$ day$^{-1}$], $G$ – soil heat flux density [MJ m$^{-2}$ day$^{-1}$], |
| Priestley-Taylor [14] | $ET_o = \alpha \frac{\Delta(R_n - G)}{\Delta + \gamma} + \beta$ | $\alpha = 1.26; \beta = 0$ | $T$ – air temperature at 2 m height [ºC], $u_2$ – wind speed at 2 m height [m s$^{-1}$], $e_s$ – saturation vapour pressure [kPa], |
| Makkink [12] | $ET_o = \alpha \frac{\Delta}{\Delta + \gamma} \frac{R_s}{2.45} + \beta$ | $\alpha = 0.61; \beta = -0.012$ | $e_a$ – actual vapour pressure [kPa], $e_s$-$e_a$ – saturation vapour pressure deficit [kPa], |
| Hargreaves [6] | $ET_o = \alpha(T + 17.78) R_s \left(\frac{238.8}{595.5 - 0.55T}\right)$ | $\alpha = 0.0135$ | $\Delta$ – slope of vapour pressure curve [kPa ºC$^{-1}$], $\gamma$ – psychrometric constant [kPa ºC$^{-1}$], |
| Hargreaves-Samani [7, 8] | $ET_o = \alpha(T + 17.78)(T_{max} - T_{min})^{0.5} R_a$ | $\alpha = 0.0023$ | $R_s$ – solar radiation [ MJ m$^{-2}$ day$^{-1}$], $R_a$ – extraterrestrial radiation [ MJ m$^{-2}$ day$^{-1}$], |
| Turc [18] | $ET_o = \alpha((23.9001 R_s) + 50)\left(\frac{T}{T+15}\right)$ | $\alpha = 0.01333$ | $T_{max}$ – maximum air temperature [ºC], $T_{min}$ – minimum air temperature [ºC]. |
| Jensen-Haise [9] | $ET_o = \alpha \frac{T R_s}{2.450} + \beta$ | $\alpha = 0.025; \beta = 0.08$ | |

The data series used in the validation was also separated into Autumn-Winter (October to March) and Spring-Summer (April to September) periods. The objective of this procedure is to assess the error that occurs during the months with more relevance for irrigation in the Mediterranean, which is the period between April and September.

# 3 Results and discussion

## 3.1 Exploratory analysis results

Table 3 shows the results of the linear regressions between the studied methods and the reference one, for the entire data series (2003-2007). These values refer to data processed by the moving average of 5 days, and were chosen because they present a better correlation between the two sets of data. The values presented in Table 3 are the calibration parameters (slope and intercept) for each method and station analyzed, and the respective average and coefficient of variation ($C_v$).

Fig.2 shows a linear regression between the FAO-PM and Jensen-Haise methods for the Beja station. This figure is an example of the several linear regressions made in this exploratory analysis, and serves to highlight the number of points considered in the regression and the proper adjustment of the results to the regression line.

From Table 3 can be observed that all the 6 methods show a good correlation with the FAO-PM method, what is in line with the conclusions achieved by Amatya *et al.*, [3], that verified a good correlation between the radiation and temperature-base methods studied with the FAO-PM. All methods, except the Hargreaves-Samani, present a considerable deviation in the slope value in relation to the unit or/and in the intercept value relative to zero. It should be emphasized that the Hargreaves-Samani method, despite being one of the methods with the lowest correlation values (0.96), almost doesn't need calibration (Table 3 and Fig.3), unlike the other methods, since its average slope is 0.96 and its average intercept at origin is -0.13. These results of the Hargreaves-Samani for the Alentejo conditions are according to the results observed by Santos and Maia [17].

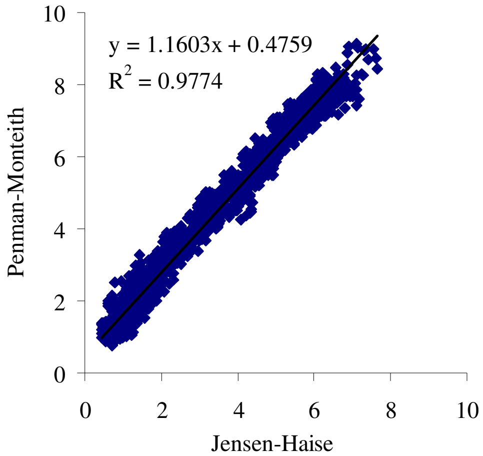


Fig.2 – Linear regression between the values computed by FAO-PM and the Jensen-Haise method, with a daily time step, for the Beja weather station during the 2003-2007 period.

Table 3 – Slope (a), intercept (b) and coefficient of determination ($r^2$) of the regression line between the studied methods and the reference Penman-Monteith method, for the 10 stations considered (from 2003 to 2007)

| | Metodhs | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hargreaves-Samani | | | Hargreaves | | | Priestley-Taylor | | | Makkink | | | Turc | | | Jensen-Haise | | |
| **Station** | **a** | **b** | **$r^2$** | **a** | **b** | **$r^2$** | **a** | **b** | **$r^2$** | **a** | **b** | **$r^2$** | **a** | **b** | **$r^2$** | **a** | **b** | **$r^2$** |
| Ferreira | 0.91 | -0.21 | 0.96 | 1.36 | -0.13 | 0.98 | 0.43 | 0.32 | 0.94 | 1.79 | -0.38 | 0.96 | 1.53 | -0.50 | 0.97 | 1.15 | 0.45 | 0.97 |
| Moura | 0.86 | -0.21 | 0.96 | 1.36 | -0.08 | 0.98 | 0.46 | 0.22 | 0.96 | 1.80 | -0.35 | 0.97 | 1.51 | -0.38 | 0.97 | 1.13 | 0.56 | 0.97 |
| Elvas | 0.94 | -0.08 | 0.94 | 1.42 | -0.08 | 0.98 | 0.46 | 0.36 | 0.93 | 1.88 | -0.37 | 0.96 | 1.59 | -0.44 | 0.97 | 1.17 | 0.58 | 0.97 |
| Redondo | 1.01 | 0.02 | 0.96 | 1.53 | -0.06 | 0.97 | 0.48 | 0.41 | 0.93 | 2.00 | -0.35 | 0.95 | 1.70 | -0.44 | 0.96 | 1.28 | 0.60 | 0.97 |
| Aljustrel | 1.01 | -0.18 | 0.96 | 1.51 | -0.13 | 0.97 | 0.48 | 0.34 | 0.93 | 1.98 | -0.40 | 0.96 | 1.69 | -0.54 | 0.97 | 1.28 | 0.50 | 0.98 |
| Alvalade | 0.96 | -0.16 | 0.97 | 1.44 | 0.06 | 0.95 | 0.46 | 0.40 | 0.93 | 1.87 | -0.14 | 0.93 | 1.62 | -0.36 | 0.95 | 1.25 | 0.56 | 0.97 |
| Beja | 1.04 | -0.14 | 0.97 | 1.38 | -0.21 | 0.97 | 0.44 | 0.37 | 0.94 | 1.80 | -0.50 | 0.96 | 1.55 | -0.59 | 0.97 | 1.16 | 0.48 | 0.98 |
| Évora | 0.93 | -0.10 | 0.96 | 1.44 | -0.06 | 0.98 | 0.45 | 0.32 | 0.96 | 1.86 | -0.31 | 0.97 | 1.58 | -0.36 | 0.98 | 1.22 | 0.56 | 0.97 |
| Odemira | 0.99 | 0.01 | 0.95 | 1.10 | 0.14 | 0.97 | 0.31 | 0.73 | 0.95 | 1.37 | 0.03 | 0.96 | 1.21 | -0.14 | 0.97 | 1.03 | 0.52 | 0.96 |
| Serpa | 0.99 | -0.26 | 0.97 | 1.26 | 0.14 | 0.96 | 0.43 | 0.27 | 0.97 | 1.65 | -0.09 | 0.96 | 1.45 | -0.30 | 0.97 | 1.08 | 0.65 | 0.94 |
| **Average** | 0.96 | -0.13 | 0.96 | 1.38 | -0.04 | 0.97 | 0.44 | 0.37 | 0.94 | 1.80 | -0.29 | 0.96 | 1.54 | -0.41 | 0.97 | 1.17 | 0.54 | 0.97 |
| **$C_v$*** | 0.05 | -0.71 | 0.01 | 0.09 | -2.84 | 0.01 | 0.12 | 0.36 | 0.02 | 0.10 | -0.57 | 0.01 | 0.09 | -0.32 | 0.01 | 0.07 | 0.11 | 0.01 |

* Coefficient of variation

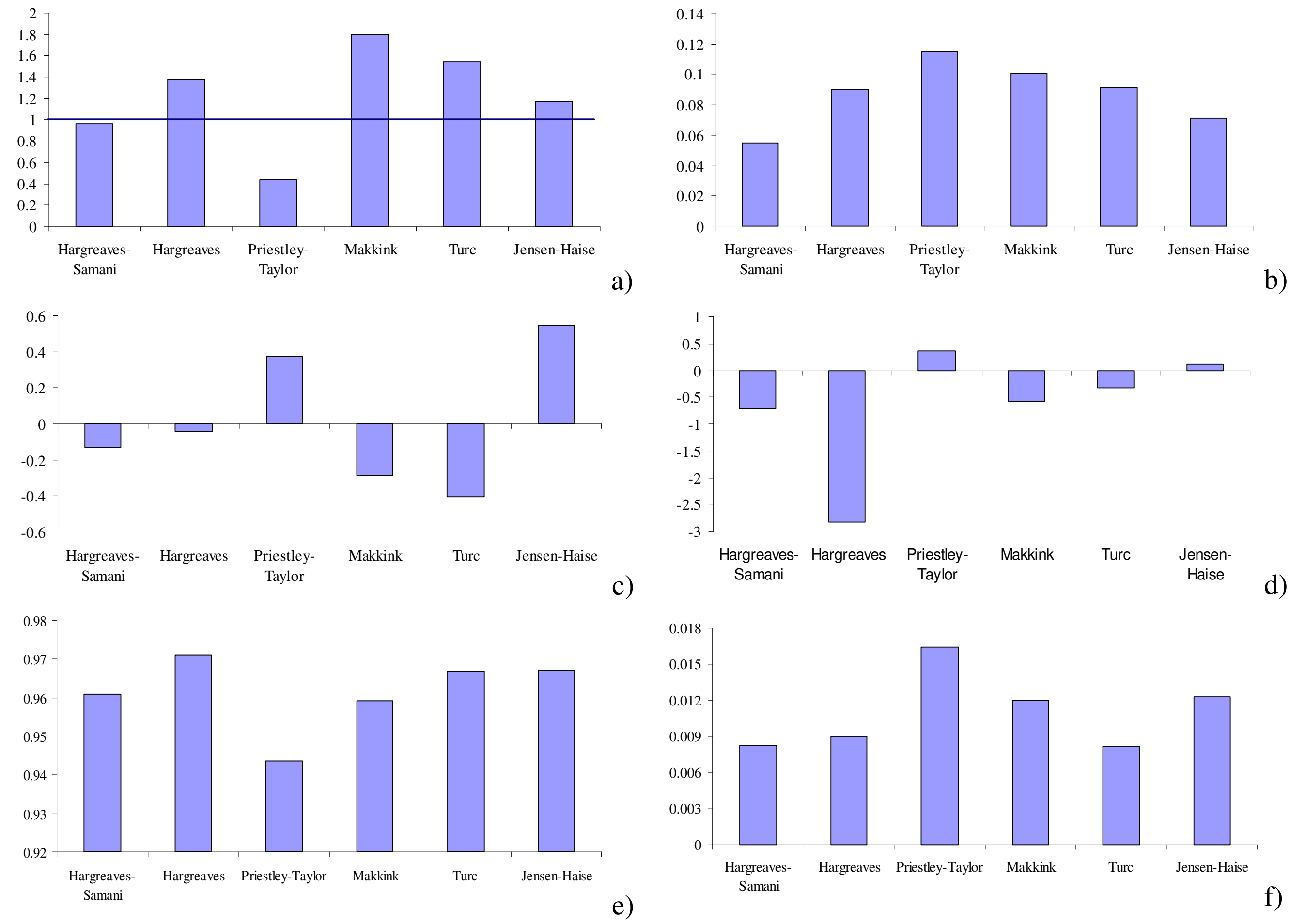


Fig.3 – Results of the regression line analysis between the studied methods and the reference FAO-PM method, for the 10 stations considered and for the 2003 to 2007 period. a) average slope of the regression line for each method; b) coefficient of variation ($C_v$) for the slope values; c) average intercept for each method; d) $C_v$ for the intercept values; e) average coefficient of determination ($r^2$) for each method and f) the $C_v$ for the coefficient of determination values.

On average (Table 3), the Jensen-Haise, Turc and Hargreaves methods are those which provide the best results in terms of coefficient of determination (all with 0.97), and the Priestley-Taylor method is the one that presents the worst results (0.94).
Moreover, the calibration parameters vary substantially from station to station and show some dispersion relative to the stations average as can be seen from the coefficient of variation ($C_v$). Thus, it can be concluded that these methods should be calibrated for each location.
From Fig.3 it is possible to observe the results achieved by the regression analysis, with Fig.3a presenting the average values for the slope (a). It is possible to observe that the Hargreaves-Samani method is the one with an average value very close to 1, while all the other methods present values significantly different. Fig.3b reinforces this observation because the Hargreaves-Samani method is the one with the lowest coefficient of variation ($C_v$) value which implies a smaller variation from weather station to weather station.
Relatively to the intercept (b) one can observe (Fig.3c) that the Hargreaves-Samani is one of the methods which result values are closer to 0, being exceeded only by the Hargreaves method which presents the higher degree of dispersion in Fig.3d.
The analysis of Fig.3e indicates that all methods shown very satisfactory results for the coefficient of determination ($r^2$), with Jensen-Haise, Hargreaves and Turc presenting the best results. The Priestley-Taylor method presents the worst values, which is confirmed by the higher value of the coefficient of variation (Fig.3f).
From the overall analysis of Fig.3 it can be established that the Hargreaves-Samani method produces similar results to the other methods and has the advantage of not needing calibration. On the other

hand, it is easy to conclude that the Priestley-Taylor method is the one with the worst performance since in general it produces the worst parameters of the linear regression analysis (a, b, $r^2$) and the respective coefficients of variation, therefore being the less accurate method.

### 3.2 Calibration and validation results

The methods were calibrated only for the first 2 years (2003 and 2004) and the remaining data (2005, 2006 and 2007) was used to validate these calibrations.

From the calibration it can be noticed that the resulting calibration parameters are slightly different from the regression parameters of the exploratory analysis using the complete data set (from 2003 to 2007), which indicate the need to use larger climatic series to obtain more representative calibrations of the average conditions. Table 4 and 5 present the values of the average error $\bar{E}$, absolute error $|\bar{E}|$ and relative error $\bar{E}_r$, for each method and weather station, respectively for the annual and Spring-Summer period (from April to September). The results of the residuals analysis, for the irrigation season (Spring/Summer) indicate that the Jensen-Haise method is the one which presents the best results with $|\bar{E}| = 0.43$ and $\bar{E}r = 8.4\%$ and the Hargreaves-Samani ($|\bar{E}| = 0.60$; $\bar{E}r = 12.2\%$) and the Priestley-Taylor ($|\bar{E}| = 0.61$; $\bar{E}r = 12.1\%$) are the methods with the worst results. It should be noted that the relative error value during the irrigation season ranges between 8.4% and 12.2%, which is an indicator of the good results obtained. The annual values in table 4 confirm the Jensen-Haise as the more accurate method but rank the Makkink as the worst method followed by the Hargreaves-Samani and the Priestley-Taylor methods.

Fig.4 shows the absolute error $|\bar{E}|$ and the relative error $\bar{E}_r$ for the Évora station for all the methods analyzed, considering the whole range of data (annual), and the Spring/Summer values. From the observation of Fig.4 is possible to conclude that once calibrated, all the methods present very satisfactory results, including Hargreaves-Samani, specially during the Spring/Summer semester. It should be noted that in this station the best results were achieved by the Turc and Hargreaves methods closely followed by the Jensen-Haise. This highlights the fact that the different methods produce very similar results, and thus, depending on the station and period considered, different methods can end up producing the best correlation and the closest $ET_o$ calculation.

Another very interesting finding (Fig. 4a) is that the absolute error (in mm) in most methods does not vary greatly from the Spring/Summer to Autumn/Winter season. However it appears that the relative error (Fig. 4b) is much smaller during the Spring/Summer due to much higher values of $ET_o$ during that period. Thus, all methods show a quite good performance during the irrigation season.

After the comparison of all the methods for a given station (Fig.4), Fig.5a presents the results obtained by the methods considered for the average of all stations and Fig.5b the results of the Jensen-Haise method for all stations.

Fig.5a shows the relative error (stations average) for all the methods analyzed, considering the whole set of data (annual), or only values from October to March (Autumn/Winter) or the values from April to September (Spring/Summer).

According to Fig.5a all methods after calibration present quite satisfactory results, including the Hargreaves-Samani. The best results for the irrigation period (Spring/Summer) are achieved by the Jensen-Haise, Hargreaves and Turc methods.

Table 4 – Average error $\bar{E}$, Absolute error $|\bar{E}|$ and relative error $\bar{E}_r$ of the calibrated methods, for the Annual data series (from 2005 to 2007).

| | Methods | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Hargreaves-S.** | | | **Hargreaves** | | | **Priestley-Taylor** | | | **Makkink** | | | **Turc** | | | **Jensen-Haise** | | |
| **Station** | $\bar{E}$ | $\lvert\bar{E}\rvert$ | $\bar{E}_r$* | $\bar{E}$ | $\lvert\bar{E}\rvert$ | $\bar{E}_r$* | $\bar{E}$ | $\lvert\bar{E}\rvert$ | $\bar{E}_r$* | $\bar{E}$ | $\lvert\bar{E}\rvert$ | $\bar{E}_r$* | $\bar{E}$ | $\lvert\bar{E}\rvert$ | $\bar{E}_r$* | $\bar{E}$ | $\lvert\bar{E}\rvert$ | $\bar{E}_r$* |
| Ferreira | -0.04 | 0.47 | 18.7 | -0.04 | 0.38 | 16.6 | -0.05 | 0.47 | 17.1 | -0.06 | 0.44 | 19.3 | -0.02 | 0.39 | 16.6 | 0.01 | 0.36 | 15.5 |
| Moura | 0.19 | 0.47 | 16.1 | 0.13 | 0.39 | 16.4 | 0.13 | 0.40 | 13.2 | 0.10 | 0.44 | 19.1 | 0.14 | 0.40 | 16.4 | 0.19 | 0.42 | 16.1 |
| Elvas | 0.03 | 0.55 | 18.1 | -0.01 | 0.38 | 14.0 | -0.01 | 0.50 | 17.6 | -0.04 | 0.44 | 16.9 | 0.01 | 0.40 | 14.8 | 0.06 | 0.41 | 14.9 |
| Redondo | 0.01 | 0.56 | 18.1 | 0.00 | 0.47 | 16.3 | 0.02 | 0.61 | 18.3 | -0.01 | 0.56 | 19.4 | 0.02 | 0.49 | 16.3 | 0.03 | 0.43 | 14.7 |
| Aljustrel | 0.11 | 0.52 | 16.5 | 0.08 | 0.44 | 15.8 | 0.12 | 0.55 | 16.0 | 0.06 | 0.52 | 18.6 | 0.09 | 0.47 | 16.0 | 0.12 | 0.41 | 14.2 |
| Alvalade | 0.12 | 0.44 | 16.3 | -0.08 | 0.48 | 17.6 | -0.04 | 0.53 | 16.9 | -0.11 | 0.56 | 20.1 | -0.06 | 0.50 | 17.3 | -0.01 | 0.41 | 15.7 |
| Beja | -0.16 | 0.47 | 14.8 | 0.29 | 0.43 | 14.9 | 0.13 | 0.52 | 15.3 | 0.30 | 0.51 | 17.6 | 0.29 | 0.46 | 16.0 | 0.25 | 0.39 | 12.7 |
| Évora | 0.03 | 0.49 | 16.3 | 0.00 | 0.36 | 14.8 | 0.00 | 0.42 | 14.0 | -0.03 | 0.41 | 17.3 | 0.02 | 0.37 | 14.8 | 0.06 | 0.39 | 14.8 |
| Odemira | 0.12 | 0.39 | 13.9 | 0.05 | 0.28 | 11.3 | 0.06 | 0.34 | 12.1 | 0.02 | 0.32 | 12.7 | 0.06 | 0.29 | 11.5 | 0.11 | 0.28 | 11.1 |
| **Average** | 0.05 | 0.48 | 16.5 | 0.05 | 0.40 | 15.3 | 0.04 | 0.48 | 15.6 | 0.03 | 0.47 | 17.9 | 0.06 | 0.42 | 15.5 | 0.09 | 0.39 | 14.4 |

* (values in fraction)

Table 5 – Average error $\bar{E}$, Absolute error $|\bar{E}|$ and relative error $\bar{E}_r$ of the calibrated methods, relative to the Spring-Summer period (from 2005 to 2007).

| | Methods | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hargreaves-S. | | | Hargreaves | | | Priestley-Taylor | | | Makkink | | | Turc | | | Jensen-Haise | | |
| **Station** | $\bar{E}$ | $\|\bar{E}\|$ | $\bar{E}_r$* | $\bar{E}$ | $\|\bar{E}\|$ | $\bar{E}_r$* | $\bar{E}$ | $\|\bar{E}\|$ | $\bar{E}_r$* | $\bar{E}$ | $\|\bar{E}\|$ | $\bar{E}_r$* | $\bar{E}$ | $\|\bar{E}\|$ | $\bar{E}_r$* | $\bar{E}$ | $\|\bar{E}\|$ | $\bar{E}_r$* |
| Ferreira | -0.05 | 0.54 | 0.12 | -0.02 | 0.38 | 0.08 | -0.08 | 0.58 | 0.12 | -0.04 | 0.45 | 0.10 | -0.04 | 0.39 | 0.08 | 0.06 | 0.37 | 0.07 |
| Moura | 0.30 | 0.62 | 0.13 | 0.24 | 0.42 | 0.09 | 0.17 | 0.51 | 0.10 | 0.20 | 0.48 | 0.10 | 0.21 | 0.43 | 0.09 | 0.35 | 0.49 | 0.10 |
| Elvas | 0.07 | 0.70 | 0.14 | 0.00 | 0.44 | 0.08 | -0.06 | 0.62 | 0.12 | -0.04 | 0.51 | 0.10 | -0.03 | 0.45 | 0.08 | 0.09 | 0.47 | 0.09 |
| Redondo | -0.03 | 0.66 | 0.13 | -0.03 | 0.53 | 0.10 | -0.05 | 0.77 | 0.15 | -0.02 | 0.63 | 0.12 | -0.03 | 0.55 | 0.10 | 0.05 | 0.48 | 0.09 |
| Aljustrel | 0.14 | 0.62 | 0.12 | 0.12 | 0.49 | 0.09 | 0.13 | 0.72 | 0.13 | 0.10 | 0.59 | 0.11 | 0.10 | 0.52 | 0.10 | 0.19 | 0.45 | 0.08 |
| Alvalade | 0.22 | 0.50 | 0.10 | -0.02 | 0.57 | 0.11 | -0.03 | 0.71 | 0.14 | -0.04 | 0.66 | 0.13 | -0.04 | 0.59 | 0.11 | 0.05 | 0.45 | 0.08 |
| Beja | -0.32 | 0.62 | 0.12 | 0.38 | 0.49 | 0.09 | 0.15 | 0.68 | 0.12 | 0.39 | 0.59 | 0.11 | 0.34 | 0.51 | 0.09 | 0.37 | 0.46 | 0.09 |
| Évora | 0.02 | 0.63 | 0.13 | 0.00 | 0.39 | 0.08 | -0.07 | 0.54 | 0.11 | -0.02 | 0.44 | 0.09 | -0.02 | 0.38 | 0.08 | 0.09 | 0.43 | 0.09 |
| Odemira | 0.19 | 0.48 | 0.12 | 0.02 | 0.27 | 0.07 | 0.01 | 0.37 | 0.09 | 0.00 | 0.34 | 0.08 | 0.02 | 0.28 | 0.07 | 0.12 | 0.27 | 0.07 |
| **Average** | 0.06 | 0.60 | 0.12 | 0.08 | 0.44 | 0.09 | 0.02 | 0.61 | 0.12 | 0.06 | 0.52 | 0.10 | 0.06 | 0.46 | 0.09 | 0.15 | 0.43 | 0.08 |

* (values in fraction)

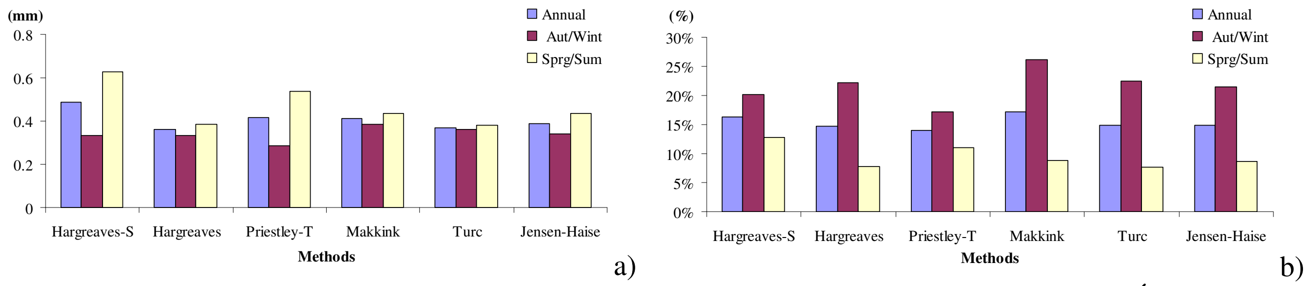


Fig.4 – a) Methods absolute error $|\bar{E}|$ and b) relative error $\bar{E}_r$ of the Jensen-Haise method for the Évora weather station, for the entire validation series (annual), for the October to March period and for the period from April to September (from 2005 to 2007).

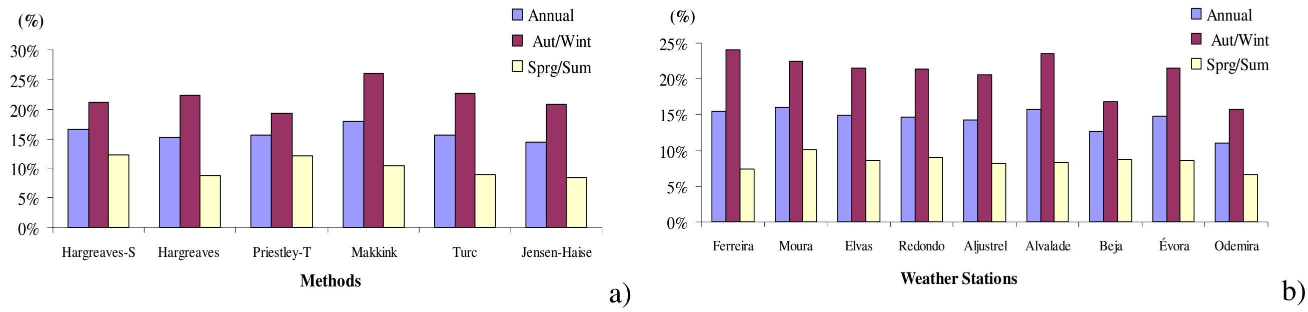


Fig.5 – a) Methods relative error $\bar{E}_r$ for the average of all stations and b) relative error $\bar{E}_r$ of the Jensen-Haise method for all weather stations, for the entire validation series (annual), for the October to March period and for the period from April to September (from 2005 to 2007).

Fig.5b shows the results obtained by the Jensen-Haise method for each station. From the observation of Fig.5b it is possible to notice the variability that exists in the distribution of the annual residuals from one station to another. Despite this variability, the relative error during the Spring/Summer semester is almost constant from one station to another, and can be observed that most of the variability occurs during the Autumn/Winter period.

It should be pointed out that the station in which were obtained the best results by the Jensen-Haise method is the Odemira station (Fig.5b), what is also true for the other methods (Table 5). This fact can be explain in part due to proximity of this station to the ocean.

## 4 Conclusion

The analysis performed using the 6 methods of $ET_o$ calculation, indicates that, in general, all methods, after calibration, show quite acceptable results.

Nevertheless the Jensen-Haise method was the one which presented the best overall performance, followed by the Hargreaves method. When using the five day moving averages it is possible to observe that the degree of correlation increases between these 6 methods and the PM method. Therefore, these values should be used to calibrate the models. It should be emphasized that the lower value for the coefficient of determination ($r^2$) achieved by any of the methods studied was 0.94 (Priestley-Taylor), which indicates the good quality of the values estimated by all methods, after calibration.
Calibration parameters for each method and for the 10 meteorological stations considered were obtained, providing a quite significant coverage of the Alentejo region. Therefore, these values can be used to calibrate the controllers to be installed in this region with a considerable degree of confidence.
Regarding the quality of the results produced, one can conclude that on average the Jensen-Haise method during the irrigation season (April to September) will present an error in the daily $ET_o$ estimation of approximately 0.43 mm, which corresponds to a relative error of 8.4%.
In the future a comparative study should be carried out to compare, at the economic and technical level, the results obtained by the solution Jensen-Haise method + radiation sensor, with the results of the Hargreaves-Samani method without a radiation sensor, since this last method presented values similar to the other methods and is the only one that doesn't need calibration. And since it is intended to incorporate a radiation sensor in this controller, the study should assess if the errors associated with this sensor do not exceed de Hargreaves-Samani error.

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