# Automatic modules to calibrate and validate models and estimate hourly and daily reference evapotranspiration series

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**Abstract:** The lack of accessible computational tools capable of processing large climate datasets and automating reference evapotranspiration ($ETo$) estimation, without the need for specific software installations or programming knowledge, hinders or limits more in-depth studies on water relations. This study aimed to develop automated modules for calibrating and validating model parameters, as well as estimating hourly and daily $ETo$ series using standard ($ASCE$) and alternative models. Using a spreadsheet and the visual basic for applications programming language, two modules were developed: "adjustments of the Moretti-Jerszurki-Silva ($MJS$) model for estimating hourly $ETo$" ($Module_{MJS-A}$); and "estimation of hourly and daily $ETo$ with standard ($ASCE$) and alternative models" ($Module_{ETo.h-d}$). Hourly and daily $ETo$ series were compared with the values estimated in the "®M.$ETo_{ASCE.e.MJS}$" module from the Moretti Platform and the "*FAO ETo Calculator*" program. Data from nine Brazilian meteorological stations representing diverse climate types were used for module validation. It was verified that: *i*) $Module_{MJS-A}$ and $Module_{ETo.h-d}$ efficiently processed large climatic datasets, enabling $ETo$ estimation on daily and hourly timescales using the $ASCE$ standard model and 14 alternative (adapted or reduced) models; *ii*) $Module_{ETo.h-d}$ stands out for its simplicity, versatility, and automation in estimating hourly and daily $ETo$, surpassing traditional programs in usability and model integration; and *iii*) Routine tests of the $ASCE$ and $MJS$ models in $Module_{ETo.h-d}$ versus ®M.$ETo_{ASCE.e.MJS}$, on both daily and hourly scales, demonstrated excellent statistical performance across all Brazilian climates, indicating high accuracy and reliability in $ETo$ estimation (daily scale: $RMSE \leq 0.08$ mm day$^{-1}$, $NSE \geq 0.97$, and $r \geq 0.99$; hourly scale: $RMSE \leq 0.04$ mm day$^{-1}$, $NSE \geq 0.97$, and $r \geq 0.99$). Comparisons between the $ASCE$ models in $Module_{ETo.h-d}$ and the "*FAO ETo Calculator*" on a daily scale showed $RMSE \leq 0.65$ mm day$^{-1}$, $NSE \geq 0.78$, and $r \geq 0.92$.

**Keywords:** Hydrological cycle, water relations, modeling, schedules, agrometeorology.

## 1 Introduction

Evapotranspiration ($ET$) occurs naturally to dissipate energy and maintain plant growth and development. It is a combined loss of water evaporated from the soil and natural water bodies, and transpired by the plant (Raza et al., 2023). $ET$ is also the main component of the hydrological cycle, and its accurate estimation is crucial in several related studies such as agricultural or hydrological water balance, agrometeorology, rainfall and runoff modeling, irrigation programming, water resources planning and

management, and ecosystem modeling (Raza et al., 2023; Mondal and Mishra, 2024).

*ET* is a complex and dynamic process that depends on several meteorological variables and the interactions between them, in addition to the interactions of the soil-plant system, in which soil water evaporation and plant transpiration occur (Bhattarai and Wagle, 2021). All these aspects, combined with the lack of physical and physiological understanding of the numerous factors related to the occurrence of *ET*, make its estimation difficult and prompt to errors (Doorenbos and Pruitt, 1975). To simplify and standardize the use of *ET*, the reference evapotranspiration (*ETo*) was introduced as the estimation of *ET* from a reference surface. Basically, it refers to the process of water loss to the atmosphere through evaporation from the soil and transpiration from a hypothetical reference crop, such as grass (with a height of 0.12 m) or alfalfa (with a height of 0.50 m), assuming perfect vegetative development and ideal water supply conditions (Allen et al., 1998). By standardizing internal factors and water supply, it is possible to verify the influence of external variables on *ETo*, in addition to its central tendency over a given period (Allen et al., 1998; ASCE-EWRI, 2005). The *ETo* can be directly determined with evapotranspirometers or lysimeters. However, these devices are expensive and require significant maintenance and qualified labor. For these reasons, the estimation of *ETo* using mathematical models has advanced in recent decades, having application in the most diverse areas involving the study of water relations (Allen et al., 1998; Dhungel et al., 2019).

The literature is rich in equations and alternative methods for estimating *ETo*. Santos (2024) presented a review of the main indirect methods currently used to estimate daily and hourly *ETo*. The most widely recommended and commonly adopted standard models in the literature are the FAO Penman-Monteith (Allen et al., 1998) and the ASCE Penman-Monteith (ASCE-EWRI, 2005). However, when the climatic input data required by the ASCE model (*RH*, *T*, $u_2$, and *Rn*) is not available, alternative (adapted or reduced) models that require fewer variables are used. The Penman-Monteith-Reduced (PMR), Turc, and Moretti-Jerszurki-Silva (MJS) models have stood out in some studies, mainly because they require fewer input variables and allow for hourly *ETo* estimation (Turc, 1961; Jerszurki et al., 2017; Paredes et al., 2020; Santos et al., 2021; Santos, 2024; Souza et al., 2025a; Souza et al., 2025b).

The Penman-Monteith-Reduced methodology (PMR; Paredes et al., 2020) requires the same inputs as the standard ASCE but with some simplifications. Turc (1961) model only considers the average temperature ($T_{ave}$) and the incident solar radiation (*Rs*). The MJS model (Jerszurki et al., 2017) allows the estimation of daily and hourly *ETo* solely based on the atmospheric water potential ($\Psi_{air}$). $\Psi_{air}$ requires only the use of relative humidity (*RH*) and air $T_{ave}$ as input. From all alternative models presented, only the MJS model had automated spreadsheets available for its calculation (module ®M .*ETo$_{ASCE.e.MJS}$*). Thus, the development and/or availability of systems containing other reduced models is required.

The use of mathematical models requires attention and care regarding the occurrence of errors in the estimates, especially when using models that require calibration and/or adjustments. Advances in remote sensing and machine learning techniques provide promising tools to improve the accuracy and spatial-temporal resolution of *ETo* estimation, complementing traditional modeling approaches (Bhattarai and Wagle, 2021; Silva et al., 2022 Souza et al., 2025a; Souza et al., 2025b). Therefore, the use of programs and automated modules that provide ease and speed, as well as more accurate *ETo* estimates, is crucial for making decisions related to hydrological processes and water resources exploration (FAO, 2009; McMahon et al., 2013; Guo et al., 2016; Jerszurki et al., 2017; Santos et al., 2021). The challenges encountered by Souza et al. (2025a) and Souza et al. (2025b), while conducting a spatiotemporal analysis of climate variables and *ETo* estimates using satellite imagery in southern Brazil, specifically in the Tibagi River Basin, highlight the importance and necessity of systems

capable of processing large data series and *ETo* estimates.

Programs for calculating *ETo* are available in the literature, such as the "*FAO ETo calculator*" (FAO, 2009), "*Fortran Morton WREVAP*" (McMahon et al., 2013), R package "*Evapotranspiration*" (Guo et al., 2016) and "®M.*ETo_{ASCE.e.MJS}* from the Moretti Platform" module. The last one can calculate annual series of daily and hourly *ETo* with the *ASCE* Penman-Monteith and Moretti-Jerszurki-Silva models (Jerszurki et al., 2017; Santos et al., 2021). However, not all available programs provide ease or enable *ETo* estimates on the hourly and daily scale. The most common are programs that estimate daily or monthly *ETo*. Furthermore, only a few free options are available, which makes their use difficult.

Despite the importance of accurate *ETo* estimation for water resource management and agricultural planning, existing methodologies (FAO, 2009; McMahon et al., 2013; Guo et al., 2016) often face limitations such as high data input requirements, expensive instrumentation, limited accessibility, or lack of automation, which restrict their practical application in various regions and operational contexts. Computational tools also require user-friendly interfaces and the flexibility to efficiently handle both daily and hourly time scales. Therefore, it is believed that there is still a lack of more effective automated modules for the calibration, validation, and estimation of hourly and daily *ETo* using both standard (ASCE) and currently recommended alternative (adapted or reduced) models such as MJS, PMR, and Turc, applied to the diverse climatic conditions of Brazil. Furthermore, it is believed that accurate *ETo* estimation could be achieved using accessible modules and routines developed in spreadsheet environments, without the need for specialized software or programming skills. Such modules could offer advantages in terms of usability, automation, and the processing of long data series when compared to existing programs (e.g., FAO ETo Calculator, R package "Evapotranspiration," and the ®M.*ETo_{ASCE.e.MJS}* module).

Given the context, to facilitate and improve *ETo* studies with the ASCE and alternative (adapted or simplified) models, this study aimed to develop automated modules for calibrating and validating model parameters, as well as estimating hourly and daily *ETo* series.

## 2 Materials and methods

### 2.1 Development of computational modules

This study was carried out at the Environmental Systems Modeling Laboratory in the Agricultural Sciences Sector of the Federal University of Paraná (LAMOSA/SCA/UFPR), located in Curitiba, Parana state, Brazil. Two computational modules were developed using an electronic spreadsheet to create the necessary schedules. The mathematical equation routines to calculate the hourly and daily *ETo* were carried out using the Visual Basic for Applications (VBA-Macro) programming language (Microsoft Corporation, 2025).

The VBA-Macro programming process involved the development of automated routines embedded within Microsoft Excel spreadsheets. Its modular structure enables users to select model types, input climatic data, and obtain hourly and daily *ETo* estimates without the need for manual coding (Microsoft Corporation, 2025). The main steps included: *i*) Creating user-friendly data input interfaces with error-checking protocols; *ii*) Integrating mathematical formulations of the selected *ETo* models (ASCE, MJS, PMR, Turc) into programmable functions; *iii*) Automating climate variable processing, including data interpolation and unit conversions; *iv*) Developing calibration routines for the *MJS* model's coefficients using historical data; and *v*) Generating comparative output dashboards with built-in charts and statistical summaries.

The *ETo* estimation models (ASCE, MJS, PMR, Turc) were selected according to the possibilities of estimates at daily or hourly intervals and the number of variables required. Eight mathematical models were selected to estimate hourly *ETo* and six for daily *ETo*. Some models were calculated as specified in the

literature, and others were adapted/reduced.

Nine meteorological stations from the National Institute of Meteorology (INMET; Figure 1) were chosen. The meteorological stations were selected based on the availability, consistency, and integrity of the hourly climatic datasets required for *ETo* estimation. The stations are located in Brazil's main climatic zones, according to Köppen's classification, encompassing equatorial (*Af, Am*), tropical savanna (*As, Aw*), semi-arid (*BSh*), and various temperate climates (*Cfa, Cfb, Cwa, Cwb*). The geographic and climatic diversity was intended to ensure that the developed modules were tested under a wide range of temperature, radiation, and humidity conditions, reflecting the variability found in Brazil's agroclimatic zones.

Relative humidity averages ($RH_{ave.p}$; %), incident solar radiation ($Rs_{ave.p}$; MJ m$^{-2}$), solar radiation balance ($Rn_{ave.p}$; MJ m$^{-2}$), wind speed at two meters height ($u_{2ave.p}$; m s$^{-1}$), actual vapor pressure ($ea_{ave.p}$; MPa) and saturation vapor pressure ($es_{ave.p}$; MPa), for the period between January 01, 2017, and December 31, 2019, were previously calculated. The daily and hourly *ETo* were estimated between January 01 and December 31, 2020.



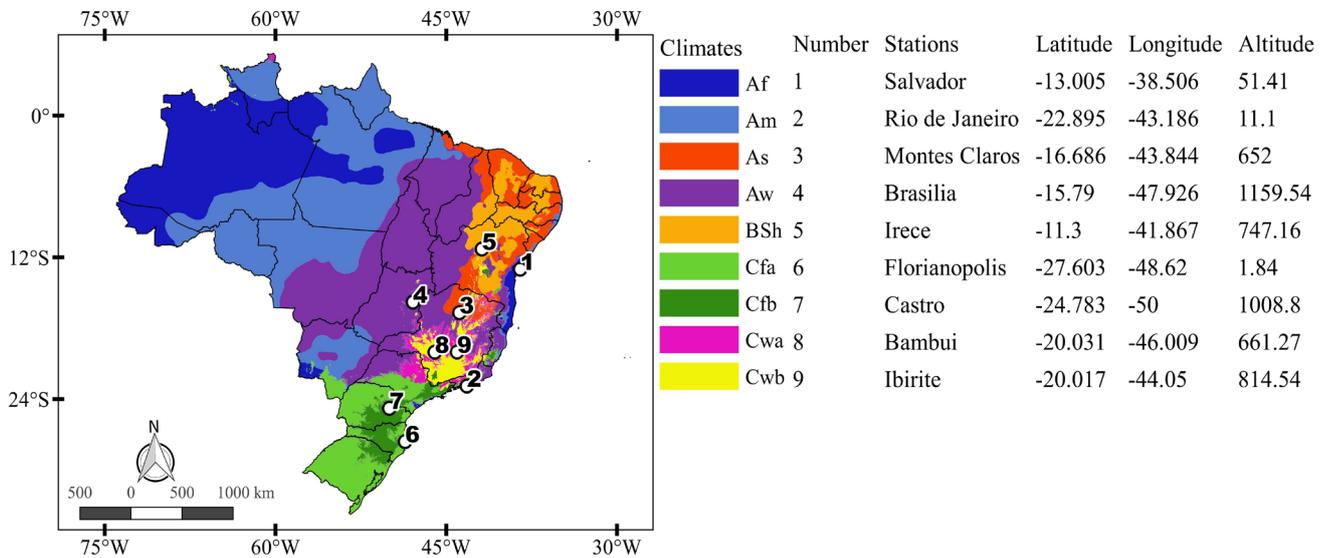| Climates | | Number | Stations | Latitude | Longitude | Altitude |
|---|---|---|---|---|---|---|
| Af | 1 | | Salvador | -13.005 | -38.506 | 51.41 |
| Am | 2 | | Rio de Janeiro | -22.895 | -43.186 | 11.1 |
| As | 3 | | Montes Claros | -16.686 | -43.844 | 652 |
| Aw | 4 | | Brasilia | -15.79 | -47.926 | 1159.54 |
| BSh | 5 | | Irece | -11.3 | -41.867 | 747.16 |
| Cfa | 6 | | Florianopolis | -27.603 | -48.62 | 1.84 |
| Cfb | 7 | | Castro | -24.783 | -50 | 1008.8 |
| Cwa | 8 | | Bambui | -20.031 | -46.009 | 661.27 |
| Cwb | 9 | | Ibirite | -20.017 | -44.05 | 814.54 |

Figure 1 Spatial distribution of the nine automatic weather stations of the National Institute of Meteorology (INMET), for the nine Brazilian climate types

## 2.2 Reference evapotranspiration (*ETo*) estimation methods

### 2.2.1 Standard *ASCE* model for hourly and daily *ETo* estimation

The hourly and daily *ETo* was estimated using the Penman-Monteith equation (Equation 1), presented by the American Society of Civil Engineers (ASCE-EWRI, 2005), using a short-crop height of 0.12 m:

$$ETo_{ASCE} = \frac{0.408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot \frac{Cn}{(T+273)} u_2 \cdot (es - ea)}{\Delta + \gamma \cdot (1 + Cd \cdot u_2)} \quad (1)$$

Where,

$ETo_{ASCE}$ – reference evapotranspiration (mm h$^{-1}$ or mm day$^{-1}$);

$\Delta$– slope of the saturated water vapor pressure curve to the air temperature (kPa $^{o}$C$^{-1}$);

$Rn$ – net radiation balance (MJ m$^{-2}$ h$^{-1}$ or MJ m$^{-2}$ day$^{-1}$);

$G$ – soil heat flux (MJ m$^{-2}$ h$^{-1}$ or MJ m$^{-2}$ day$^{-1}$);

$\gamma$ – psychrometric constant (kPa $^{o}$C$^{-1}$);

$T$ – average air temperature ($^{o}$C);

$u_2$ – wind speed at 2 m height (m s$^{-1}$ h$^{-1}$ or m s$^{-1}$ day$^{-1}$);

$es$ – saturation vapor pressure (kPa h$^{-1}$ or kPa day$^{-1}$);

$ea$ – actual vapor pressure (kPa h$^{-1}$ or kPa day$^{-1}$);

$Cn$ and $Cd$ – constant related to the type of vegetation and time scale, respectively (for short-crop plants, such as grass: $Cn_{hourly}$ = 37 K mm s$^3$ Mg$^{-1}$ h$^{-1}$ for hourly scale and $Cn_{daily}$ = 900 K mm s$^3$ Mg$^{-1}$ day$^{-1}$ for daily scale;

$Cd_{daytime}$ = 0.24 s m$^{-1}$ for hourly daytime；

$d_{nighttime}$ = 0.96 s m$^{-1}$ for hourly nighttime and $Cd_{daily}$ = 0.34 s m$^{-1}$ for daily scale).

### 2.2.2 Penman-Monteith-Reduced model

The *ETo* estimation with the PMR model, at hourly ($ETo_{PMR.h}$) and daily ($ETo_{PMR.d}$) scale, was carried out based on the Penman-Monteith equation (Equation 2), presented by the American Society of Civil Engineers (ASCE-EWRI, 2005), using a short-crop height of 0.12 m. In the calculations, only the variation of air temperature was considered. The other input climate variables were considered equal to the average (for hour or day):

$$ETo_{PMR} = \frac{0.408 \cdot \Delta \cdot (Rn_{ave.p} - G) + \gamma \cdot \frac{Cn}{(T_{ave} + 273)} \cdot u_{2\,ave.p} \cdot (es_{ave.p} - ea_{ave.p})}{\Delta + \gamma \cdot \left(1 + Cd \cdot u_{2\,ave.p}\right)}$$

(2)

Where,

$ETo_{PMR.h}$ and $ETo_{PMR.d}$ – hourly and daily reference evapotranspiration, respectively (mm h$^{-1}$ or mm day$^{-1}$);

$\Delta$ – slope of the saturated water vapor pressure curve to the air temperature (kPa $^o$C$^{-1}$);

$Rn_{ave.p}$ – average radiation balance of the period for each hour or day (MJ m$^{-2}$ h$^{-1}$ or MJ m$^{-2}$ day$^{-1}$);

$G$ – soil heat flux (MJ m$^{-2}$ h$^{-1}$ or MJ m$^{-2}$ day$^{-1}$);

$\gamma$ – psychrometric constant (kPa $^o$C$^{-1}$);

$T_{ave}$ – average air temperature for the day or hour under analysis ($^o$C);

$u_{2ave.p}$ – average wind speed at two meters high for the period, for each hour or day (m s$^{-1}$ h$^{-1}$ or m s$^{-1}$ day$^{-1}$);

$ea_{ave.p}$ and $es_{ave.p}$ – average actual and saturation vapor pressure for the period, respectively, for each hour or day (MPa h$^{-1}$ or MPa day$^{-1}$; ASCE-EWRI, 2005);

$Cn$ and $Cd$ – constant related to the type of vegetation and time scale, respectively (for short-crop plants, such as grass: $Cn_{hourly}$ = 37 K mm s$^3$ Mg$^{-1}$ h$^{-1}$ for hourly scale and $Cn_{daily}$ = 900 K mm s$^3$ Mg$^{-1}$ day$^{-1}$ for daily scale;

$Cd_{daytime}$ = 0.24 s m$^{-1}$ for hourly daytime, $Cd_{nighttime}$ = 0.96 s m$^{-1}$ for hourly nighttime and $Cd_{daily}$ = 0.34 s

m$^{-1}$ for daily scale).

The Module provides the averages of the climate variables required in the reduced models, for each Brazilian climate type, per hour and/or per day.

### 2.2.3 Moretti-Jerszurki-Silva (MJS) model

By its simplicity, the linear Moretti-Jerszurki-Silva (MJS) model was chosen to be used at hourly ($ETo_{MJS(\Psi air)L.h}$) and daily ($ETo_{MJS(\Psi air)L.d}$) scale. It is based on the sole used of the atmospheric water potential ($\Psi_{air}$), which allows for accounting the nighttime *ETo* (Jerszurki et al., 2017; Santos et al., 2021).

For hourly scale, the delay (Santos et al., 2021) verified between the *ASCE* and *MJS* model was also considered, in which the "*a*" in the "$ETo_{MJS(\Psi air)La.h}$" symbol means "adjustment". Equations 6 and 10 were used to estimate *ETo* with the *MJS* model varying only the temperature at hourly ($ETo_{MJS(\Psi air)La.ht}$) and daily ($ETo_{MJS(\Psi air)L.dt}$) scale. The *ea* and *es* values were considered equal to the hourly or daily average of the local climate type (*Af, Am, As, Aw, BSh, Cfa, Cfb, Cwa,* and *Cwb*).

The *ETo* estimates at a daily scale ($ETo_{MJS(\Psi air)L.d}$ and $ETo_{MJS(\Psi air)L.dt}$) and the values of atmospheric water potential were obtained by the following equations:

$$ETo_{MJS(\Psi_{air})L.d} = a + b \cdot \Psi_{air.d} \tag{3}$$

$$ETo_{MJS(\Psi_{air})L.dt} = a + b \cdot \Psi_{air.dt} \tag{4}$$

$$\Psi_{air.d} = \frac{R \cdot T_{ave}}{M_v} \cdot ln\left(\frac{ea}{es}\right) \tag{5}$$

$$\Psi_{ar.dt} = \frac{R \cdot T_{ave}}{M_v} \cdot ln\left(\frac{ea_{ave.p}}{es_{ave.p}}\right) \tag{6}$$

Where,

$ETo_{MJS(\Psi air)L.d}$ – reference evapotranspiration estimated with the linear *MJS* model at daily scale (mm day$^{-1}$);

$ETo_{MJS(\Psi air)L.dt}$ – reference evapotranspiration estimated with the linear *MJS* model at daily scale, varying only the air temperature (mm day$^{-1}$);

"*a*" and "*b*" – linear and angular coefficients, respectively, obtained in the associations between "$\Psi_{air}$ vs $ETo_{ASCE}$" in the calibration at a daily scale ("*a*" in mm day$^{-1}$ and "*b*" in mm day$^{-1}$ MPa$^{-1}$);

$\Psi_{air.d}$ – daily atmospheric water potential (MPa);

$\Psi_{air.dt}$ – daily atmospheric water potential, varying only as a function of temperature (MPa);

$R$ – gas constant (8.314 J mol$^{-1}$ K$^{-1}$);

$T_{ave}$ – average daily air temperature (K);

$M_v$ – partial molar volume of water (18 . 10$^{-6}$ m$^3$ mol$^{-1}$);

$ea$ and $es$ – actual and saturation daily vapor pressure, respectively (MPa; ASCE-EWRI, 2005);

$ea_{ave.p}$ and $es_{ave.p}$ – daily average of actual and saturation vapor pressure, respectively, according to Brazilian climate type and season of the year (MPa day$^{-1}$; ASCE-EWRI, 2005).

The $ETo$ estimates at the hourly scale, without considering the delay adjustment ($ETo_{MJS(\Psi_{air})L.h}$ and $ETo_{MJS(\Psi_{air})L.ht}$), and the hourly values of the atmospheric water potential were obtained with the equations:

$$ETo_{MJS(\Psi_{air})L.h} = a + b \cdot \Psi_{air.h} \tag{7}$$

$$ETo_{MJS(\Psi_{air})L.ht} = a + b \cdot \Psi_{air.ht} \tag{8}$$

$$\Psi_{air.h} = \frac{R \cdot T_{ave}}{M_v} \cdot ln\left(\frac{ea}{es}\right) \tag{9}$$

$$\Psi_{air.ht} = \frac{R \cdot T_{ave}}{M_v} \cdot ln\left(\frac{ea_{ave.p}}{es_{ave.p}}\right) \tag{10}$$

Where,

$ETo_{MJS(\Psi_{air})L.h}$ – reference evapotranspiration estimated with the linear $MJS$ model at an hourly scale (mm day$^{-1}$);

$ETo_{MJS(\Psi_{air})L.ht}$ – reference evapotranspiration estimated with the linear $MJS$ model at an hourly scale, varying only the air temperature (mm day$^{-1}$);

$"a"$ and $"b"$ – linear and angular coefficients, respectively, obtained in the associations between $"\Psi_{air}\ vs\ ETo_{ASCE}"$ in the calibration at an hourly scale ($"a"$ in mm h$^{-1}$ and $"b"$ in mm h$^{-1}$ MPa$^{-1}$);

$\Psi_{air.h}$ – hourly atmospheric water potential (MPa); $\Psi_{air.ht}$ – hourly atmospheric water potential, varying only as a function of temperature (MPa);

$R$ – gas constant (8.314 J mol$^{-1}$ K$^{-1}$);

$T_{ave}$ – average hourly air temperature (K);

$M_v$ – partial molar volume of water (18 . 10$^{-6}$ m$^3$ mol$^{-1}$);

$ea$ and $es$ – actual and saturation hourly vapor pressure, respectively (MPa; ASCE-EWRI, 2005);

$ea_{ave.p}$ and $es_{ave.p}$ – hourly average of actual and saturation vapor pressure, respectively, according to Brazilian climate type and season of the year (MPa h$^{-1}$; ASCE-EWRI, 2005).

The $ETo$ estimates at the hourly scale, considering the delay adjustment ($ETo_{MJS(\Psi_{air})La.h}$ and $ETo_{MJS(\Psi_{air})La.ht}$) and the hourly values of the atmospheric water potential were obtained with the equations:

$$ETo_{MJS(\Psi_{air})La.h} = a + b \cdot \Psi_{ar(h \pm d)} \tag{11}$$

$$ETo_{MJS(\Psi_{air})La.ht} = a + b \cdot \Psi_{art.(h \pm d)} \tag{12}$$

$$\Psi_{air.(h \pm d)} = \frac{R \cdot T_{(h\pm d)}}{M_v} \cdot ln\left(\frac{ea_{(h\pm d)}}{es_{(h\pm d)}}\right) \tag{13}$$

$$\Psi_{air.(h \pm d)t} = \frac{R \cdot T_{(h\pm d)}}{M_v} \cdot ln\left(\frac{ea_{ave.p(h\pm d)}}{es_{ave.p(h\pm d)}}\right) \tag{14}$$

Where,

$ETo_{MJS(\Psi_{air})La.d}$ – reference evapotranspiration estimated with the linear $MJS$ model, at the hourly scale, considering the delay adjustment (mm h$^{-1}$);

$ETo_{MJS(\Psi_{air})La.dt}$ – reference evapotranspiration estimated with the linear $MJS$ model, on an hourly scale, considering the delay adjustment and having only the air temperature as a variable (mm h$^{-1}$);

$"a"$ and $"b"$ – Linear and angular coefficients, respectively, obtained in the associations between $"\Psi_{air}\ vs\ ETo_{ASCE}"$ in the calibration at an hourly scale ($"a"$ in mm h$^{-1}$ and $"b"$ in mm h$^{-1}$ MPa$^{-1}$);

$\Psi_{air.(h\pm d)}$ – hourly atmospheric water potential considering the delay adjustment $"d"$ (MPa);

$\Psi_{air.(h\pm d)t}$ – hourly atmospheric water potential, considering the delay adjustment $"d"$ and having only the air temperature as a variable (MPa);

$R$ – gas constant (8.314 J mol$^{-1}$ K$^{-1}$);

$T_{(h\pm d)}$ – hourly average air temperature, considering the delay $"d"$ (K);

$M_v$ – partial molar volume of water (18 . 10$^{-6}$ m$^3$ mol$^{-1}$);

$ea$ and $es$ – actual and saturation hourly vapor pressure, respectively (MPa; ASCE-EWRI, 2005);

$ea_{ave.p}$ and $es_{ave.p}$ – hourly average of actual and saturation vapor pressure, respectively, according to

Brazilian climate type and season of the year (MPa h$^{-1}$; ASCE-EWRI, 2005).

The delay "$d$", observed between the *ETo* estimated with the *MJS* and *ASCE* models, was identified and automated in the developed Module. For this purpose, the geographical arrangement of the selected weather stations was considered, associated with each climate type. The hourly and daily coefficient values were added to the developed Module, also providing automation of their uses. The linear "$a$" and angular "$b$" coefficients of the *MJS* model (Jerszurki et al., 2017), at the hourly intervals, were established according to previous calibration and automation (Table 1). The entire methodological procedure for calibration and validation of the *MJS* "$a$" and "$b$" coefficients was automatically computerized in one of the Modules developed to allow their determination for any location. For the daily scale, the coefficients provided by Jerszurki et al. (2017) were used for the Brazilian climate types.

The calibration and validation of the *MJS* model coefficients ("$a$" and "$b$") were carried out using independent datasets. The climate data from the years 2017 to 2019 were used for calibration, while the year 2020 was reserved exclusively for model validation. The separation ensured an unbiased performance evaluation. Calibration involved regression analysis between *ETo* estimated by the standard *ASCE* model and $\Psi_{air}$ to obtain the best-fit coefficients for each climate type. Validation consisted of applying the calibrated coefficients to the 2020 data and comparing *ETo* estimates with the *ASCE* reference values using statistical indicators such as *RMSE*, *NSE*, and Pearson's *r*.

2.2.4  Turc model

The Turc (1961) model modified by Fisher and Pringle (2013) estimates the *ETo* at the daily scale. Thus, the model needs as input the average daily air temperature ($T_{ave}$), obtained by averaging the maximum and minimum temperatures of the day, and the daily incident solar radiation ($Rs$):

$$ETo_{T.d} = 0.013 \cdot \left(\frac{T_{ave}}{T_{ave}+15}\right) \cdot (23.88 \cdot Rs + 50) \qquad (15)$$

$$ETo_{Ta.h} = 0.00055 \times \left(\frac{T_{ave}}{T_{ave}+15}\right) \times (573.12 \cdot Rs + 50) \qquad (16)$$

Where,

$ETo_{T.d}$ and $ETo_{Ta.h}$ – daily and hourly reference evapotranspiration estimated with the Turc model, respectively (mm day$^{-1}$ or mm h$^{-1}$);

$T_{ave}$ – average temperature, considering maximum and minimum values of the day or hour (°C);

$Rs$ – daily or hourly incident solar radiation (MJ m$^{-2}$ day$^{-1}$ or MJ m$^{-2}$ h$^{-1}$).

In the calculation of ETo using the Turc (1961) method, the daily or hourly average incident solar radiation of the period ($Rs_{ave.p}$) was considered. Thus, the only input was the average air temperature ($T_{ave}$; calculated as the mean of the maximum and minimum air temperatures, at the hourly or daily scale).

$$ETo_{T.dt} = 0.013 \cdot \left(\frac{T_{ave}}{T_{ave}+15}\right) \cdot (23.88 \cdot Rs_{ave.p} + 50) \qquad (17)$$

$$ETo_{T.aht} = 0.00055 \cdot \left(\frac{T_{ave}}{T_{ave}+15}\right) \cdot (573.12 \cdot Rs_{ave.p} + 50) \qquad (18)$$

Where,

$ETo_{T.dt}$ and $ETo_{T.aht}$ – daily and hourly reference evapotranspiration, respectively, with only the average air temperature as a variable (mm day$^{-1}$ or mm h$^{-1}$);

$T_{ave}$ – average air temperature, obtained with the maximum and minimum air temperatures average, at the daily or hourly scale (°C);

$Rs_{ave.p}$ – average incident solar radiation for the period, obtained according to the Brazilian climate type and season of the year, at the daily or hourly scale (MJ m$^{-2}$ day$^{-1}$ or MJ m$^{-2}$ h$^{-1}$).

2.3 Verification of the developed module and statistical analysis

After the inclusion of the *ASCE* and alternative (adapted/reduced) models (hourly and daily) in the proposed Module, tests were carried out to verify: *i*) differences between the *ETo* estimates obtained with the Module developed concerning the "®M.*ETo*$_{ASCE.e.MJS}$ from the Moretti Platform" module and the "*FAO ETo Calculator*" program; and, *ii*) positive and negative aspects in the operations using the developed Module.

The identification of the advantages and disadvantages of the developed Module were based on

its simplicity and difficulties that were observed when using the "$^{®}\text{M}.ETo_{ASCE.e.MJS}$" module and the "*FAO ETo Calculator*" program. Focus was given to the calculation options, *ETo* periodicities, needed input data, ease of use, and possibility of exporting results. Comparisons were also made regarding the required variable units, conversions, and maximum and minimum boundaries.

In the same way as the Module developed in the present study, the "$^{®}\text{M}.ETo_{ASCE.e.MJS}$" module was also developed in a spreadsheet, using routines made with the VBA-Macro language. The $^{®}\text{M}.ETo_{ASCE.e.MJS}$ has already been used and tested in several studies (Jerszurki et al., 2017; Santos et al., 2021; Rosa, 2023). The "*ETo Calculator*" program, being from FAO, makes it possible to validate new models and/or *ETo* estimation systems (Guo et al., 2016). In the analyses, the respective daily and/or hourly *ETo* values obtained with the Module developed were associated and compared in linear regression analyses with the *ETo* estimated in the $^{®}\text{M}.ETo_{ASCE.e.MJS}$ module ($ETo_{ASCE.e.MJS}$; Jerszurki et al., 2017) and with the *FAO ETo Calculator* program, version 3.2 ($ETo_{FAOcalculator}$; FAO, 2009).

Performance assessment in the associations was carried out using the statistical indicators set out in Equations 19 to 21 (Tegos et al., 2017). The calculations were performed with the "*hydroGOF*"

package, version 0.04 (Zambrano-Bigiarini, 2020), and its "*GOFF*" function in the R software (RStudio Team, 2023; version 4.2.3).

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n}(ETo_{E_i} - ETo_{DM_i})^2} \qquad (19)$$

$$r = \frac{\sum_{i=1}^{n}\left[\left(ETo_{E_i} - \overline{ETo}_E\right) \cdot \left(ETo_{DM_i} - \overline{ETo}_{DM}\right)\right]}{\sqrt{\sum_{i=1}^{n}\left(ETo_{E_i} - \overline{ETo}_E\right)^2 \cdot \sum_{i=1}^{n}\left(ETo_{E_i} - \overline{ETo}_{DM}\right)^2}}$$
(20)

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(ETo_{E_i} - ETo_{DM_i}\right)^2}{\sum_{i=1}^{n}\left(ETo_{E_i} - \overline{ETo}_E\right)^2} \qquad (21)$$

Where,

*RMSE* – Root mean square error (mm day$^{-1}$ or h$^{-1}$);

*r* – Pearson correlation coefficient (unitless); *NSE* – Nash-Sutcliffe efficiency (unitless);

*n* – number of days or hours analyzed (unitless);

$ETo_{E_i}$ – reference evapotranspiration estimated with the "$^{®}\text{M}.ETo_{ASCE.e.MJS}$" or "*FAO ETo Calculator*" at each *i*-th day or hour analyzed (mm day$^{-1}$ or h$^{-1}$);

$ETo_{DM_i}$ – reference evapotranspiration estimated with the developed Module at each *i*-th day or hour analyzed (mm day$^{-1}$ or h$^{-1}$);

$\overline{ETo}_E$ – average reference evapotranspiration estimated with the "$^{®}\text{M}.ETo_{ASCE.e.MJS}$" or "*FAO ETo Calculator*" (mm day$^{-1}$ or h$^{-1}$);

$\overline{ETo}_{DM}$ – average reference evapotranspiration estimated with the developed Module (mm day$^{-1}$ or h$^{-1}$).

**Table 1 Hourly and daily parameters of the Moretti-Jerszurki-Silva (*MJS*) model and hourly delay observed according to the main Brazilian climate types**

| Climates | ------- Hourly parameters ------- | | Hourly Delay | ------- Daily parameters ------- | |
| | "*a*" | "*b*" | | "*a*" | "*b*" |
|---|---|---|---|---|---|
| *Af* | –5.32E-02 | –7.03E-08 | one hour | 2.35E+00 | –4.90E-02 |
| *Am* | –3.04E-03 | –4.45E-08 | one hour | 1.79E+00 | –7.63E-02 |
| *As* | –5.92E-02 | –6.67E-08 | two hours | 1.40E+00 | 7.91E-02 |
| *Aw* | 2.65E-02 | –3.14E-08 | two hours | 1.66E+00 | –8.61E-02 |
| *BSh* | 1.23E-02 | –3.25E-08 | two hours | 2.34E+00 | –3.81E-02 |
| *Cfa* | –1.33E-02 | –5.87E-08 | two hours | 7.88E-01 | –6.70E-02 |
| *Cfb* | 2.36E-02 | –4.82E-08 | two hours | 1.58E+00 | –3.86E-02 |
| *Cwa* | 1.66E-02 | –3.74E-08 | two hours | 2.69E+00 | –1.92E-02 |
| *Cwb* | 1.21E-02 | –4.06E-08 | two hours | 2.56E+00 | –1.71E-02 |

# 3 Results and discussion

## 3.1 Developed computational modules

In the developed computational module named "*Adjustments of the Moretti-Jerszurki-Silva (MJS) model for estimating hourly ETo*" ($Module_{MJS-A}$), the user can perform calibration, validation, and analysis of the hourly delay of *ETo* estimated with the *MJS* model concerning *ASCE*.

In the structure of the $Module_{MJS-A}$ (Figure 2), more details about the command buttons are presented: "Pre-calibration"; "Cleanliness and Calibration"; "Pre-validation"; "Cleaning and Validation"; "*MJS* Delay"; "Attachments"; and, information about general and climatic data, and necessary options, as input into the hourly and daily *ETo* (ASCE and MJS) estimation models.

The form accessed with the command buttons "Pre-calibration", "Cleanliness and Calibration", "Pre-validation", "Cleaning and Validation" and "MJS Delay" enables the creation of graphs of the *ETo* hourly central tendency and respective climate variables used, to improve the preliminary view and interpretation of the obtained results.

The "Pre-calibration" form is used to check outliers and includes input data to calculate $ETo_{ASCE}$ and $\Psi_{air}$, which are used to determine the linear and quadratic coefficients of the *MJS* model. The "Cleanliness and calibration" form is used to check and exclude outliers, making it possible to subsequently calibrate the coefficients of the linear ("*a*" and "*b*") *MJS* models. The coefficient adjustment is based on associations between "$ETo_{ASCE}$ and $\Psi_{air}$", and can be performed for the annual period or by seasons. The form allows the automatic import of data entered into the "Pre-calibration" spreadsheet, resulting in graphical analysis and exclusion of inconsistent data (Figure 2).

The "Pre-validation" form makes it possible to obtain the hourly $ETo_{ASCE}$ and $ETo_{MJS}$, considering the validation period and using the linear coefficients obtained with the *MJS* in the calibration.

According to Arsenault et al. (2018), to ensure the effective transfer of the calibrated parameters and the robustness of the analyzed model, the calibration and validation processes are normally carried out with different data ranges. The practice of using two periods is named as "Split-Sample Approach." Therefore, to carry out the "Pre-validation" it is necessary to include a new series of climate data in the analyzed location (Figure 2).

The "Cleanliness and validation" form identify outliers and exclude them from the series. Subsequently, linear regression analysis is automatically performed between the respective $ETo_{ASCE}$ and $ETo_{MJS}$ values. The data used is automatically imported from "Pre-validation" (Figure 2).

The "MJS Delay" form routines analyze the existence of a delay between the respective hourly *ETo* estimated with the *ASCE* and *MJS* model. Adjustments are made automatically for "zero", "one" and "two" hour delays for the *MJS*. The adjusted delay values are presented numerically in the forms (per hour) as well as the central tendency curves of the calculated hourly *ETo* for visualization and graphical analysis (Figure 2).

The "Attachments" form describes the models used in the Module to estimate *ETo* (Figure 2).

In the main form (Start) of the computational module "Estimation of hourly and daily *ETo* with standard (ASCE) and alternative models" ($Module_{ETo.h-d}$; Figure 3), the user can estimate the "Hourly *ETo*" and "Daily *ETo*" and check "Attachments" in the form activating the respective command buttons.

In the $Module_{ETo.h-d}$, the user can select the model to estimate the *ETo* series (Models: standard ASCE; and Reduced, with only hourly or daily temperature as a variable). The selection box contains eight hourly *ETo* estimation options (Figure 3; $ETo_{ASCE.h}$, $ETo_{PMR.h}$, $ETo_{MJS(\Psi air)L.aht}$, $ETo_{MJS(\Psi air)L.ah}$, $ETo_{MJS(\Psi air)L.ht}$; $ETo_{MJS(\Psi air)L.h}$, $ETo_{T.aht}$, and $ETo_{T.ah}$). The same models were used for the daily estimates. Therefore, after the necessary adaptations, six daily *ETo* estimation

options are available in the selection box (Figure 3; $ETo_{ASCE.d}$, $ETo_{PMR.d}$, $ETo_{MJS(\Psi air)La.dt}$, $ETo_{MJS(\Psi air)La.d}$, $ETo_{T.dt}$ and $ETo_{T.d}$). By choosing the $ETo$ estimation model options, the cells are automatically marked with the necessary input data. Depending on the available climate database, the user will be able to check which models will be used.

To improve the visualization and interpretation of the results, the "Hourly $ETo$" and "Daily $ETo$" forms also enable the generation of hourly and daily $ETo$ averages graphs, respectively, according to the selected model.

The delay adjustments, depending on the climate, are set out in the "Attachments" of the $Module_{ETo.h-d}$. The hourly or daily "$a$" and "$b$" coefficients of the MJS model are automatically available, according to the "Attachments" form in the $Module_{ETo.h-d}$ database and the climate chosen in the options box. In case of questions regarding the internal calculations, which are carried out with routines developed in the VBA-Macro programming language (Microsoft Corporation, 2025), the user simply needs to check the functions that are described in the "Attachments" form (Figure 3). All equation routines used were written in VBA-Macro programming language as functions, allowing estimates of $ETo$ with the $ASCE$, $MJS$, $PMR$ or Turc models, in hourly and daily basis. There is no need to manually include the equation in the spreadsheet, as each model has its respective function in the $Module_{ETo.h-d}$.

Accurate estimation of $ETo$ is essential for efficient irrigation management and the sustainable use of water resources in agriculture. However, this estimation is subject to multiple sources of uncertainty, particularly when there is a lack of, or poor-quality, meteorological data such as temperature, solar radiation, relative humidity, and wind speed. Furthermore, the application of empirical methods without appropriate regional calibration can introduce significant systematic errors, compromising the reliability of the results. The spatial and temporal variability of Brazilian climates, combined with sensor deficiencies

and gaps in historical data series, underscores the need for tools capable of minimizing such uncertainties. In this context, the computational modules developed in the present study ($Module_{MJS-A}$ and $Module_{ETo.h-d}$) represent a significant methodological advancement by automating the calibration and validation of models for estimating $ETo$ at both hourly and daily scales. These modules offer enhanced control over uncertainty sources by enabling specific adjustments based on the availability and quality of local meteorological data. Moreover, they support comparative analyses between standard and simplified models, facilitating the selection of the most suitable methodology for different climatic contexts, and thereby promoting greater robustness in $ETo$ estimates and reliability in irrigation recommendations.

The integration of the modules into a spreadsheet environment and the automated execution of calibration and validation routines provide practical support for water management, optimizing resource use and reducing the risk of irrigation management errors. The developed modules use meteorological data from multiple stations and allow for the spatialization of $ETo$ estimates across different agricultural areas in a more accessible and practical manner. This functionality is essential for efficient irrigation management in extensive regions, as $ETo$ is fundamental for estimating crop evapotranspiration ($ETc$) and for determining when and how much to irrigate (Allen et al., 1998). Therefore, the use of these modules facilitates strategic decision-making that promotes sustainability and water resource savings in agriculture.

### 3.2  Comparison of $Module_{ETo.h-d}$ with other programs that estimate $ETo$

Numerous models that estimate $ETo$ are not automated, as is the case of $PMR$, Turc, and $MJS$ models (Turc, 1961; Jerszurki et al., 2017; Paredes et al., 2020). The Turc model allows the user to estimate the hourly and daily $ETo$, but the hourly periodicity has not been explored yet. The $ETo_{h-d}$ Module enables the calculation of models commonly used in the literature

to estimate *ETo* with a simple interface. As it is included in an electronic spreadsheet, the user does not need to worry about installing or modifying files to import or export data.
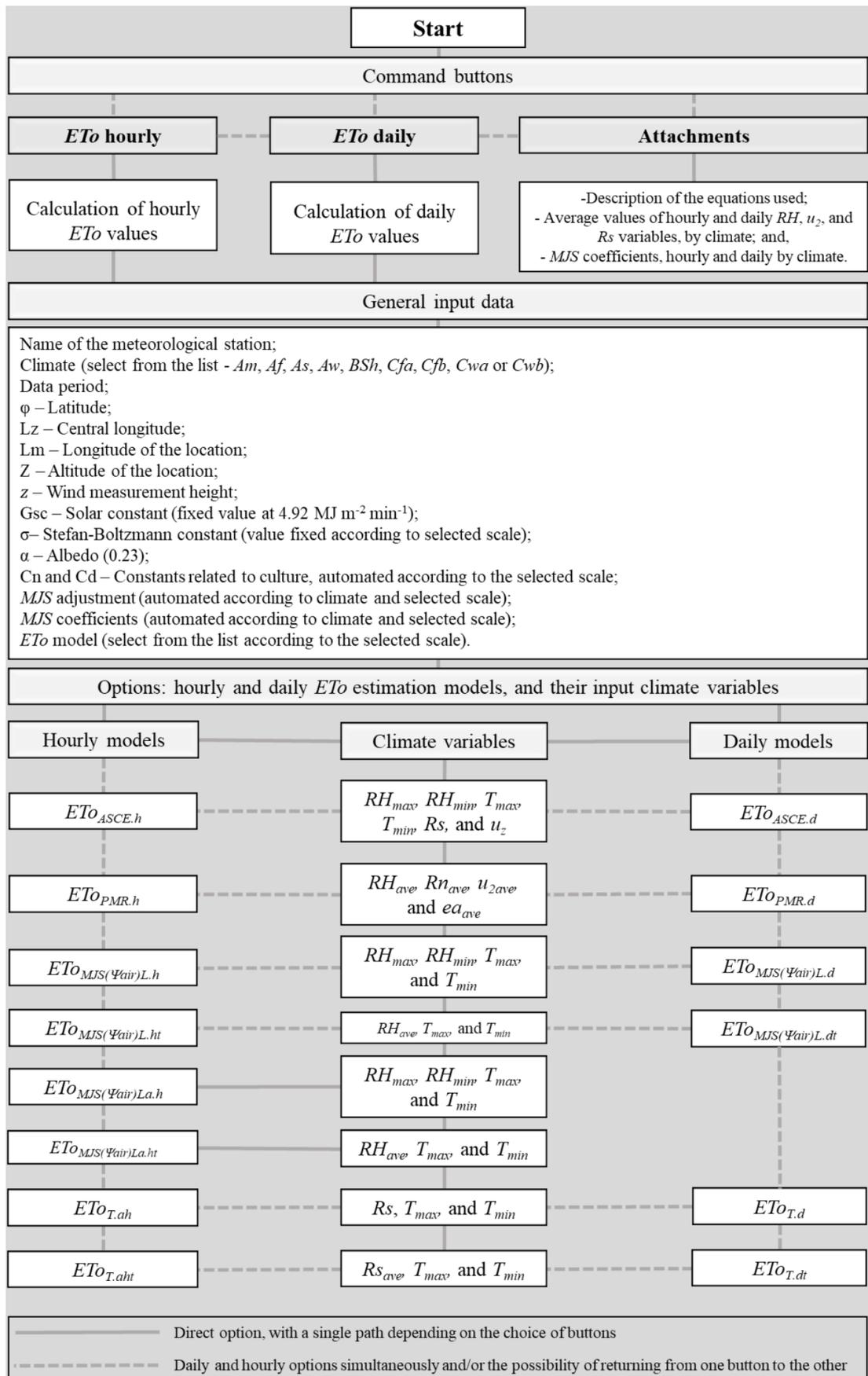


Figure 2 Structure of the module "Adjustments of the Moretti-Jerszurki-Silva (*MJS*) model for estimating hourly reference evapotranspiration (*ETo*)" (*Module*$_{MJS-A}$)

The "*FAO ETo Calculator*" program stands out and was developed by the "Food and Agricultural Organization of the United Nations" in 2009 (FAO, 2009). The program has already been extensively tested to estimate *ETo* in different locations and climates worldwide and is usually used for comparisons with new programs/systems developed to estimate *ETo* (Guo et al., 2016). The "*FAO ETo Calculator*" is easy to access and it is free, but it needs to be installed on the user's computer.

The *Module_{ETo.h-d}* interface compared to the "*FAO ETo Calculator*" presents facilities regarding the frequency of analysis and the number of models included to estimate *ETo*. The "*FAO ETo Calculator*" estimates daily *ETo* with the standard Penman-Monteith model only. The *Module_{ETo.h-d}* makes it possible to estimate *ETo* with models for hourly and daily scale (Figure 3) and the user can establish or group monthly *ETo* values, if desired.

Importing data into the "*FAO ETo Calculator*" requires organizing unnamed columns in a "CXT" file. Subsequently, the user needs to select the name of the variable and its unit of measurement in the program, according to the respective data column. The process, being manual, can lead to errors and takes time from the user. In the *Module_{ETo.h-d}* the operation is simpler, the user simply needs to "copy" and "paste" the input values that are already indicated with their respective units of measurement, facilitating use and avoiding selection errors. The "*FAO ETo Calculator*" also allows manual data inclusion. However, it does not have "copy" and "paste" commands and the values need to be entered individually (one by one). Therefore, estimating monthly *ETo* (30 days) for some locations is possible, but laborious. The procedure becomes unfeasible when the study analyses many locations and/or long data series.

A positive aspect of the "*FAO ETo Calculator*" is the export of *ETo* estimation results together with the imported climate data. Despite being saved in a CXT file, the columns of the exported CXT file are identified, facilitating subsequent analysis of the results. However, this facility is also available in *Module_{ETo.h-d}*.

The "Evapotranspiration" developed in the R software (Guo et al., 2022), is also free, but the user needs to know the R programming language to use the commands in the package. There is a need to import data, and too many calculation routines are necessary depending on the ETo estimation model used. The Evapotranspiration database is also limited in terms of periodicity and locations, in addition to those existing in the package. Until now, there are still no R packages that calculate the MJS, PMR, and modified Turc models for hourly periodicity.

The "®M.EToASCE.e.MJS" module (Jerszurki et al., 2017) has already been used and tested in several studies (Oliveira, 2018; Santos et al., 2021; Rosa, 2023), but despite allowing hourly and daily estimates with the ASCE and MJS models, it does not calculate the PMR and Turc models in the daily and hourly scales. ®M.EToASCE.e.MJS also does not have the option to import hourly meteorological data for reuse on a daily scale, and the user needs to add the data manually, which may cause errors.

The *Module_{ETo.h-d}* was developed in a spreadsheet, and most people who use and analyze environmental data are familiar with this workplace. Therefore, operations in *Module_{ETo.h-d}* are very intuitive. The file containing the module just needs to be opened, without need for installation. The form command buttons and option boxes are associated with routines in the VBA-Macro programming language (Microsoft Corporation, 2025), which perform practically all the necessary calculations and procedures.

### 3.3 Routines tests of the ASCE and MJS models of *Module_{ETo.h-d}*, on a daily and hourly scale

3.3.1 Comparison of estimated daily *ETo* with *Module_{ETo.h-d}* and ®M.*ETo_{ASCE.e.MJS}*

The linear regression analyses between the respective daily *ETo* values estimated in the "®M.*ETo_{ASCE.e.MJS}*" and *Module_{ETo.h-d}* modules were narrow and close to the 45º straight line (dashed 1:1 line found in the graphs; Figure 4), for the ASCE and MJS models.
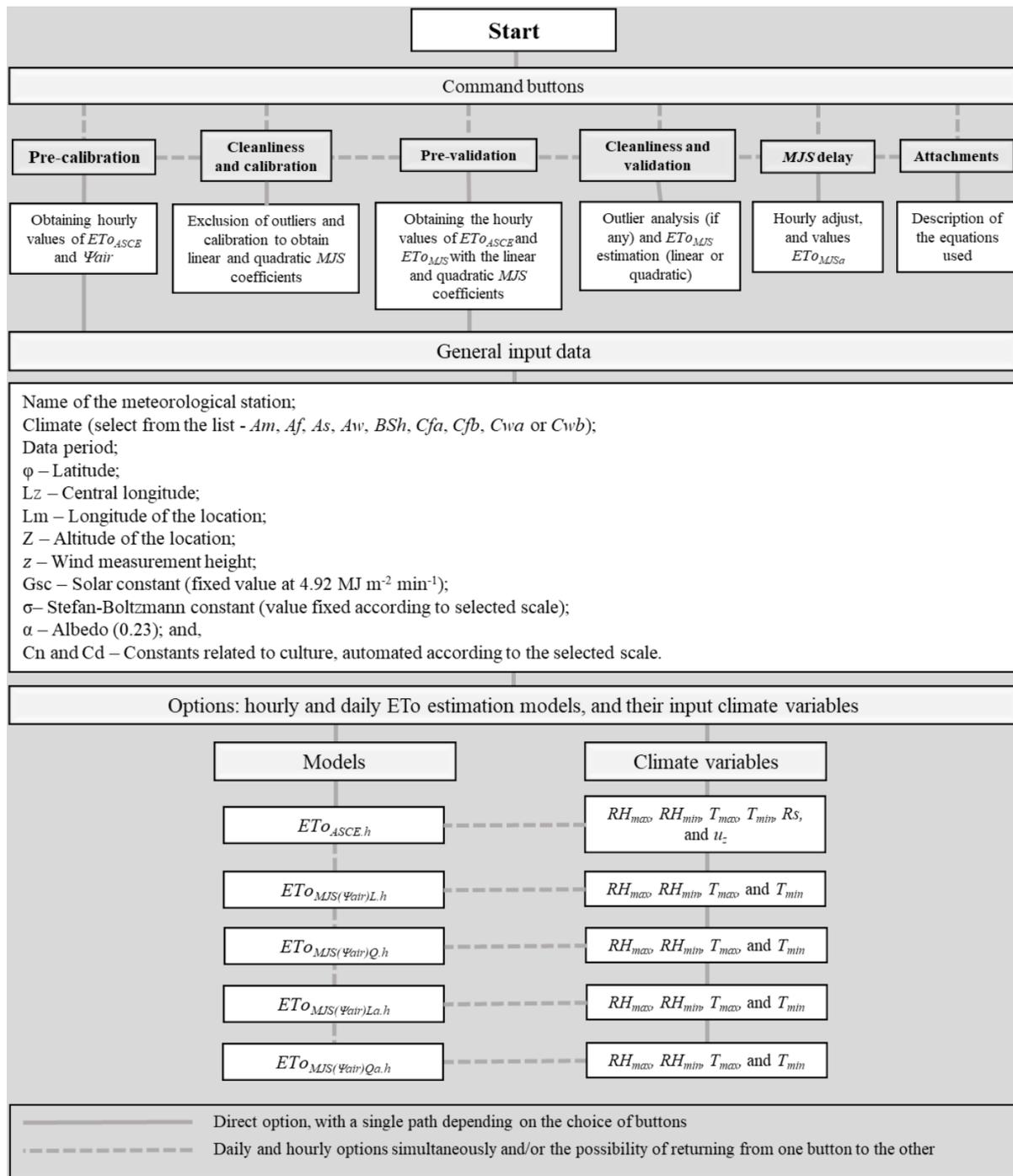
**Start**

Command buttons

| Pre-calibration | Cleanliness and calibration | Pre-validation | Cleanliness and validation | *MJS* delay | Attachments |
|---|---|---|---|---|---|
| Obtaining hourly values of $ETo_{ASCE}$ and $\Psi_{air}$ | Exclusion of outliers and calibration to obtain linear and quadratic *MJS* coefficients | Obtaining the hourly values of $ETo_{ASCE}$ and $ETo_{MJS}$ with the linear and quadratic *MJS* coefficients | Outlier analysis (if any) and $ETo_{MJS}$ estimation (linear or quadratic) | Hourly adjust, and values $ETo_{MJSa}$ | Description of the equations used |

General input data

Name of the meteorological station;
Climate (select from the list - *Am, Af, As, Aw, BSh, Cfa, Cfb, Cwa* or *Cwb*);
Data period;
$\varphi$ – Latitude;
Lz – Central longitude;
Lm – Longitude of the location;
Z – Altitude of the location;
z – Wind measurement height;
Gsc – Solar constant (fixed value at 4.92 MJ m$^{-2}$ min$^{-1}$);
$\sigma$ – Stefan-Boltzmann constant (value fixed according to selected scale);
$\alpha$ – Albedo (0.23); and,
Cn and Cd – Constants related to culture, automated according to the selected scale.

Options: hourly and daily ETo estimation models, and their input climate variables

| Models | Climate variables |
|---|---|
| $ETo_{ASCE.h}$ | $RH_{max}, RH_{min}, T_{max}, T_{min}, Rs$, and $u_z$ |
| $ETo_{MJS(\Psi air)L.h}$ | $RH_{max}, RH_{min}, T_{max}$, and $T_{min}$ |
| $ETo_{MJS(\Psi air)Q.h}$ | $RH_{max}, RH_{min}, T_{max}$, and $T_{min}$ |
| $ETo_{MJS(\Psi air)La.h}$ | $RH_{max}, RH_{min}, T_{max}$, and $T_{min}$ |
| $ETo_{MJS(\Psi air)Qa.h}$ | $RH_{max}, RH_{min}, T_{max}$, and $T_{min}$ |

———————— Direct option, with a single path depending on the choice of buttons
- - - - - - - - Daily and hourly options simultaneously and/or the possibility of returning from one button to the other

Figure 3 Arrangement of the module "Estimation of hourly and daily reference evapotranspiration (*ETo*) with standard (*ASCE*) and alternative models" (*Module$_{ETo.h-d}$*)

The statistical indicators showed excellent associations between the daily *ETo* obtained with the *ASCE* and *MJS* models in the ®M.*ETo$_{ASCE.e.MJS}$* and *Module$_{ETo.h-d}$* (Table 2) for all Brazilian climate types. The results indicated the reliability of the calculation routines developed in *Module$_{ETo.h-d}$*.

3.3.2 Comparison between hourly *ETo* estimated with *Module$_{ETo.h-d}$* and ®M.*ETo$_{ASCE.e.MJS}$*

The linear regression analyses between the respective hourly *ETo* values estimated in the

®M.*ETo$_{ASCE.e.MJS}$* and *Module$_{ETo.h-d}$* modules were also narrow and close to the 45º straight line (dashed 1:1 line found in the graphs; Figure 5). The hourly *MJS* model did not show as close a relationship as the *ASCE* model.

The statistical indicators showed excellent associations between the hourly *ETo* obtained with the *ASCE* model in ®M.*ETo$_{ASCE.e.MJS}$* and *Module$_{ETo.h-d}$* (Table 3) for all Brazilian climate types analyzed. The results also indicated the reliability of the calculation

routines developed in $Module_{ETo.h-d}$ for hourly frequency. The *MJS* model, concerning the ASCE, did not perform as well as the statistical indicators (Table 3). The difference in *ETo* estimates with the *MJS* model in the two modules was due to the methodological procedure considered at night. In $Module_{ETo.h-d}$, *ETo* values are recorded at night, while in $^{®}M .ETo_{ASCE.e.MJS}$, the *MJS* model always returns $ETo_{hourly} = 0$ when $Rn = 0$.
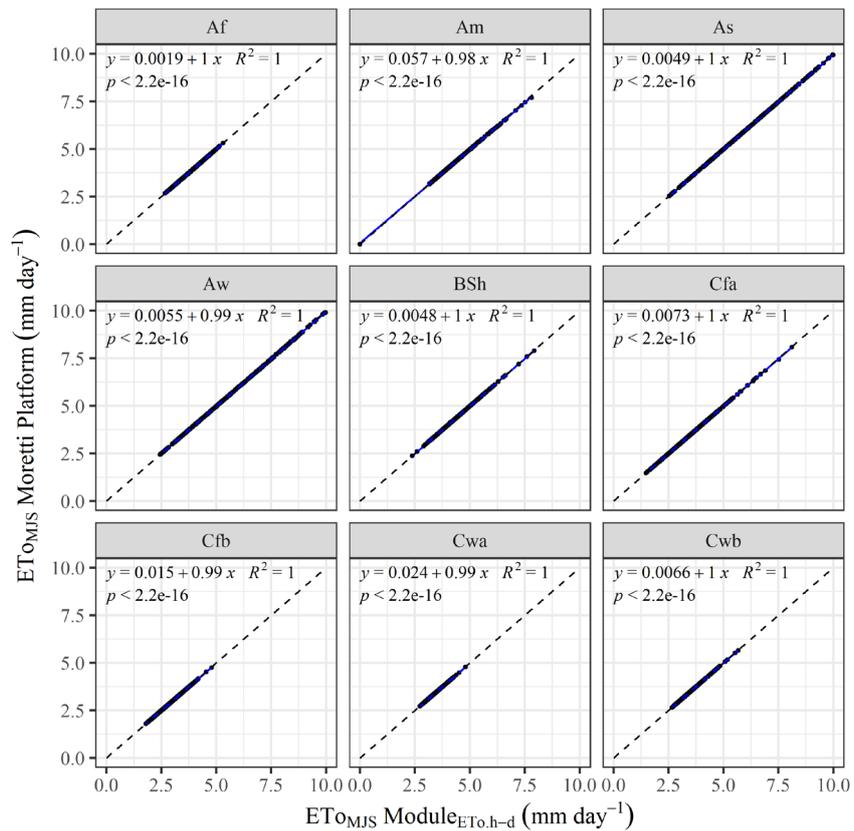
**Table 2 Statistical indicators obtained in the associations between daily reference evapotranspiration estimated with the " $^{®}M.ETo_{ASCE.e.MJS}$" and $Module_{ETo.h-d}$ modules, with the models: American Society of Civil Engineers (ASCE) and Moretti-Jerszurki-Silva (MJS)**

| Climate type | -------------- ASCE -------------- | | | -------------- MJS -------------- | | |
|---|---|---|---|---|---|---|
| | $r$ [1] | $RMSE$ [2] | $NSE$ [3] | $r$ [1] | $RMSE$ [2] | $NSE$ [3] |
| Af | 1.00 | 0.08 | 0.99 | 1.00 | 0.00 | 1.00 |
| Am | 1.00 | 0.00 | 1.00 | 1.00 | 0.01 | 1.00 |
| As | 1.00 | 0.00 | 1.00 | 1.00 | 0.01 | 1.00 |
| Aw | 1.00 | 0.00 | 1.00 | 1.00 | 0.01 | 1.00 |
| BSh | 1.00 | 0.00 | 1.00 | 0.99 | 0.04 | 0.97 |
| Cfa | 1.00 | 0.00 | 1.00 | 1.00 | 0.00 | 1.00 |
| Cfb | 1.00 | 0.00 | 1.00 | 1.00 | 0.00 | 1.00 |
| Cwa | 1.00 | 0.00 | 1.00 | 1.00 | 0.00 | 1.00 |
| Cwb | 1.00 | 0.00 | 1.00 | 1.00 | 0.00 | 1.00 |

Note: [1] $r$ – correlation coefficient (unitless); [2] $RMSE$ – root mean square error (mm day$^{-1}$); [3] $NSE$ – efficiency (unitless).
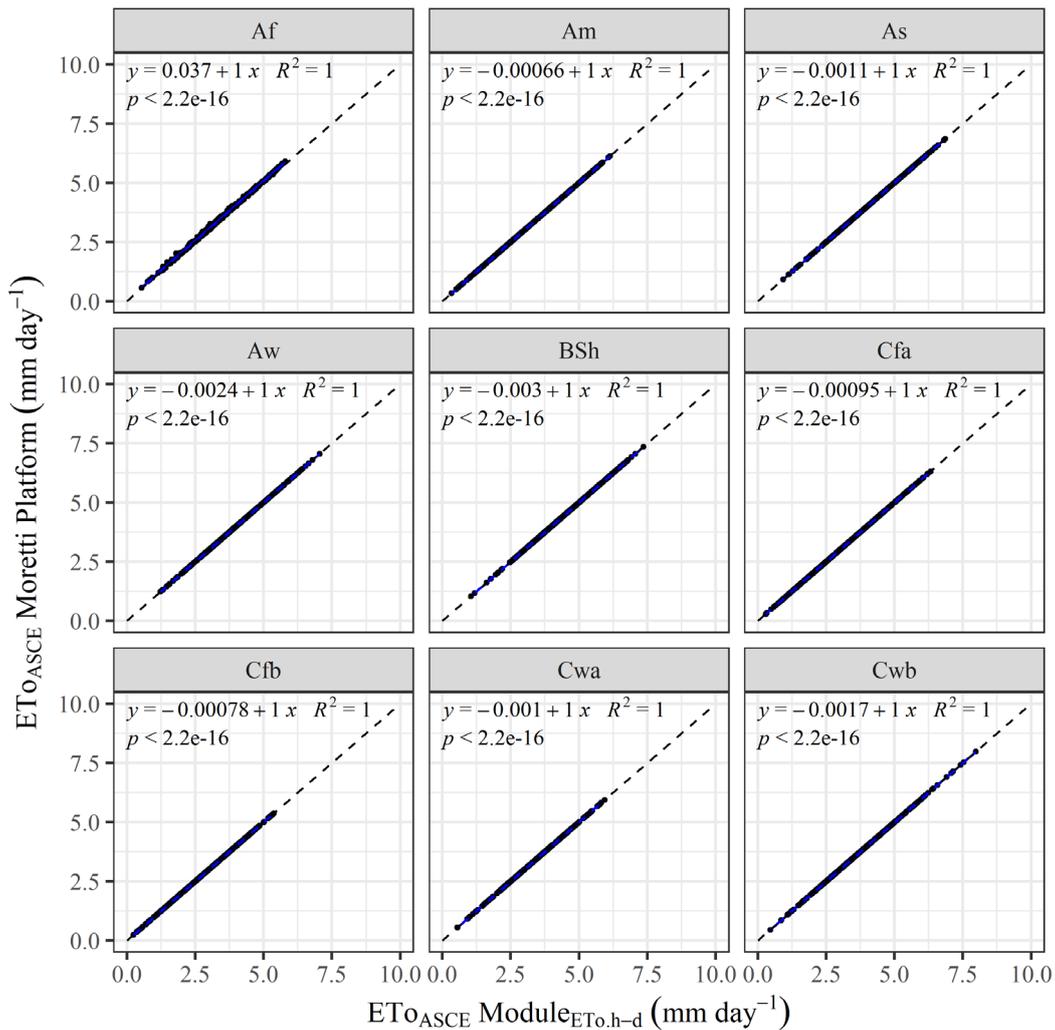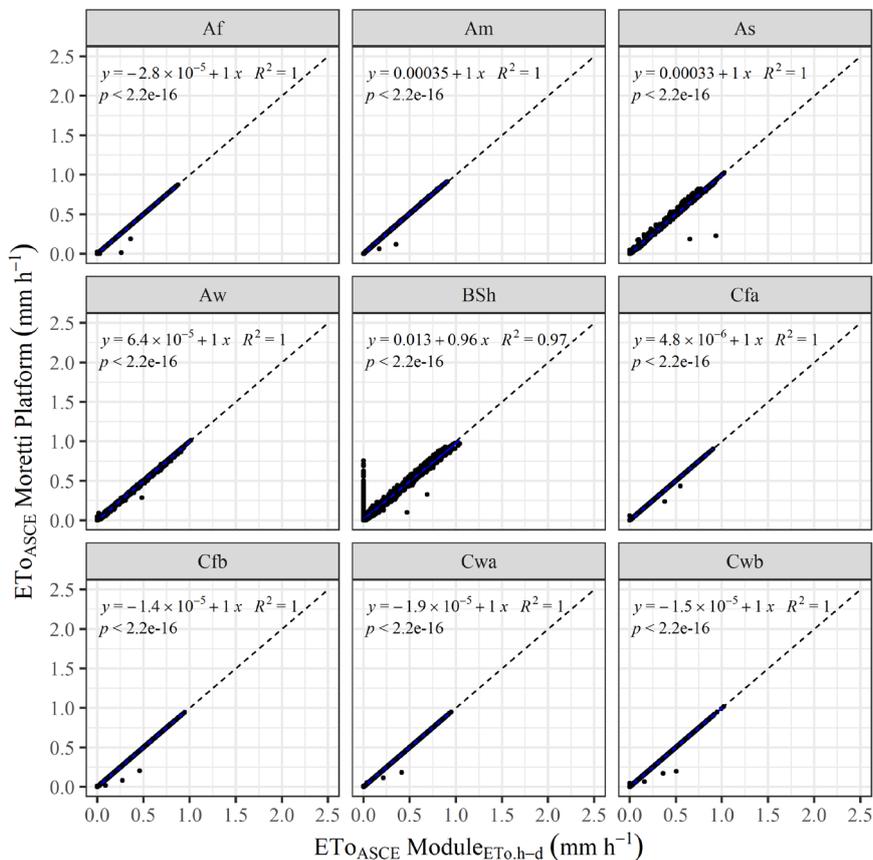


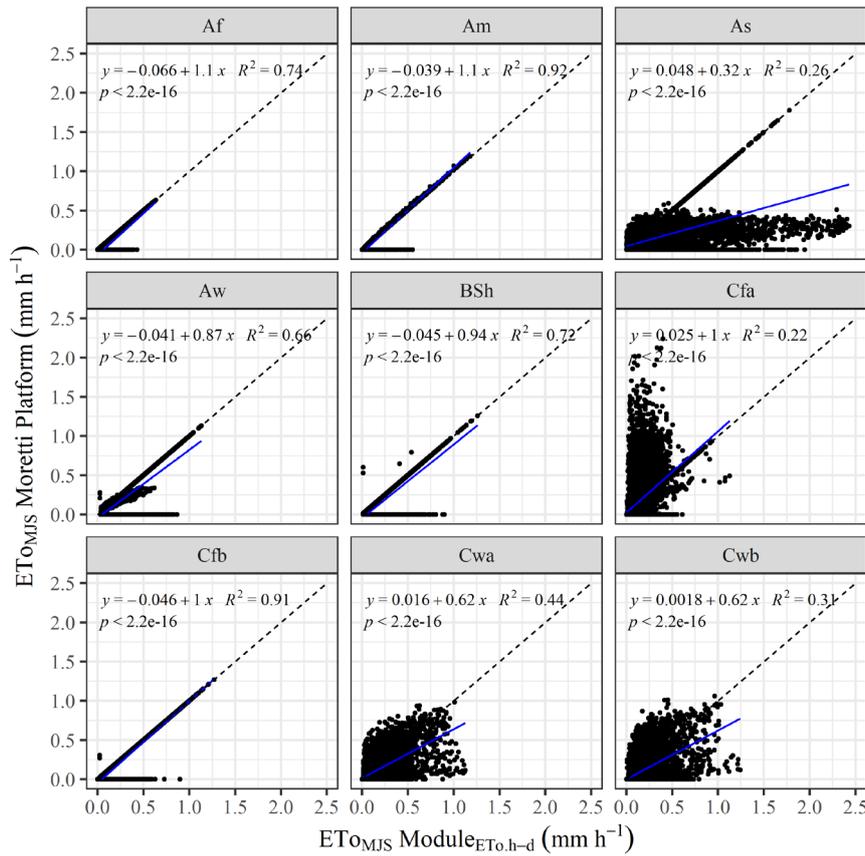(a) American Society of Civil Engineers (ASCE)

(b) Moretti-Jerszurki-Silva (MJS)

Figure 4 Linear regressions between the respective daily reference evapotranspiration (*ETo*) values, estimated with the "®M.*ETo_{ASCE.e.MJS}* module" and *Module_{ETo.h-d}*, carried out for the Brazilian climate types (*Af*, *Am*, *As*, *Aw*, *BSh*, *Cfa*, *Cfb*, *Cwa* and *Cwb*), for the models: a)



(a) American Society of Civil Engineers (ASCE)

(b) Moretti-Jerszurki-Silva (MJS)

Figure 5 Linear regressions between the respective hourly reference evapotranspiration (*ETo*) values estimated with the "®M.*ETo_ASCE.e.MJS*" and *Module_ETo.h-d*, modules carried out for Brazilian climate types (*Af*, *Am*, *As*, *Aw*, *BSh*, *Cfa*, *Cfb*, *Cwa* and *Cwb*), for the models

Table 3 Statistical indicators obtained in the associations between hourly reference evapotranspiration, estimated with "®M.*ETo_ASCE.e.MJS*" and *Module_ETo.h-d* modules, with models: American Society of Civil Engineers (ASCE) and Moretti-Jerszurki-Silva (MJS) *ETo* estimates with nighttime and with zero values in nighttime (*MJS_sn*)

| Climate type | -------- ASCE -------- | | | -------- MJS -------- | | | $MJS_{sn}$ Association with zero values in nighttime | | |
|---|---|---|---|---|---|---|---|---|---|
| | $r$ [1] | $RMSE$ [2] | $NSE$ [3] | $r$ [1] | $RMSE$ [2] | $NSE$ [3] | $r$ [1] | $RMSE$ [2] | $NSE$ [3] |
| *Af* | 1.00 | 0.00 | 1.00 | 0.86 | 0.09 | 0.60 | 1.00 | 0.00 | 1.00 |
| *Am* | 1.00 | 0.01 | 1.00 | 0.96 | 0.06 | 0.89 | 1.00 | 0.01 | 1.00 |
| *As* | 1.00 | 0.01 | 1.00 | 0.86 | 0.23 | 0.67 | 1.00 | 0.02 | 1.00 |
| *Aw* | 1.00 | 0.01 | 1.00 | 0.81 | 0.12 | 0.50 | 0.99 | 0.02 | 0.99 |
| *BSh* | 0.99 | 0.04 | 0.97 | 0.85 | 0.11 | 0.63 | 1.00 | 0.01 | 1.00 |
| *Cfa* | 1.00 | 0.00 | 1.00 | 0.88 | 0.09 | 0.66 | 1.00 | 0.02 | 0.99 |
| *Cfb* | 1.00 | 0.00 | 1.00 | 0.96 | 0.07 | 0.87 | 1.00 | 0.00 | 1.00 |
| *Cwa* | 1.00 | 0.00 | 1.00 | 0.95 | 0.06 | 0.89 | 1.00 | 0.01 | 1.00 |
| *Cwb* | 1.00 | 0.00 | 1.00 | 0.87 | 0.10 | 0.65 | 1.00 | 0.01 | 1.00 |

Note: [1] *r* – correlation coefficient (unitless); [2] *RMSE* – root mean square error (mm day$^{-1}$); [3] *NSE* – efficiency (unitless).

In the scenario with the *Module_ETo.h-d* resetting the nighttime *ETo* values estimated with the *MJS* model (Table 3 and Figure 6), excellent statistical indicators were observed in the associations between the hourly *ETo* with ®M.*ETo_ASCE.e.MJS* and *Module_ETo.h-d*. The result showed that the differences in hourly *ETo*

occurred due to the methodological aspects. However, even in this scenario, it is important to note that small methodological differences remained in the two modules, as ®M.*ETo_ASCE.e.MJS* allows negative *ETo* values for the *ASCE* and *MJS* models.
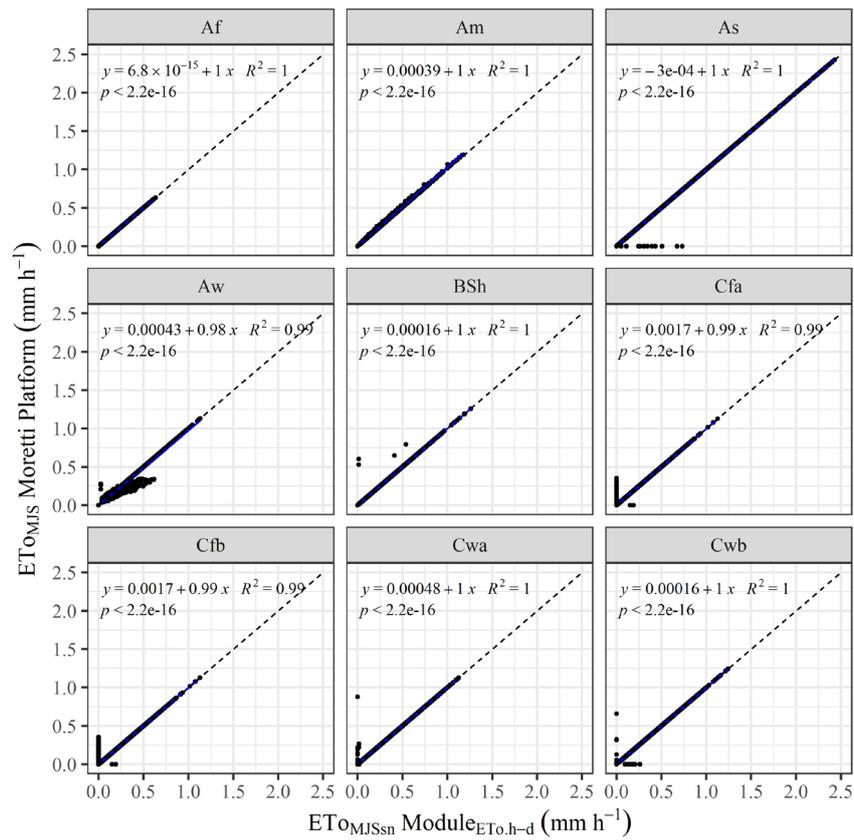
Figure 6 Linear regressions between the hourly reference evapotranspiration (*ETo*) values estimated with the "$^{®}$M.*ETo$_{ASCE.e.MJS}$*" and *Module$_{ETo.h-d}$* modules, whit Moretti-Jerszurki-Silva model disregarding nighttime *ETo* values (*MJS$_{sn}$*)
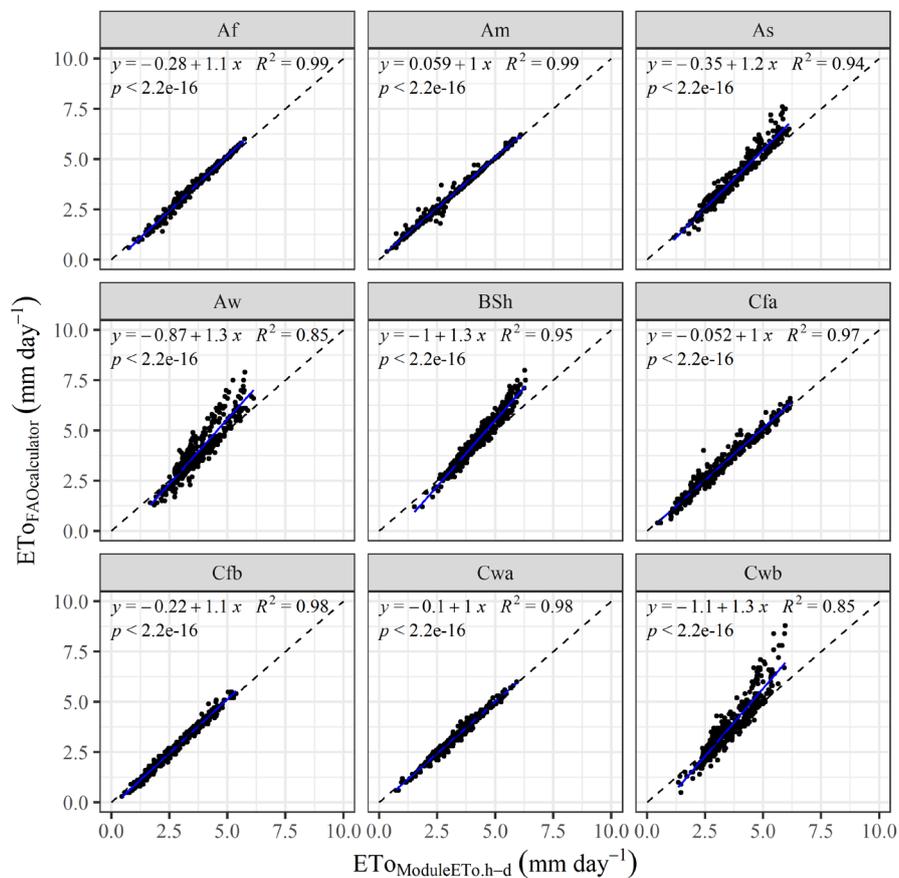


Figure 7 Linear regressions between the respective values of daily reference evapotranspiration (*ETo*) estimated with the "*FAO ETo Calculator*" program (*ETo$_{FAOcalculator}$*) and *Module$_{ETo.h-d}$*, for Brazilian climate types (*Af, Am, As, Aw, BSh, Cfa, Cfb, Cwa* and *Cwb*)

**Table 4 Statistical indicators obtained in the associations between daily reference evapotranspiration estimated with the "*FAO ETo Calculator*" program (*ETo_FAOcalculator*) and *Module_ETo.h-d*, for Brazilian climate types (*Af*, *Am*, *As*, *Aw*, *BSh*, *Cfa*, *Cfb*, *Cwa* and *Cwb*)**

| Climate type | --------- Associations between daily values of $ETo_{FAOcalculator}$ vs $ETo_{ModuleETo.h-d}$ ---------- | | |
| | --------------------------- Statistical indicators ------------------------- | | |
| | $r$ [1] | $RMSE$ [2] | $NSE$ [3] |
| *Af* | 0.99 | 0.16 | 0.98 |
| *Am* | 0.99 | 0.16 | 0.99 |
| *As* | 0.97 | 0.46 | 0.88 |
| *Aw* | 0.92 | 0.61 | 0.78 |
| *BSh* | 0.97 | 0.51 | 0.84 |
| *Cfa* | 0.98 | 0.26 | 0.97 |
| *Cfb* | 0.99 | 0.18 | 0.98 |
| *Cwa* | 0.99 | 0.16 | 0.98 |
| *Cwb* | 0.92 | 0.65 | 0.78 |

Note: [1] $r$ – correlation coefficient (unitless); [2] $RMSE$ – root mean square error (mm day$^{-1}$); [3] $NSE$ – efficiency (unitless).

### 3.3.3 Comparison between daily *ETo* estimated with *Module_ETo.h-d* and "*FAO ETo Calculator*"

Calculations of daily *ETo* with *Module_ETo.h-d* (which considers the *ASCE* model) and the "*FAO ETo Calculator*" program (which considers the *FAO* model) present similar, but not equal, values. Small variations occurred due to differences in the methodologies, as some internal equations used in the "*FAO ETo Calculator*" to estimate *ETo* are not described in full detail.

The associations of the linear regression analyses between respective values of "*ETo_FAOcalculator* vs *ETo_ModuleETo.h-d*" were close to the 45° straight line (dashed 1:1 line found in the graphs; Figure 7). The statistical indicators also demonstrated the reliability of the routines developed in *Module_ETo.h-d*, to calculate *ETo* with the standard ASCE model, on a daily scale (Table 4).

The indicators of associations between estimated *ETo*, carried out for the *Aw* and *Cwb* climates, showed lower statistical performance (Table 4), being: $r = 0.92$ and $NSE = 0.78$ for both climates; and *RMSE* equal to 0.61 mm day$^{-1}$ in the *Aw* and 0.65 mm day$^{-1}$ in the *Cwb* climate. Sousa (2012) obtained a maximum difference of 0.56 mm day$^{-1}$ between the *ETo* estimated with the PROCAL_ETo program and the "*FAO ETo Calculator*", in the locations where the best results were observed. However, in some locations, the author obtained differences between 3.91 and 3.11 mm day$^{-1}$ due to estimated values of *Rs*. In the *Module_ETo.h-d*, *Rs* is not estimated but rather obtained with values

measured at selected weather stations, which favored the occurrence of smaller differences, which were observed only in the *Aw* and *Cwb* climates (*RMSE* equal to 0.61 and 0.65 mm day$^{-1}$ for the *Aw* and *Cwb* climates, respectively).

Oliveira (2018) associating daily *ETo* estimates, obtained *RMSE* values between 0.33 and 1.4 mm day$^{-1}$. The author considered the results adequate based on the literature (Djaman et al., 2016; Liu et al., 2017). Although the *Aw* and *Cwb* climates presented the highest *RMSE* (Table 4) in the comparative analyses, the values were lower than 1.4 mm day$^{-1}$, comprising low differences and good results. Oliveira (2018) considered associations with correlation coefficients (*r*) above 0.50 to be good, and Tegos et al. (2017) considered *NSE* < 0.50 to be low, indicating low predictive capacity. In the present analyses, $r \geq 0.92$ and $NSE \geq 0.78$ were obtained for all Brazilian climate types (Table 4), indicating acceptable results for the *Module_ETo.h-d*. In general, the *Module_ETo.h-d* obtained great estimates of daily and hourly *ETo* series, with easy-to-use mechanisms, containing *ASCE* and adapted/reduced models (*PMR*, *MJS*, and Turc) in the same environment.

### 3.4 Developed modules and their limitations

The analyses conducted with the developed modules (*Module_MJS-A* and *Module_ETo.h-d*) showed good results, as well as excellent statistical indicators when compared to other software tools aimed at estimating *ETo*. However, it is important to note that the modules may also present some limitations, as described below:

The developed modules estimate *ETo* but do not perform extrapolation, simulation, or automatic gap-filling of missing climatic data. Therefore, they require consistent series of measured hourly or daily data without gaps;

The developed modules represent an advancement in data processing and *ETo* estimation and facilitate the calibration and validation of the included models. However, even though they are well-explained and operationally simple, their use requires qualified users who understand the models and have knowledge of the data being generated. The user must also be proficient and familiar with the electronic spreadsheet environment;

The *Module*$_{MJS-A}$ was developed specifically for calibration, validation, and analysis of the hourly delay between *ETo* estimated using the *MJS* model and the *ASCE* model, and it is not applicable to other models;

The *Module*$_{ETo.h-d}$ includes only the ability to calculate hourly and daily *ETo* using the standard model (ASCE) and a few alternative models (ASCE, MJS, PMR or Turc: $ETo_{ASCE}$, $ETo_{PMR.d}$, $ETo_{PMR.h}$, $ETo_{MJS(\Psi air)L.d}$, $ETo_{MJS(\Psi air)L.dt}$, $ETo_{MJS(\Psi air)L.h}$, $ETo_{MJS(\Psi air)L.ht}$, $ETo_{MJS(\Psi air)La.d}$, $ETo_{MJS(\Psi air)La.dt}$, $ETo_{T.d}$, and $ETo_{Ta.h}$), currently among the most promising. Using the modules to implement or evaluate other model(s) not included in *Module*$_{ETo.h-d}$ would be very limited;

Depending on the spreadsheet version, some configurations or formatting of the module forms may be altered. These changes do not affect the structure of the computational routines or the results of the *ETo* calculations, but they may hinder the operational workflow;

Caution is recommended when extrapolating results to climatic regimes different from those used in the model's original calibration, reinforcing the need for local adjustments and regional validations to ensure the reliability of *ETo* estimates;

Unlike the *Module*$_{MJS-A}$, which is specific to the *MJS* model, the *Module*$_{ETo.h-d}$ does not correct for uncertainties inherent in the *ETo* estimation process, which may arise from the methods used or the quality and continuity of meteorological data. Recent studies indicate that simplified models may present systematic errors whose magnitude varies according to the regional climate and the availability of meteorological variables such as solar radiation, temperature, humidity, and wind speed (Cordão, 2023). The absence or poor quality of these data can lead to under or overestimation of *ETo*, directly impacting irrigation management and the efficient use of water resources in agriculture (Guo et al., 2016). Therefore, local calibrations and regional validations are recommended to minimize uncertainties and ensure greater reliability in irrigation recommendations (Djaman et al., 2016).

## 5 Conclusions

The developed modules demonstrated effective capabilities for rapid and accurate estimation of (*ETo* on both daily and hourly scales, integrating the *ASCE* model and alternative simplified approaches within a single, user-friendly environment.

The intuitive interface of *Module*$_{ETo.h-d}$ facilitates efficient data input and output processes, enhancing usability without demanding complex installations or specific data formats. Overall, the modules showed consistent and reliable performance when compared to established reference calculators, supporting their applicability across diverse Brazilian climatic conditions.

For future research, we suggest extending the evaluation of these modules to other climatic regions, particularly those with more extreme or highly variable microclimates, to further assess model adaptability and calibration needs. Investigations into integrating remote sensing data and machine learning techniques could also enhance the precision and automation of *ETo* estimates, contributing to improved irrigation management and water resource optimization.

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