ESTIMATION OF REFERENCE EVAPOTRANSPIRATION FOR COFFEE IRRIGATION MANAGEMENT IN A PRODUCUTIVE REGION OF MINAS GERAIS CERRADO

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ABSTRACT: Evapotranspiration (evaporation and transpiration) represents vegetated soil water loss to the atmosphere and can be estimated by various empirical methods. The aim of this study was to evaluate the performance of methods of Blaney-Criddle, Jensen-Haise, Linacre, Solar Radiation, Hargreaves-Samani, Makkink, Thornthwaite, Camargo, Priestley-Taylor and Penman in the estimation of potential evapotranspiration comparing to the standard method Penman-Monteith (FAO56) regarding the climatic conditions of the city of Araxá, MG. A set of 35 years of monthly data (1976 to 2010) was used, working with the climatic elements: temperature, relative humidity, wind speed and insolation. The empirical methods to estimate reference evapotranspiration were compared with the standard method using linear regression, simple statistical analysis, Willmott agreement index (d) and performance index (c). The method of Makkink showed the best performance according to the set of parameters evaluated and it is recommended to calculate ETo in Cerrado of Minas Gerais, for coffee irrigation management.

Index terms: Climatic elements, empirical equations, FAO Penman-Monteith, irrigation, Cerrado.

ESTIMATIVA DA EVAPOTRANSPIRAÇÃO DE REFERÊNCIA PARA O MANEJO DA IRRIGAÇÃO DO CAFEEIRO EM UMA REGIÃO PRODUTIVA DO CERRADO DE MINEIRO

RESUMO: A evapotranspiração representa a perda de água do solo com vegetação para a atmosfera, podendo ser medida por métodos diretos ou estimada empiricamente. O objetivo deste estudo foi avaliar o desempenho dos seguintes métodos empíricos: Blaney-Criddle, Jensen-Haise, Linacre, Radiação Solar, Hargreaves-Samani, Makkink, Thornthwaite, Camargo, Priestley-Taylor e Penman na estimativa da evapotranspiração potencial, comparando-os com o método padrão Penman-Monteith (FAO56) quanto às condições climáticas da cidade de Araxá, MG. Utilizaram-se 35 anos de dados mensais (1976 a 2010), das seguintes variáveis climáticas: temperatura, umidade relativa do ar, velocidade do vento e insolação. Os métodos empíricos utilizados para estimar a evapotranspiração de referência foram comparados com o método padrão por meio de regressão linear, análise estatística simples, índice de concordância de Willmott (d) e índice de desempenho (c). Dentre os métodos alternativos, o de Makkink apresentou melhor desempenho, portanto, pode ser utilizado para estimar a ETo para fins de manejo da irrigação do cafeeiro cultivado no cerrado mineiro.

Termos para indexação: Dados meteorológicos, métodos empíricos, FAO Penman-Monteith, Irrigação, Cerrado.

1 INTRODUÇÃO

The hydrologic cycle is a planetary phenomenon caused by water movement, mainly affected by gravity action and solar energy. Rainfall, infiltration, surface runoff, evaporation and transpiration are the main processes which dynamically interact with each other and are influenced by human actions caused by industry and agricultural activities development (BORGES; MENDIONDO, 2007). The actual evapotranspiration is a key process to hydrological cycle and the element that associates land surface water and energy balance (ZHAO et al., 2013).

The water balance relates data on deficiency, surplus, withdrawal and water replacement throughout the year. The analysis of these components is crucial to agricultural activities planning and implantation (CASTRO et al., 2010). Certainly, one of the great interests in understanding the water balance of an agricultural area is to infer about water volume availability, mainly due to the possibility of increasing the crop production activity through irrigation practices and consequently, the regional economic income. The most important variables to water balance calculation are evapotranspiration and rainfall (BORGES; MENDIONDO, 2007). Crop evapotranspiration is necessary to design and management irrigation systems (ESTEVES et al., 2010; SOUZA et al., 2010).

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Evapotranspiration is the combination of two distinct process, the loss of water of land surface from evaporation and the vegetables transpiration through the plant stomata (ALLEN et al., 1998). Reference evapotranspiration (ETo) is defined as the evapotranspiration of a hypothetic crop with a fixed high of 0.12 m, albedo equal to 0.23 and surface resistance to water transport equal to 70 s.m^{-1}.

According to Alves Sobrinho et al. (2011), evapotranspiration can be directly measured by specific equipment, as the weighing lysimeter, however the high cost restricts its use to research institutes and for regional calibration of indirect methods (MELO; FERNANDES, 2012), hence several authors develop and test empirical methods to estimate evapotranspiration indirectly. Serrat-Capdevila et al. (2011) presented an approach to quantify reference evapotranspiration under climate changes, employing field observations, theoretical models and meteorological predictions of global climate models using a watershed from southern Arizona - USA. Sun et al. (2009) developed a simple evapotranspiration model based only on remote sensing data. The authors adjusted a model that showed a good performance for instantaneous estimations.

The climatic features of the Brazilian Cerrado region have induced agricultural producers (i.e., coffee, soybean, corn and others) to use irrigation systems in order to reduce the loss risk associated to water deficit in dryer periods (FERNANDES et al., 2012). The region is a hot spot zone to agriculture production of crops as coffee, grains and fruits, covering about 200 million hectares on the states of Minas Gerais, Mato Grosso, Mato Grosso do Sul, Tocantins, Bahia, Piauí, Maranhão e Distrito Federal.

Cerrado region requires irrigation to supply water during important crop phenological phases on the dry months of the year (FERNANDES et al., 2012). However, there are conflicts for water availability in some locations, which makes difficult the implementation of large-scale irrigation techniques. Efficiency on water use allows greater economic viability and environmental sustainability of irrigated agriculture (LEVIDOW et al., 2014). Hence, one way of increasing the efficiency on water use is through accurate evapotranspiration estimates.

Accurate estimation of reference evapotranspiration is required to rational water resource use (SHIRI, 2017). The Food and Agriculture Organization (FAO) recommends using the Penman-Monteith method (FAO56-PM) as standard to evapotranspiration estimation (ALLEN et al., 1998). This method, beside is used to compute evapotranspiration as well as calibration of other models (BEZERRA et al., 2010a; TABARI et al., 2013) . However, this method depends on several meteorological data, frequently unavailable, what makes difficult the large-scale usage, especially to smaller farmers. This implies the need for simpler approaches to estimate evapotranspiration, through developing methods that require fewer parameters but able to provide reliable on ETo (PEREIRA et al., 2009; SHIRI, 2017).

The assessment of simpler approaches applied to ETo estimation has been receiving considerable attention in developing countries, where the data required by the FAO56-PM method are often incomplete and/or unavailable (TABARI; GRISMER; TRAJKOVIC, 2013). Therefore, empirical methods to ETo estimation, founded on physic properties, empirical equations or the combination of both, have become alternative approaches in the last decades (ALENCAR et al., 2011a). Additionally, considering that: i) ETo is necessary to design and manage irrigation systems (ESTEVES et al., 2010; SOUZA et al., 2010); ii) the role played by irrigation to improve agricultural production in semi-arid environments; iii) the representability of Brazilian Cerrado of Minas Gerais state agricultural production to the national total production; iv) the need for irrigation on scarcity periods of the year (i.e., from April to September); We aimed to assess the performance of different methodologies to estimate the ETo in relation to the FAO56-PM method (ALLEN et al., 1998), to the Cerrado region from Minas Gerais state.

2 MATERIALS AND METHODS

Meteorological data used to ETo estimation were obtained from a conventional land surface meteorological station, OMN code 83579, located at the Cerrado biome, specifically in Araxá municipal district, Minas Gerais state at coordinates 19º 36’ 36” S, 46° 57’ 00” W and 1023.61m above the sea level (Figure 1).

According with the Köopen climatic classification (ALVARES et al., 2013), the climate of region is of the type Cwa, associated to humid temperate climate of rainy summer and dry winter (SÁ JÚNIOR, 2009) with annual mean rainfall about 1500 mm. The dry period varies from four to seven months and the rainfalls occur from October to March (Figure 2).

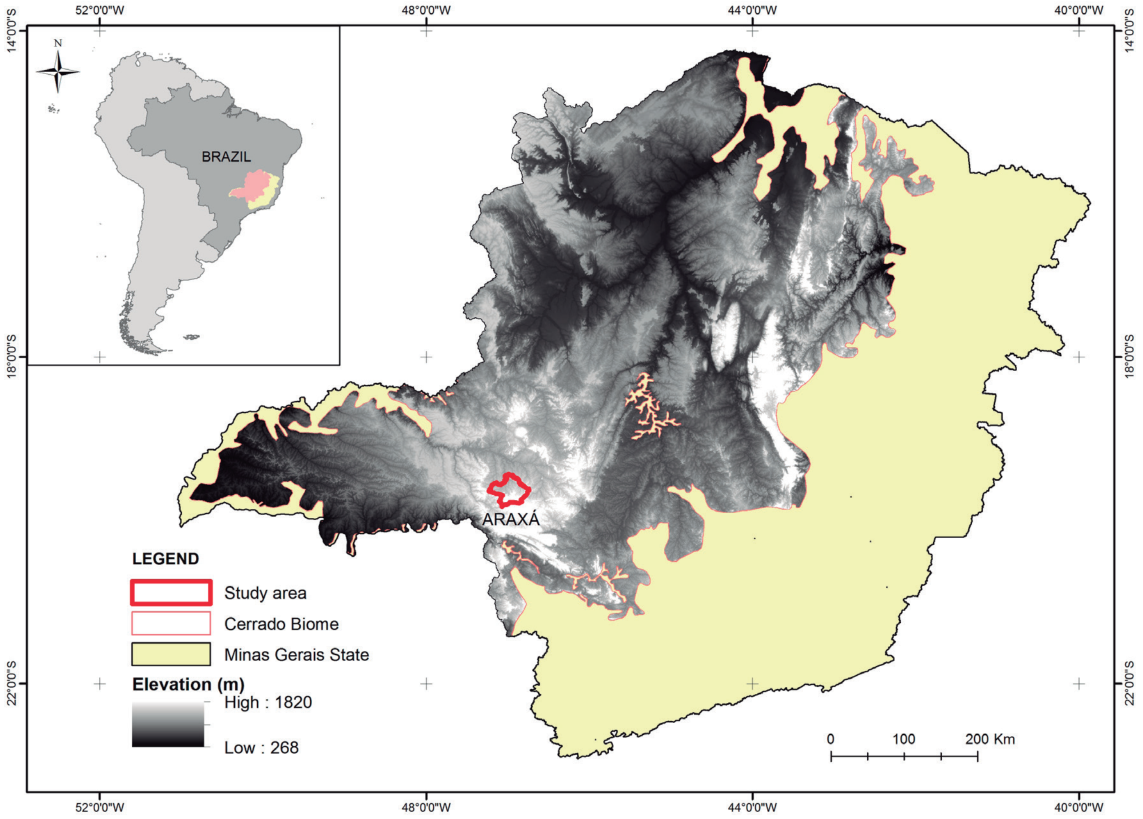


FIGURE 1 – Location of study area, which highlight to Araxá municipality (red boundary) at the Cerrado biome.

Figure 2 also shows mean monthly variation of the parameters used by the methods to compute evapotranspiration: maximum, minimum and mean temperature and relative humidity, wind speed measured at 2 m height and insolation, of 35 years of records, from January 1976 to December 2010. Note that maximum temperature is in February; the driest month is August; in September there is the highest wind speed and in November the greatest solar radiation. The Eto methods were categorized according to their premises, as: i) energy-based; ii) temperature-based, and iii) mass transfer-based (ZHAO et al., 2013).

Eventual missing data were discarded to avoid compromising the comparison procedure. Hence, all methods were analyzed with the same dataset. The mean monthly values of ETo estimation were calculated according to the following empirical methods: Blaney-Criddle (BLANEY; CRIDDLE, 1950), Jensen-Haise (JENSEN; HAISE, 1963), Linacre (LINACRE, 1977), Solar Radiation (DOORENBOS; PRUITT, 1977), Hargreaves-Samani (HARGREAVES; SAMANI, 1985), Makkink (MAKKINK, 1957), Thornthwaite (THORNTHWAITE, 1948), Camargo (CAMARGO, 1971), Priestley-Taylor (PRIESTLEY; TAYLOR, 1972) and Original Penman (PENMAN, 1948). Then, the results were evaluated by level of agreement to Penman-Monteith standard method. The empirical methods were selected because of their applicability features to the study area. The next sections present the methods by type (i.e., based on temperature, energy or mass-transfer).

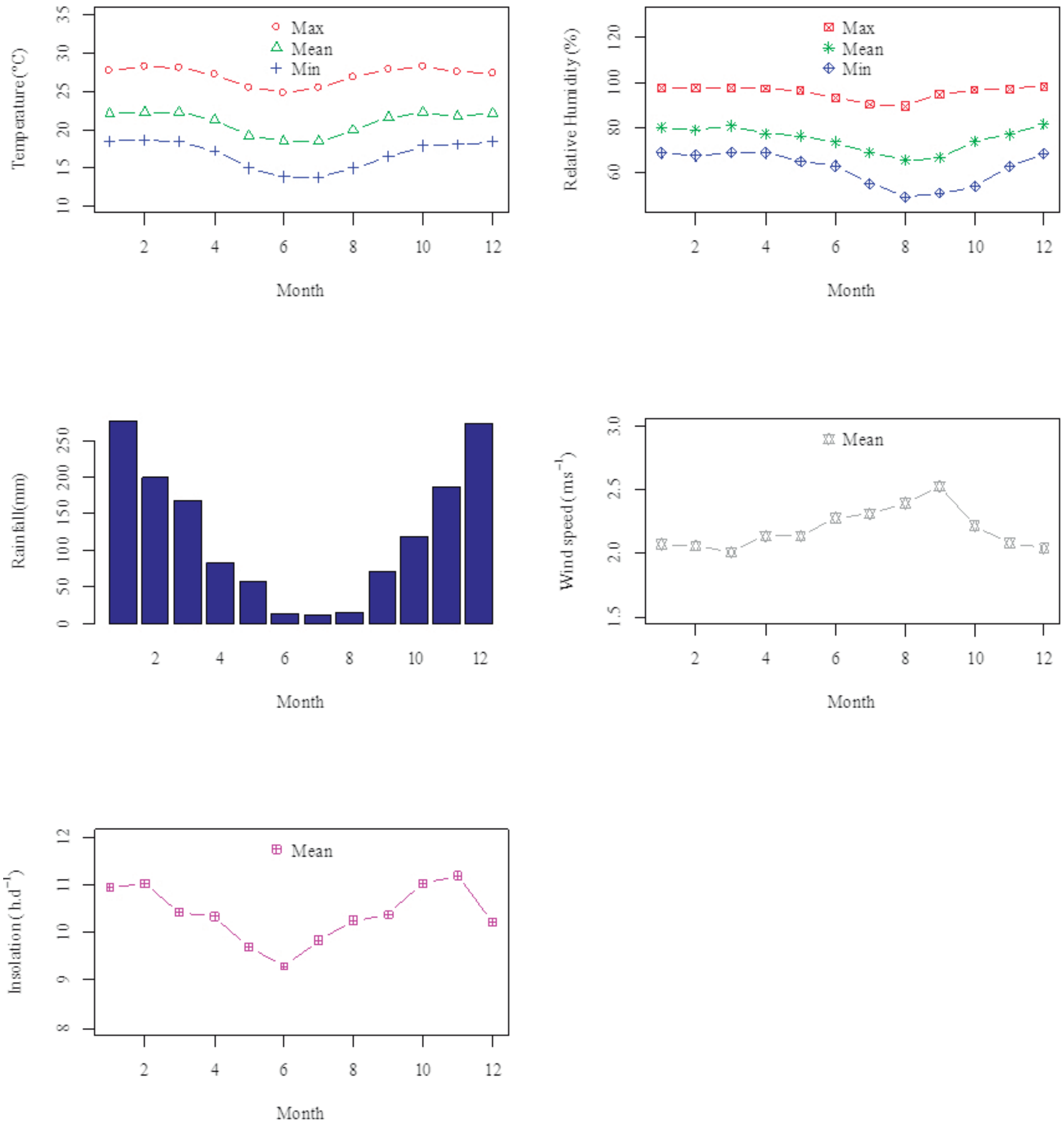


FIGURE 2 - Mean monthly values of climatic parameters from 1976 to 2010; Maximum, minimum and mean temperature; Maximum, minimum and mean relative humidity; Rainfall; Wind speed; and insolation**.**

Temperature-based methods

The temperature-based methods are some of the earliest methods (TABARI; GRISMER; TRAJKOVIC, 2013); they are recommended under limited climate data conditions (ZHAO et al., 2013).

Blaney and Criddle (1950): initially, the method was developed for semi-arid region from New Mexico and Texas in the West of United States. Doorenbos and Pruitt (1977) proposed a correction factor to the original equation, using humid variables as wind speed and insolation, enabling the application to several climatic conditions. To easy calculus and avoid interpolations, (FREVERT; HILL; BRAATEN, 1984) proposed the following change on Blaney-Criddle FAO-24 method (Equation 1):

$$ETo_{BC} = a + b\ p\left(0.46T_m + 8.13\right) \quad (1)$$

Where a and b are the coefficient values, obtained from:

$$a = 0.0043\ RH_{min} - \frac{n}{N} - 1.41$$

$$b = a_0 + a_1 RH_{min} + a_2 \frac{n}{N} + a_3 U_2 + a_4 RH_{min} \frac{n}{N} + a_5 RH_{min} U_2$$

Were RH_{min} is the monthly relative humidity minimum (%); *p* is the percent of the total mean monthly photoperiod (°C) relative to the total annual photoperiod, according to Table 1; *n* is the total insolation (h); N is the photoperiod (h); U_2 is the wind speed at 2m above ground ($m\ s^{-1}$). The coefficients are: $a_0 = 0.81917$, $a_1 = -0.0040922$, $a_2 = 1.0705$, $a_3 = 0.065649$, $a_4 = -0.0059684$ e $a_5 = -0.0005967$.

Thornthwaite (1948): the method was based on the water balance of watersheds and lysimeter measures, using only air temperature as independent variable. The mean monthly potential evapotranspiration for grass surface is obtained through the Equation 2:

$$ETP = 16\left(10\frac{T_m}{I}\right)^a \quad (2)$$

$$T_m > 0°C$$

$$a = 6.75\ 10^{-7} I^3 - 7.71\ 10^{-5} I^2 + 0.01791\ I + 0.49239$$

$$I = \sum_{i=1}^{12} \left(0{,}2T_m\right)^{1{,}514}$$

Where I is the regional heat index; Tm is the mean temperature (ºC).

The Thornthwaite method estimates evapotranspiration to a standard condition of 12 hours of sun shining and a month of 30 days and can be calculated through the Equation 3:

$$ETo_{Th} = ETP\ \frac{N}{12}\ \frac{ND}{30} \quad (3)$$

Where ND is the number of days in a month.

Hargreaves-Samani (1985): the method was developed using lysimeter data in Davis-CA under grass surface and semi-arid climatic condition. The Equation 4 is as follows:

$$ETo_{HS} = 0.0023\ Qo\ \left(Tmax - Tmin\right)^{0.5}\left(T + 17.8\right) \quad (4)$$

Where Qo is the total daily solar radiation incident in horizontal surface ($mm\ d^{-1}$)

Linacre (1977): the method was originally proposed to the Australian climatic conditions, based on a Penman-Monteith simplification. It uses only temperature and relativity humid data, associated to the location in terms of latitude and elevation. Evapotranspiration values are obtained from the Equation 5:

$$ETo_{Lin} = \frac{\dfrac{J\left(T_m + 0.006h\right)}{100 - \left|\ \Phi\ \right|} + 15\left(T_m - T_0\right)}{80 - T_m} \quad (5)$$

$$\left(T_m - T_0\right) = 0.023h + 0.37T_m + 0.53\left(T_{max} - T_{min}\right) + 0.35R - 10.9$$

Where J is a constant equal 500 in case of vegetation (albedo = 0.25); Φ is the latitude in degrees; Tmax is the monthly maximum temperature (°C); Tmin is the monthly minimum temperature (°C); T0 is the monthly mean temperature of the dew point (°C); R is the difference among the mean temperatures of the hottest and coldest months (°C); h is the local height (m).

Camargo (1971): from the results of Thornthwaite, Camargo propose a simpler method, however, as efficient as the one mentioned. The method uses only mean air temperature and extraterrestrial solar radiation data and the evapotranspiration is given by the Equation 6:

$$ETo_{Cam} = F\ Qo\ T_m\ ND \quad (6)$$

Where F is an adjustment factor dependent on annual mean temperature ($T_a < 23.5$ ºC, F = 0.01).

TABLE 1 - P factor as function of Latitude and month according to Doorenbos & Pruitt (1977).

Month	South Latitude		
	15º	19,73º	20º
January	0.29	0.299	0.30
February	0.28	0.289	0.29
March	0.28	0.280	0.28
April	0.27	0.261	0.26
May	0.26	0.251	0.25
June	0.25	0.250	0.25
July	0.26	0.251	0.25
August	0.26	0.260	0.26
September	0.27	0.270	0.27
October	0.28	0.280	0.28
November	0.29	0.290	0.29
December	0.29	0.299	0.30

Energy-based methods

The energy-based method applies the energy balance concept to estimate potential evapotranspiration (ZHAO et al., 2013).

Jensen-Haise (1963): this method was defined to calculate evapotranspiration from temperature and solar radiation data, applied to arid and semi-arid regions, through the Equation 7:

$$ETo_{JH} = Sr\left(0.0252T_m + 0.078\right) \qquad (7)$$

Where Sr is the solar radiation at ground level (mm d^{-1}).

Makkink (1957): based on Penman method, Makkink uses solar radiation at ground level to estimate evapotranspiration. Developed in the Netherlands, it is well known at European western region and can be calculated through the Equation 8:

$$ETo_{Mak} = 0.61 \quad W \quad Sr - 0.12 \qquad (8)$$

$$W = \frac{\Delta}{\Delta + \gamma}$$

Where W is a weighting factor representing proportion of Sr (solar radiation) used by evapotranspiration, adjusted to different height and temperature values; Δ is the slope of the pressure curve of water vapor in the air atmosphere (kPa ºC^{-1}); γ is the psychometric constant (kPa ºC^{-1}).

Solar Radiation: The method is a Doorenbos & Pruitt (1977) adaptation of FAO-24 method of solar radiation proposed by Makkink (1957), previously developed to humid conditions of the Netherlands, according to the Equation 9:

$$ETo_{RS} = c_0 + c_1 \quad W \; Sr \qquad (9)$$

The value of c1 is determined as follows:

$$c_1 = a_0 + a_1 RH \;\; + a_2 U_2 + a_3 RH \;\; U_2 + a_4 RH \;^2 + a_5 U_2{}^2$$

Where C$_0$ is a constant equal to -0,3 (mm d^{-1}); and the coefficients: a_0 = 1.0656, a_1 = -0.0012795, a_2 = 0.044953, a_3 = -0.00020033, a_4 = -0.000031508 and a_5 = -0.0011026.

Priestley & Taylor (1972): the method approximates Penmans' method through simplification, maintaining only the solar radiation balance corrected by an empirical coefficient known as the Priestley and Taylor parameter, what incorporates the additional energy to the process of evapotranspiration as function of the aerodynamic term. The method follows the Equation 10:

$$ETo_{PT} = \frac{\alpha \; W\left(Rn - G\right)}{\lambda} \qquad (10)$$

Where α is the Priestley and Taylor parameter equals to 1.26; λ is the evaporation latent heat equals to = 2.45 MJ Kg^{-1}; Rn is the daily amount of liquid solar radiation – or radiation balance (MJ m^{-2} d^{-1}); G is the soil heat flux (MJ m^{-2} d^{-1}).

Mass transfer-based method

Known as one of the oldest evapotranspiration methods, the mass transfer-based method estimates the free water surface potential evaporation mainly considering the effect of air pressure deficit and wind speed (ZHAO et al., 2013).

Penman original (1948): is one of the most used methods applied to evapotranspiration estimative; the equation is derived assuming proportionality among water evaporation and sub-irrigated grass evapotranspiration. The method is obtained by the Equation 11:

$$ETo_{PE} = \frac{W\,Rn}{\lambda} + (1 - W)\ E_a \qquad (11)$$

Where E_a is the power of air evaporation ($MJ\ m^{-2}\ d^{-1}$).

Reference Method (Penman-Monteith)

The Penman-Monteith method assume evapotranspiration as an outcome of the energy and aerodynamic terms which are governed by the resistance transport of water vapor to the atmosphere (FERNANDES; FRAGA JÚNIOR; TAKAY, 2011). The Penman-Monteith method (FAO56-PM) is parametrized by Allen et al. (1998) in the Equation 12:

$$ETo_{PM} = \frac{0.408\ \Delta\ (Rn - G) + \left[\frac{\gamma\ 900\ U_2\ (e_s - e_a)}{T_m + 273}\right]}{\Delta + \gamma\ (1 + 0.34\ U_2)} \qquad (12)$$

Where ETo_{PM} is the reference evapotranspiration ($mm.d^{-1}$); Δ is the slope of the pression curve of water vapor in the air atmosphere ($kPa\ ^{o}C^{-1}$); Rn is the daily amount of liquid solar radiation – or radiation balance ($MJ\ m^{-2}\ d^{-1}$); G is the soil heat flux ($MJ\ m^{-2}\ d^{-1}$); γ is the psychometric constant ($kPa\ ^{o}C^{-1}$); U_2 is the wind speed at 2m above ground ($m\ s^{-1}$); e_s is the water vapor saturation pressure (kPa); e_a is the current water vapor pression (kPa); T_m is the mean air temperature (ºC); r is the grass surface reflection coefficient, assumed equal 0.25.

Evaluation of methodologies

The ETo data obtained through the different methodologies were compared with the data obtained by the FAO56-PM method. The performance of the methods in relation to the FAO56-PM method was verified by comparing the linear regression parameters, mean bias (MB), root of mean squared error (RMSE), mean absolute error (MAE), standard error (SE) and, coefficient of performance (c). Table 2 was used to interpret the confidence coefficient.

The mean bias (MB) of each method was calculated from the Equation 13:

$$MB = N^{-1} \sum_{i=1}^{N} (P_i - O_i) \qquad (13)$$

Where O_i is the ETo estimated FAO56-PM method ($mm\ d^{-1}$); P_i is the ETo estimated by the empirical methods ($mm\ d^{-1}$); N is the number of observation.

The discrepancy was calculated by the root of mean squared error (RMSE) and the mean absolute error (MAE) by the Equations 14 and 15:

$$RMSE = \sqrt{\left(N^{-1} \sum_{i=1}^{N} (P_i - O_i)^2\right)} \qquad (14)$$

$$MAE = N^{-1} \sum_{i=1}^{N} |P_i - O_i| \qquad (15)$$

The standard error (SE) was calculated by the Equation 16:

$$SE = \sqrt{\frac{\sum_{i=1}^{N} (O_i - P_i)^2}{N - 1}} \qquad (16)$$

The agreement was given by the determination coefficient (R^2), the correlation coefficient (r) and the agreement index (d) as proposed by Willmott et al. (1985), by the Equation 17:

$$d = 1 - \left[\frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left(|P_i - O| - |O_i - O|\right)^2}\right] \qquad (17)$$

The agreement index is an efficiency measure of the analyzed methods that takes into account the dispersion over the straight line 1:1. Reliability was determined by the confidence index (c) proposed by Camargo & Sentelhas (1997) as the product of r and c, i.e., c = r.d. The confidence results are classified according the c values as Table 2.

TABLE 2 - Confidence index classification (c) according to Camargo & Sentelhas (1997).

c values	Classification
> 0.85	Excelent
0.76 a 0.85	Very good
0.66 a 0.75	Good
0.61 a 0.65	Moderate
0.51 a 0.60	Inadequate
0.41 a 0.50	Bad
< 0.41	Very bad

3 RESULTS AND DISCUSSION

The evaluation criteria of the empirical methods analyzed are in Table 3. Note that considering the global mean of the entire period, Thornthwaite and Camargo methods underestimate evapotranspiration according to the Mean Bias (MB) criterion; whereas Hargreaves-Samani and Blaney-Criddle are close to the standard reference method. In general, the methods that overestimate evapotranspiration show greater discrepancy as well, as exhibited by the RMSE, MAE and SE criteria results relative to Jensen-Haise, Solar Radiation and Penman Original methods. Similar results were observed by Melo & Fernandes (2012) evaluating these methods to estimate evapotranspiration of a neighboring region (i.e., at Uberaba-MG) in the period from 1990 to 2010.

Alencar et al. (2011a) used Blaney-Criddle, Solar Radiation and Hargreaves-Samani methods to estimate evapotranspiration at Uberaba-MG region in the period from 1996 to 2005 and verified that, these methods overestimate the ETo based on VM criteria.

A graphical analysis was performed where the regression graphs of the empirical methods against the standard reference method (FAO56-PM) for the long-term period (35 years) are exhibited in Figure 3 (first column - left margin).

Hence, each blue line in the Figure 3 (left column graphs) shows the graphical analysis of each one of the specific empirical methods according to regression line, residuals and time-series of monthly ETo estimates.

Visual analysis of the graphs in Figure 3 based in time-series of monthly evapotranspiration estimation, residuals and regression line shows a better performance of Jensen-Haise, Solar Radiation, Makkink and Camargo methods, highlighting the Solar Radiation method relative to the residuals. This is confirmed by the residual standard error (RSE) and determination coefficient (R^2) of Table 4.

However, Jensen-Haise and Solar Radiation were not as good as Makkink and Hargreaves-Samani considering the agreement index (d) and performance index (c), which represents respectively bad and inadequate classification for the first two, and, very good and good for the last two ones. Solar Radiation showed the better performance according to the coefficient of determination but was categorized as inadequate by the Confidence index classification. Among Hargreaves-Samani and Makkink, the former was not categorized as very good by the confidence index classification as the later did. In the light of evidence, the best set of results highlights Makkink as the most adequate empirical method to estimate potential evapotranspiration to the Cerrado region of Minas Gerais state. Additionally, Makkink method uses information about air temperature and solar radiation only, which are easy obtainable parameters.

Ørum et al., 2010 point alternatives to save water by using new irrigation systems as well as technology of water saving devices. Public policies must support these alternatives as proposals to reduce the water demand and expand irrigated area over the Cerrado region based on the perspective of water rational use. The crops water requirement on the drier months at Cerrado are not supplied by rainfalls, they need to be fulfilled by efficient irrigation management practices. Therefore, effective evapotranspiration estimation methods play an important role. Makkink and Hargreaves-Samani methods have exhibited good performance on evapotranspiration estimation to the study area and have a low cost in terms of parameters required, such as temperature and solar radiation, which make them accessible to the Cerrado farmers in Minas Gerais state.

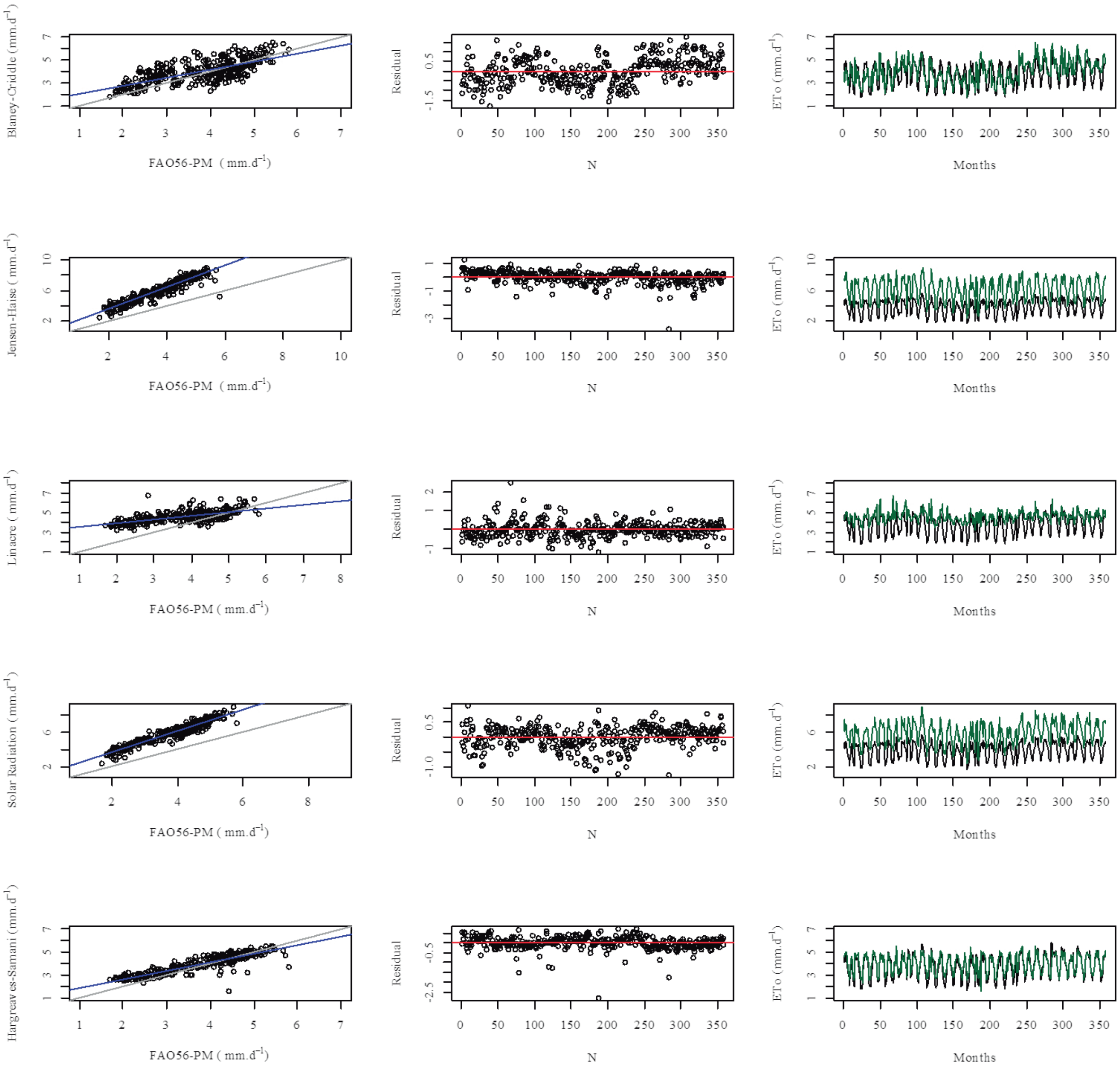
TABLE 3 - Evaluation criteria of the empirical methods.

Method	Evaluation criteria			
	MB (mm d^{-1})	RMSE (mm d^{-1})	MAE (mm d^{-1})	SE (mm) d^{-1})
Blaney-Criddle	0.22	0.79	0.65	0.79
Jensen-Haise	2.36	2.44	2.36	2.44
Linacre	0.78	1.08	0.86	1.08
Solar radiation	2.06	2.10	2.06	2.11
Hargreaves-Samani	0.17	0.46	0.34	0.46
Makkink	0.50	0.61	0.55	0.61
Thornthwaite	-1.09	1.22	1.10	1.22
Camargo	-0.85	0.94	0.85	0.94
Priestley-Taylor	0.42	0.96	0.81	0.96
Penman Original	2.11	2.28	2.11	2.28

TABLE 4 - Evaluation of the empirical methods performance.

Methods	Intercept p-value	Coefficient p-value	RSE	R^2	d	c	Classification
Blaney-Criddle	1.414 2e-16’	0.687 2e-16’	0.69	0.49	0.83	0.58	Inadequate
Jensen-Haise	0.776 9.57e-15’	1.413 2e-16’	0.45	0.9	0.53	0.5	Bad
Linacre	3.16 2e-16’	0.375 2e-16’	0.42	0.44	0.65	0.44	Bad
Solar radiation	1.215 2e-16’	1.218 2e-16’	0.36	0.92	0.57	0.55	Inadequate
Hargreaves-Samani	1.144 2e-16’	0.744 2e-16’	0.34	0.82	0.94	0.84	Very good
Makkink	1.048 2e-16’	0.854 2e-16’	0.31	0.88	0.9	0.85	Very good
Thornthwaite	0.508 9.29e-13’	1.577 2e-16’	0.32	0.75	0.69	0.6	Inadequate
Camargo	0.3 1.94e-7’	0.697 2e-16’	0.27	0.86	0.78	0.73	Good
Priestley-Taylor	-0.894 1.31e-7’	1.347 2e-16’	0.79	0.74	0.86	0.74	Good
Penman	1.861 2e-16’	1.066 2e-16’	0.87	0.59	0.53	0.41	Very bad

Significance level: #1; *0.1; **0.01; ***0.001;’. < 0.0001; RSE residual standard error at 356 degrees of freedom; Adjusted R^2; d – index of agreement and c – index of performance.


Blaney-Criddle (mm.d^{-1})
FAO56-PM (mm.d^{-1})
Residual
N
ETo (mm.d^{-1})
Months
Jensen-Haise (mm.d^{-1})
FAO56-PM (mm.d^{-1})
Residual
N
ETo (mm.d^{-1})
Months
Linacre (mm.d^{-1})
FAO56-PM (mm.d^{-1})
Residual
N
ETo (mm.d^{-1})
Months
Solar Radiation (mm.d^{-1})
FAO56-PM (mm.d^{-1})
Residual
N
ETo (mm.d^{-1})
Months
Hargreaves-Samani (mm.d^{-1})
FAO56-PM (mm.d^{-1})
Residual
N
ETo (mm.d^{-1})
Months
0 50 100 150 200 250 300 350

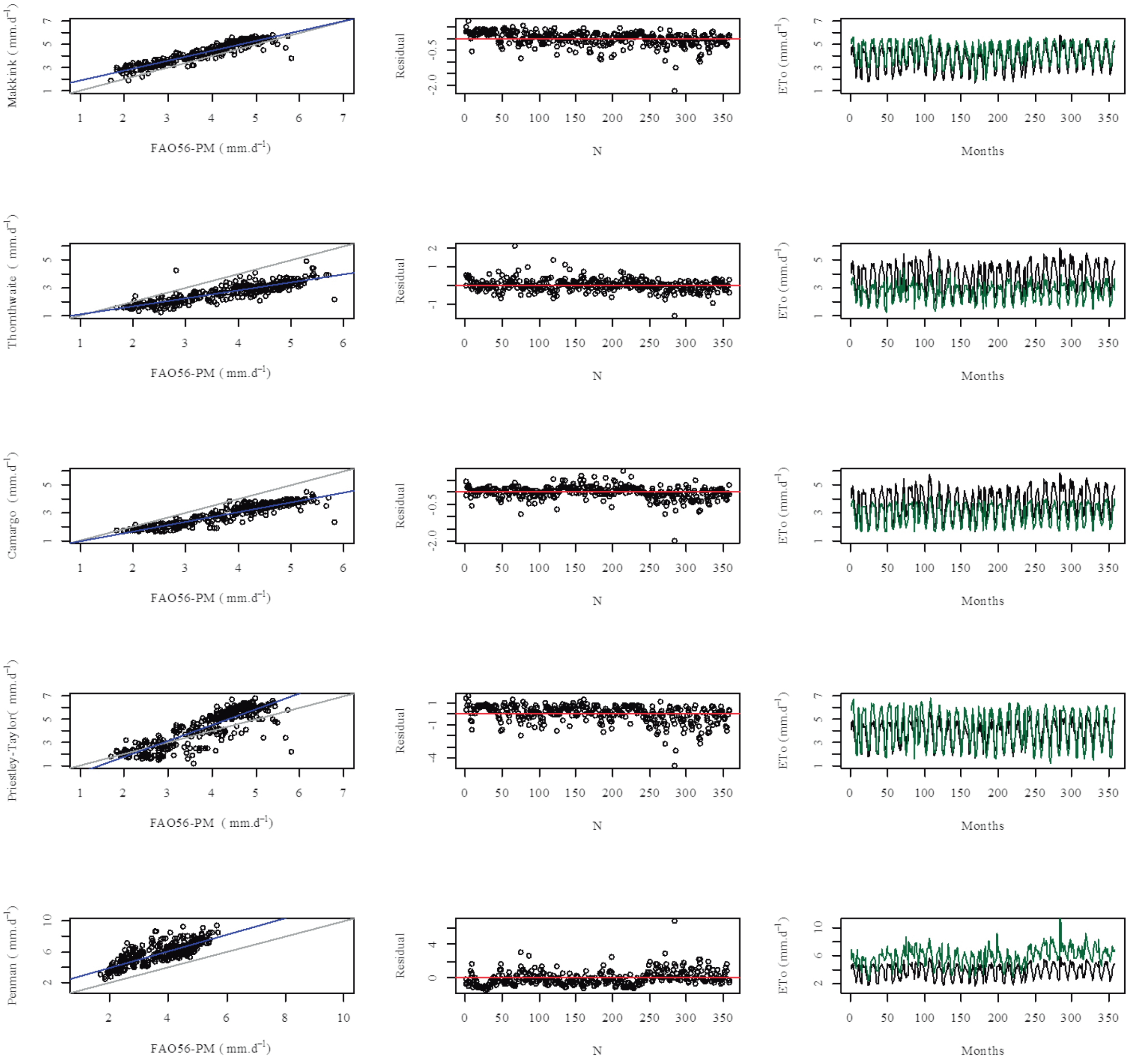


FIGURE 3 - Monthly evapotranspiration values (FAO56 Penman-Monteith versus empirical methods) compared by linear regression. The grey line shows the 1:1 relation. Residuals are in the middle column and time-series of evapotranspiration estimation values in the right column.

4 CONCLUSION

Among the alternative methods, the Makkink method presented better performance, therefore can be used to estimate the reference evapotranspiration for irrigation management purposes of coffee crop in the Cerrado region from Minas Gerais. As a second option, the Hargreaves-Samani and Camargo temperature-based methods also can be used to reference evapotranspiration estimation.

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