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Models for Estimating Reference Evapotranspiration in Different Periods in Rio Verde, Goiás, Brazil

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Abstract

The water management in irrigated agriculture begins determining the need of water for the culture. Therefore, it was intended to evaluate the performance of the models of estimation reference of evapotranspiration (ETo) with regard to the method Penman-Monteith (PM), standard method, for Brazilian Cerrado Region (tropical grassland/savannah). The climate elements were obtained from the conventional weather station of Rio Verde from January/1972 to December/2016. It was compared the performance of the daily average ETo, during the dry, rainy and annual periods, by the PM method with regard to another 26 methods. Through the coefficient of determination, it was verified the methods of Turc (T) and Radiation-Temperature (RT) approached more to the PM, at any time of the year, being able to replace the standard method. The ETo average in the annual period was 3.8 mm day^{-1}, for the dry period due to the smallest amount of solar radiation, the period submitted lower levels of ETo. The other models in which were used fewer amounts of climate data, they overestimated or underestimated the PM model by up to 57.9% and 60.7% respectively. With the management of water in agriculture, water availability can be increased in the hydric bodies, characterizing it as a tool for water management with the rational use of water resources.

Keywords: water balance, water requirement, irrigation, penman-monteith

1. Introduction

The use of irrigation in regions where rainfall does not meet or partially meets the water requirement of crops is one strategy to promote food production and the controlled expansion of arable land (Hallal et al., 2013).

Water management in agriculture involves determining the water requirement of the crops (Caporusso & Rolim, 2015; Melo et al., 2013); it is the most relevant variable in the hydrological cycle (Oliveira et al., 2017) and the primary component of water balance. Furthermore, water management strategies need to be included in projects of management of irrigation systems and river basins, and small errors can compromise the water resources of specific regions (Cunha et al., 2017).

Many of the water users in agricultural areas do not know how to make rational use of this resource. The correct estimation of reference evapotranspiration (ETo) becomes indispensable to determine the amount of water needed to be added to the soil for irrigation control (Lozano et al., 2017; Lacerda & Turco, 2015), optimizing the use of water resources, electrical energy, and equipment. Therefore, it is necessary to evaluate the effectiveness of different water management methods, which may present errors due to meteorological variations in each region (Landeras et al., 2018; Hallal et al., 2013; Sales, 2008).

ETo is a key component of the hydrological cycle, determining it in a correct way is essential to generate scientific information, including hydrology, management of water resources, numerical models of simulation, climatology, agricultural management, eco-hydrology and Biodiversity (Córdova et al., 2015).

Zhao et al. (2013) affirmed evapotranspiration plays a key role in the water balance, according to statistical data the evapotranspiration of humid areas is responsible for 50% of the annual precipitation, while in the semi-arid regions it is responsible for 90%.

The standard method for estimating ETo is the Penman-Monteith (PM) method, proposed by Allen et al. (1998). This model is used worldwide and does not require local calibration and certification. Furthermore, the obtained results are accurate (Fernandes et al., 2012). Carvalho et al. (2015) reported that the main disadvantage of the

PM method is the large number of meteorological variables required for its application, and many weather stations do not have the necessary sensors to measure all variables.

Because of the large number of regions without meteorological data, the use of models of estimation of ETo that require few meteorological elements is essential (Caporusso & Rolim, 2015; Moura et al., 2013).

Cavalcante et al. (2011) argue that other methods that require fewer weather elements can be used accurately provided these methods are compared with historical data.

Almorox et al. (2018), compared in his study two methods of ETo, temperature equation of Penman-Monteith (PMT) using only data of maximum and minimum temperatures and the Hargreaves-Samani equation, evaluating both of them comparing the quality of the PMT method to different climates, calculated on a monthly time scale, they observed that the PMT equation produced better results, especially in tropical climates.

The characterization of the water demand related to the weather is important for the expansion of the irrigation in farmlands in Brazilian Cerrado Regions. Studies held in this region it was observed that the best methods for estimation of evapotranspiration were ASCE Penman-Monteith, Penman (1948/1963) and Blaney-Criddle, recommended for Cerrado in rainy or dry areas (Gotardo et al., 2016).

Therefore, this work evaluated estimation models of reference evapotranspiration with the regard to the method of Penman-Monteith (FAO Standard) for the municipality of Rio Verde, Goiás, Brazil, observing the efficiency of the use of water in areas with shortage of equipment of measurement of meteorological elements.

Other methods that estimate the ETo in Rio Verde need to be evaluated because this region has a significant economic importance related to agriculture and livestock, which require large amounts of water. The municipality of Rio Verde is the largest grain producer in the state of Goiás, with a yield of approximately 1.2 million tons per year and is responsible for 1.2% of the national grain production.

Therefore, this work evaluated estimation models of reference evapotranspiration with the regard to the method of Penman-Monteith (FAO Standard) observing the efficiency of the use of water in areas with shortage of equipment of measurement of meteorological elements.

2. Material and Methods

2.1 Study Sites

The municipality of Rio Verde is located in the southwest region of the state of Goiás, at the coordinates 17°47′33″ S and 50°55′10″ W, with a geographical area of 8,379,661 km².The relief is slightly undulating, with a slope of 5% and altitudes from 600 to 860 m, except for some hills with higher altitudes. The predominant soil is Red Latosol and Red Yellow Latosol (Acqua et al., 2013). The biomes include Cerrado sensu stricto (savannas) and semi-deciduous seasonal forest (Rocha et al., 2014).

2.2 Weather Data

The meteorological data were obtained from the National Institute of Meteorology (INMET) of the Conventional Meteorological Station of Rio Verde (WMO: 83470) in collaboration with the University of Rio Verde (UniRV) located at the latitude 17°47′07″ S, longitude 50°57′53″ W, with an altitude of 774.62 m.

Meteorological data were collected daily from January, 1972, to December, 2016, with the exception of the years 1975, 1978, 1979, and 1991 to 1996, which were not accounted for because of data unavailability, thus comprising a total of 36 years. The evaluated climatic elements were minimum air temperature (Tmin), maximum air temperature (Tmax), mean relative humidity (RH) of the air, wind velocity (WV), solar brightness (SB), and precipitation (P), and the latter variable was used for determining the climatological water balance (CWB).

The daily mean Tmin, Tmax, RH and WV at a height of 10 m. Solar radiation (SR) was estimated according to Allen et al. (1998) (Equation 1).

$$SR = 0.25 + \left[0.5\left(\frac{n}{N}\right)\cdot Ra\right] \quad (1)$$

where, SR is solar radiation (MJ m^{-2} d^{-1}); n is solar brightness (h); N is insolation (h), and Ra is extraterrestrial radiation (MJ m^{-2} d^{-1}).

The estimated daily ETo values were calculated in Microsoft Excel using the standard Penman-Monteith model as a reference (Allen et al., 1998) (Equation 2).

$$ETo = \frac{0.408 \cdot \Delta\,(Rn - G) + \gamma \cdot \frac{900}{(Tmean + 273)} \cdot U_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot U_2)} \tag{2}$$

where, Rn = Surface radiation balance (MJ m^{-2} d^{-1}); G = soil heat flow (MJ m^{-2} d^{-1}); Tmean = Mean air temperature (°C); U_2 = Wind speed at a height of 2 m (m s^{-1}); e_s = Mean vapor saturation pressure (kPa); e_a = Current vapor pressure (kPa); Δ = Declination of the saturation pressure curve (kPa $°C^{-1}$); γ = Psychometric constant (kPa $°C^{-1}$).

The methods used in the study (Table 1) were: Hargreaves (Hg), Priestley-Taylor (PT), Linacre (Ln), Jensen-Haise (JH), Makkink (M), Romanenko (R), Hansen (Hs), Hamon (Hm), Blaney-Criddle (BC), Benevides-Lopez (BL), Caprio (Cp), Turc (T), Camargo (Cm), Budyko (B), Tanner-Pelton (TP), Stephens-Stewart (SS), Radiation-Temperature (RT), Net Radiation (NR), Global Radiation (GR), Hicks-Hess (HH), Lungeon (Lg), McGuiness-Bordne (MB), Kharrufa (K), Blaney-Morin (BM), Ivanov (I) e FAO Radiation (FR).

Table 1. Equations for the proposed methods of estimation of reference evapotranspiration in Rio Verde, Goiás, Brazil

Method	Equation	Reference
Hg	$ETo = 0.0023 \cdot (Tmean + 17.8) \cdot (Tmax - Tmin)^{0.5} \cdot Rae$	Sousa et al. (2010)
PT	$ETo = \frac{\alpha \cdot w \cdot (Rn - G)}{\lambda}$	Sousa et al. (2010)
Ln	$ETo = \frac{700 \cdot \frac{(Tmean + 0.006Z)}{(100 - \phi)} + 15 \cdot (Tmean - To)}{80 - Tmean}$	Sales (2008)
JH	$ETo = Rse \cdot (0.025 \cdot Tmean + 0.08)$	Sousa et al. (2010)
M	$ETo = Rse \cdot \left(\frac{\Delta}{\Delta + \gamma}\right) + 0.12$	Sousa et al. (2010)
R	$ETo = 4.5 \cdot \left(1 + \frac{Tmean}{25}\right)^2 \cdot \left(1 - \frac{e_a}{e_s}\right)$	Tanaka et al. (2016).
Hs	$ETo = 0.7 \cdot \left(\frac{\Delta}{\Delta + \gamma}\right) \cdot \left(\frac{Rse}{\lambda}\right)$	Tanaka et al. (2016).
Hm	$ETo = 0.55 \cdot \left(\frac{N}{12}\right)^2 \cdot \left(\frac{4.95 \cdot e^{0.062 \cdot Tmean}}{100}\right) \cdot 25.4$	Cavalcante et al. (2011)
BC	$ETo = 0.75 \cdot (0.457 \cdot Tmean + 8.13) \cdot p$	Cunha et al. (2013)
BL	$ETo = 1.21 \times 10^{\left(\frac{7.45 - Tmean}{243.7 + Tmean}\right)} \cdot \left(1 - 0.01 \cdot UR\right) + 0.21 \cdot Tmean - 2.3$	Cavalcante et al. (2011)
Cp	$ETo = \left[\frac{6.1}{10^6} \cdot Rs' \cdot (1.8 + Tmean + 1.0)\right]$	Tanaka et al. (2016).
T	For RU < 50% $ETo = 0.013 \cdot \left[\frac{Tmean}{Tmean + 15}\right] \cdot (SRe \cdot 58.5 + 50) \cdot \left(1 + \frac{50 - RU}{70}\right)$ For RU ≥50% $ETo = 0.013 \cdot \left[\frac{Tmean}{Tmean + 15}\right] \cdot (SRe \cdot 58.5 + 50)$	Xu (2002)
Cm	$ETo = 0.01 \cdot Rae \cdot Tmean$	Cunha et al. (2013)
B	$ETo = 0.2 \cdot Tmean$	Budyko (1956)
TP	$ETo = 0.457 \cdot Rns - 0.11$	Cunha et al. (2013)
SS	$ETo = 0.4047 \cdot SR \cdot [(0.01476 \cdot Tmean) + 0.0724]$	Cunha et al. (2013)
RT	$ETo = \frac{1}{\lambda} \cdot \left(\frac{SR \cdot Tmax}{56}\right)$	Cunha et al. (2013)
NR	$ETo = 0.86 \cdot \frac{Rns}{\lambda}$	Cunha et al. (2013)
GR	$ETo = 0.9 + 0.115 \cdot SR$	Cunha et al. (2013)
HH	$ETo = \frac{1}{\lambda} \cdot \left(\frac{\Delta}{0.90 \cdot \Delta + 0.63 \cdot \gamma}\right) \cdot Rns$	Cunha et al. (2013)
Lg	$ETo = 0.2985 \cdot \left(e_s - e_a\right) \cdot \left(\frac{273 + Tmean}{273}\right) \cdot \left(\frac{760}{P - e_s}\right)$	Cunha et al. (2013)
MB	$ETo = \left(\frac{Ra}{\lambda}\right) \cdot \left(\frac{Tmean + 5}{68}\right)$	Cunha et al. (2013)
K	$ETo = 0.34 \cdot p \cdot (Tmean)^{1.3}$	Cunha et al. (2013)
BM	$ETo = p \cdot (0.457 \cdot Tmean + 8.13) \cdot (1.14 - 0.01 \cdot RU)$	Cunha et al. (2013)
I	$ETo = 0.006 \cdot (25 + Tmean)^2 \cdot \left(1 - \frac{RU}{100}\right)$	Cunha et al. (2013)
RF	$ETo = -0.3 + 0.75 \cdot \left(\frac{\Delta}{\Delta + \gamma} \cdot SRe\right)$	Cunha et al. (2013)

Note. Tmean = Mean air temperature (°C); Tmax = maximum temperature (° C); Tmin = minimum temperature (°C); Rae = extraterrestrial radiation (mm d^{-1}); α = Priestley and Taylor parameter; w = weighting factor; Rn = surface radiation balance (MJ m^{-2} d^{-1}); G = soil heat flow (MJ m^{-2} d^{-1}); λ = latent heat of water evaporation (MJ Kg^{-1}); Z = altitude (m); To = dew point temperature (°C); φ = latitude (º); SRe = global solar radiation (mm d^{-1}); Δ = declination of the saturation pressure curve (kPa $ºC^{-1}$); γ = psychometric constant (kPa $ºC^{-1}$); a = saturation pressure at dew point (KPa); es = mean vapor saturation pressure (KPa); N = insolation (h); p = percentage of hours of daily sunshine relative to the total hours of sunshine per year (%); RH = relative air humidity (%); SR' = global solar radiation (KJ m^{-2} d^{-1}); Rns = radiation balance (MJ m^{-2} d^{-1}); p = atmospheric pressure (KPa); Ra = extraterrestrial radiation (MJ m^{-2} d^{-1}).

2.3 Statistical Analysis

The methods of estimation of ETo were compared in three periods: annual period, dry season, and rainy season, according to the CWB. Statistical performance was assessed using the Pearson correlation coefficient (r) to determine the degree of accuracy. Accuracy was determined using the Willmott index (d) according to Carvalho et al. (2015) and the performance index “c” proposed by Camargo and Sentelhas (1997).

Standard error estimates (SEEs) were used to evaluate the accuracy of the estimates, and the comparative analysis was based on linear regression and coefficient of determination (R^2) between the standard method and the methods that presented performance indexes ≥ 0.70 (Table 2) and SEEs ≤ 0.7 mm d^{-1}, in which the independent variable was the ETo measured using the PM method and the dependent variable was the ETo measured using the other methods.

Table 2. Criterion of interpretation of the confidence index “c” of the methods of estimation of reference evapotranspiration using the Penman-Monteith method as a reference

I	Performance index						
	Excellent	Very good	Good	Moderate	Fair	Poor	Very poor
c	> 0.85	0.76-0.85	0.66-0.75	0.61-0.65	0.51-0.60	0.41-0.50	≤ 0.40

Note. I = Index; c = performance index.

Source: Camargo and Sentelhas (1997).

3. Results and Discussion

3.1 Reference Evapotranspiration in the Annual Period

The estimation of ETo using the PM method presented a mean of 3.8 mm d^{-1}, with the lowest value in June (2.9 mm d^{-1}) and the highest value in September and October (4.5 mm d^{-1}) (Table 3). The TP and MB methods ad the highest mean (6.0 mm d^{-1}) where as the Hs method presented the lowest mean (1.5 mm d^{-1}). The T and RT models presented mean ETo values similar to those of the PM method, and SEE was 0.5 and 0.6 mm d^{-1}, respectively. Therefore, the T and RT models overestimated the ETo from March to July and from February to July respectively, and underestimated the ETo from August to December and from September to December, respectively.

Table 3. Mean daily reference evapotranspiration (mm) in Rio Verde, Goiás, Brazil, using different methods

Methods	Months												Ẍ	UE (%)	OE (%)	SEE
	J	F	M	A	M	J	J	A	S	O	N	D				
PM	3.8	4.0	3.7	3.6	3.1	2.9	3.3	4.1	4.5	4.5	4.1	3.5	3.8	-	-	-
Hg	5.0	5.0	4.7	4.2	3.6	3.4	3.7	4.5	5.2	5.4	5.2	5.1	4.6	-	20.1	0.8
PT	4.5	4.7	4.4	4.0	3.2	2.8	2.9	3.4	3.9	4.5	4.6	4.1	3.9	-	3.0	0.7
Ln	4.4	4.5	4.5	4.5	4.3	4.4	4.5	4.9	5.1	4.9	4.5	4.4	4.6	-	20.6	0.5
JH	5.0	5.3	5.0	4.9	4.1	3.8	4.1	4.8	5.0	5.4	5.2	4.4	4.8	-	25.1	0.8
M	5.5	5.9	5.6	5.5	4.9	4.6	4.8	5.4	5.5	5.9	5.7	4.9	5.3	-	40.5	0.8
R	3.6	3.9	3.9	4.8	5.2	6.0	7.3	9.0	5.6	6.7	4.5	3.7	5.6	-	47.3	2.4
Hs	1.5	1.7	1.6	1.5	1.4	1.3	1.4	1.5	1.5	1.7	1.6	1.4	1.5	60.7	-	0.2
Hm	3.7	3.5	3.2	2.9	2.4	2.2	2.2	2.7	3.2	3.6	3.6	3.7	3.1	19.5	-	0.6
BC	4.3	4.2	4.0	3.8	3.5	3.3	3.4	3.7	4.0	4.2	4.3	4.3	3.9	-	2.6	0.4
BL	3.0	3.1	3.1	3.0	2.7	2.6	2.7	3.1	3.4	3.4	3.1	3.0	3.0	20.9	-	0.4
Cp	4.8	5.2	4.9	4.8	4.0	3.7	3.9	4.6	4.9	5.3	5.0	4.3	4.6	-	21.4	0.8
T	3.8	4.0	3.8	3.8	3.3	3.2	3.5	4.1	4.2	4.2	3.9	3.4	3.8	0.9	-	0.5
Cm	4.1	4.0	3.7	3.1	2.5	2.2	2.3	2.9	3.5	4.0	4.1	4.1	3.4	11.5	-	0.7
B	4.9	4.9	4.9	4.8	4.4	4.3	4.3	4.6	4.9	5.0	4.9	4.9	4.7	-	24.3	0.4
TP	6.1	6.5	6.2	6.1	5.5	5.2	5.6	6.1	6.1	6.5	6.3	5.4	6.0	-	56.7	1.0
SS	3.1	3.3	3.1	3.0	2.6	2.4	2.5	3.0	3.1	3.4	3.2	2.7	3.0	22.2	-	0.5
RT	3.8	4.1	3.9	3.8	3.3	3.1	3.4	4.0	4.1	4.3	4.0	3.3	3.8	0.8	-	0.6
NR	4.8	5.1	4.8	4.8	4.3	4.1	4.4	4.8	4.8	5.1	4.9	4.2	4.7	-	22.8	0.8
GR	2.9	3.1	2.9	2.9	2.7	2.6	2.8	2.9	2.9	3.0	3.0	2.7	2.9	24.2	-	0.3
HH	5.0	5.3	5.1	5.0	4.4	4.1	4.4	4.9	5.0	5.3	5.2	4.4	4.8	-	27.6	0.8
Lg	1.8	2.0	2.0	2.4	2.5	2.9	3.6	4.7	4.6	3.6	2.3	1.9	2.9	24.4	-	1.3
MB	7.3	7.1	6.5	5.6	4.5	4.0	4.2	5.1	6.2	7.0	7.2	7.3	6.0	-	57.9	1.2
K	6.4	6.2	6.0	5.6	4.8	4.6	4.6	5.3	6.0	6.4	6.4	6.4	5.7	-	50.5	0.8
BM	2.0	2.0	1.9	2.1	2.2	2.3	2.8	3.3	3.3	2.8	2.2	2.0	2.4	36.7	-	0.6
I	3.0	3.2	3.2	4.0	4.3	5.0	6.4	7.5	7.1	5.6	3.8	3.1	4.7	-	22.8	2.0
RF	2.4	2.6	2.5	2.4	2.1	2.0	2.1	2.4	2.4	2.6	2.5	2.1	2.3	38.2	-	0.4

Note. PM = Penman-Monteith, Hg = Hargreaves, PT = Priestley-Taylor, Ln = Linacre, JH = Jensen-Haise, M = Makkink, R = Romanenko, Hs = Hansen, Hm = Hamon, BC = Blaney-Criddle, BL = Benevides-Lopez, Cp = Caprio, T = Turc, Cm = Camargo, B = Budyko, Tp = Tanner-Pelton, SS = Stephens-Stewart, RT = Radiation-Temperature, NR = Net Radiation, GR = Global Radiation, HH = Hicks-Hess, Lg = Lungeon, MB = McGuiness-Bordne, K = Kharrufa, BM = Blaney-Morin, I = Ivanov, FR = FAO radiation, Ẍ = Mean, UE (%) = Percentage of underestimation of the mean relative to the Penman-Monteith method, OE (%) = Percentage of overestimation of the mean relative to the Penman-Monteith method, SEE = standard error estimate.

The models of Hs, Hm, BL, Cm, SS, GR, Lg, BM, and RF presented mean ETo values lower than those of the PM method whereas the other analyzed methods produced mean ETo values higher than those of the PM method. The most discrepant results were those of the Hs method, which underestimated the ETo value in 60.7%, and the MB method, which overestimated the ETo value in 57.9%.

Alencar et al. (2015) evaluated the ETo values reported in FAO Bulletin 56 in the absence of some climatic variables and concluded that the performance of the methods was excellent in the absence of wind speed data, adequate in the absence of relative humidity data, and poor in the absence of solar radiation data.

The month of June presented the lowest ETo values in 82% of the analyzed methods, which is explained by the lower amount of net radiation.

The methods of Hm, BC, Cm, and K presented poor performance (Table 4) and the MB method presented very poor performance, which leads to considerable errors in water level quantification and therefore may cause severe water deficits or limit the productivity of irrigated crops in the analyzed region. The T model was the only method with excellent performance, which qualifies it as a method with greater efficiency when replacing the PM method annually in Rio Verde, and requires fewer variables in the equation (Tmean, SRe, and RH).

Table 4. Performance of the methods of estimation of annual reference evapotranspiration in Rio Verde, Goiás, Brazil

Methods	r	d	c	Performance index	Methods	r	d	c	Performance index
Hg	0.64	0.99	0.63	Moderate	B	0.54	0.99	0.53	Fair
PT	0.75	1.00	0.75	Good	TP	0.79	0.95	0.75	Good
Ln	0.65	0.99	0.64	Moderate	SS	0.85	0.99	0.83	Very good
JH	0.85	0.99	0.84	Very good	RT	0.85	1.00	0.85	Very good
M	0.82	0.97	0.80	Very good	NR	0.80	0.99	0.79	Very good
R	0.58	0.96	0.56	Fair	GR	0.79	0.98	0.78	Very good
Hs	0.82	0.81	0.67	Good	HH	0.82	0.98	0.81	Very good
Hm	0.48	0.99	0.47	Poor	Lg	0.60	0.98	0.59	Fair
BC	0.44	1.00	0.44	Poor	MB	0.41	0.95	0.38	Very poor
BL	0.65	0.99	0.64	Moderate	K	0.51	0.96	0.49	Poor
Cp	0.85	0.99	0.84	Very good	BM	0.65	0.95	0.61	Moderate
T	0.86	1.00	0.86	Excellent	I	0.58	0.99	0.57	Fair
Cm	0.42	1.00	0.42	Poor	RF	0.82	0.95	0.78	Very good

Note. r = Pearson correlation coefficient, d = Willmott index, c = Performance index.

The remaining methods were very good (JH, M, Cp, SS, RT, NR, GR, HH, and RF), good (PT, Hs, and TP), moderate (Hg, Ln, BL, and BM), and poor (R, B, Lg, and I). Allen et al. (1998) found that the Hg method might be used to replace the PM method and provided reliable data on the daily ETo. However, the Hg method was not effective, with moderate performance by overestimating the mean ETo by 20%, thus requiring calibration for use in Rio Verde to prevent water deficits and unnecessary costs.

Similarly, studies conducted in Santo Antônio de Goiás, Goiás (Fernandes et al., 2012), reported that the Hg method overestimated the ETo values. However, studies that compared a few methods (Lacerda & Turco, 2015; Palaretti et al., 2014) concluded that the Hg method was the closest to the PM method.

The SS and RF methods underestimated the ETo values considerably, and therefore the use of these methods might lead to water deficits in the irrigated crops (Figure 1). The methods of PT, T, RT, and GR presented variability, either overestimating or underestimating the ETo values. The RT model presented a lower variability, and its line was very close to the line of intersection with the PM method, indicating the similarity of the ETo values.

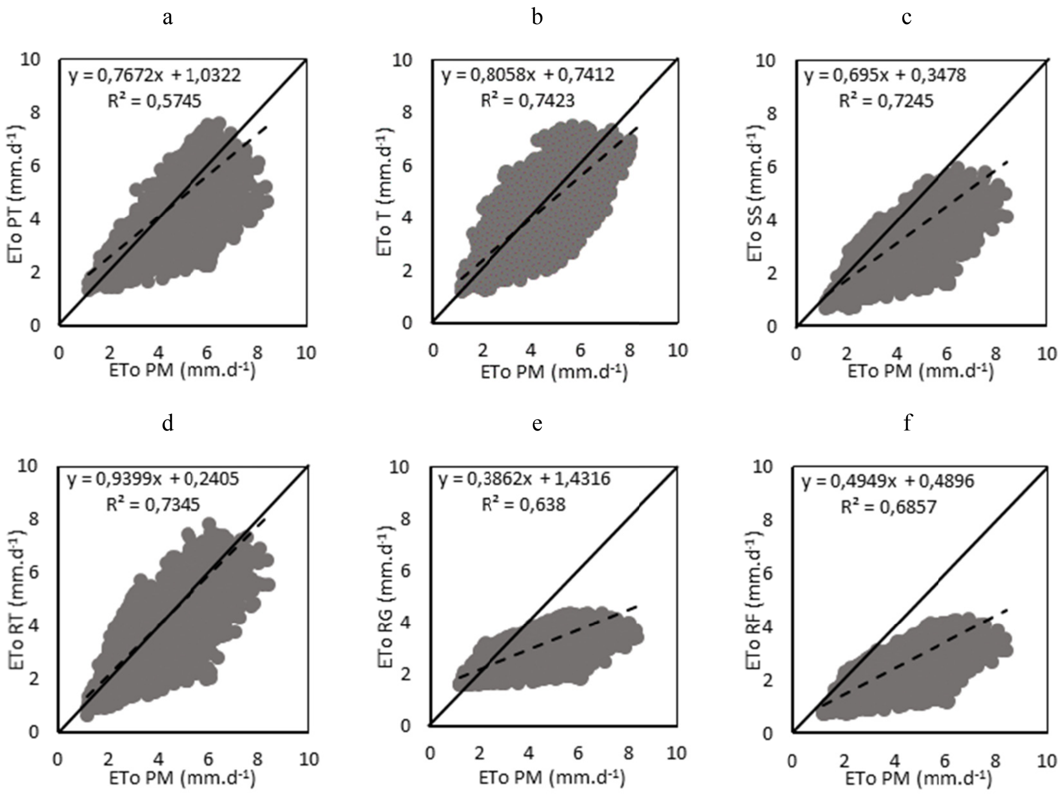

Figure 1. Equations and coefficients of determination of the methods of Priestley-Taylor (a), Turc (b), Stephens-Stewart (c), Radiation Temperature (d), Global Radiation (e), and FAO-Radiation (f) correlate to the standard Penman-Monteith method for estimating the annual reference evapotranspiration in Rio Verde, Goiás, Brazil

The highest coefficient of determination was 74% for the T method, indicating that 74% of the variation in estimating ETo using this method was explained by the variability of the PM method and generated the linear equation ETo PM = 0.8058·ETo·T + 0.7412. The lowest coefficient was 57% for the PT method.

The models T and RT were efficient to estimate ETo in the annual period in Rio Verde relative to the standard method.

3.2 Potential Evapotranspiration in the Dry Season

The performance was poor in the dry period, which is justified by the lower amount of SR in this period. Only four methods (T, SS, RT, and BM) reached the minimum values expected for the dry period (c ≥ 0.70 and SEE ≤ 0.7 mm d^{-1}). However, the T method presented the highest performance index (classified as very good), with variability of ETo of 0.62 mm d^{-1} relative to the standard model (Table 5).

Table 5. Performance of the methods of estimation of reference evapotranspiration in the dry season in Rio Verde, Goiás, Brazil

Methods	r	d	C	Performance index	SEE	Methods	r	d	c	Performance index	SEE
Hg	0.68	1.00	0.68	Good	0.62	B	0.52	0.99	0.52	Fair	0.45
PT	0.64	1.00	0.64	Moderate	0.61	TP	0.64	0.95	0.61	Moderate	1.05
Ln	0.66	0.98	0.65	Moderate	0.48	SS	0.73	0.98	0.72	Good	0.51
JH	0.73	0.99	0.72	Good	0.83	RT	0.74	1.00	0.74	Good	0.69
M	0.69	0.97	0.67	Good	0.88	NR	0.65	0.99	0.64	Moderate	0.81
R	0.69	0.90	0.63	Moderate	2.11	GR	0.64	0.99	0.63	Moderate	0.34
Hs	0.69	0.82	0.56	Fair	0.25	HH	0.68	0.98	0.67	Good	0.82
Hm	0.58	0.97	0.57	Fair	0.42	Lg	0.71	1.00	0.71	Good	1.18
BC	0.57	1.00	0.57	Fair	0.25	MB	0.56	0.98	0.55	Fair	0.76
BL	0.64	0.99	0.63	Moderate	0.47	K	0.56	0.97	0.54	Fair	0.70
Cp	0.74	0.99	0.73	Good	0.82	BM	0.72	0.98	0.70	Good	0.59
T	0.76	1.00	0.76	Very good	0.62	I	0.69	0.95	0.66	Good	1.76
Cm	0.57	0.98	0.56	Fair	0.46	RF	0.69	0.95	0.65	Moderate	0.40

Note. r = Pearson correlation coefficient, d = Willmott index, c = Performance index.

The performance of the other methods was good (Hg, JH, M, Cp, SS, RT, HH, Lg, BM, and I), moderate (PT, Ln, R, BL, TP, NR, GR, and RF), or poor (Hs, Hm, BC, Cm, B, MB, and K). The SEE using the R method was 2.11 mm d^{-1}, demonstrating a large discrepancy between the ETo estimates using this method and the PM method.

The coefficient of determination for the T and RT methods indicated that 60% of their variations were explained by the variation of the PM method (Figure 2).

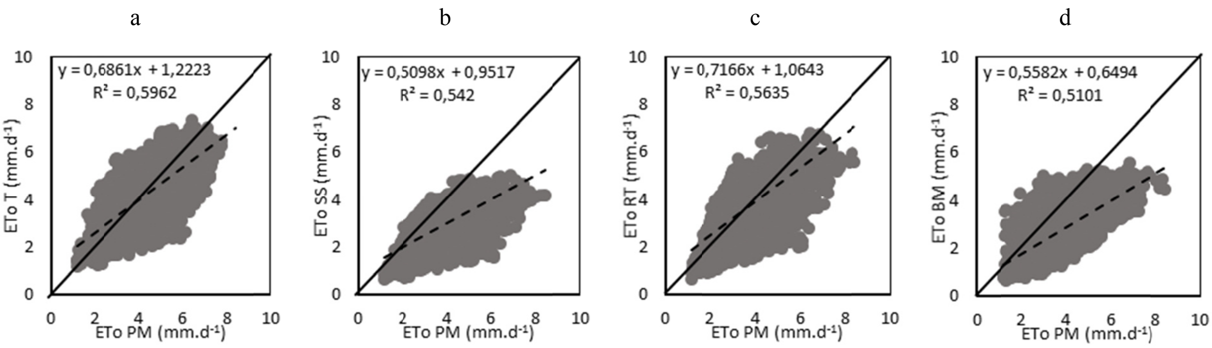

Figure 2. Equations and coefficients of determination of the methods of Turc (a), Stephens-Stewart (b), Radiation-Temperature (c), and Blaney-Morin (d) correlate to the standard Penman method-Monteith for estimating the annual reference evapotranspiration in Rio Verde, Goiás, Brazil

The SS and BM models underestimated ETo for values > 2.0 mm d^{-1}. The T and RT methods underestimated ETo for values > 4.0 mm d^{-1}, overestimated for values < 3.5 mm d^{-1}, and were adequate for values between 3.5 and 4.0 mm d^{-1}.

With regard to mean ETo values in the dry season, the PM method recommended the use of 36 m^3 of water per day to irrigate 1 ha of vegetated area, with a crop coefficient equal to one. The methods of T, SS, RT, and BM recommended the use of 37, 28, 36, and 49 m^3, respectively. The use of the T and BM models will result in a water deficit of 1 and 13 m^3 of water per day, respectively. The use of the SS model will cause a water deficit of 8 m^3 of water per day, possibly reducing cellular volume and impairing the physiological processes of the crops. The mean ETo was similar between the RT and PM methods in the dry season, with a variability of 7 m^3 per day.

3.3 Potential Evapotranspiration in the Rainy Season

For the rainy season, the analyzed methods presented better performance (Table 6) than for the dry season and annual period. Twelve methods (PT, JH, M, Cp, T, TP, SS, RT, NR, GR, HH, and RF) presented excellent performance, and seven methods (Ln, R, Hs, BL, Lg, BM, and I) presented good performance.

Table 6. Performance of the methods of estimation of the reference evapotranspiration in the rainy season in Rio Verde, Goiás, Brazil

Methods	r	D	C	Performance index	SEE	Methods	r	d	c	Performance index	SEE
Hg	0.62	0.98	0.61	Moderate	0.67	B	0.56	0.99	0.55	Fair	0.28
PT	0.90	1.00	0.90	Excellent	0.50	TP	0.91	0.95	0.87	Excellent	0.78
Ln	0.68	0.99	0.68	Good	0.44	SS	0.94	0.99	0.93	Excellent	0.36
JH	0.94	0.98	0.92	Excellent	0.58	RT	0.94	1.00	0.94	Excellent	0.47
M	0.92	0.97	0.90	Excellent	0.65	NR	0.91	0.99	0.90	Excellent	0.60
R	0.75	1.00	0.75	Good	1.58	GR	0.91	0.98	0.89	Excellent	0.26
Hs	0.93	0.81	0.75	Good	0.18	HH	0.92	0.98	0.91	Excellent	0.60
Hm	0.48	1.00	0.48	Poor	0.36	Lg	0.75	0.93	0.69	Good	0.91
BC	0.43	1.00	0.43	Poor	0.17	MB	0.42	0.92	0.39	Very poor	0.47
BL	0.67	0.99	0.67	Good	0.32	K	0.52	0.95	0.50	Poor	0.49
Cp	0.94	0.99	0.93	Excellent	0.56	BM	0.76	0.92	0.70	Good	0.48
T	0.93	1.00	0.93	Excellent	0.40	I	0.75	1.00	0.75	Good	1.32
Cm	0.45	1.00	0.45	Poor	0.29	RF	0.92	0.95	0.87	Excellent	0.29

Note. r = Pearson correlation coefficient, d = Willmott index, c = Performance index.

The performance was very poor for the MB method, poor for methods Hm, BC, Cm, and K, fair for the B method, and moderate for the Hg method. The estimated SEE varied between 0.17 (BC) and 1.58 (R) mm d^{-1} for the rainy season.

The methods that underestimated the SEE were Hs, T, SS, GR, BM, and RF (Figure 3). However, model T presented a regression line very close to the line of intersection with the PM method. The models PT, JH, Cp, NR, and HH overestimated the SEE value, and model RT presented variability, underestimating values < 4.0 mm d^{-1} and overestimating values > 4.0 mm d^{-1}. R^2 varied from 0.57 (BM) to 0.89 (JH, SS and RT), and 89% of the variations found in methods JH, SS, and RT were explained by the variation of the PM method, with SEE of 0.58, 0.36, and 0.47 mm d^{-1}, respectively.

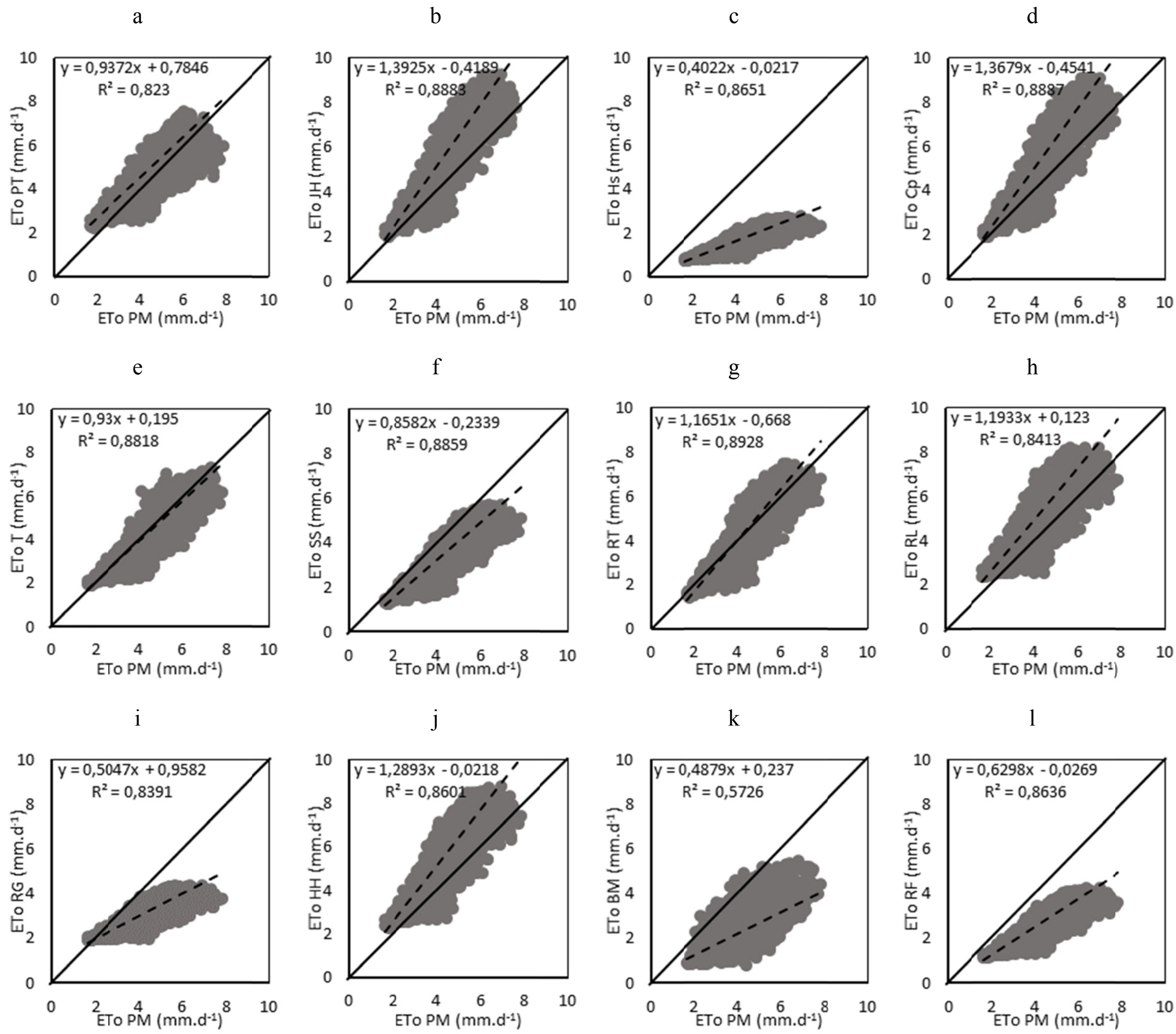

Figure 3. Equations and coefficients of determination of the methods of Priestley-Taylor (a), Jensen-Haise (b), Hansen (c), Caprio (d), Turc (e), Stephens-Stewart (f), Radiation-Temperature (g), Net Radiation (h), Global Radiation (i), Hicks-Hess (j), Blaney-Morin (k), and FAO Radiation (l) correlate to the standard Penman-Monteith method for estimating the annual reference evapotranspiration in the rainy season in Rio Verde, Goiás, Brazil

The T and RT methods outperformed the others using the PM method as a standard. Similar results were obtained by Cunha et al. (2017) in Cassilândia, by Lozano et al. (2017) in Maringá, and by Tanaka et al. (2016) in the state of Mato Grosso.

4. Conclusions

The T and RT methods presented the best performance for estimating annual ETo in Rio Verde during the dry and rainy season, facilitating the management of irrigated agriculture by simplifying the quantification of the water requirement of the crops, thus saving water and energy and increasing agricultural productivity.

Adequate water management in agriculture may increase water availability in water bodies, mitigating existing conflicts, and serve as a tool for promoting the rational use of water resources.

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