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Assessment of empirical methods for estimation of reference evapotranspiration in the Brazilian Savannah

Lucas da Costa Santos[*1], Guilherme Henrique Terra Cruz[1], Frank Freire Capuchinho[1], Jeffersom Vieira José[2], Elton Fialho dos Reis[1]

[1]Department of Agricultural Engineering, University of Goiás, Anápolis, Goiás, Brazil
[2]Institute of Agricultural and Technological Science, Federal University of Mato Grosso, Rondonópolis, Mato Grosso, Brazil

***Corresponding author: lucas.cs21@gmail.com**

Abstract

Evapotranspiration can be sufficiently estimated when meteorological data are available to implement robust models such as Penman-Monteith (PM). However, due to data scarcity, alternative approaches are necessary. In this context, this study aims to compare the reference evapotranspiration (ETo) obtained from the PM standard method with eight empirical equations to identify the simplest method that can be alternative to the reference method (Penman Monteith method) for ten places in state of Goiás (located in west-central Brazil, Brazilian Savanna). To estimate the ETo, air temperature and relative humidity air, wind speed, sunshine and solar radiation data, which were obtained from the data platform National Institute of Meteorology and the Meteorological and Hydrological System of the State of Goiás, were used. For comparison of empirical methods with PM standard method, we used the following statistical indicators: slope and intercept coefficients (β_0 and β_1) of regressions equations, the coefficient of determination (r^2), Pearson's correlation (r), mean bias error (MBE), root mean square error (RMSE) concordance index refined (d_r) and performance index (P_i). Our results indicated that the Turc method is the best option for the state of Goiás when meteorological data are not suffeciently available to use the standard PM method. On the other hand, the method of Romanenko did not present acceptable performance in nine of the ten studied localities. Therefore, its use is advised only in the municipality of the Itumbiara. Among evaluated methods the Hargreaves-Samani method is the best alternative, when there is only air temperature data.

Keywords: climatic elements; empirical methods; irrigated agriculture; methods comparison; Penman Monteith.

Introduction

Evapotranspiration (ET) is generally defined as the combined process of water loss or evaporation present on the soil and plant surfaces, and vegetative canopy transpiration. Previous studies such as those involved hydrological and climatological are of great importance in many areas, since they included a range of applicability, design and management of irrigation systems (Irmak and Haman, 2003; Sentelhas et al., 2010).

Still in the context of the application of ET for agricultural purposes, particularly in irrigated agriculture, crop water requirement is defined by crop evapotranspiration (ETc) influenced by meteorological elements, soil and crop types and management practicals, which together make it difficult to measure the exact water requirements of plants. To circumvent these constraints, ET is commonly estimated from the conceptual approach of a hypothetical reference culture, which supposedly has a height of 0.12 m, surface resistance of 70 s m^{-1} and albedo of 0.23. In agreement with Allen et al. (1998), these characteristics would be similar to the evapotranspiration of an extensive grass surface, with uniform height, which grows actively, totally shadows the soil without any water limitation. This hypothetical condition is known as reference evapotranspiration (ETo), and when multiplied by a specific crop coefficient (kc), satisfactorily estimates the water demand of a plant community, since it normalizes the ET observed in variable climatic conditions (Kumar et al., 2017).

In the last decades, several methods were developed to estimate ETo (Penman, 1948; Blaney and Criddle, 1950; Makkink, 1957; Turc, 1961; Priestley and Taylor, 1972; Hargreaves and Samani, 1985; Oudin et al., 2005). Lu et al. (2005) raised more than 50 equations, involving various types of formulations. In spite of the diversity of methodologies were used for this purpose, only Penman-Monteith FAO/56 (PM) method is considered as a standard by agronomists, irrigators, scientists and even the Food and Agriculture Organization of the United Nations because high degree of empiricism is involved in the formulation of the other methods.

In spite of the robustness of the PM model, which is conferred by the thermo-aerodynamic approach being used in its development, it has the drawback of needing available meteorological data, especially in remote regions, where the low technological level of the climate monitoring system is impossible to obtain complete meteorological data. Thus, alternative approaches that support limited data are needed, which has led to a large number of related studies applied to various climatic conditions.

Evapotranspiration, regardless of evaluated spatiotemporal scale, is extremely variable, because it is driven by the evaporative demand of the atmosphere (Kumar et al., 2017). This feature justifies the knowledge of its dynamics in a delimited geographical area, as these are areas of federal units, the states. Studies by Lemos FIlho et al. (2007), Silva et al. (2015) and Tanaka et al. (2016) with regional scope for the Brazilian states of Minas Gerais, Ceará and Mato Grosso, respectively, are needed to promote public policies to assist more efficient management of water resources. Therefore, in this study, we aimed to compare ETo obtained from the standard method PM-FAO/56 determined by empirical equations, to identify the simplest methods that can be alternative to the reference method for ten places of the state of Goiás.

Results and discussion

Regional approach

The results of the reference evapotranspiration estimated from the standard Penman-Monteith FAO/56 method for the municipalities of Formosa, Goianésia, Ipameri, Itumbiara, Jataí, Mineiros, Posse, Quirinópolis, Rio Verde and Santa Helena de Goiás are presented in Figure 2. Mean ETo values ranged from 3.6 to 4.8 mm day^{-1}, which were verified in the municipalities of Santa Helena de Goiás and Itumbiara, respectively, with the mean value of ETo for the ten localities equal to 4.3 mm day^{-1}. The variability of the data was relatively low, with average coefficient of variation values equal to 15.7%.

The results of the statistical indices based on the comparisons of the ETo estimates between the modified Penman (PMod), Turc (TC), Radiation (Rad), Hargreaves-Samani (HS), Blaney-Criddle (BC), Priesltley-Taylor PT), Makkink (MK) and Romanenko (RM) against the standard method of Penman Monteith FAO/56 (PM56) are presented in Table 1.

Comparison of the reference evapotranspiration equations in each local

Individual analysis of each studied locations verified that in Formosa municipality, located in the eastern portion of the State of Goiás, the PMod and TC methods were classified as optimum, with P_i values equal to 0.84 and 0.82, respectively. Specifically for the PMod method, we observed overestimations of the order of 24%, which corresponded to a MBE of 0.99 mm d^{-1}. In these conditions, it is possible to infer that although the method has been well classified in function of the P_i index, its use requires calibrations for the climatic conditions of the municipality of Formosa, indicating the TC method as alternative to this place.

Similar to Formosa, the TC method presented the best statistical indicators for the municipality of Goianésia (located in the center-north region of the state of Goiás), (d_r = 0.89, RMSE = 0.32 mm d^{-1}; MBE = -0.19 mm d^{-1}), being also classified as optimum. With satisfactory performances, the methods of Rad and BC were classified as very good. Also for this locality, the methods of PT, MK and RM presented poor performance, being classified as poor, tolerable and bad, respectively.

The Goiás state Southeast is located in the city of Ipameri, presented mean ETo equal to 4.14 mm d^{-1}, a value obtained from the PM56 method. Comparison between the empirical methods and those considered as the standard by the FAO, we observed that the method of TC in Ipameri, remained the best performing (optimum) between the studied localities, with indexes of P_i equal to 0.87 and 0.82, respectively. The methods of Rad, PT and HS were classified as very good. In turn, the PMod, BC and MK methods achieved good performance. Specifically for this location, we recommend the HS method, which requires only maximum and minimum air temperature data for its implementation, thus consisting of the simplest method among the eight evaluated.

In Itumbiara, a municipality located in Southeast Goiás, the Rad and BC methods were classified as optimum, both with low data scattering levels (RMSE = 0.3 mm d^{-1}). The PMod, HS and RM methods were considered good for the region. The PT and MK methods presented low performance and were classified as poor.

As representatives of the southwestern region of Goiás, this study evaluated the municipalities of Quirinópolis, Santa Helena de Goiás, Rio Verde and Jataí together due to their proximity. In these four municipalities, the Rad method was classified as optimum, which presented the highest values of the concordance index in Jataí (d_r = 0.93), Rio Verde (d_r = 0.87) and Santa Helena de Goiás (d_r = 0.93). the methods of PMod, HS and BC performed between good and very good. The RM method presented the worst performance, being classified as poor in Quirinópolis, Rio Verde and Santa Helena de Goiás. However, in Jataí, its performance was considered tolerable to estimate Eto, where in this locality only air temperature and relative humidity data are available.

In relation to Mineiros, a municipality located in the southwestern region of Goiás, we verified that the TC method presented the best statistical indicators, with the highest concordance value (d_r = 0.89) and the lowest spreading of the data (RMSE = 0.35 mm d^{-1}). The methods of PMod, Rad, HS, BC, PT and MK performed varying between good and very good. The RM method presented the worst performance (r = 0.49) and was classified as poor.

Finally, in Posse, located in the Northeast region of the state of Goiás, we verified that the TC method was the best evaluated, being classified as optimum to estimate ETo in this locality. the methods of PMod, Rad, HS and BC performed varying between good and very good. The PT and MK methods were classified as tolerable performance. As for the RM method, it was once again classified as poor perfomance, with an overestimate of 24% over the standard FAO method.

In general, we found that methods with formulation based on radiation variable (PMod, TC, Rad and BC), except for PT and MK methods, showed the best performance among all the locations, where they presented performance (P_i) between good and optimum. On the other hand, the method proposed by Romanenko (1961) showed the worst performance in nine of the ten study sites, where the

Table 1. Statistical analysis for comparison among reference evapotranspiration (mm d^{-1}) estimation value estimated by reference Penman-Monteith/FAO56 method against empirical methods in ten localities of the Goiás state (west-central Brazil).

Weather Station	Method	Slope	Intercept	r^2	r	d_r	P_i	RMSE	MBE	Performance	ETo (mm d^{-1})
Formosa	PM56										4.19
	PMod	0.11	1.21	0.99	0.99	0.85	0.84	1.00	0.99	Optimum	5.18
	TC	1.30	0.64	0.89	0.94	0.87	0.82	0.31	-0.19	Optimum	4.00
	Rad	-0.11	1.10	0.82	0.91	0.61	0.55	0.79	0.72	Good	4.9
	HS	0.86	0.83	0.56	0.75	0.79	0.59	0.45	0.15	Good	4.33
	BC	0.46	0.90	0.58	0.76	0.78	0.59	0.45	0.05	Good	4.24
	PT	1.11	0.73	0.41	0.64	0.75	0.48	0.52	-0.02	Good	4.17
	MK	1.08	0.55	0.88	0.94	0.57	0.53	0.84	-0.79	Good	3.40
	RM	-2.31	1.72	0.40	0.64	0.54	0.34	1.44	0.70	Tolerable	4.89
Goianésia	PM56										4.36
	PMod	0.77	1.07	0.94	0.97	0.51	0.50	1.09	1.08	Good	5.44
	TC	0.95	0.74	0.83	0.91	0.89	0.81	0.34	-0.19	Optimum	4.17
	Rad	0.10	1.11	0.90	0.95	0.73	0.69	0.65	0.59	Very Good	4.95
	HS	1.59	0.68	0.53	0.73	0.81	0.59	0.51	0.17	Good	4.53
	BC	0.10	1.02	0.68	0.82	0.81	0.66	0.51	0.18	Very Good	4.54
	PT	2.43	0.40	0.13	0.35	0.68	0.24	0.84	-0.20	Poor	4.17
	MK	1.52	0.43	0.55	0.74	0.55	0.41	1.10	-0.99	Tolerable	3.37
	RM	-3.96	2.29	0.46	0.68	0.17	0.11	2.53	1.68	Bad	6.03
Ipameri	PM56										4.14
	PMod	-0.29	1.29	0.99	0.99	0.55	0.55	0.92	0.90	Good	5.04
	TC	1.09	0.68	0.89	0.94	0.87	0.82	0.32	-0.22	Optimum	3.92
	Rad	0.32	1.06	0.84	0.92	0.72	0.66	0.61	0.55	Very Good	4.69
	HS	0.24	1.03	0.76	0.87	0.80	0.70	0.48	0.34	Very Good	4.48
	BC	1.51	0.66	0.53	0.73	0.81	0.59	0.42	0.09	Good	4.23
	PT	-0.55	1.12	0.67	0.82	0.79	0.64	0.47	-0.05	Very Good	4.09
	MK	0.79	0.61	0.87	0.93	0.57	0.53	0.87	-0.84	Good	3.31
	RM	0.23	1.05	0.19	0.44	0.77	0.34	1.31	0.42	Tolerable	4.56
Itumbiara	PM56										4.78
	PMod	0.15	1.14	0.93	0.97	0.69	0.67	0.85	0.80	Very Good	5.58
	TC	2.04	0.41	0.53	0.73	0.70	0.51	0.96	-0.77	Good	4.02
	Rad	1.04	0.82	0.88	0.94	0.89	0.84	0.33	0.17	Optimum	4.95
	HS	1.44	0.66	0.48	0.69	0.81	0.56	0.65	-0.19	Good	4.59
	BC	1.00	0.78	0.85	0.92	0.89	0.82	0.32	-0.06	Optimum	4.72
	PT	1.88	0.46	0.18	0.42	0.69	0.29	1.13	-0.69	Poor	4.09
	MK	1.74	0.33	0.45	0.67	0.44	0.30	1.57	-1.45	Poor	3.33
	RM	-1.87	1.40	0.61	0.78	0.68	0.53	0.95	0.01	Good	4.79
Jataí	PM56										4.53
	PMod	-0.78	1.32	0.96	0.98	0.73	0.71	0.64	0.59	Very Good	5.11
	TC	1.46	0.50	0.64	0.80	0.62	0.49	0.92	-0.82	Good	3.71
	Rad	0.32	0.92	0.92	0.96	0.93	0.89	0.19	-0.05	Optimum	4.48
	HS	0.53	0.95	0.68	0.82	0.80	0.65	0.52	0.30	Very Good	4.83
	BC	0.82	0.79	0.85	0.92	0.87	0.80	0.30	-0.15	Optimum	4.38
	PT	0.89	0.66	0.30	0.55	0.67	0.38	0.94	-0.64	Tolerable	3.89
	MK	1.08	0.45	0.66	0.81	0.49	0.40	1.49	-1.44	Tolerable	3.10
	RM	-2.64	1.52	0.54	0.73	0.58	0.42	1.02	-0.31	Tolerable	4.22
Mineiros	PM56										4.13
	PMod	-0.56	1.39	0.99	0.99	0.55	0.54	1.08	1.04	Good	5.17
	TC	1.20	0.68	0.80	0.89	0.89	0.79	0.35	-0.13	Optimum	4.00
	Rad	0.35	1.04	0.90	0.95	0.77	0.74	0.57	0.52	Very Good	4.64
	HS	0.66	0.99	0.83	0.91	0.73	0.66	0.69	0.62	Very Good	4.74
	BC	1.19	0.74	0.65	0.81	0.84	0.68	0.43	0.12	Very Good	4.25
	PT	0.07	1.01	0.58	0.76	0.77	0.59	0.60	0.13	Good	4.26
	MK	0.80	0.62	0.79	0.89	0.67	0.59	0.83	-0.76	Good	3.37
	RM	-0.40	1.12	0.24	0.49	0.50	0.24	1.37	0.079	Poor	4.21
Posse	PM56										4.56

	PMod	0.32	1.15	0.97	0.99	0.51	0.51	0.99	0.99	Good	5.54
	TC	0.81	0.75	0.89	0.94	0.82	0.77	0.42	-0.35	Optimum	4.21
	Rad	-0.35	1.23	0.85	0.92	0.66	0.61	0.77	0.69	Very Good	5.24
	HS	1.67	0.61	0.36	0.60	0.76	0.46	0.58	-0.09	Good	4.47
	BC	0.12	0.99	0.66	0.81	0.80	0.65	0.46	0.11	Very Good	4.66
	PT	1.71	0.57	0.32	0.57	0.74	0.42	0.64	-0.24	Tolerabble	4.32
	MK	1.03	0.54	0.81	0.90	0.48	0.43	1.10	-1.05	Tolerable	3.51
	RM	-2.89	1.87	0.42	0.65	0.38	0.25	1.85	1.10	Poor	5.65
Quirinópolis	PM56										4.08
	PMod	-0.09	1.28	0.99	0.99	0.58	0.58	1.06	1.04	Good	5.12
	TC	1.29	0.66	0.83	0.91	0.90	0.82	0.35	-0.10	Optimum	3.99
	Rad	0.34	1.04	0.90	0.95	0.79	0.75	0.57	0.51	Optimum	4.59
	HS	0.72	0.99	0.77	0.88	0.71	0.63	0.78	0.69	Very Good	4.78
	BC	1.04	0.80	0.64	0.80	0.84	0.67	0.51	0.21	Very Good	4.30
	PT	0.45	0.91	0.52	0.72	0.77	0.55	0.66	0.09	Good	4.17
	MK	0.911	0.59	0.79	0.89	0.69	0.61	0.86	-0.77	Very Good	3.32
	RM	0.15	1.13	0.22	0.47	0.45	0.21	1.69	0.68	Poor	4.76
Rio Verde	PM56										4.40
	PMod	0.12	1.16	0.97	0.98	0.62	0.61	0.85	0.83	Very Good	5.23
	TC	1.46	0.53	0.75	0.87	0.71	0.61	0.74	-0.64	Very Good	3.77
	Rad	0.63	0.91	0.86	0.93	0.88	0.81	0.33	0.22	Optimum	4.62
	HS	0.85	0.83	0.58	0.76	0.82	0.62	0.49	0.08	Very Good	4.49
	BC	0.83	0.81	0.71	0.84	0.85	0.71	0.37	-0.02	Very Good	4.38
	PT	1.30	0.56	0.28	0.53	0.72	0.38	0.87	-0.53	Tolerable	3.88
	MK	1.32	0.41	0.64	0.80	0.41	0.33	1.35	-1.28	Tolerable	3.13
	RM	-1.45	1.40	0.31	0.55	0.41	0.23	1.48	0.34	Poor	4.74
Santa Helena de Goiás	PM56										3.60
	PMod	-0.68	1.36	0.99	0.99	0.73	0.73	0.68	0.63	Very Good	4.22
	TC	0.52	0.75	0.84	0.91	0.84	0.76	0.48	-0.38	Optimum	3.22
	Rad	-0.35	1.09	0.94	0.97	0.94	0.91	0.20	-0.01	Optimum	3.59
	HS	0.88	1.09	0.89	0.94	0.48	0.45	1.23	1.20	Good	4.79
	BC	0.44	0.87	0.88	0.94	0.91	0.85	0.24	-0.02	Optimum	3.58
	PT	-0.31	1.05	0.71	0.84	0.82	0.69	0.49	-0.14	Very Good	3.46
	MK	0.15	0.69	0.84	0.92	0.57	0.52	1.03	-0.99	Good	2.61
	RM	0.63	0.79	0.26	0.51	0.55	0.28	1.32	0.38	Poor	3.98

Slope and Intercept: coefficients of the regression equation; r^2: determination coefficient; r: Pearson's correlation; determination coefficient; d_r: refined Willmott agrément index; P_i: performance index; RMSE: root mean square error; and MBE: mean bias error; PM56: Penman Monteith FAO 56 method; PMod: modified Penman method; TC: Turc meethod; Rad: Radiation method; HS: Hargreaves-Samani method; BC: Blaney-Criddle method; PT: Priestley-Taylor method; MK: Makkink method and RM: Romanenko method.

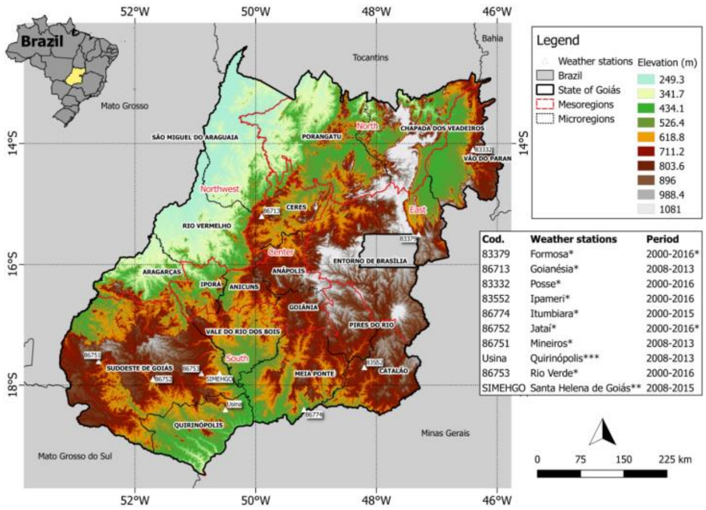

Fig 1. Identification, location and time of observation of the collected meteorological data for synoptic stations in the state of Goiás, Brazil. *Station code at the World Meteorological Organization – WMO; ** Station belonging to the Meteorology and Hydrology System of the State of Goiás – SIMEHGO; and ***Data obtained in an installed meteorological station in the sugar cane industry.

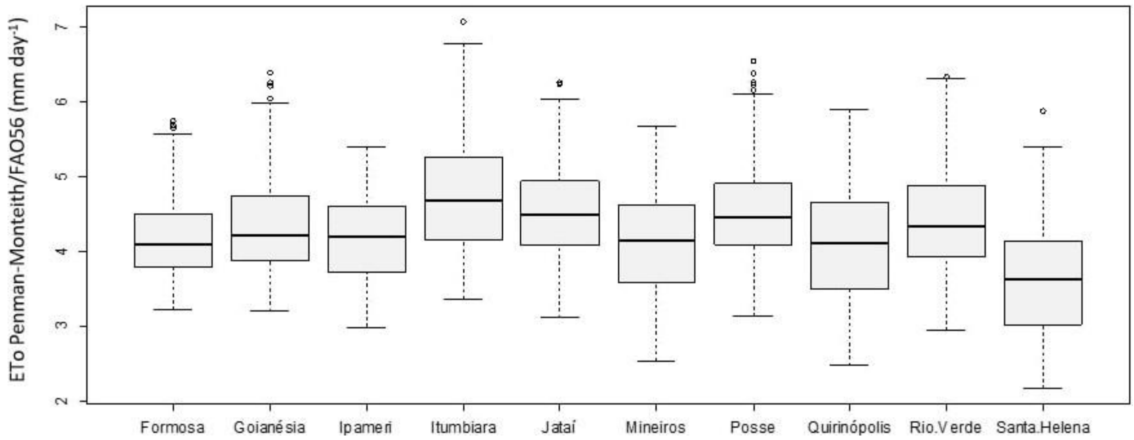

Fig 2. Daily variability of the estimation of reference evapotranspiration (ETo, mm day^{-1}) estimated by the Penman-Monteith/FAO56 method for ten municipalities in Goiás. Data obtained from the period 2000 to 2016.

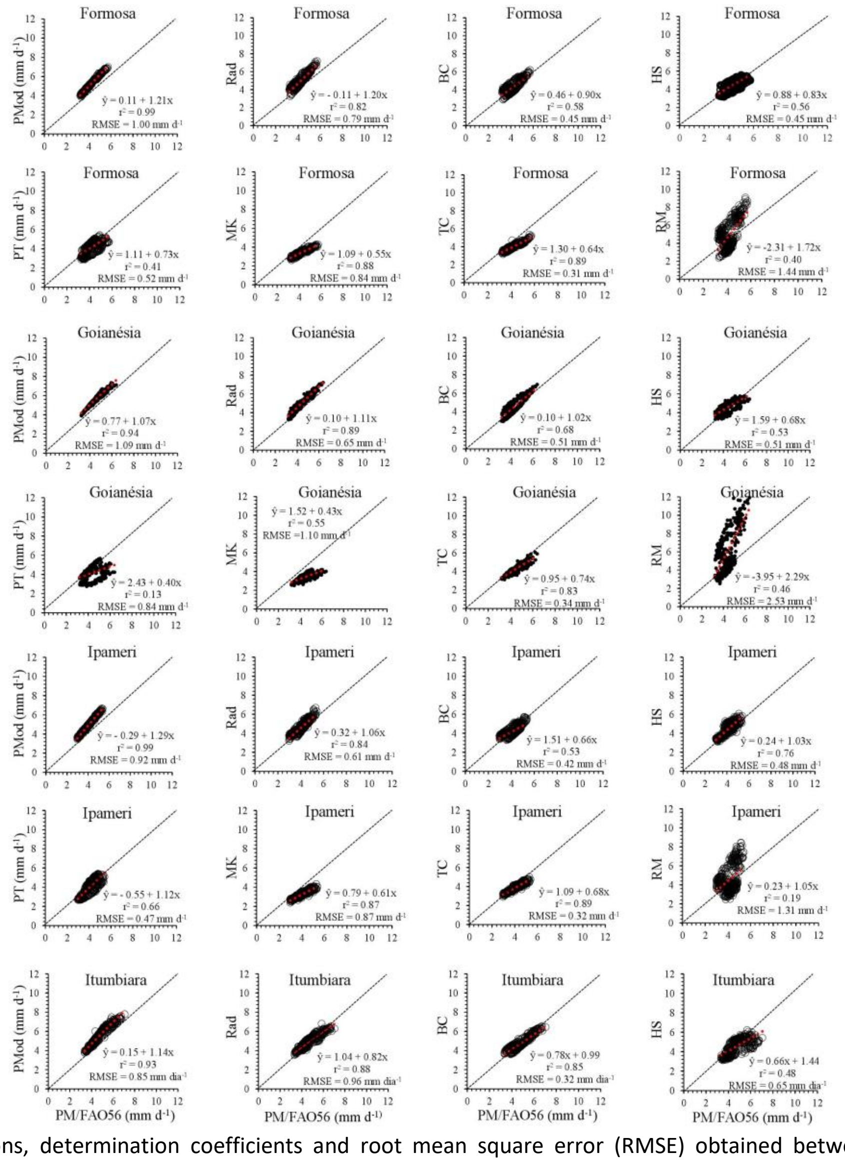

Fig 3. Regression equations, determination coefficients and root mean square error (RMSE) obtained between the reference evapotranspiration (ETo) values estimated by Modified Penman (PMod), Radiation (Rad), Blaney-Criddle (BC), Hargreaves-Samani (HS), Priestley-Taylor (PT), Makkink (MK), Turc (TC) and Romanenko (RM) against ETo values determined by the Penman-Monteith/FAO56 method in daily scale for Formosa, Goianésia, Ipameri and Itumbiara (located in the center-west of Brazil).

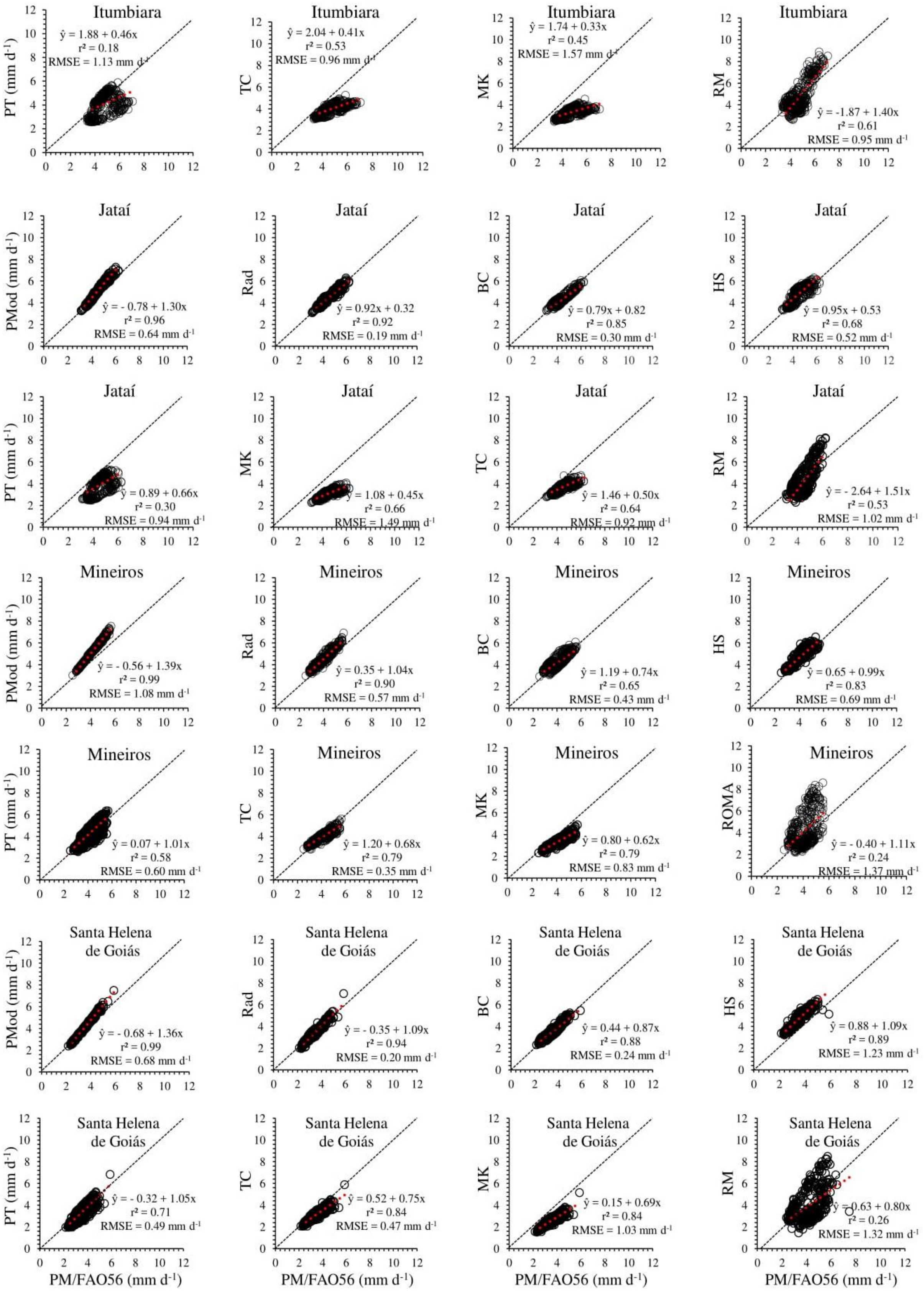

Fig 4. Regression equations, determination coefficients and root mean square error (RMSE) obtained between the reference evapotranspiration (ETo) values estimated by Modified Penman (PMod), Radiation (Rad), Blaney-Criddle (BC), Hargreaves-Samani (HS), Priestley-Taylor (PT), Makkink (MK), Turc (TC) and Romanenko (RM) against ETo values determined by the Penman-Monteith/FAO56 method in daily scale for Itumbiara, Jataí, Mineiros and Santa Helena de Goiás (located in the center-west of Brazil).

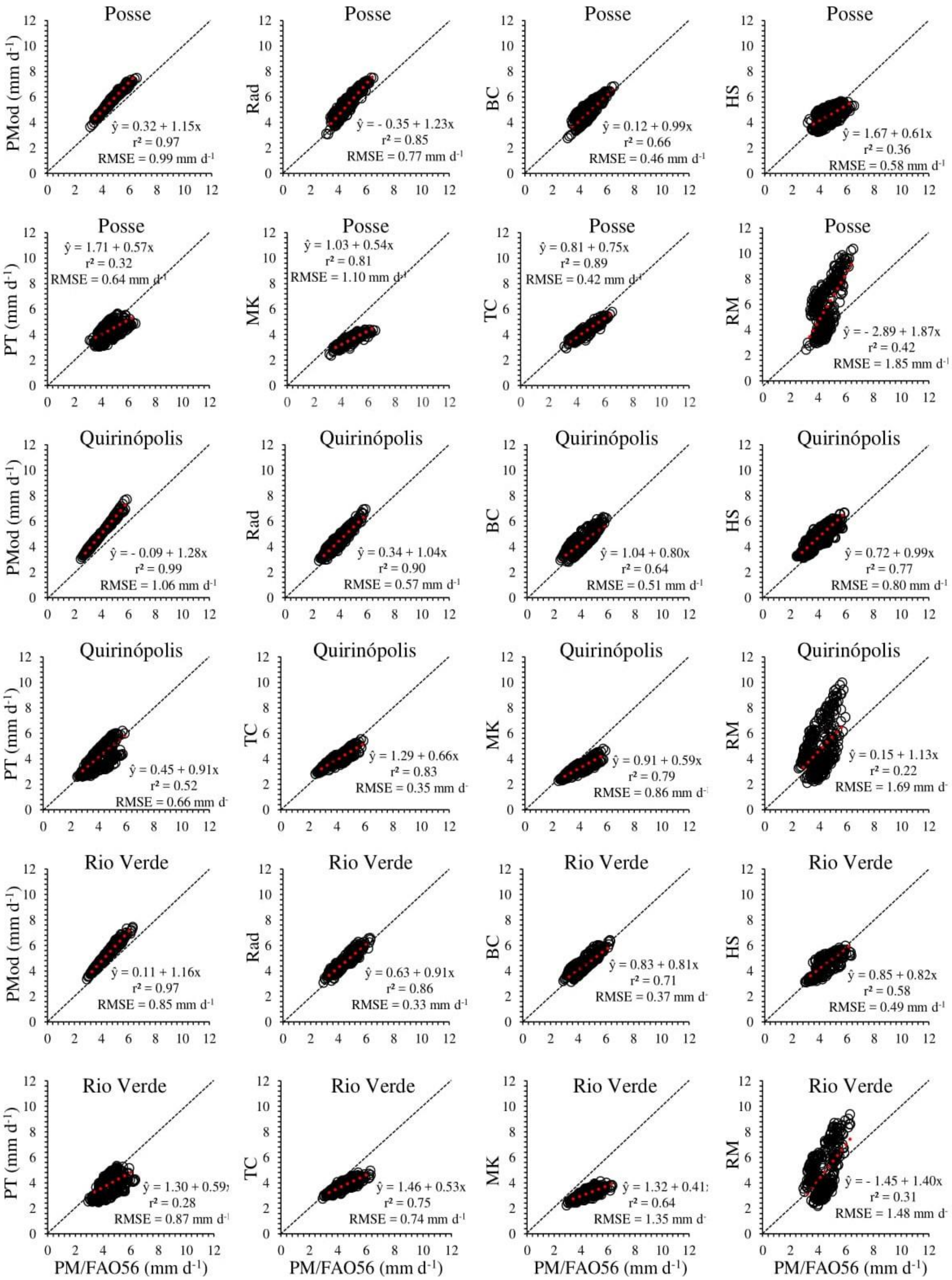

Fig 5. Regression equations, determination coefficients and root mean square error (RMSE) obtained between the reference evapotranspiration (ETo) values estimated by Modified Penman (PMod), Radiation (Rad), Blaney-Criddle (BC), Hargreaves-Samani (HS), Priestley-Taylor (PT), Makkink (MK), Turc (TC) and Romanenko ((RM) against ETo values determined by the Penman-Monteith/FAO56 method in daily scale for Posse, Quirinópolis and Rio Verde (located in the center-west of Brazil).

performance of this method has been ranked among tolerable and bad. The poor performance of RM method can be explained by the fact that, in addition to having a low requirement of meteorological variables for its implementation, it is calculated on the monthly scale, and have been adjusted to the daily scale in this work. Similar behavior was observed in the state's northeastern Mato Grosso when Cunha et al. (2017) which evaluated the performance of 30 ETo estimation methods.

The TC method was the one that most stood out among the eight models tested, evaluated as optimum in seven out of ten investigated locations, presenting a good correspondence among the estimates (r≥0.73), associated with one of the lowest scattering degrees of the data (RMSE≤0.52 mm d^{-1}). However, this method presented generalized underestimations (Figures 4, 5 and 5) about 10%. Similar behavior and magnitude were also verified by Rojas and Sheffield (2013), Carvalho et al. (2015) and Diouf et al. (2016), in studies conducted in the USA (Louisiana), Senegal (West Africa) and Brazil (Southeast), respectively. In contrast, Tagliaferre et al. (2012) verified the overestimation with the TC method when evaluating empirical methods in the coastal region of Brazil. Both the negative and positive deviations observed by these authors are predicted when the TC method is applied in dry and humid climate conditions, respectively, and this behavior is attributed to the model formulation itself.

The PT and MK methods demand data on solar radiation and relative humidity (inclination of the vapor pressure curve) in their application. Besides, they need a coefficient that incorporates aerodynamic energy to the evapotranspiration process (specifically for the method of PT). However, their results were considered only as tolerable in the municipalities of Goianésia, Posse, Itumbiara, Jataí, Rio Verde and Formosa, with general underestimations for both methods. Particularly for the MK method, we observed negative deviations up to 30% (Figures 3, 4 and 5). Similar performance was also observed by Bezerra et al. (2014) and Costa et al. (2017) in the Northeast of Brazil and also by Tabari (2010) in locations with four climatic types of Iran. Such behavior justifies that for these places we need modifications to use the models, which must be properly calibrated using only local meteorological data.

In summary, we observed that among the eight methods of ETo estimation, only the RM method presented poor performance in the ten municipalities studied. On the other hand, the HS method, by virtue of requiring only air temperature data, can be used satisfactorily in these locations, since the estimated ETo values presented satisfactory agreement when compared to the values obtained from the standard method of FAO.

Materials and Methods

Area description and weather data source

The area of study is the state of Goiás, located in the Center-West region of Brazil between latitudes of 45.9 and 49.2° W and longitudes of 12.5 and 19.4° S. According to the climatic classification of Köppen, there are four climatic types that occur in this state such as: Aw (prevails throughout the state), Am (northern mesoregion), Cwa (south-west mesoregion) and Cwb (east center mesoregion). The region presents average temperature of 23.4 °C, with maximum and minimum values varying between 26.5 and 20.5 °C in the northwest and southwest mesoregions, respectively. As for precipitation, the average value of the annual accumulated for the Goian territory is 1500mm, with variations of ±35% throughout the state (Cardoso et al., 2014).

Meteorological data from synoptic stations located in the ten municipalities (Formosa, Goianésia, Ipameri, Itumbiara, Jataí, Mineiros, Posse, Quirinópolis, Rio Verde and Santa Helena de Goiás) belong to the National Institute of Meteorology and to the Meteorology and Hydrology System of the State of Goiás. The meteorological data used for the estimation of ETo were: air temperature, relative humidity, wind speed, sunshine and solar radiation.

Methods of Modified Penman - FAO 24, Radiação - FAO 24, Blaney-Criddle - FAO 24, Hargreaves-Samani (Hargreaves and Samani, 1985), Priestley-Taylor (Priestley and Taylor, 1972), Turc (Turc, 1961), Makkink (Makkink, 1957) and Romanenko (Romanenko, 1961) were used to compare their estimates from the ETo with the Penman-Monteith method - FAO 56, all of them evaluated at a daily scale. The following show the formulations for each of these methods.

Models for estimation of reference evapotranspiration

Penman Monteith – FAO 56

This method is considered as the standard for estimation of ETo, since it is the closest to the values observed in lysimeter tanks. It is expressed as presented by Equation 1.

$$ET_0\ (\text{mm dia}^{-1}) = \frac{0.408\ \Delta\ (R_n - G) + \gamma\ [900 / (T + 273)]\ U_2 (e_a - e_s)}{\Delta + \gamma\ (1 + 0.34\ U_2)}$$

Where; Rn is the net radiation (MJ m^{-2} day^{-1}); T is the mean temperature of the day, measured at two meters high (°C); U_2 is the average wind speed at two meters high (m s^{-1}); Δ is the slope of the saturated vapor curve (kPa $°C^{-1}$); G is the heat flow of the soil (MJ m^{-2} day^{-1}); γ is the psychrometric constant (kPa $°C^{-1}$); ea is the current vapor pressure (kPa) and; es is the saturation vapor pressure (kPa).

The net radiation was determined by Equation 2, proposed by Allen et al. (1998).

$$Rn = Q_g (1 - \alpha) - \left[4.903 \cdot 10^{-9} \left[\frac{T_{max}^4 + T_{min}^4}{2}\right] \left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{Q_g}{Q_{cs}} - 0.35\right)\right]$$

Where; α is the albedo, which was considered as 0.23; T_{max} and T_{min} are the maximum and minimum daily temperatures, respectively; Q_g is the global solar radiation (MJ m^{-2} day^{-1}), and Q_{cs} is the hypothetical solar radiation on a clear-sky day (MJ m^{-2} day^{-1}), which was determined by Equation 3.

$$Q_{gcs} = \left(0.75 + 2 \cdot 10^{-5}\ z\right) Q_o \quad (3)$$

Where; z is the local altitude (m), and Q_o is the extraterrestrial radiation (MJ m^{-2} day^{-1}), based on the latitude of the area and time of the year, based on the expressions described by Allen et al. (1998).

Penman modified – FAO 24

The equation of the modified Penman method, which was developed by Doorenbos and Pruitt (1977) is described by Equation 4.

$$ET_0 \text{ (mm day}^{-1}) = C\left[W \cdot R_n + (1-W) \cdot f(u) \cdot (e_a - e_s)\right] \quad (4)$$

Where, C is the formula correction factor (dimensionless) to offset the effect of day and night in contrasting climatic conditions and involves the solar radiation, maximum relative humidity, and wind speed variables. W is the weighting factor related to temperature and altitude (dimensionless); f(u) and the function related to the wind velocity (dimensionless); and u is the average daily wind speed (km h^{-1}). The detailing of the modified Penman method can be seen in Doorenbos and Pruitt (1977).

Turc (Turc, 1961)

This method allows the calculation of ETo as a function of air temperature, solar radiation and relative humidity. It has been developed for wetlands in Europe, but it is possible to adjust it to climatic conditions where the air relative humidity (RH) is less than 50%. The formulas for determining ETo from this method are presented in Equations 5 and 6.

For average relative air relative humidity less than 50%

$$ET_0 \text{ (mm day}^{-1}) = 0.013 \left(\frac{T}{T+15}\right) \cdot (R_s \cdot 23.8846 + 50) \cdot \left(1 + \frac{50 - RH}{70}\right) \quad (5)$$

For average relative air relative humidity greater than 50%

$$ET_0 \text{ (mm day}^{-1}) = 0.013 \left(\frac{T}{T+15}\right) \cdot (R_s \cdot 23.8846 + 50) \quad (6)$$

where RH represents the mean relative air humidity (%).

Radiation method – FAO 24

This method was presented by Doorenbos and Pruitt (1977) and uses solar radiation to estimate evapotranspiration values. Equation 7 presents the formulation of this method.

$$ET_0 \text{ (mm day}^{-1}) = a + b\,(W \cdot R_s) \quad (7)$$

Where; a and b are the linear and angular coefficients of the regression equation (dimensionless), respectively, which are obtained from relations established between the relative humidity and the local wind speed. Values of coefficients a and b can be found in Doorenbos and Pruitt (1977).

Hargreaves-Samani (Hargreaves and Samani, 1985)

This method is used when solar radiation, relative humidity and wind speed are not available. Its formulation is presented in Equation 8.

$$ET_0 \text{ (mm day}^{-1}) = 0.408 \cdot 0.0023\,(T + 17.8) \cdot (T_{max} - T_{min})^{0.5} \cdot Q_o \quad (8)$$

Blaney-Criddle (Blaney and Criddle, 1950)

The Blaney-Criddle method was developed in the 1950s for the western portion of the United States, a semi-arid region, and was adjusted by Doorenbos and Pruitt (1977) during the 1970s. Its application considers air temperature data, relative humidity, wind speed, and sunshine. Equation 9 is used to estimate ETo from the Blaney-Criddle method.

$$ET_0 \text{ (mm day}^{-1}) = a_{BC} + b_{BC}\left[p \cdot (0.46 \cdot T + 8.13)\right] \quad (9)$$

Where; a_{BC} is a correction factor that depends on the minimum daily relative humidity (RH_{min},%) and the ratio between insolation and photoperiod (n/N); b_{BC} is a correction factor that depends on the minimum value of daily relative humidity (RH_{min},%), the ratio between insolation and photoperiod (n/N) and average daily wind speed (U_2) and; p is the percentage of the total monthly average photoperiod over the total annual photoperiod, which can be found in Doorenbos and Pruitt (1977). The correction factors a_{BC} and b_{BC} are given by equations 10 and 11.

$$a_{BC} = 0.0043 \cdot UR_{min} - {}^{n}/_{N} - 1.41 \quad (10)$$

$$b_{BC} = a_0 + a_1 \cdot RH_{min} + a_2 \cdot {}^{n}/_{N} + a_3 \cdot U_2 + a_4 \cdot UR_{min} \cdot {}^{n}/_{N} + a_5 \cdot RH_{min} \cdot U_2 \quad (11)$$

Where in; a_0, a_1, a_2, a_3, a_4 and a_5 correspond to 0.8197, -0.0040922, 1.0705, 0.065649, -0.0059584, and -0.0005967, respectively; n is the insolation (in hours) and N is the photoperiod (in hours).

Priestley-Taylor (Priestley and Taylor, 1972)

The Priestley-Taylor method was developed for Australia's climatic conditions and is an approximation of the Penman method (Penman, 1948), with only the radiation balance corrected by an empirical coefficient, called the Priestley-Taylor parameter. This parameter incorporates additional energy to the evapotranspiration process resulting from the aerodynamic term. The estimation of ETo from the Priestley-Taylor method is presented in Equation 12.

$$ET_0 \text{(mm day}^{-1}) = 1.26\,\frac{\Delta}{\Delta + \gamma}\,(R_n + G) \quad (12)$$

Makkink (Makkink, 1957)

Developed by Makkink (1957) in the Netherlands, the method (Equation 13) is based on the formulation proposed by Penman (1948) and uses global solar radiation data.

$$ET_0 \text{ (mm day}^{-1}) = 0.61 \cdot Q_g \cdot \frac{\Delta}{\Delta + \gamma} - 12 \quad (13)$$

Romanenko (Romanenko, 1961)

The Romanenko method (Romanenko, 1961) is derived from an evaporation equation based on the relation of the mean temperature and relative humidity of the air (equation 14).

$$ET_0 \text{ (mm day}^{-1}) = 0.0018 \cdot (T + 25)^2 \cdot (100 - RH) \quad (14)$$

Performance evaluations

The analysis of the performance of the methods studied was performed by comparing the reference evapotranspiration values obtained by each empirical method with those obtained using the standard Penman-Monteith method/FAO56, on a daily scale. Comparisons were carried out in pairs (PM-FAO/56 x empirical methods). We used linear (intercept) and angle (slope) coefficients of the regression equations for analytical purposes. In addition, we used the coefficients of determination (r^2, equation 15), Pearson's correlation (r, equation 16), refined Willmott agreement index (d_r, Willmott; Robeson; Matsuura (2012), equation 17), root mean square error (RMSE, equation 18), the mean bias error (MBE, equation 19) and the performance index (P_i, equation 20) of Alvares et al. (2013), which combine precision and accuracy. Precision is provided by r, which indicates the degree of dispersion of the mean data, where the random error and the precision is related to the dispersion of the estimated values of those observed and is estimated by the index d_r. The best method to estimate ETo in each of the studied locations was the one that presented the highest r^2 and r, the lowest RMSE and MBE and the value of the slope closest to 1. As for the P_i index, the criteria for interpreting it are: $P_i \geq 0.75$, optimum performance; $0.6 \leq P_i < 0.75$, very good performance; $0.45 \leq P_i < 0.6$, good performance; $0.3 \leq P_i < 0.45$, tolerable performance; $0.15 \leq P_i < 0.3$, poor performance; $0 \leq P_i < 0.15$, bad performance; and $P_i < 0$, very bad performance (Willmott et al., 2012), thus allowing the hierarchy of ETo estimation methods.

$$r^2 = \left\{ \frac{\sum_{i=1}^{n} (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\left| \sum_{i=1}^{n} [(x_i - \bar{x})^2]^{0.5} \right| \cdot \left| \left[\sum_{i=1}^{n} (y_i - \bar{y})^2 \right]^{0.5} \right|} \right\}^2 \quad (15)$$

$$r = \frac{(x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{[(x_i - \bar{x})^2] \left[\left[(y_i - \bar{y})^2 \right] \right]}} \quad (16)$$

$$MBE = \frac{1}{n} \sum (x_i - y_i) \quad (17)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - x_i)^2}{n}} \quad (18)$$

$$d_r = \begin{cases} 1 - \dfrac{\sum_{i=1}^{n} |y_i - x_i|}{2 \sum_{i=1}^{n} |y_i - \bar{x}|}, & \text{when } \sum_{i=1}^{n} |y_i - x_i| \leq 2 \sum_{i=1}^{n} |x_i - \bar{x}| \\ \dfrac{2 \sum_{i=1}^{n} |x_i - \bar{x}|}{\sum_{i=1}^{n} |y_i - x_i|} - 1, & \text{when } \sum_{i=1}^{n} |y_i - x_i| > 2 \sum_{i=1}^{n} |x_i - \bar{x}| \end{cases} \quad (19)$$

$$P_i = r \cdot d_r \quad (20)$$

Where; r^2, r, MBE, RMSE dr and P_i are the coefficient of determination, Pearson's correlation, mean absolute error, root mean square error, agreement index, and performance index, respectively; y_i is the ETo value estimated by empirical methods (mm dia^{-1}), x_i is the ETo value estimated by the standard PM-FAO/56 method; and $\bar{x}$ and $\bar{y}$ are the means of the values of y_i and x_i.

Conclusion

The estimation of reference evapotranspiration in different regions of the state of Goiás can be satisfactorily achieved from the Penman-modified, Turc, Radiation, Blaney-Criddle, Priestley-Taylor, Hargreaves-Samani and Makkink methods.
The Turc method is the best option when meteorological data are not available to use the Penman-Monteith/FAO standard method. On the other hand, the Romanenko method did not present acceptable performance in nine of the ten studied localities and it is advisable to use them only in the municipality of Itumbiara. For the Goias state conditions, the Hargreaves-Samani method is the best alternative among those evaluated when there is only air temperature data available.

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