CONVENTIONAL WEATHER STATIONS: IMPROVING REFERENCE EVAPOTRANSPIRATION ESTIMATES

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ABSTRACT: Adequate estimates of reference evapotranspiration (ETo) are essential for sustainable water resources management. Therefore, the objective of this study was to propose a methodology to improve the ETo estimation from conventional weather stations (CWS). Reliability of meteorological data from a CWS was assessed using a nearby automatic weather station (AWS) data. Two simple analyses based on linear correlation were carried out to assess meteorological variables agreement and the relationship between their differences and errors in ETo estimation. The analyses were used to indicated which variables measured by the CWS required calibration most. After calibration, the improvement in ETo estimation was assessed. Solar radiation and wind speed were found to be the major sources of errors in ETo estimation from the CWS. Calibrating these variables resulted in a substantial increase in performance of ETo estimation using CWS data.

KEYWORDS: irrigation; Penman-Monteith; water resources management.

ESTAÇÕES METEOROLÓGICAS CONVENCIONAIS: APRIMORANDO ESTIMATIVAS DE EVAPOTRANSPIRAÇÃO DE REFERÊNCIA

RESUMO: A estimativa adequada da evapotranspiração de referência (ETo) é fundamental para um gerenciamento de recursos hídricos de forma sustentável. O objetivo deste trabalho foi propor uma metodologia capaz de aprimorar as estimativas de ETo a partir de dados de estações meteorológicas convencionais (CWS). A confiabilidade de dados meteorológicos de uma CWS foi avaliada utilizando-se dados de uma estação meteorológica automática (AWS) próxima.

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Duas análises baseadas na correlação linear foram utilizadas para avaliar a concordância das variáveis e a relação entre a diferença das mesmas e os erros na estimativa de ETo. As análises foram utilizadas para indicar quais variáveis mensuradas pela CWS necessitavam calibração. Após a calibração, a melhoria nas estimativas de ETo foi avaliada. Radiação solar e velocidade do vento foram as variáveis consideradas como maiores fontes de erros na estimativa de ETo pela CWS. A calibração dessas variáveis resultou em um aumento substancial no desempenho da estimativa de ETo utilizando dados da CWS.
PALAVRAS-CHAVE: irrigação; Penman-Monteith; gestão de recursos hídricos.

INTRODUCTION

Agriculture dependence on rainfall is one of the major holdups for agricultural productivity and food security (Landeras et al., 2018), especially in regions with well-defined wet and dry seasons. Thus, irrigated areas have vastly increased across the Brazilian territory (ANA, 2019), reducing the risk of losses and guaranteeing food security. However, in order that farmers obtain the economic return of their investments, knowledge on crop water requirements is crucial in developing sustainable irrigation practices.

The combined process of water evaporation from plant and soil surfaces and transpiration from crop, known as evapotranspiration (ET), represents the process of water loss to the atmosphere (Allen et al., 1998). Measuring ET is not only difficult, but costly, and to overcome the difficulties of the direct measurement, climatic data has long been used in its estimation. ET is commonly estimated via reference evapotranspiration (ETo), the measurement of ET from a well-watered and hypothetical crop of defined characteristics (Allen et al., 1998). Accurately estimating ETo is, therefore, essential for designing irrigation systems, carrying out efficient irrigation management and conducting climatological and hydrological studies (Jerszurki et al., 2019).

The numbers of automatic weather stations (AWS), that collect weather data on an hourly basis, is increasing. It is also clear that AWS observations better represent daily average climatic conditions. However, there is still a large number of conventional weather stations (CWS) from the Brazilian National Institute of Meteorology (INMET) network that are useful in regions lacking meteorological information. Unfortunately, the CWS meteorological data, used to estimate ETo, are estimated from only a few daily observations, resulting in less reliable ETo estimate when compared to the AWS.

Considering the importance of adequately estimating ETo, the objective of this study was to investigate the differences between AWS and CWS observations and propose a methodology to improve ETo estimation from CWS data.

MATERIALS AND METHODS

The study was carried out for the city of Brasília – DF, Brazil. Brasília is located in the core of the Cerrado biome and is characterized by a tropical wet/savanna climate - Aw (Alvares et al., 2013).

The data used in the study were collected by an AWS and a CWS covering the period from 01/01/2013 to 31/12/2016. The stations are property of the Brazilian National Institute of Meteorology (INMET) network and are within Brasília's territory. The AWS provides hourly observations of maximum (Tx), mean (Tm) and minimum air temperature (Tn), maximum (RHx), mean (RHm) and minimum relative humidity (RHn), solar radiation (Rs) and wind speed at 10 m above ground (u10). CWS daily measurements are taken only at 12, 18 and 24 UTC, providing three daily measures of temperature, relative humidity and wind speed, along with total insolation/sunshine hours (n). Daily Tx, Tm, Tn, RHm and u10 for CWS are then estimated from the three daily measures, as described in Equations 1-5:

$$Tx = \max(T_{12}, T_{18}, T_{24}) \quad (1)$$

$$Tn = \min(T_{12}, T_{18}, T_{24}) \quad (2)$$

$$Tm = \frac{(Tx + Tn + T_{12} + 2\ T_{24})}{5} \quad (3)$$

$$RHm = \frac{(RH_{12} + RH_{18} + 2\ RH_{24})}{4} \quad (4)$$

$$u10 = \frac{(u10_{12} + u10_{18} + u10_{24})}{3} \quad (5)$$

where, T – air temperature (°C); RH – relative humidity (%); x, n, m – indicate maximum, minimum and mean values; u10 – wind speed at 10 m above ground (m s^{-1}); $_{12,18,24}$ – indicate measurements realized at 12, 18 and 24 UTC, respectively.

Sunshine hours were converted to solar radiation (Rs, MJ m^{-2} day^{-1}) and wind speed at 10 m above ground to wind speed at 2 m above ground (u2, m s^{-1}), both adopting the methodology proposed by Allen et al. (1998) (Equations 6 and 7):

$$Rs = (a + b\ n/N)Ra \quad (6)$$

$$u2 = u_z \frac{4.87}{\ln(67.8\ z - 5.42)} \quad (7)$$

where, n – actual duration of sunshine hours (hour); N – maximum possible duration of sunshine or daylight hours (hour); Rs and Ra – solar and extraterrestrial radiation (MJ m^{-2} day^{-1}); a and b – regression constant and slope, expressing the fraction of extraterrestrial radiation reaching the earth; u2 and u_z = wind speed at 2 m and "z" m above ground (m s^{-1}), respectively; and z = height above ground (m). In Equation 6, "a + b" (n = 1) represents clear days, while only "a" (n = 0) represents overcast days. When calibration has not yet been carried out, a = 0.25 and b = 0.50 are recommended.

Daily reference evapotranspiration (ETo) was then calculated for both stations using Penman-Monteith equation (Equation 8), as described in the FAO-56 (Allen et al., 1998):

$$ETo = \frac{0.408\ (Rn - G) + \gamma \frac{900}{Tm+273} u2\ (e_s - e_a)}{\Delta + \gamma\ (1 + 0.34\ u2)} \quad (8)$$

where, ETo – reference evapotranspiration (mm day^{-1}); Rn – net radiation (MJ m^{-2} day^{-1}); G – soil heat flux (MJ m^{-2} day^{-1}); Tm – average daily mean air temperature (°C); u2 – average daily wind speed at 2 m above ground (m s^{-1}); e_s – saturation vapor pressure (kPa); e_a – actual vapor pressure (kPa); Δ – slope of saturation vapor pressure curve (kPa $°C^{-1}$); γ – psychrometric constant (kPa $°C^{-1}$). All required variables were assumed or calculated according to Allen et al. (1998).

ETo calculated from AWS data (ETo_{AWS}) was used as reference to assess the performance of ETo calculated from CWS data (ETo_{CWS}). The performance criteria used were the mean bias error (MBE), mean absolute error (MAE) and root mean squared error (RMSE), as described in Equations 8-10:

$$MBE = \frac{1}{no} \sum_i^{no} \left(ETo_{CWS_i} - ETo_{AWS_i} \right) \quad (8)$$

$$MAE = \frac{1}{no} \sum_i^{no} \left(\left| ETo_{AWS_i} - ETo_{CWS_i} \right| \right) \quad (9)$$

$$RMSE = \sqrt[2]{\frac{1}{no} \sum_i^{no} \left(ETo_{AWS_i} - ETo_{CWS_i} \right)^2} \quad (10)$$

where, ETo – reference evapotranspiration (mm d^{-1}); $_{AWS}$, $_{CWS}$ – indicate whether ETo was calculated using AWS or CWS data; and no – number of observations.

In order to improve ETo_{CWS} estimates, we assessed sources of errors using two different analyses: A1 - the linear correlation (r) between daily averages of corresponding meteorological variables (VAR) from the AWS and CWS (A1 - cor(VAR_{CWS}, VAR_{AWS})); and A2 - the linear correlation between the ETo estimates errors and the differences between AWS and CWS variables daily averages (A2 – cor((VAR_{CWS} – VAR_{AWS}), (ETo_{CWS} – ETo_{AWS}))). The variables presenting r values close to 0 for A1, and r values closer to 1 and -1 for A2, were considered source of errors in the estimation of ETo using CWS data and, therefore, calibrated.

The period from 01/01/2013 to 31/12/2015 was used for the calibration of variables and from 01/0/2016 to 31/12/2016 for their validation. Calibration was carried out with a linear regression and by minimizing the sum of squares of the difference between values observed by the AWS and values estimated by the CWS.

RESULTS AND DISCUSSION

Figure 1 presents the monthly variability between meteorological variables obtained from AWS and CWS. With an exception to wind speed, all variables seem to have a similar behavior throughout the year, that is, similar ranges and distribution of values within each month. As for wind speed, the conventional weather station presented larger ranges and higher concentration of values between 0 and 2 m s^{-1}. This alone is a strong indicative that the variable could be a major source of errors in ETo estimation, and will be better investigated by analyses A1 and A2.

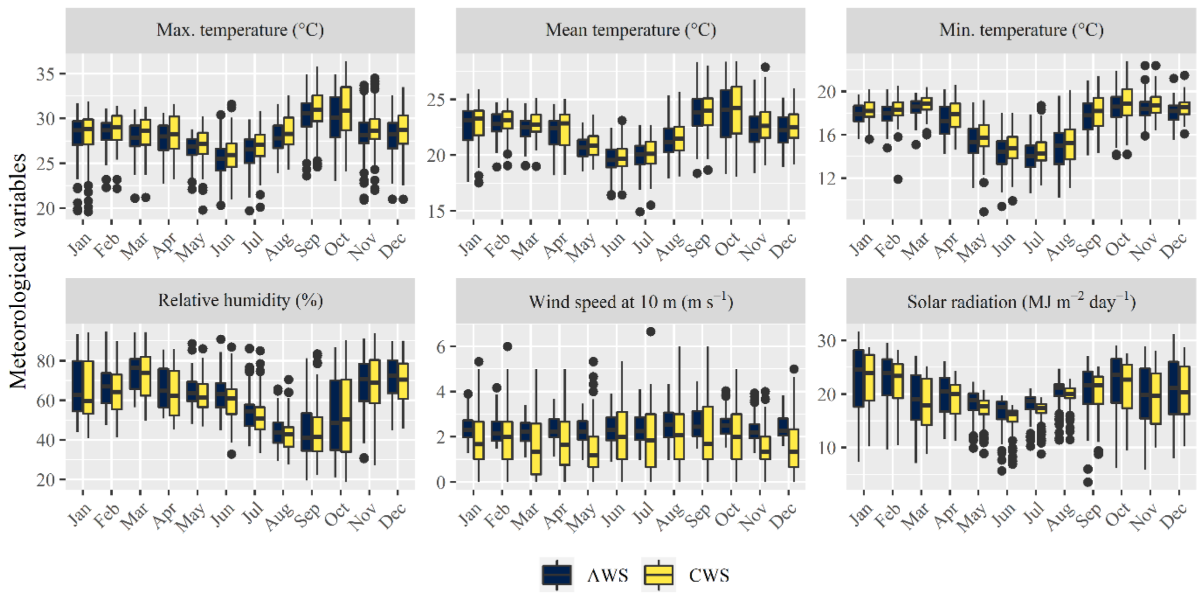

Figure 1. Automatic (AWS) and conventional weather station (CWS) meteorological variables from 2013 to 2016 for Brasília – DF, Brazil.

For the analysis A1, Tx, Tm, Tn, RHm and Rs showed high agreement, with r values equal to 0.974, 0.976, 0.964, 0.954 and 0.943, respectively, while u10 showed poor agreement, with r equal to 0.672. This poor agreement is noticed in the visual analysis of Figure 1, where u10 obtained by CWS presented monthly ranges much larger than u10 obtained by the AWS.

As for analysis A2, the r values were low for Tx, Tm, Tn and RHm, with values equal to -0.135, 0.084, 0.038 and -0.154, respectively. On the other hand, r values were higher for Rs (0.286) and u10 (0.754). The two analyses, A1 and A2, make it clear that wind speed measurements from CWS should be calibrated before estimating ETo. Although presenting high r in analysis A1, the "a" and "b" parameters used in Rs estimation (Equation 6) were also chosen for calibration, for the differences between Rs observed by AWS and estimated by CWS showed higher correlation to errors in ETo estimation than most variables.

The results comparing uncalibrated and improved parameters (a = 0.259 and b = 0.519) from Equation 6 may be seen in Figure 2. It is noted that the slope from fitted regression became closer to 1, bringing Rs estimates by the CWS closer to the ideal fit (1:1).

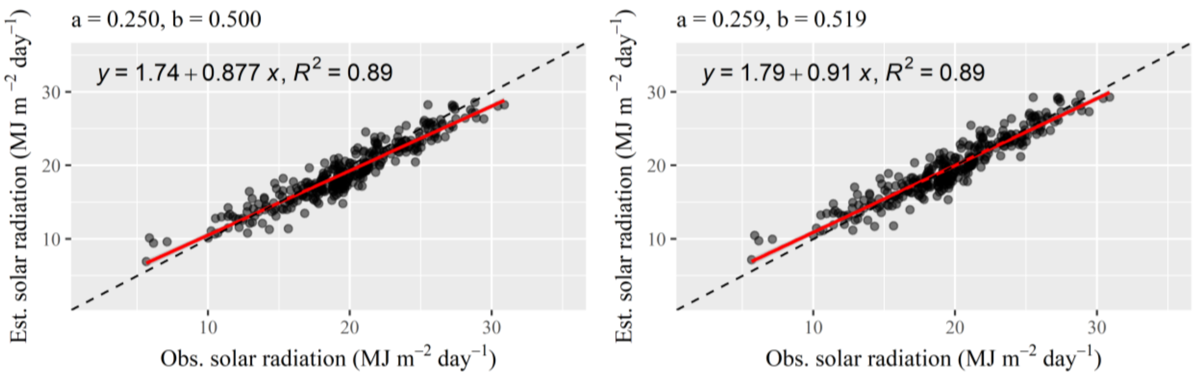

Figure 2. Solar radiation (Rs) observed by automatic meteorological stations versus Rs estimated from sunshine hours using uncalibrated and calibrated parameters for the validation period (01/0/2016 to 31/12/2016) in Brasília – DF, Brazil.

The calibration equation obtained for u10 has intercept = 1.750 and slope = 0.335 ($u10_{calibrated} = 1.750 + 0.335\ u10_{uncalibrated}$), which means that u10 estimated from CWS has a much larger dispersion than AWS 24 hours averages. Figure 3 presents the scatterplots between daily averages of u10 obtained by the AWS and u10 estimated by CWS prior and after calibration. Although the fit line is still far from the desired, the points became much closer to 1:1 and the dispersion of values showed a severe reduction.

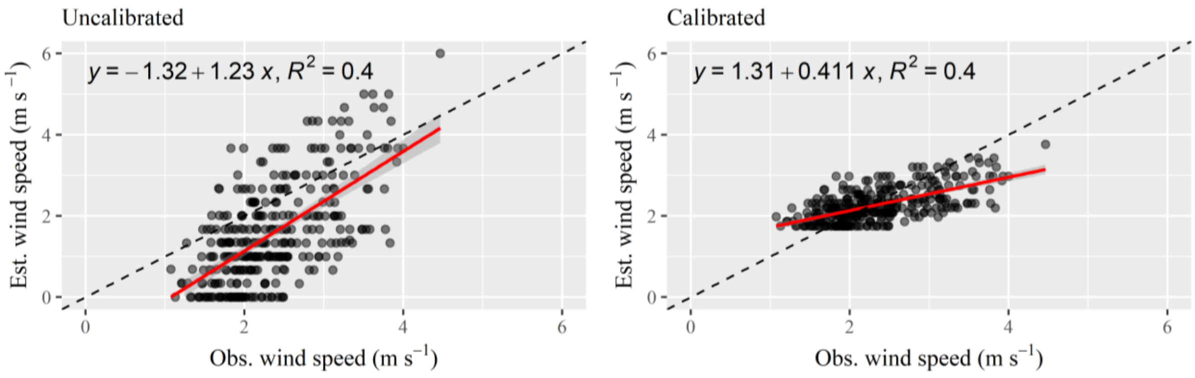

Figure 3. Observed wind speed at 10 m above ground (u10) versus u10 estimated by uncalibrated and calibrated values from conventional weather stations for the validation period (01/0/2016 to 31/12/2016) in Brasília – DF, Brazil.

The calibration performed for Rs estimated via CWS reduced its MAE from 1.33 to 1.17 MJ m^{-2} day^{-1}, while the calibration of u10 resulted in a MAE decrease for u2 from 0.80 to 0.29 m s^{-1}. The performance of estimating ETo using CWS data are shown in Table 1 prior and after these calibration procedures.

Table 1. Performance of ETo_{CWS} estimates with uncalibrated and calibrated meteorological variables for the validation period (01/0/2016 to 31/12/2016) in Brasília – DF, Brazil

	MBE	MAE	RMSE	R^2
ETo_{CWS} – uncalibrated	-0.27	0.46	0.59	0.76
ETo_{CWS} – Rs calibrated	-0.18	0.43	0.55	0.76
ETo_{CWS} – Rs and u10 calibrated	0.10	0.25	0.31	0.91

Rs - solar radiation (MJ m^{-2} day^{-1}); u10 - wind speed at 10 m above ground (m s^{-1}); ETo_{CWS} - reference evapotranspiration estimated using conventional weather station data (mm day^{-1}); MBE - mean bias error (mm day^{-1}); MAE - mean absolute error (mm day^{-1}); RMSE - root mean squared error (mm day^{-1}); R^2 - coefficient of determination.

Adopting improved parameters for estimating Rs resulted only in a slight decrease in its underestimation (negative MBE) and in its errors magnitude. However, also using calibrated u10 resulted in a large performance improvement, with MAE dropping by more than 40%, and MBE becoming closer to 0.

The scatterplot between ETo_{AWS} and ETo_{CWS} are shown in Figure 4 for the scenarios considering ETo_{CWS} with uncalibrated variables, ETo_{CWS} with only Rs calibrated and with both Rs and u10 calibrated. It is noted that calibrating Rs resulted in a regression slope closer to 1, but a slight increase in the intercept. For ETo_{CWS} estimated using calibrated Rs and u10, the intercept became larger, which is undesired, however, its coefficient of determination increased substantially (R^2 = 0.91).

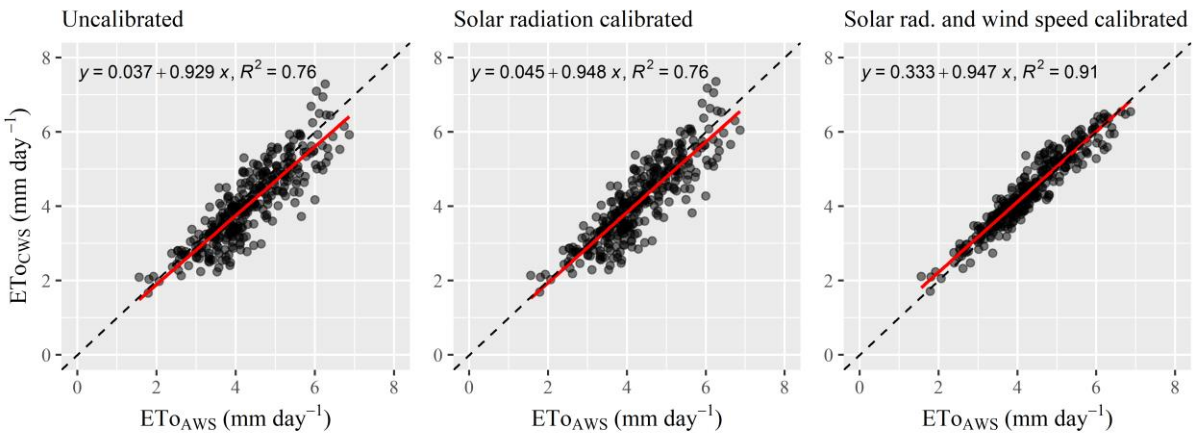

Figure 4. Reference evapotranspiration (ETo) estimated by meteorological variables from automatic weather station (AWS) and conventional weather station (CWS) for the validation period (01/0/2016 to 31/12/2016) in Brasília – DF, Brazil.

The increase in performance for ETo_{CWS} during validation period show that the calibrated parameters for estimating Rs and the developed equation for adjusting u10 are appropriate for Brasília – DF. However, cloud cover and wind speed may be very dynamic. Therefore, the equation and parameters presented here should not be used in regions distant from Brasília. Instead, this calibrating procedure should be performed for other regions in order to result in adequate ETo estimates.

CONCLUSIONS

This study assessed the differences between meteorological variables obtained by automatic (AWS) and conventional weather stations (CWS) and their impact in estimating reference evapotranspiration (ETo). A simple procedure of two analyses was proposed for the investigation of source of errors in ETo estimates and a linear regression was used to calibrate troublesome meteorological variables.

Among the meteorological variables, solar radiation and wind speed were acknowledged as the major sources of errors in ETo estimation. The calibration of solar radiation resulted in only a small increase in performance of CWS ETo estimates. On the other hand, calibrating both solar radiation and wind speed resulted in a much more substantial increase in performance, reducing the root mean square error by more than 40%.

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