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**REMOTE SENSING AND EMPIRICAL MODELS IN THE ESTIMATION OF REFERENCE
EVAPOTRANSPIRATION IN A SEMI-ARID REGION****SENSORIAMENTO REMOTO E MODELOS EMPÍRICOS NA ESTIMATIVA DA
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ABSTRACT: Correct estimation of reference evapotranspiration (ET_o) values is of paramount importance for water management at basin level as well as in agricultural production areas. The objective of this study was to compare ET_o estimates obtained by means of remote sensing and empirical mathematical models for the Cariri region, CE, Brazil. Remote sensing data were obtained using the MOD16A2 product (8 days) of the MODIS instrument. Raster images were obtained with a resolution of 500 x 500 m, downloaded from the Earth Explorer website. ET_o was calculated with terrestrial data by the Penman-Monteith-FAO method and by the alternative models of Hargreaves and Samani, Jensen and Haise, and Makkink. The period evaluated was from 2021 to 2022. The evaluation of the results was based on statistical parameters. ET_o data obtained through satellite images showed low accuracy and a high tendency to overestimate the values calculated by the Penman-Monteith-FAO model. The Makkink model proved to be accurate in the ET_o estimates, and can be used, when necessary, to replace the standard Penman-Monteith-FAO model.

KEYWORDS: *Water management, MODIS, satellite images.*

RESUMO: A estimativa correta dos valores de evapotranspiração de referência (ET_o) é de suma importância para o manejo hídrico a nível de bacia bem como em áreas de produção agrícola. Objetivou-se comparar as estimativas de ET_o por meio de sensoriamento remoto e por modelos matemáticos empíricos para a região do Cariri, CE. Os dados de sensoriamento remoto foram obtidos por meio do produto MOD16A2 (8 dias) do instrumento MODIS. As imagens raster foram obtidas com resolução de 500 x 500 m, e o download foi realizado a partir do portal Earth Explorer. A ET_o foi calculada com dados terrestres pelo método de Penman-Monteith-FAO e pelos modelos alternativos de Hargreaves e Samani, Jensen e Haise, e Makkink. O período avaliado foi de 2021 a 2022. A avaliação dos resultados foi baseada em parâmetros estatísticos. Os dados de ET_o obtidos por meio das imagens de satélite, apresentaram baixa precisão e alta tendência a superestimar os valores calculados pelo modelo de Penman-Monteith-FAO. O modelo de Makkink mostrou-se preciso nas estimativas de ET_o, podendo ser utilizado, quando necessário, em substituição ao modelo padrão de Penman-Monteith-FAO.

PALAVRAS-CHAVE: *Manejo hídrico, MODIS, imagens de satélite.*

INTRODUCTION

In view of the intensification of periods of climate instability, which are increasingly frequent, knowing and monitoring the water variations of a region is essential for hydrological and agricultural planning, which is aimed at water and food security for future generations. According to Hadria et al. (2021), precise understanding of the hydrological cycle as well as its components is fundamental for increasing water efficiency, especially in the rational management of irrigated agriculture.

In this context, evapotranspiration (ET) is considered a vital process of the entire climate system because it connects the cycles of water, energy, and carbon with each other, playing a significant role in the transfer of energy from one place to another by evaporation and transpiration (JUNG et al., 2010; KUMAR et al., 2023). Obtaining accurate ET data is a fundamental step in the identification of temporal and spatial variations in the needs and allocation of water resources, especially for irrigation purposes (MENEZES et al., 2024).

Given the difficulty of direct measurement of ET, hydrometeorological models have been developed to estimate reference evapotranspiration (ET_o). Allen et al. (1998) define ET_o as the ET rate of a reference surface, where the reference surface is a hypothetical grass with specific and well-known characteristics.

Accurate estimation of ET on a spatial scale is a challenge, due to the complexity of the process and the high variation in space and time, in addition to being influenced by multiple factors associated with climate and landscape (BAI, 2023; HU et al., 2021). In this context, remote sensing and geographic information system (GIS) provide multifunctional, systematic, and continuous data at a variety of scales and resolutions with global coverage, which make the spatial and temporal study of ET convenient and feasible (KUMAR et al., 2023).

According to Guo et al. (2022), in recent decades, the rapid development of remote

sensing satellite-based models has made it possible to capture the spatial and temporal variability of ET at regional, continental, and even global scale. However, these remote sensing satellite-based models often have varying degrees of uncertainty depending on their theories, structural assumptions, and input parameterization (XU et al., 2015).

In view of the above, the objective of this study was to compare ET_o estimates obtained by means of remote sensing and empirical mathematical models for the Cariri region, CE, Brazil.

MATERIAL AND METHODS

The study was conducted at the Center for Agrarian Sciences and Biodiversity (CCAB), Campus of the Federal University of Cariri (UFCA), Crato, CE, Brazil. The climate of the region is classified as tropical – Aw, with humid climatic characteristics, and well-defined rainy and dry seasons, with annual temperatures ranging between 24 °C and 27 °C. Remote sensing data were obtained by a moderate resolution imaging spectroradiometer (MODIS).

Potential evapotranspiration (PET) data were obtained by the analysis of the 8-day product (MOD16A2) of the MODIS instrument based on the logic of the Penman-Monteith-FAO equation, whose input consists of data from daily meteorological reanalysis and dynamics of vegetation properties. For being based on the soil surface generally composed of grass, potential evapotranspiration and reference evapotranspiration (ET_o) can be considered with the same magnitude (KIM et al., 2020).

Raster images were obtained with a resolution of 500 x 500 m; these images are matrices of pixels, and each pixel has its value and position. The images were downloaded from the Earth Explorer website, referring to the period from 2021 to 2022. To estimate ET_o with terrestrial data, the meteorological variables related to air temperature (average, minimum and maximum, in °C), solar radiation (MJ m⁻² day⁻¹), wind speed (m s⁻¹)

and relative humidity (average, minimum and maximum, in %), were obtained in an automatic weather station, model HOBO RX3000, installed at the CCAB campus of Crato (geographic coordinates: 7°14' S, 39°22' W and 425 masl).

The data series used corresponded to the period from 2021 to 2022 and was employed to calculate ETo by the Penman-Monteith (PMFAO) methods, considered the standard by FAO (ALLEN et al., 1998), and in comparison with the simplified models of Hargreaves and Samani (HS), Jensen and Haise (JH) and Makkink (MK).

The performance of ETo estimates was tested through the application of simple linear regression and the analysis of statistical indices, such as the coefficient of determination (R²) and root mean square error (RMSE).

The accuracy of the estimates was evaluated based on Pearson's correlation coefficient (*r*), Willmott's index of agreement (*d*) and the performance index (*c*), which can be interpreted as follows: terrible, ≤ 0.40 ; very poor, from 0.41 to 0.50; poor, from 0.51 to 0.60; average, 0.61 to 0.65; good, from 0.66 to 0.75; very good, from 0.76 to 0.85; and excellent, > 0.85 (CAMARGO; SENTELHAS, 1997).

RESULTS AND DISCUSSION

It is observed that the ETo estimated by the remote sensing technique (MODIS) showed low accuracy when compared to the PMFAO model, with *r* of 0.85 and *d* of 0.26, leading to classification as "Terrible" (Table 1).

Table 1. Statistical parameters referring to the data obtained by satellite images derived from the MODIS instrument and by the simplified empirical models of Hargreaves and Samani, Jensen and Haise and Makkink

Methods	Validation Parameters			
	<i>r</i>	<i>d</i>	<i>c</i>	Performance
MODIS	0,85	0,26	0,22	Very poor
Hargreaves-Samani	0,88	0,92	0,81	Very good
Makkink	0,94	0,94	0,89	Excellent
Jensen-Haise	0,96	0,60	0,58	Average

For this same method, the regression analysis showed R² of 0.74, representing a low performance and a tendency to overestimate (RMSE of 18.9 mm 8 days⁻¹) the values obtained with the PMFAO model, which can be observed by the high dispersion of the data around the trend line (Figure 1A). Similar results were obtained by Kim et al. (2020),

who compared ETo data obtained by satellite (MOD16A2 product) with data obtained by the Penman-Monteith method and observed a consistent trend in the estimates by the MODIS instrument, overestimating the PMFAO values, with RMSE of 9.7 mm 8 days⁻¹ and R² of 0.79.

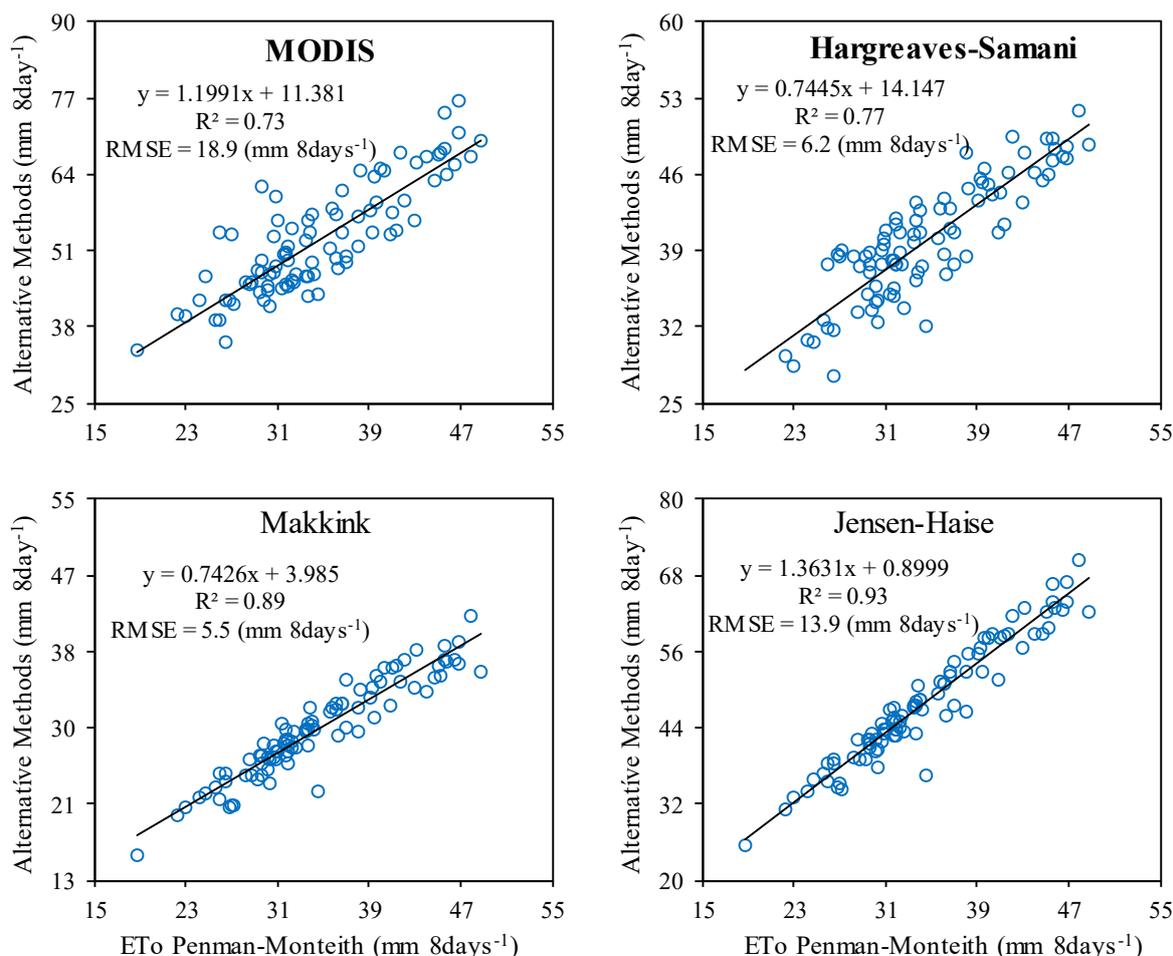


Figure 1. Analysis of the performance of ETo estimates derived from the MODIS instrument and obtained by the simplified empirical models of Hargreaves and Samani, Jensen and Haise and Makkink.

The low accuracy in the ETo estimation by the MODIS instrument compared to the PMFAO model may be related to the short period of time analyzed and also to the fact that it was analyzed based on only one pixel (500 x 500 m) that represented the study area and the location of the automatic weather station used to obtain the terrestrial climatic variables used in the other ETo estimation methods.

On this aspect, Nouri et al. (2016) state that as long as the target area is large enough to be sampled with MODIS images (each pixel is 6.25 ha), evapotranspiration estimates will be reliable and accurately represent the water needs of the landscape.

Among the alternative ETo estimation models, the MK and HS methods were the most accurate compared to the PMFAO model, with r of 0.94 and 0.88 and index of

0.94 and 0.92, classified as “Excellent” and “Very Good”, respectively (Table 1). The performance of these methods was satisfactory, with RMSE of 5.5 and 6.2 mm 8 days⁻¹ for MK and HS, respectively (Figures 1B and 1C).

However, it is worth noting that the HS model showed R^2 of 0.78, which justifies the greater dispersion of the data around the trend line, suggesting greater instability and possible errors associated with the results. In their study, Zhan et al. (2018) also observed that Makkink model was more accurate in estimating ETo. Sharafi and Ghaleni (2021) obtained R^2 of 0.71 for the MK equation in semi-dry climate regions.

Regarding the JH model, it showed a good correlation with the PMFAO method (r of 0.96), but the d index was low (0.60), suggesting a low agreement with to the

PMFAO model, leading to classification as “Poor” (Table 1). Although this method has R2 of 0.93 and there is no major dispersion of the data around the trend line, it showed a strong tendency to overestimate the values obtained with the PMFAO model, with RMSE of 13.9 mm 8 days-1 (Figure 1D). The JH model is based on solar radiation and, in this regard, Celestin et al. (2020) point out that radiation-based methods tend to underestimate higher ETo values.

In general, alternative ETo estimation models that show unsatisfactory performance may be influenced by the simplicity of their equations, as they lead to less accuracy in the method due to a reduced number of input parameters (SANTANA et al., 2018).

However, the accuracy of these estimates may be compromised by periods in which the thermal amplitude, wind speed, and incidence of solar radiation are higher, mainly due to the reduced number of climatological variables considered by some models (MENEZES et al., 2024). This is one of the biggest challenges to overcome with regard to hydrological monitoring in semi-arid regions.

CONCLUSIONS

The ETo data for the Cariri region of Ceará, obtained through satellite images, showed low accuracy and a high tendency to overestimate the values obtained by the Penman-Monteith-FAO model. Among the alternative models, Makkink model proved to be accurate in the ETo estimates for the Cariri region of Ceará, and can be used, when necessary, to replace the standard Penman-Monteith-FAO model.

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