ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

ANÁLISE DA DINÂMICA TEMPORAL DA EVAPOTRANSPIRAÇÃO REAL EM UMA BACIA HIDROGRÁFICA DO SEMIÁRIDO ATRAVÉS DE MODELAGEM HIDROLÓGICA E SENSORIAMENTO REMOTO

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1 RESUMO

A evapotranspiração é uma das componentes mais relevantes do ciclo hidrológico, especialmente, em regiões semiáridas, onde há elevadas temperaturas e alta demanda hídrica pelas culturas, sendo sua análise essencial para o planejamento e gestão dos recursos hídricos. Objetivou-se calibrar e validar o modelo *Soil and Water Assessment Tool* (SWAT) com informações de evapotranspiração real advindas de sensoriamento remoto, e investigar a sua dinâmica temporal em uma bacia hidrográfica experimental do Semiárido. O estudo foi desenvolvido na Bacia Experimental do Riacho Jatobá (13,5 km²). Dados de evapotranspiração (ET) foram obtidos do produto MOD16A2, do sensor MODIS. A simulação hidrológica foi realizada com o modelo hidrológico SWAT. Foram realizadas análises estatísticas descritivas e análise de tendência pelo teste de Mann-Kendall. Os valores de R^2 encontrados para a evapotranspiração, foram de 0,61 e 0,81 para a calibração e validação, respectivamente. As análises de tendência apontaram que há tendência de decréscimo da evapotranspiração real no período de 2006 a 2018. Da precipitação média anual na bacia (722,9 mm), 26% corresponde à precipitação efetiva e 74% retorna à atmosfera como evapotranspiração (534,7 mm). A utilização de dados alternativos para a calibração do modelo SWAT é de grande relevância, especialmente em bacias semiáridas.

Palavras-chave: MODIS, SWAT, balanço hídrico.

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ANALYSIS OF THE TEMPORAL DYNAMICS OF ACTUAL EVAPOTRANSPIRATION IN A SEMIARID RIVER BASIN USING HYDROLOGICAL MODELING AND REMOTE SENSING

Recebido em 25/01/2021 e aprovado para publicação em 03/11/2021
DOI: http://dx.doi.org/10.15809/irriga.2021v26n3p543-564

2 ABSTRACT

Evapotranspiration is one of the most relevant components of the hydrological cycle, especially, in semiarid regions, where there are high temperatures and great water demand for crops, and its analysis is essential for the planning and management of water resources. The objective was to calibrate and validate the Soil and Water Assessment Tool (SWAT) model with real evapotranspiration information from remote sensing, and to investigate its temporal dynamics in an experimental river basin of the Semiarid. The study was conducted in the Riacho Jatobá Experimental River Basin (13.5 km²). Evapotranspiration (ET) data were obtained from the product MOD16A2, from the MODIS sensor. The hydrological simulation was carried out with the SWAT hydrological model. Descriptive statistical analysis and trend analysis were performed using the Mann-Kendall test. The R^2 values found for evapotranspiration were 0.61 and 0.81 for calibration and validation, respectively. The trend analysis test showed that there is a trend of decrease for actual evapotranspiration for the 2006–2018 period. Of the average annual precipitation in the river basin (722.9 mm), 26% corresponds to the effective precipitation and 74% returns to the atmosphere as evapotranspiration (534.7 mm). The use of alternative data for calibrating the SWAT model is highly relevant, especially for semiarid watersheds.

Keywords: MODIS, SWAT, water balance.

3 INTRODUCTION

Evapotranspiration (ET) is one of the main components of the water balance and is defined as the set of processes of evaporation of water from the soil and transpiration of vegetation, with the capacity to transfer large volumes of water from the Earth's surface to the atmosphere (ALLEN *et al*., 1998; ARAÚJO *et al*., 2017). Salama *et al*. (2015) highlighted that estimating actual evapotranspiration is essential for water resource management and planning and is an important part of water management in agriculture and in local and regional water balance studies, particularly in semiarid regions. According to Chun *et al*. (2018), ET plays an important role in the hydrological cycle of arid regions since most of the precipitation is evaporated or transpired by plants. Furthermore, water scarcity scenarios are frequent in semiarid regions because of changes in natural vegetation cover and regional climate variability, compromising the basic uses of these resources, such as human supplies and agriculture (food production) (FERREIRA *et al*., 2020).

The semiarid region of Brazil has limited water resources due to irregular rainfall patterns, with little rainfall distributed across time and space. This makes water management in agriculture extremely important, as water issues in the Brazilian semiarid region strongly influence the social and agricultural development of this region. Several studies have focused on reliable estimates of ET in time and space, also considering scenarios of both dry and rainy periods (FILGUEIRAS *et al*., 2020; ABIODUN *et al*., 2018; VANINO *et al*., 2018; MIRANDA *et al*., 2017; TABARI *et al*., 2013).

With the advancement of technology, ET estimates from satellite-based products have become relevant among researchers and government agencies since direct ET measurements in the field are costly and difficult (MIRANDA *et al*., 2017).

Additionally, indirect methods of assessing variables, which are based on remote sensing and hydrological modeling, can increase the reliability of water and energy balances. According to Ruhoff *et al*. (2013), remote sensing is considered an effective tool for estimating evapotranspiration (ET), particularly at large spatial scales. For small scales, it is necessary to investigate the representativeness of such estimates, since point data need to be extrapolated to large areas, increasing uncertainties, especially in semiarid regions, where there is great spatial variability in land use and, consequently, in ET (JOVANOVIC *et al*., 2015).

Evapotranspiration estimates through remote sensing have been increasingly improved via different orbital sensors and for different areas of the planet, including in the semiarid region of Pernambuco. Lins *et al*. (2017) estimated actual evapotranspiration via Landsat 8 OLI/TIRS images for a city near the study area. Additionally, in a region near the current study area, Coelho *et al*. (2017) used evapotranspiration data estimated from the MODIS sensor to determine the water balance and estimate groundwater recharge in an alluvial valley.

Given the increasing use of data from remote sensing, many researchers have used such indirect information, especially evapotranspiration, as an alternative for the calibration and validation of hydrological models (CHUN *et al*., 2018; PARAJULI *et al*., 2017; FRANCO; BOUNUMÁ, 2017; ABIODUN *et al*., 2018; MIRANDA *et al*., 2017) in basins with limited availability of field measurements since the costs for field monitoring of hydrological variables can be high.

One of the main hydrological models that has been widely used for watershed management is the *Soil Model and Water Assessment Tool* (SWAT); however, few studies have been conducted to evaluate the actual evapotranspiration in basins of semiarid regions via estimates produced by this model (CHUN *et al*., 2018), which can be verified in terms of representativeness via comparative analyses with remote sensing products. Notably, Miranda (2017) studied the Pontal River Basin, a semiarid region of Pernambuco.

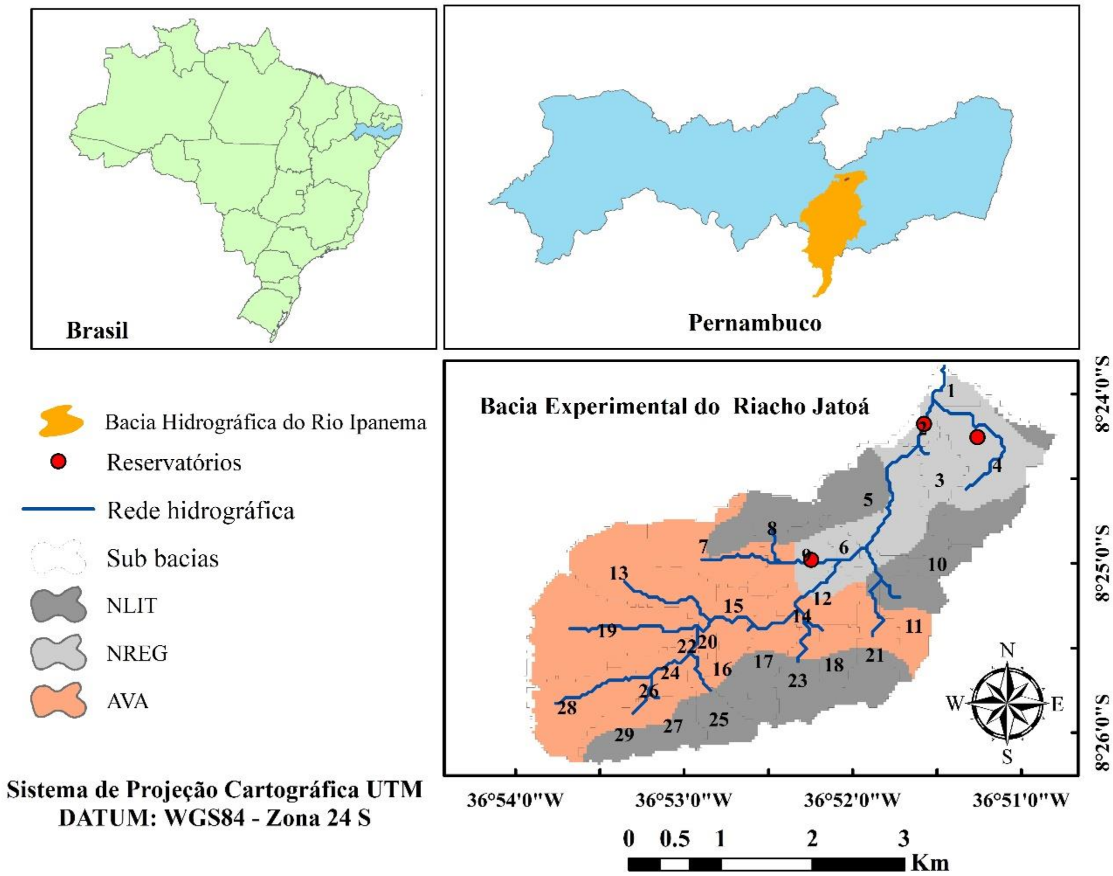
Thus, the present work aimed to calibrate and validate the *Soil Model and Water Assessment Tool* (SWAT) with real evapotranspiration information from remote sensing and investigate its temporal dynamics in an experimental basin in the semiarid region.

4 MATERIALS AND METHODS

4.1 Study area

The study was developed in the Experimental Basin of Riacho Jatobá (BERJ), which is approximately 13.5 km² and is located in the municipality of Pesqueira, PE, Brazil, between coordinates 8° 34' 17” and 8° 18' 11” South latitude 37° 1' 35” and 36° 47' 20" West longitude (Figure 1).

Figure 1 Location of the Jatobá Stream Experimental Basin and presentation of the predominant soils and monitoring sites, as well as the number of subbasins**.**



NLIT – Neosol Litholic, NREG – Neosol Regolith, AVA – Red–Yellow Argisol.
Source: Authors.

The Jatobá Stream is a tributary of the Ipanema River, is 6.5 km long, has a perimeter of 16 km and a compactness coefficient of 1.27 (ARAÚJO, 2016), with a watercourse of order 4. Its sources are located in the Serra da Cruz, at a topographic elevation of 830 m, with the top located 200 m above the basin's mouth, which has been suffering from deforestation.

The climate of the region is BSsh (semiarid, very hot, steppe type), according to the Köppen classification. The average annual precipitation of the basin is approximately 600 mm (with the rainy season between April and July), the average temperature is 23°C, and the potential evapotranspiration is approximately 2000 mm/year (MELO; MONTENEGRO, 2015; SILVA JUNIOR *et al* ., 2016).

The main soil types found in the basin are yellow argisols, with the presence of rocky impediments, such as the Neossolo Litholic and Neosol Regolithic (ARAÚJO *et al*., 2018). The BERJ is a typical rural basin, with predominantly hyperxerophilic Caatinga vegetation, exhibiting seasonality over time depending on rainfall and local climate indices (SILVA JÚNIOR, 2016). Over the past few years, due to different land uses and inadequate management, the basin has undergone landscape changes, which interfere with hydrological processes and the water balance.

4.2 Acquisition of orbital evapotranspiration (ET) data

Evapotranspiration (ET) and leaf area index (LAI) data were obtained from the MODIS sensor MOD16A2 and MOD15A products, respectively, which are available at https://earthexplorer.usgs.gov/. Both products have a spatial resolution of 500 m and a temporal resolution of 8 days. The spatial database for each product used in the analyses consisted of mean ET and LAI values for pixels in each subbasin and HRU (Hydrologic Response Unit), respectively. These values were extracted via zonal statistics, and to ensure that even the smallest zones would return valid values, the pixels of all the products were resampled to a 10 m spatial resolution *via nearest interpolation. Neighbor*. All downloaded products were processed via the GDAL (*Geospatial Data Abstraction) library. Library*; https://gdal.org/).

In this study, the start and end dates of the growing seasons for each HRU were determined from observations of the leaf area index for the study area obtained from the MOD15A product of the MODIS sensor. This approach is novel and has not been previously used in Brazil. To this end, the LAI time series for each HRU were subjected to a decomposition process via the simple moving average method (BOUZADA, 2012). The seasonal component was subsequently binarized, where 0 was defined as a negative value and 1 as a positive value. With each binarized series (SB), the start date of the vegetation growing season (g_i) was chosen when$SB_j = 1$ and $SB_{j+1} = 0$, where j refers to the date of the 8-day IAF composition. The season end date (g_t) was defined when$SB_j = 0$ and $SB_{j+1} = 1$. All the dates were inserted directly into the respective ".mgt " files of each HRU of the SWAT model, which will be described below, via Python programming.

4.3 Description of the SWAT model

The *Soil and Water Assessment Tool* (SWAT), which is freely available at (http://swat.tamu.edu/), is a semiconceptual, semidistributed, physically based, and continuous-time model (ARNOLD *et al*., 2012). It is a model frequently used in the simulation of different physical processes, such as climate, hydrology (surface runoff, percolation, interception, infiltration, subsurface flow, base flow, and evapotranspiration), and soil management at daily, monthly, and annual time scales (FONTES JÚNIOR *et al*., 2019; BRESSIANI *et al*., 2015).

SWAT considers the water balance equation (Equation 1) and estimates runoff via the curve-number (CN) method, which was developed by the *Soil Conservation Service*. In addition, the model considers the so-called hydrologic response units (HRUs), which represent homogeneous areas in relation to soil type, land use and slope, for the calculation of hydrological processes (NEITSCH *et al*., 2005).

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(P - Q_S - ET - W_S - Q_{gw} \right) \qquad (1)$$

where SW_t and SW_0 represent the soil water storage at the final and initial times, respectively (mm); t represents time (days); P represents precipitation (mm); Q_s represents surface runoff (mm); ET represents evapotranspiration (mm); W_s represents percolation (mm); and Q_{gw} represents baseflow (mm).

4.4 SWAT input data

The SWAT model requires four main types of input data, three types of spatial data, namely, digital elevation models (DEMs), soil type maps and land use maps, and tabular or temporal data of meteorological variables.

For this work, the DEM was obtained from the Brazilian Agricultural Research Corporation (Embrapa), as was the soil type map obtained from the Agroecological Zoning of Pernambuco (ZAPE). The physical characteristics of the soils included in the model are described in Table 1 and were specified on the basis of the study by Montenegro and Ragab (2010).

Table 1. Physical-hydraulic properties of the soils of the Jatobá Stream Experimental Basin (BERJ), Pesqueira, PE.

No	Soil	Physical and water properties of soil							
		Z (mm)	D_s (g/cm ^{3})	CAD (mm/mm)	k_{sat} (mm/hr)	Texture (%)			CO (%)
						Clay	Silt	Sand	
1.	AVA	950	1.38	0.30	3.80	32	31	37	1.74
		1300	1.32	0.32	1.29	34	27	39	0.58
		2000	1.59	0.37	36.43	5.5	30.5	64	1.30
2.	NLIT	500	1.48	0.33	17.96	19	25	56	1.74
3.	NREG	170	1.56	0.34	18:00	11	8	81	1.74
		450	1.54	0.34	18:00	13	16	71	0.58
		850	1.56	0.33	0.05	13	11	76	0.05

AVA – Red–Yellow Argisol, NLIT – Neosol Litholic, NREG – Neosol Regolith, Z – depth (mm), D_s – soil density (g/^{cm3}), CAD – available water capacity (mm/mm), k_{sat} – saturated soil hydraulic conductivity (mm/hr), CO – organic carbon. **Source:** adapted from Montenegro and Ragab (2010).

The land use map was sourced from the Mapbiomas Project (Collection 4.1 Caatinga), considering the map for the year 2018. The project details can be found at http://mapbiomas.org (VIANA, 2019). The different land use classes existing in BERJ were reclassified according to the classes available in the SWAT database. The related classes were water (WATR), agricultural area (AGRL), pasture (PAST), shrubby Caatinga (RNGB), and arboreal Caatinga (FRST), corresponding to 0.05%, 0.95%, 26.48%, 71.96%, and 0.56% of the basin area, respectively.

Rainfall data were collected from three automatic rain gauges installed in the basin and operated by the Water and Soil Laboratory of the Federal Rural University of Pernambuco (UFRPE). The precipitation data were subjected to consistency analysis according to the double mass method (BERTONI; TUCCI, 2013), obtaining coefficient of determination (R^2) values of 0.99, thus indicating adequate consistency between the data used (CHAGAS *et al*., 2020). The time series data for this study covered the period from 2000--2019, operating in a daily time step. The first three years (2000--2002) were used for warming the SWAT model and were therefore not considered in the hydrological analysis.

The study area was also included. Three reservoirs were included in the BERJ: Nossa Senhora de Fátima, Fuba I, and Fuba II.

Information about the reservoirs was obtained from the UFRPE Water and Soil Laboratory and is presented in Table 2.

Table 2. Characteristics of existing reservoirs in the Jatobá Stream Experimental Basin (BERJ), Pesqueira, PE.

Number	Reservoir	Start of operation	Maximum capacity (m³)
1	Our Lady of Fatima	2000	80.00 x 10³
2	Fuba I (under 9)	2000	24.84 x 10³
3	Fuba II (under 4)	2000	24.84 x 10³

Source: Authors.

4.5 Performance of the SWAT model

The SWAT model's performance was assessed via three statistical indicators: the Nash–Sutcliffe coefficient (NS), the percentage of trend (PBIAS), and the coefficient of determination (R^2). These indicators are represented by the equations below (Equations 2, 3, and 4):

$$NS = 1 - \frac{\sum_i (Q_{obs} - Q_{sim})_i^2}{\sum_i (Q_{obs,i} - \bar{Q}_{obs})^2} \quad (2)$$

$$PBIAS = 100 \frac{\sum_{i=1}^{n} (Q_{obs} - Q_{sim})_i}{\sum_{i=1}^{n} (Q_{obs,i})} \quad (3)$$

$$R^2 = \frac{\left[\sum_i (Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})\right]^2}{\sum_i (Q_{obs,i} - \bar{Q}_{obs})^2 \sum_i (Q_{sim,i} - \bar{Q}_{sim})^2} \quad (4)$$

where Qobs represents the observed data; Qsim represents the simulated data; $\overline{Q}$obs represents the mean of the observed data; and $\overline{Q}$sim represents the mean of the simulated data.

Calibration and validation were carried out at the subbasin level, with subbasin 19 being chosen for this purpose, as it is one of the largest subbasins and presents greater heterogeneity, with different uses of water and soil; this subbasin is one of the most representative for the entire BERJ.

4.6 Descriptive statistics

The results were subjected to statistical evaluation via measures of central tendency (mean) and dispersion (minimum, maximum, standard deviation (SD) and coefficient of variation (CV)). The temporal variability of the data was assessed according to the criteria of Warrick & Nielsen (1980), with low variability (CV < 12%), medium variability (12 < CV < 60%), and high variability (CV > 60%).

4.7 Trend Analysis – Mann–Kendall

Trend analysis was performed via the nonparametric Mann (1945) and Kendall (1975) tests, which, because it is a nonparametric method, do not require a normal distribution of the data (Equation 5). The analysis is performed under the null hypothesis (H0) that the time series data do not present a trend and the alternative hypothesis (HA) that the data present a trend in the time series. The trend test indicates whether there is a positive or negative trend according to the S test for a given confidence level.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sinal\ (x_j - x_i) \quad (5)$$

where n is the number of data points; xi and xj are the data values of the time series (j>i), respectively; and sign (xj -xi) can be expressed via Equation (6):

$$sinal\ (x_j - x_i) = \begin{cases} +1;\ x_j - x_i > 0 \\ 0;\ x_j - x_i = 0 \\ -1;\ x_j - x_i < 0 \end{cases} \quad (6)$$

Sen also used *slope* (Equation (7)), which is an estimator for assessing the slope of a trend. These analyses have been widely used and are considered efficient tools for identifying trends in hydrological variables (PAULINO *et al*., 2019).

$$\int \beta = \left(\frac{x_j - x_k}{j - k}\right), para\ i = 1,2,3, \ldots n \quad (7)$$

where β is Sen's slope estimator. When the values are positive, the trend is positive; when the values are negative, the trend is negative; and xj and xk are the values given at times j and k (j > k), respectively.

5 RESULTS AND DISCUSSION

5.1 Statistical analysis of data

Table 3 presents the descriptive statistics for the 8-day accumulated real evapotranspiration, estimated by the SWAT model and by remote sensing from the MODIS sensor, for representative subbasins of the BERJ. Among the 29 subbasins delimited by the SWAT model, subbasins 2, 5, 19 and 27 were selected, and criteria such as the subbasin area (largest and smallest), spatial distribution (upper, middle and lower subbasins) and different land uses were evaluated.

Table 3. Descriptive statistics of evapotranspiration data from the MODIS sensor and the SWAT model

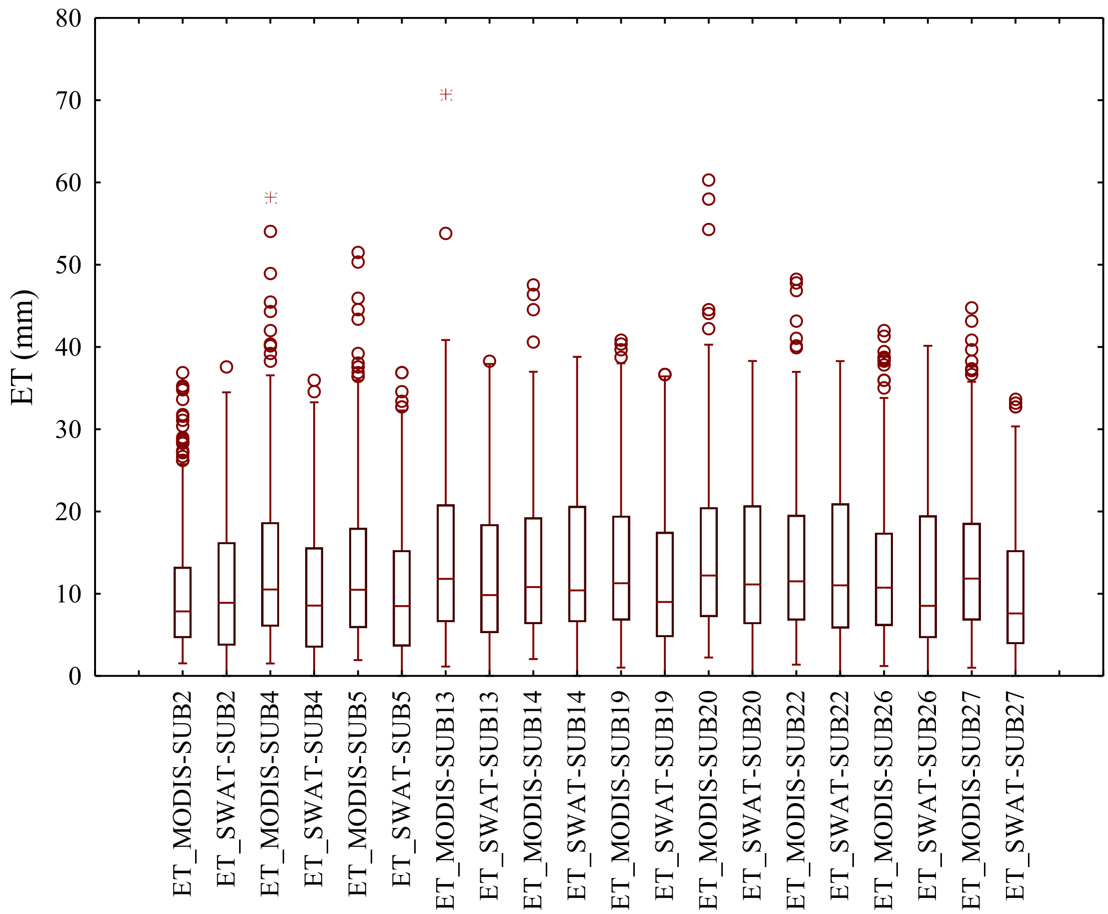
Subbasin	Area (km²)	Average	Minimum	Maximum	DP	CV
SUB 2 -MODIS	0.16	9.89	1.53	36.92	6.75	0.68
SUB 2 -SWAT		10.43	0.00	37.67	8.05	0.77
Sub 5 -MODIS	1.20	12.99	1.93	51.43	8.86	0.68
Sub 5 -SWAT		10.07	0.00	36.95	7.75	0.77
Sub 19 -MODIS	1.31	13.78	1.01	40.73	8.79	0.64
Sub 19 -SWAT		11.42	0.00	36.74	8.47	0.74
Sub 27 - MODIS	0.30	13.40	0.99	44.73	8.26	0.62
Sub 27 - SWAT		10.07	0.00	33.68	7.77	0.77

SD – standard deviation; CV – coefficient of variation
Source: Authors.

For the period from 2003--2018, the average ET values ranged from 9.89 to 13.78 mm for the 8-day MODIS accumulated data and from 10.07 to 11.42 mm for the ET estimated by the SWAT model. The maximum values obtained were greater for the MODIS ET than for the ET from the SWAT model, with the exception of subbasin 2, where the ET calculated by the SWAT model was slightly greater. The standard deviations were similar for all the data, ranging from 6.75 to 8.86 mm. According to the criteria of Warrick and Nielsen (1980), all subbasins presented high temporal variability in evapotranspiration.

For a better visualization of the behavior of the ET data, Figure 2 presents *box plots* for the ETs estimated by the SWAT model and the MODIS product for subbasins 2, 4, 5, 13, 14, 19, 20, 22, 26 and 27. In general, it is possible to observe a similar pattern in the distributions of the data generated by SWAT and those from MODIS.

Figure 2. *Box plots* of evapotranspiration data from the MODIS sensor and the *Soil Model and Water Assessment Tool* (SWAT).



Source: Authors.

5.2 Analysis of the calibration of the SWAT model

The parameters used in the calibration of the SWAT model with evapotranspiration data, as well as their calibrated values, are presented in Table 4. These parameters are similar to those obtained in research carried out in semiarid regions, such as the studies developed by Miranda (2017) in the Pontal River Basin, Pernambuco; Andrade *et al*. (2018), in the Mundaú River basin, Pernambuco; Magalhães *et al*. (2018) in the same area as the present study; and Fontes Júnior and Montenegro (2019) in the Riacho do Mimoso basin, also in Pernambuco. These parameters are related to surface runoff, groundwater, and crops.

Table 4. Parameters used for calibrations with evapotranspiration data in the *Soil Model and Water Assessment Tool* (SWAT).

Parameter	**Description**	**Home**	**Calibrated**
CN2 (. mgt)	Flow number curve.	-	72.51
ALPHA_BF (. gw)	Base flow alpha factor (days).	0.048	0.05
GWQMN (. gw)	Limiting depth of water in the shallow aquifer for return flow to occur (mm).	0	700
GW_REVAP (. gw)	Groundwater " revap " coefficient .	0.02	0.2
EPCO (. hru)	Compensation factor for water absorption by plants.	1.0	0.6
ESCO (. hru)	Soil water evaporation compensation factor.	0.95	0.6
CANMX (. hru)	Maximum canopy water storage (mm).	0	10

Source: Authors.

The curve-number parameter is considered one of the most sensitive and relevant parameters in calibration processes (ARNOLD *et al*., 2012). CN varies depending on land use, land cover, and antecedent moisture conditions and is used to estimate hydrological losses due to infiltration and excess rainfall (KAFFAS *et al*., 2018; TANKSALI; SORAGANVI, 2020). In the present study, the calibrated CN consisted of a relative change, that is, a percentage change, which preserves its spatial heterogeneity. The change represented a 6% increase in the original CN values, resulting in an average value of 72.51.

The soil water evaporation compensation factor (ESCO) is related to the depth required to meet soil evaporation requirements. The parameter ranges from 0.01 to 1 and has a default value of 0.95. A decrease in the ESCO value represents a greater withdrawal of water from the lower levels of the soil layer to meet evaporative demands (KAFFAS *et al*., 2018), which justifies a lower calibrated value (0.60), since evaporative demand is greater in semiarid regions.

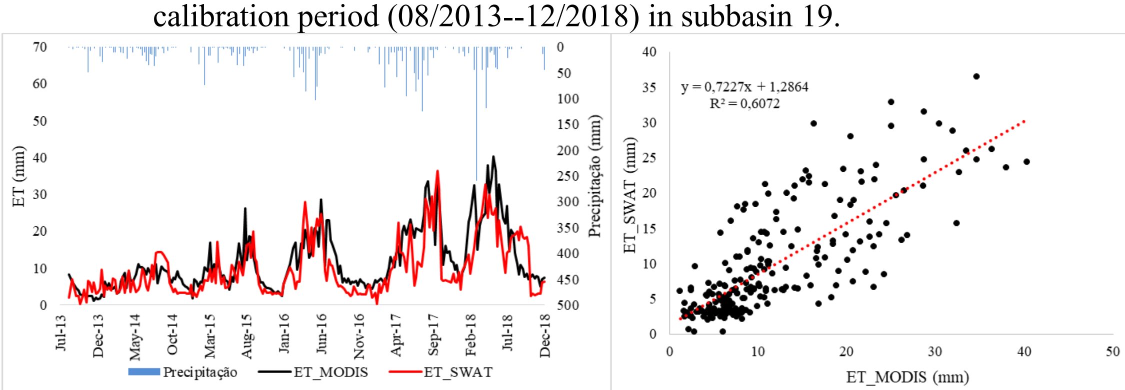
The plant water uptake compensation factor (EPCO) defines the soil depth range used to control plant water uptake and is considered to be between 0.01 and 1. When EPCO approaches 1, the deeper soil layers contribute to plant water uptake, and as EPCO approaches 0, the plant's water uptake demands are met by the upper soil layers (KAFFAS *et al*., 2018; TANKSALI; SORAGANVI, 2020). The decrease in the standard EPCO from 1 to the calibrated value of 0.6 may be related to the presence of shallow soils in the semiarid region, where absorption demands are not met by the deep layers but rather by the upper soil layers. Miranda (2018) obtained a calibrated EPCO of 0.24 for a watershed in the semiarid region of Pernambuco.

The GW_REVAP parameter controls the movement of water from the shallow aquifer to the upper soil layers. The closer it is to 0, the more restricted the movement of water from the aquifer is to the unsaturated zone. As the parameter approaches 1, the evaporation rate increases, thus reducing the baseflow (KAFFAS *et al*., 2018). In the present study, the calibrated GW_REVAP corresponded to a value of 0.2, indicating low movement of water from the groundwater table to the surface soil layers.

CANMX represents the maximum amount of water that can be retained within the canopy when it is fully developed (mm). According to Tobin & Bennett (2017), CANMX represents one of the five parameters that directly impact potential and actual evapotranspiration. The authors reported that this parameter, together with ESCO, exhibited high sensitivity in the calibration of an experimental basin in Oklahoma, USA, which has a transitional climate between humid and semiarid climates and an average precipitation of 800 mm. The CANMX values calibrated by the authors ranged from 12.7 to 51.7 mm. Miranda (2017) reported a calibrated CANMX value of 0.42 mm for a semiarid watershed. The value found for the present study was 10 mm.

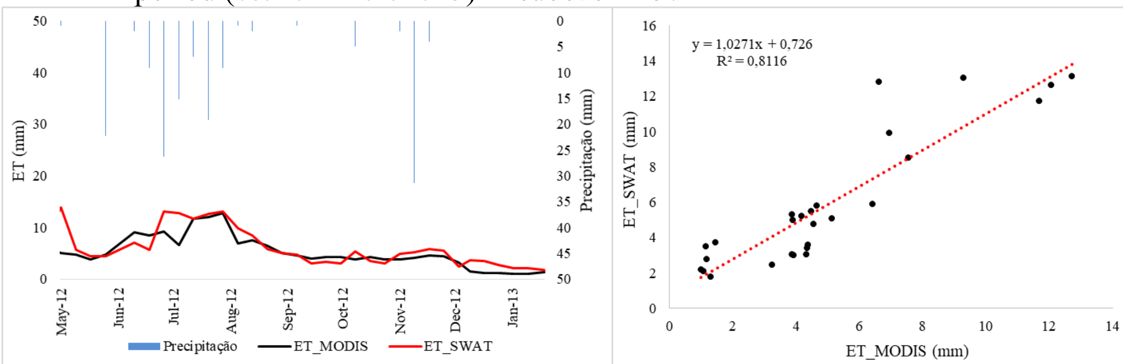
Figure 3 shows the ET values simulated by the SWAT model compared with the corrected MODIS data during the calibration period (August 2013--December 2018). The validation period (May 2012--February 2013) is shown in Figure 4. The subbasin-level comparison between the monthly ET data simulated by the SWAT model and the MODIS data indicates good agreement between them. Abiodun *et al.* (2018), comparing real MODIS evapotranspiration data with those simulated by the SWAT model in a semiarid river basin in South Australia, reported good agreement between the annual mean data, with a maximum difference of less than 13% and an average difference of less than 6%, from 2007--2013. In the present study, the average differences between the SWAT and MODIS model data were even smaller, being less than 0.02% in the calibration period and less than 0.01% in the validation period, for time intervals of 8 days.

Figure 3 Time series of accumulated evapotranspiration (ET) for 8 days, simulated by the *Soil Model and Water Assessment Tool* (SWAT) and corrected from MODIS in the calibration period (08/2013--12/2018) in subbasin 19.



Source: Authors.

Figure 4 Time series of accumulated evapotranspiration (ET) for 8 days, simulated by the *Soil Model and Water Assessment Tool* (SWAT) and corrected MODIS in the validation period (05/2012--02/2013) in subbasin 19.



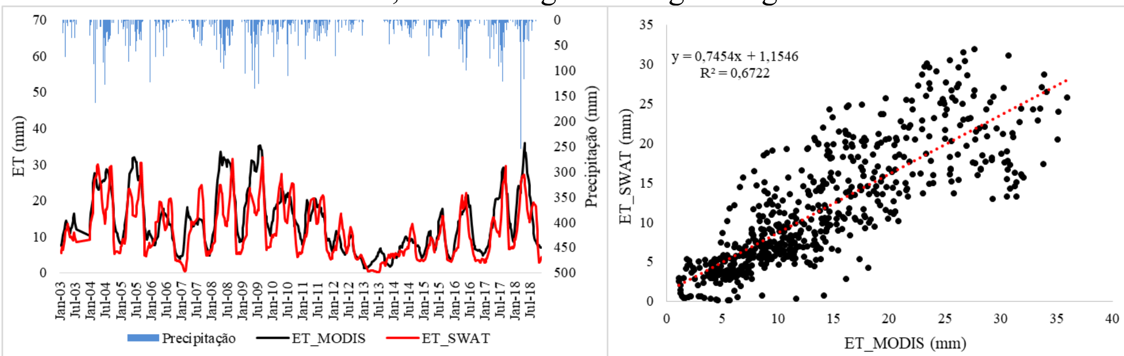
Source: Authors.

In this study, the NS values found for evapotranspiration (0.53 and 0.68 for calibration and validation, respectively) are comparable to those reported by Miranda (2018) for the Pontal River Basin, who calibrated and validated ET via the SWAT model (0.61 and 0.63). Parajuli *et al*. (2017) reported NS values of up to 0.80 in the calibration model and 0.75 in the validation of the SWAT model when only evapotranspiration data were used.

The R^2 values found for evapotranspiration were 0.61 and 0.81 for calibration and validation, respectively. Parajuli *et al*. (2017) reported R^2 values of up to 0.82 in the calibration model and 0.78 in the validation of the SWAT model when only evapotranspiration data were used. Franco and Bonumá (2017), when performing a multivariable calibration of the SWAT model with evapotranspiration from remote sensing, reported R^2 values of 0.51 for the calibration and 0.80 for the validation. However, according to the authors, the performance of the evapotranspiration simulation was unsatisfactory because of the high PBIAS values found (between 37.6 and 43.1 for the calibration and between 33.0 and 41.4 for the validation). On the other hand, in the present study, for BERJ, PBIAS values of 16.7% were verified for calibration and -17.2% for validation with evapotranspiration data, suggesting that the SWAT model is capable of satisfactorily simulating real evapotranspiration for the experimental Jatobá Stream basin. During the calibration period, the resulting PBIAS indicated that the SWAT model underestimated the MODIS data, whereas during the validation period, the data were overestimated by the model. Parajuli *et al*. (2017), who evaluated the use of evapotranspiration data from the MODIS sensor in the SWAT model in the Mississippi River Basin, USA, reported that the model overestimated ET compared with MODIS data.

Figure 5 shows the time series graph from 2003--2018 of ETs generated by the SWAT and MODIS models, with five-period 8-day moving averages. This analysis showed a better fit, despite the smoothing of the series, which would occur in a monthly or annual series. An intensification of seasonality was observed, as were a decrease in residuals and the effects of extreme values.

Figure 5 Precipitation and evapotranspiration (ET) time series simulated by the **Soil** *Model and Water Assessment Tool* (SWAT) and corrected from MODIS in the period from 2003--2019 in subbasin 19, considering a moving average.



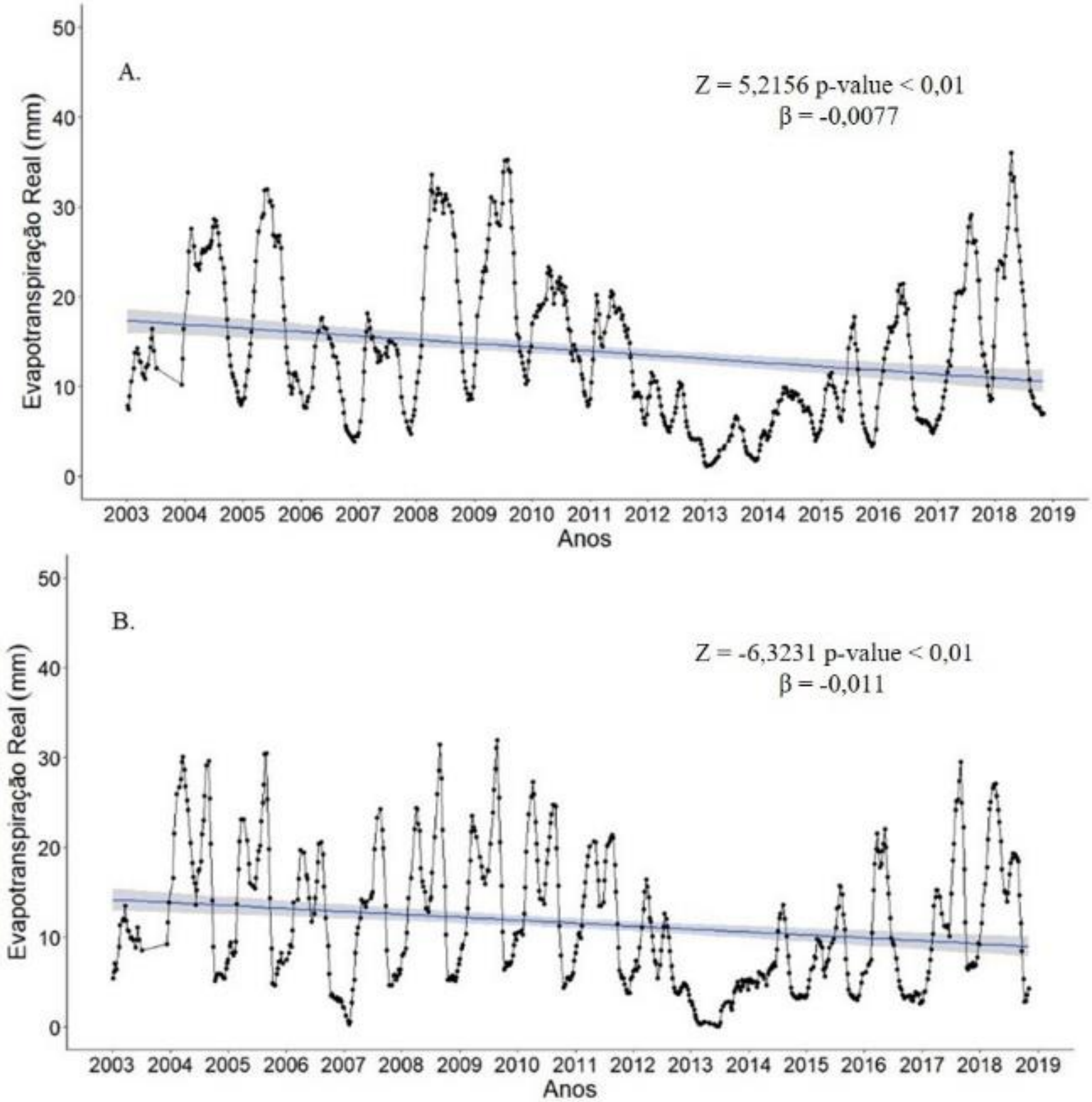
Source: Authors.

For the smoothed series, the performance parameters R^2, NS and PBIAS improved considerably, with values of 0.68, 0.59 and 17.1, respectively, for the entire time series evaluated. For the calibration (08/2013--12/2018) and validation (05/2012--02/2013) periods, the values of the performance parameters also improved considerably, with NS=0.73, R^2=0.78 and PBIAS=16.5 for the calibration period and NS=0.80, R^2=0.91 and PBIAS=-14.7 for the validation period. When calibrating the SWAT model with monthly evapotranspiration estimated from MODIS data, Siresena *et al.* (2020) reported R^2, NS and PBIAS values of up to 0.86, 0.80 and -7.8, respectively, at the subbasin level, which indicates good model performance when working on at a longer time step.

5.3 Trend analysis

Figure 6 presents the eight-day cumulative trend analyses for SWAT-simulated actual evapotranspiration for subbasin 19 (Figure 6A) and MODIS-observed actual evapotranspiration for subbasin 19 (Figure 6B) from January 2003 to December 2018 in the Jatobá Basin.

Figure 6 Evapotranspiration trend simulated by the *soil model and water assessment tool* (SWAT) for subbasin 19 (A) and the evapotranspiration trend observed by the MODIS sensor (B).

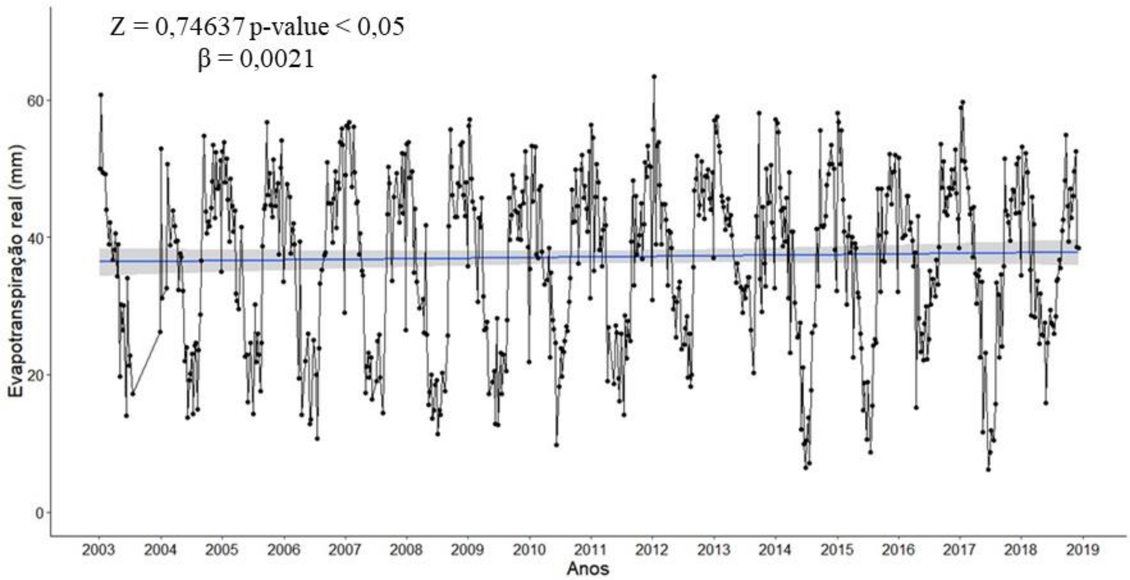


Source: Authors.

The trend analysis via the Mann–Kendall test for evapotranspiration revealed a significant result for the accumulated evapotranspiration over eight days (P>0.05), indicating that there was a trend for evapotranspiration in subbasin 19. The actual evapotranspiration simulated by the SWAT model was similar to the evapotranspiration observed by the MODIS sensor, and the negative signs of Z reflected a downward trend (PINHEIRO *et al*., 2013; XU *et al*., 2018) of -0.008 mm/8 days and 0.011 mm/8 days, respectively. Cabral Júnior *et al*. (2019), Xu *et al* . (2018) and Costa *et al*. (2020) reported that the negative trend in evapotranspiration can be explained by the increase in humidity caused by extreme precipitation events and the increase in consecutive 5-day rainfall.

Figure 7 presents the trend analysis for the moving averages of five 8-day periods of evapotranspiration from 2003--2018 in the Jatobá Basin.

Figure 7 averages of five 8-day periods of evapotranspiration in the Jatobá Stream Experimental Basin.



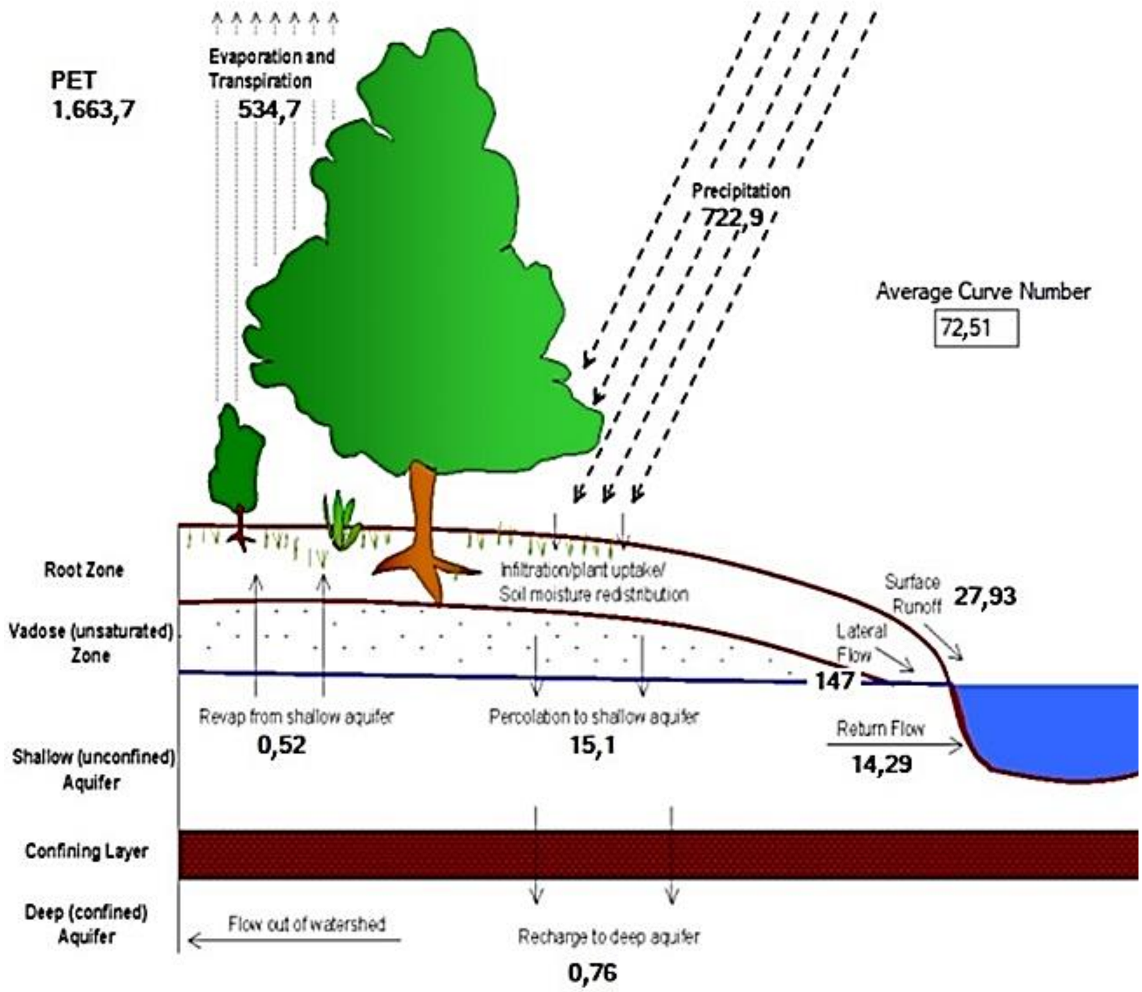
Source: Authors.

The trend analysis via the nonparametric Mann–Kendall method did not reveal a significant trend (p>0.05) for the five-period 8-day moving averages of evapotranspiration. However, unlike the results presented for the eight-day accumulated trend (Figure 6), the trend for the moving average was positive for Z, indicating an increasing trend (XU *et al*., 2018). Rocha Júnior *et al*. (2021) and Costa *et al*. (2020), when analyzing the evapotranspiration trend in Northeast Brazil, reported that positive ET trends may be associated with an increase in local temperature and intensification of the desertification process.

5.4 BERJ water balance

Figure 8 presents the results of the hydrological processes simulated by the SWAT model for the period 2000--2019. The average annual precipitation in BERJ was 722.9 mm, the average annual potential evapotranspiration was 1,663.7 mm, and the actual evapotranspiration was 534.7 mm. The average annual shallow aquifer rise was 0.52 mm, and the average annual surface runoff was 27.93 mm. These results indicate that of all the precipitation that occurred in the basin, 26% corresponds to effective precipitation and that 74% of the total precipitation returns to the atmosphere as evapotranspiration. The average water balance values obtained in this study were similar to those reported by Magalhães *et al*. (2018) in the same study area, and the actual evapotranspiration verified by the authors was higher than that of the present work, with a value of 588.2 mm, in addition to an average precipitation of 654.3 mm. Andrade *et al*. (2017), carrying out hydrological modeling under data scarcity in a basin of Alto Mundaú, Northeast Brazil, verified ET values of 674.2 mm and average precipitation of 1,075 mm in the period between 2000 and 2016.

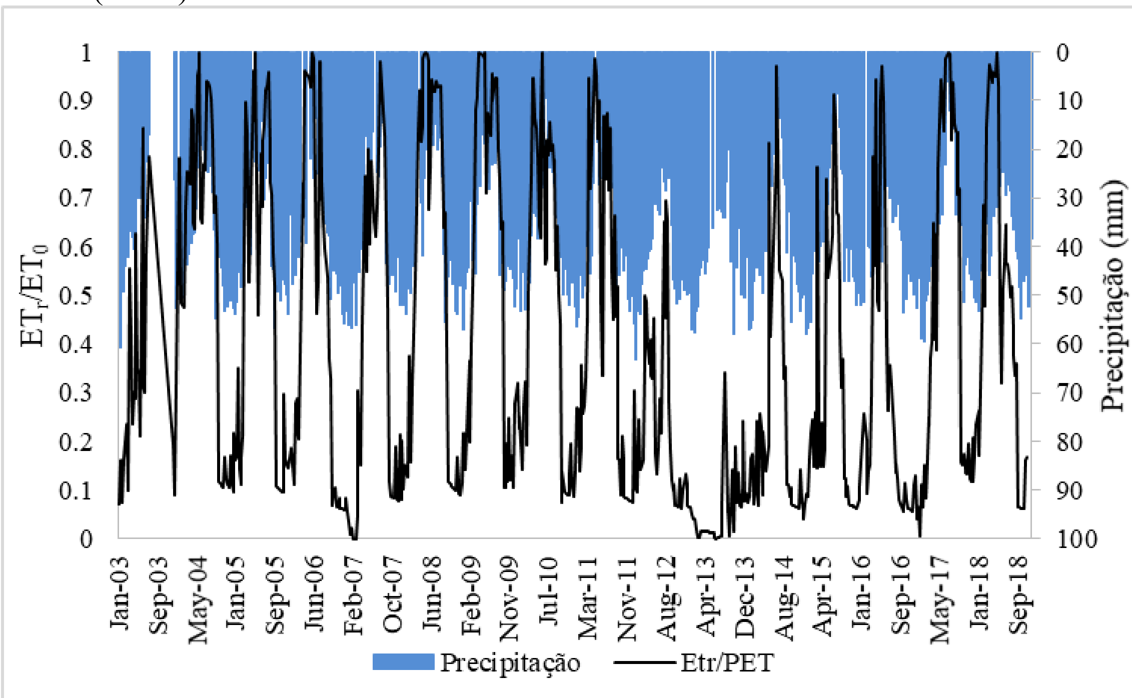
Figure 8 Representation of the water balance of the Jatobá Stream Experimental Basin (BERJ) simulated by the **Soil** *Model and Water Assessment Tool* (SWAT) for the period 2000--2019.



Precipitation = precipitation; *average curve number* = *average curve parameter; surface runoff* = surface runoff; lateral flow = lateral flow; *return flow* = return flow; percolation to shallow aquifer = percolation into the shallow aquifer; *revap from shallow aquifer* = rise of water from the shallow aquifer; *recharge to deep aquifer* = recharge to the deep aquifer.
Source: Authors.

Figure 9 shows the relationships between actual evapotranspiration and potential evapotranspiration, both of which were accumulated over 8 days, as estimated by the SWAT model, and their interactions with accumulated precipitation over 8 days. The ETr/ET0 ratio is also called the evaporative fraction, as it refers to the percentage of potential evapotranspiration that is actually evapotranspired (TEIXEIRA, 2018).

Figure 9 Precipitation and ETr/ET0 ratios for subbasin 19 of the Jatobá Stream Experimental Basin (BERJ).



Source: Authors.

A strong influence of previous precipitation on evapotranspiration can be observed, with higher evapotranspiration rates being observed when there is greater previous precipitation. Teixeira (2018), when evaluating the dynamics of evapotranspiration in natural vegetation of the Caatinga Biome, reported that the highest values of the evaporative fraction in the rainy periods and in the dry periods (ETr/ET0 values) fluctuated around 20--40%.

6 CONCLUSIONS

Hydrological modeling via the SWAT model produced estimates of actual evapotranspiration that were consistent with values from MODIS-based remote sensing after the model parameters for the experimental Jatobá Stream basin were refined. These results highlight the importance of using alternative data for calibrating the SWAT model, such as remotely sensed evapotranspiration, especially in semiarid river basins characterized by irregular rainfall events, intermittent rivers, and little or no runoff generation. Furthermore, such indirect data can support hydrological studies in basins lacking field information.

The trend analysis for evapotranspiration revealed a decreasing trend in actual evapotranspiration over eight days, both for simulated and observed actual evapotranspiration, indicating that the SWAT model adequately represents the data observed by the MODIS sensor. No trend was identified for the five-period eight-day moving averages of actual evapotranspiration.

7 ACKNOWLEDGMENTS

This work was supported by the Pernambuco Science and Technology Support Foundation – FACEPE (APQ 0300-5.03/17; APQ 0646-9.25/16; IBPG-0446-5.03/18), the National Council for Scientific and Technological Development – CNPq, the Coordination for the Improvement of Higher Education Personnel – CAPES, and the Financing Agency for Studies and Projects – FINEP. The authors are grateful for all the valuable comments from the anonymous reviewers, which contributed to a significant update of the manuscript.

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