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Application of the SMAP monthly model to the Piauitinga river basin located in the State of Sergipe, Brazil

Aplicación del modelo mensual SMAP a la cuenca del río Piauitinga situada en el Estado de Sergipe, Brasil

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Abstract: The generation of flow data allows the assessment of the capacity to meet water demands, predict floods, and estimate the potential for hydraulic exploitation for electrical energy generation. In Brazil, precipitation data series, due to their ease of measurement, are more extensive compared to flow data series, enabling the use of hydrological models called rainfall-runoff models capable of estimating flows from precipitation data. Therefore, utilizing the Brazil Gridded Meteorological Data (BR-DWGD) database, this study aims to generate, calibrate, and validate flow data for the Piauitinga river basin located in the state of Sergipe, Brazil, using the monthly rainfall-runoff SMAP model. The soil parameters considered in the validation for the studied region showed a good fit to the observed data, achieving a Nash-Sutcliffe (NS) of 84% and log-Nash-Sutcliffe (NSLog) of 85% in calibration, and Nash-Sutcliffe (NS) of 70% and a log-Nash-Sutcliffe (NSLog) of 80% in validation. Therefore, since the rainfall-runoff model used exhibited good performance for the studied hydrographic basin, it becomes feasible to use the generated synthetic series to fill possible gaps in the historical series of monthly average flows.
Keywords: *Rainfall-runoff; Hydrology; Modeling.*

Resumen: La generación de datos de caudales permite evaluar la capacidad de satisfacer las demandas de agua, predecir inundaciones y estimar el potencial de explotación hidráulica para la generación de electricidad. En Brasil, las series de datos de precipitación, debido a su facilidad de medición, son más extensas en comparación con las series de datos de caudal, lo que permite el uso de modelos hidrológicos denominados modelos lluvia-escorrentía capaces de estimar caudales a partir de datos de precipitación. Por lo tanto, utilizando la base de datos Brazil Gridded Meteorological Data (BR-DWGD), este estudio tiene como objetivo generar, calibrar y validar los datos de caudal para la cuenca del río Piauitinga, ubicada en el estado de Sergipe, Brasil, utilizando el modelo mensual de precipitación-escorrentía SMAP. Los parámetros de suelo considerados en la validación para la región estudiada mostraron un buen ajuste a los datos observados, alcanzando un Nash-Sutcliffe (NS) del 84% y un log-Nash-Sutcliffe (NSLog) del 85% en la calibración, y un Nash-Sutcliffe (NS) del 70% y un log-Nash-Sutcliffe (NSLog) del 80% en la validación. Por tanto, dado que el modelo lluvia-escorrentía utilizado mostró un buen comportamiento para la cuenca hidrográfica estudiada, resulta factible utilizar las series sintéticas generadas para rellenar posibles lagunas en las series históricas de caudales medios mensuales.
Palabras clave: *Lluvia-escorrentía; Hidrología; Modelización.*

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INTRODUCTION

The generation of flow data enables us to make a certain plan for evaluating the guarantee of meeting water demands, forecasting floods, and even estimating the hydraulic potential in generating electrical energy (Tucci, 2005). In engineering, estimates of these fluviometric data are essential in managing water resources and can be used in preparing water resource plans for river basins (Debastiani et al., 2019). Furthermore, these estimates can be useful tools for predicting scenarios, assessing risks, and obtaining information about hydrological phenomena (Spruill *et al.,* 2000).

Often, due to the lack of data for efficient planning, especially flow data, modeling techniques have a unique ability to simplify and understand the hydroclimatic processes that occur in river basins. These hydrological models are essential tools in the construction of effective water resource management, making it possible to fill the gaps in the observed data series using synthetic data capable of internalizing changes in the analyzed water system (Hartnett *et al*., 2007).

In Brazil, the density of rainfall gauging stations is much higher than the number of available river gauging stations, and many of these gauging stations have been in operation since the beginning of the last century, resulting in longer historical precipitation series than flow series (Souza *et al*., 2022). Based on the need for larger flow series, rainfall-runoff hydrological models are robust techniques capable of generating synthetic flow data from historical precipitation data (Almeida; Serra, 2017), and can be used to find appropriate solutions that can support possible decision-making.

The general aim of this work is to evaluate the performance of the Soil Moisture Accounting Procedure (SMAP) rainfall-runoff model in generating fluviometric data for the Piauitinga river basin, located in the state of Sergipe, using precipitation and evapotranspiration data from the Brazilian meteorological database known as BR-DWGD. Reliability and precision in data generation are essential in assessing the behavior of a given water system.

THEORETICAL BACKGROUND

Rainfall-runoff hydrological models are mathematical techniques that calculate flow from observed data, taking precipitation and evapotranspiration as the main inputs (Collischonn; Dornelles, 2013). These models are classified as empirical, in which they relate the calculated variable to the observed one, or conceptual, which represents the physical behavior of the process involved (Tucci, 2005). Some examples of these models are SWB, which made it possible to develop a simple water balance model considering the spatial variability of inputs and soil moisture capacity (Schaake *et al*., 1996), SHE, as a way of modeling distributed basins using mass and energy distribution equations or empirical formulas (Abbott *et al*., 1986a, 1986b); SWAT, to assist water resource managers in evaluating water supply and diffuse source pollution in river basins (Arnold *et al*., 1998); HEC-HMS, designed to simulate the precipitation-runoff processes of dendritic river basin systems (Feldman, 2000), GR4J, which is based on a priori concepts in the construction of a model structure and emphasizes the value of large catchment samples to evaluate them (Perrin *et al.*, 2003), MGB-IPH, 2003), MGB-IPH, in order to calculate the soil water balance, evapotranspiration, flow propagation within a cell and flow routing through the drainage network (Collischonn et al., 2007), 2007), HBV, used for forecasting, design studies, hydrological mapping, reservoir operation, environmental analysis, water resource management, climate change impact studies, fire risk assessment, among others (Bergström; Lindström, 2015), and the Soil Moisture Accounting Procedure - SMAP, (Lopes *et al*., 1982) which will be used in this study.

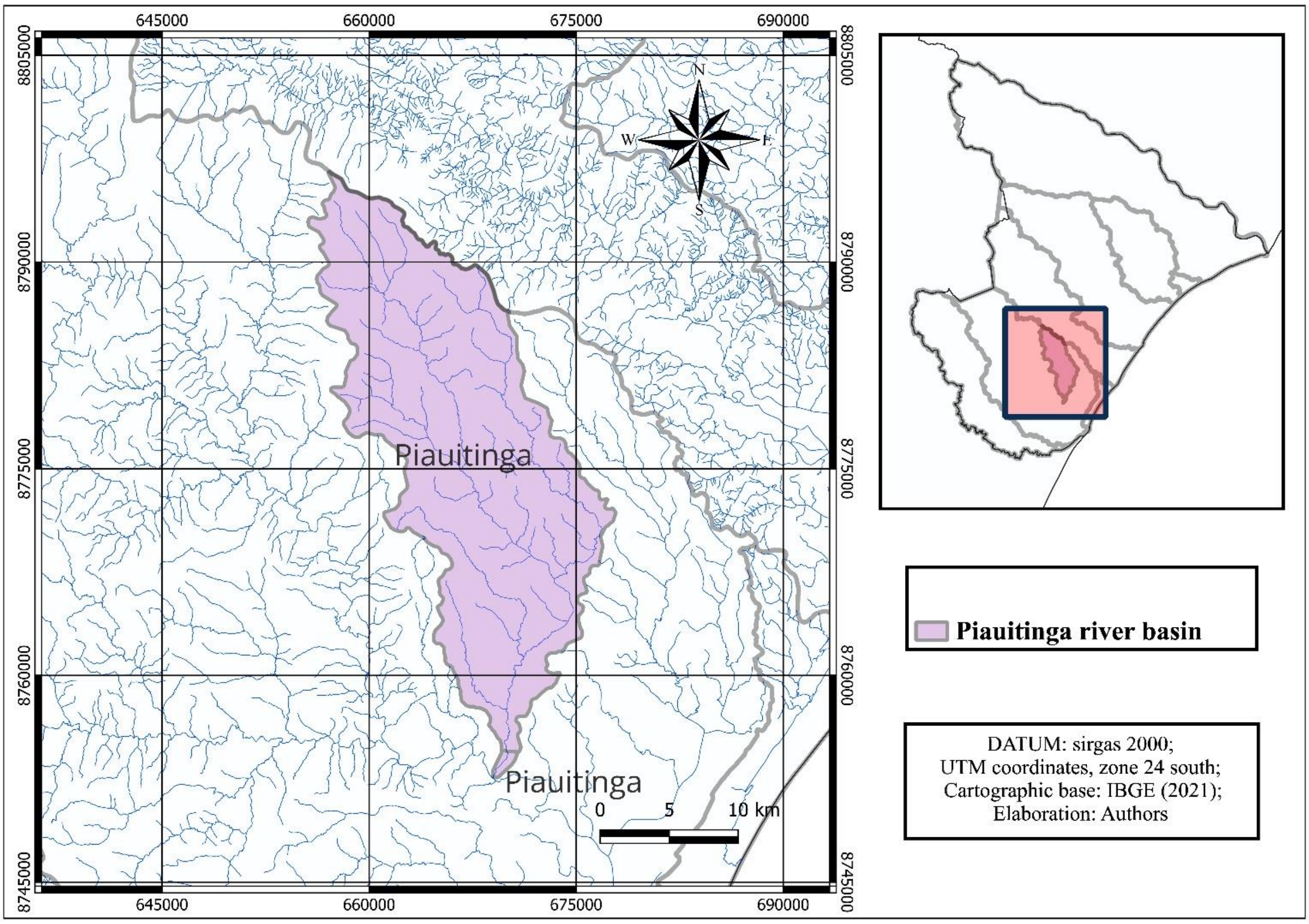
Nunes *et al.* (2014) used the SMAP model to simulate monthly flows in the Piancó River basin, located in the state of Paraíba. Miranda *et al.*, (2017) demonstrated in their study that it can reproduce the long-term average flows of the basin upstream of the Três Marias hydroelectric plant on the São Francisco River. Souza *et al.* (2022) found in their study a 67% increase in the Q90 of the extended series using the model when compared to the Q90 of the historical series for the catchment of the Santa Rosa de Lima fluviometric station on the Sergipe River.

METHODOLOGY

Study area

The study will be applied to the Piauitinga river basin, located in the state of Sergipe, as shown in Figure 1. The basin has an area of 417.42 km² and its main river is 59.11 km long, which is a left-bank tributary of the Piauí River. This watershed partially covers the municipalities of Estância, Boquim, Itaporanga D'Ajuda, Lagarto and Salgado (Martins *et al*., 2022).

FIGURE 01: Piauitinga river basin



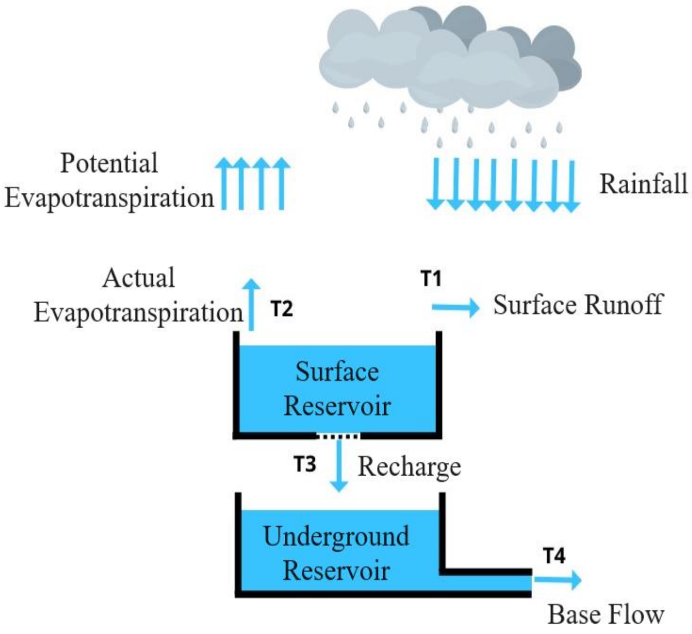
SOURCE: Prepared by the authors (2023).

SMAP hydrological model

Developed by Lopes *et al*. (1982), SMAP simulates the hydrological cycle, represented by reservoirs, which are equivalent to surface storage, the *topsoil* and underground storage, and is based on the *Soil Conservation Service* (SCS) method. In this work, the SMAP monthly scale will be used, as shown in Figure 2.

The SMAP hydrological model considers the following variables: precipitation, evaporation from the class A tank (EVA) and flow, on a monthly scale, with the last variable being used only in the calibration and validation stage. The soil parameters to be found in SMAP modeling are: soil saturation capacity (Str), surface runoff parameter (Pes), underground recharge parameter (Crec) and the basic runoff recession constant (Kkt).

FIGURE 02: SMAP structure in the monthly version.



SOURCE: Adapted from Lopes *et al*. (2014).

Input data

Precipitation and evapotranspiration data were collected from the BR-DWGD meteorological database (Xavier *et al*., 2016), which is available in 0.25° spatial resolution and provides information for the period from 1980 to 2013. It should also be noted that the class A tank coefficient of 0.7 was used to calculate evaporation, so the EVA is equivalent to dividing evapotranspiration by this coefficient.

The flow data was collected from the *HidroWeb* portal of the National Water and Sanitation Agency (ANA). Table 01 shows the information on the fluviometric station used in this study.

TABLE 01: Fluviometric station used in the study.

Code	Name	Type	Latitude	Longitude	Municipality	Operator
50230000	Estancia	Fluviometric	-11,2644	-37,4425	Estancia	CPRM

SOURCE: ANA (2023).

Calibration and Validation

To calibrate the SMAP hydrological model, it is necessary to adjust the parameters through the available observed readings, by trial and error, which demonstrates the internalization of the dynamics of the watershed to be analyzed (Fujita, 2018). In the SMAP model, the soil parameters of the watershed, are adjusted to estimate flows with the smallest possible deviation when compared to observed flows. When choosing the calibration period, the aim was to choose time sequences made up of dry, medium and wet years, so that the model would adjust well to these hydrological conditions. The years chosen for calibration were 1983, 1984 and 1985.

In validation, it is checked whether the calibrated parameters maintain the model's good performance for a different historical period from the one used in calibration. Thus, the years chosen for this stage were 2012, 2013 and 2014.

To assess the model's performance, the Nash-Sutcliffe (NS) and log-Nash-Suttcliffe (NSLog) efficiency coefficients were used, which can vary from -∞ to 1, with the closer to 1 the better the fit (Nash; Sutcliffe, 1970). In addition, NS and NSLog are calculated by:

$$NS = 1 - \frac{\sum_{t=1}^{T}(Q_{obs}(t) - Q_{cal}(t))^2}{\sum_{t=1}^{T}(Q_{obs}(t) - \overline{Q_{obs}})^2} \quad [1]$$

$$NSLog = 1 - \frac{\sum_{t=1}^{T}(log(Q_{obs}(t)) - log(Q_{cal}(t)))^2}{\sum_{t=1}^{T}(log(Q_{obs}(t)) - \overline{log(Q_{obs})})^2} \quad [2]$$

Where: (t) = Observed flow (m³/s); $Q_{ca}(t)$ = Calculated flow (m³/s); $\underline{Q_{obs}}$ = Observed flow averaged over time T = 1, ..., T (m³/s).

NS is easily affected by peak values, so adjusting the model to maximize this coefficient can result in poor calibration during periods when flows are lower. For this reason, NSLog will also be used, which is less sensitive to peaks and more sensitive to periods of flow recession (Adam *et al.*, 2015).

According to Baltokoski *et al.* (2010), the Nash-Sutcliffe coefficient is classified as: "very good" ($NS \geq 0.75$), "good" ($0.65 < NS \leq 0.75$), "satisfactory" ($0.50 < NS \leq 0.65$) and "unsatisfactory" ($NS \leq$ 0,50). It should be noted that this same classification was used for NSLog.

RESULTS AND DISCUSSION

Once the calibration period had been defined (1983-1985), the soil parameters were initially sought, and the NS values were observed to check whether the model calibration resulted in estimated flows close to those observed. So, the parameters shown in Table 02 were obtained. It can be seen that in the parameter referring to the saturation capacity of the soil, the value was close to the upper limit, which reveals the high permeability of the soil in the basin.

TABLE 02: Parameters of the SMAP model calibrated for the Piauitinga River Basin.

Parameter	Value	Unit	Limits
Str	3000	mm	400 < Str <5000
Pes	1,7	dimensionles s	1 < Pes <10
Crec	15,64	%	0 < Crec <100
Kkt	3	months	1 < Kkt < 24

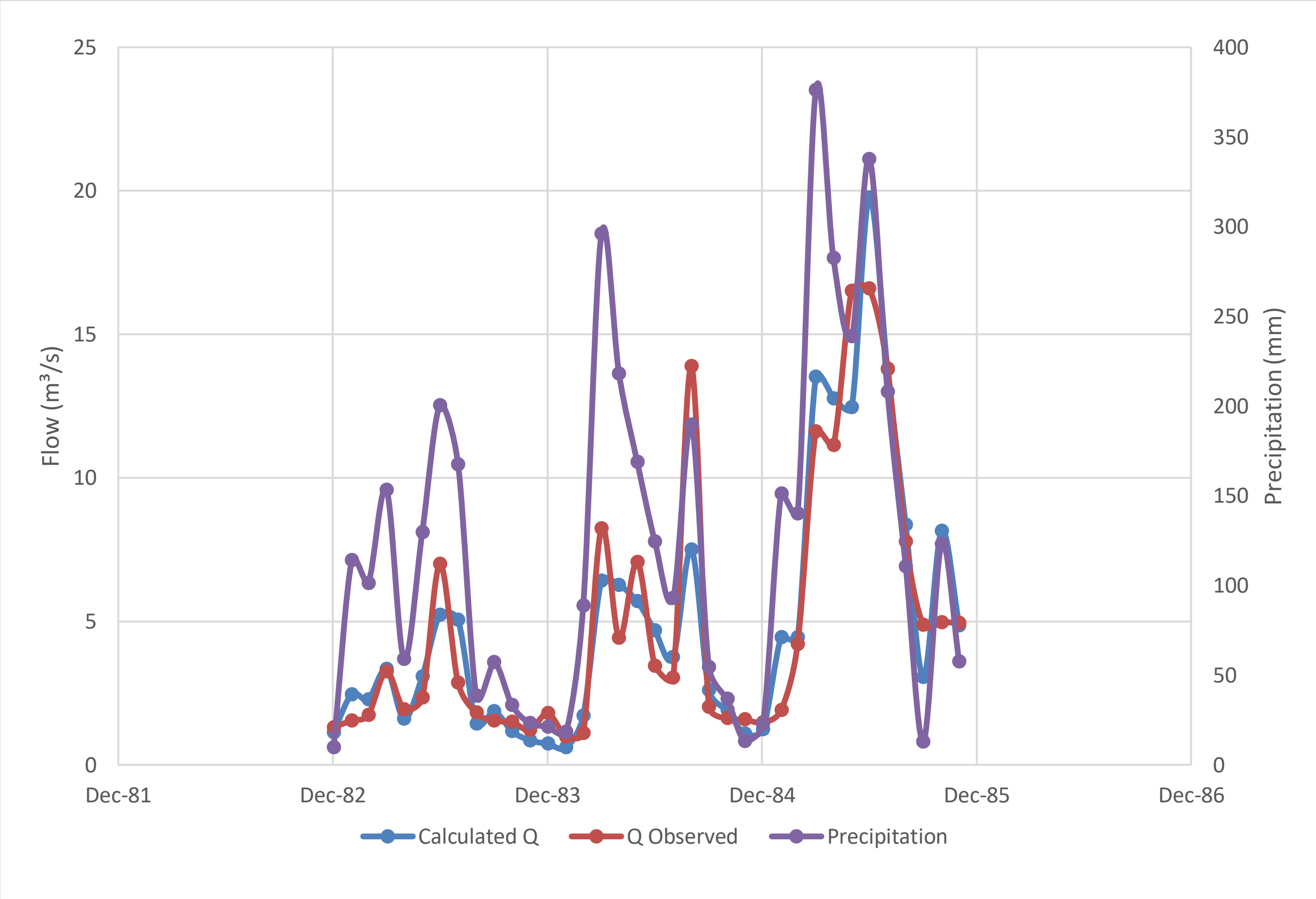
SOURCE: Prepared by the authors (2023).

The Str value found is expected for basins with sandy soils, which does not occur in the watershed in question, which has predominantly clay soil and Cambissolo (Magalhães *et al*., 2012), which usually results in small values for this parameter. However, according to Brandão (2006), well-structured clay soils can have high hydraulic conductivity and a higher infiltration rate, which justifies the Str equal to 3000 mm. It is worth noting that different results were found in the Piancó-PB Basin, whose Str was 1,371, demonstrating a low saturation capacity. According to Nunes *et al*. (2014) the basin of the Santa Rosa de Lima fluviometric station on the Sergipe River, the Str was even closer to the lower limit, 950, due to its shallow soil (Souza *et al*., 2022).

The recharge coefficient of the underground reservoir was 15.64, which is higher than that found by Miranda *et al*. (2017) in the basin upstream of the Três Marias Plant, and by Souza *et al*. (2022) for the basin of the Santa Rosa de Lima fluviometric station on the Sergipe River, which were 6.0 and 4.0, respectively. It can be said that the flows estimated by the model are due to both surface runoff and underground runoff. A different situation was described by Nunes *et al.* (2014), who in their calibration for the Piancó basin found the *Crec* equal to 0 (zero), which indicates that there is no recharge from the soil reservoir. It happens due to the predominance of a geology with crystalline formations, which results in a low availability of groundwater.

With these parameters obtained in the calibration of the rainfall-runoff model, the Calculated Flow series (Q_{cal}) was generated, which was compared with the Observed Flow series (Q_{obs}), with NS equal to 0.84 and NSLog equal to 0.85, classified as "very good", according to Baltokoski *et al.* (2010). The result is shown in Figure 3. The NS value found here was the same as that found by Souza *et al*. (2022) for the catchment area of the Santa Rosa de Lima fluviometric station on the Sergipe River and higher than that of the Piancó-PB river basin, which was 0.73, classified as only "satisfactory" (Nunes *et al.*, 2014).

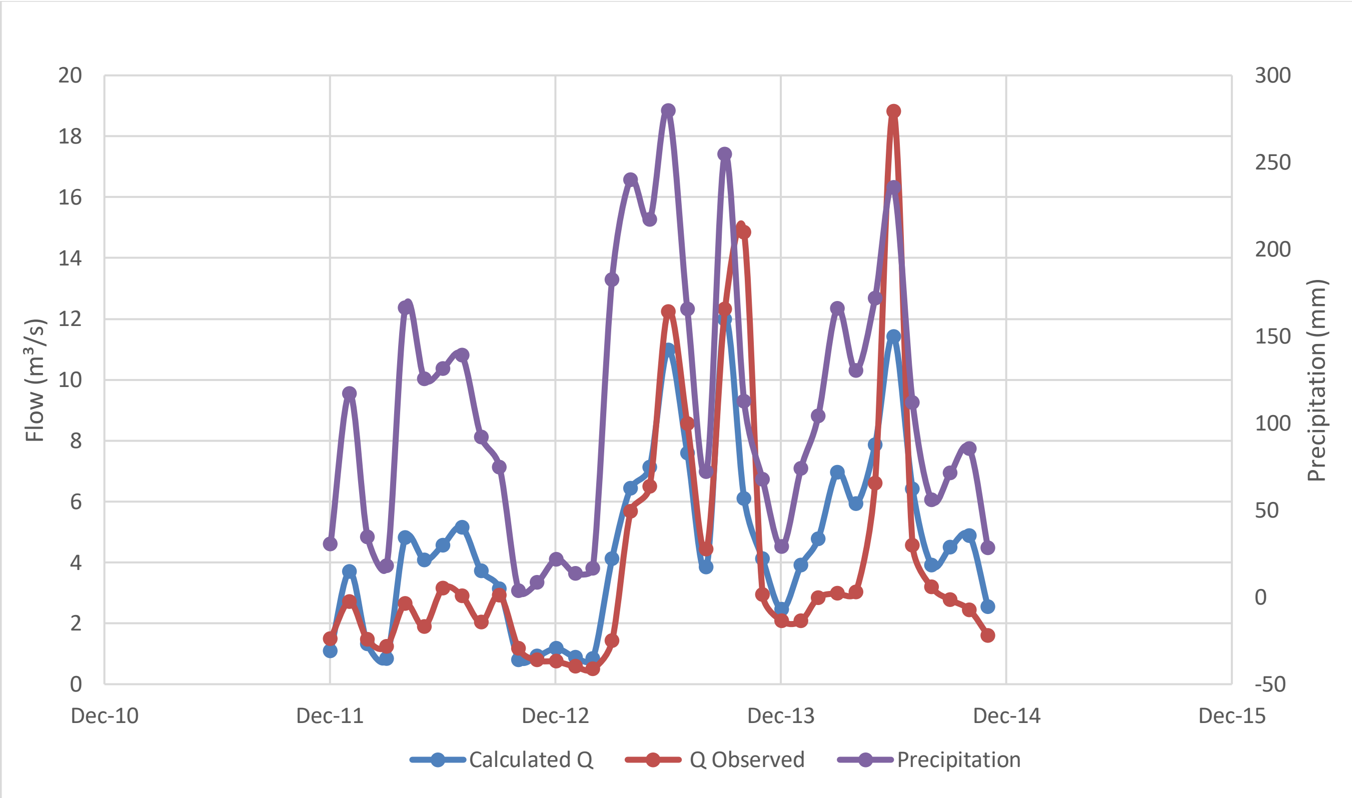
FIGURE 03: Results obtained for the SMAP calibration



SOURCE: Prepared by the authors (2023).

To check that the model was adjusted properly, the parameter values found in the calibration were preserved, and the period was changed to 2012, 2013 and 2014 years. This change resulted in an NS of 0.70, similar to the NS found for the Piancó River basin, 0.69 (Nunes *et al.*, 2014), and an NSLog of 0.80, classified as "good" and "very good", respectively, according to Baltokoski *et al*. (2010). Furthermore, it should be noted that the difference between these coefficients may be linked to the sensitivity of the peak flows characteristic of the NS (Figure 04).

FIGURE 04: Results obtained for the SMAP validation.



SOURCE: Prepared by the authors (2023).

CONCLUSIONS

The application of the monthly version of the SMAP model in the Piauitinga river basin, located in the state of Sergipe, showed good results. The parameters reproduced well the hydrological behavior of the watershed studied in the historical periods used for calibration, showing a NS equal to 0.84 and NSLog equal to 0.85 and validation NS equal to 0.70 and NSLog equal to 0.80 of the model. Consequently, the NS was classified as "very good" and "good", respectively, and the NSLog was classified as "very good". This attests to the good performance of the SMAP model, which makes it possible to use it to fill in the gaps in the historical series of average monthly flows in the basin under study.

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