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Spatial modeling of nitrogen and phosphorus in an agricultural basin in northeastern Brazil

Modelagem espacial de nitrogênio e fósforo numa bacia agrícola no nordeste do Brasil

Modelado espacial de nitrógeno y fósforo en una cuenca agrícola en el noreste de Brasil

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Abstract
Hydrological models can help in predicting the behavior of aquatic systems in watershed, and are able to simulate both hydrological processes and nutrient dynamics. The SWAT model is used in water resource management to estimate the production of water, sediments, and nutrients, as well as to identify diffuse sources of pollution. The objective of this work was to evaluate spatial and temporal variability in the dynamics of the nutrients nitrogen and phosphorus derived from agricultural activities, at the sub-basin level, in the watershed of the Poxim-Açu River. The model was subjected to tests of sensitivity, calibration, and validation in terms of the discharge and the behavior of the nutrients. Statistical analysis showed that the performance of the model was satisfactory. It was found that more than 40% of the areas of the main subbasins that produced sediments and nutrients was occupied by pasture, and that the predominant soil types were Red-Yellow Argisols and Gleysols. These subbasins corresponded to 30% of the hydrographic basin studied and produced 65% of the sediments, 84% of the total nitrogen, 93% of the phosphate, and 86% of the total phosphorus.
Keywords: SWAT; Water production; Water resources; Nutrients.

Resumo
Modelos hidrológicos podem auxiliar na previsão do comportamento de sistemas aquáticos em bacias hidrográficas, e são capazes de simular tanto processos hidrológicos quanto a dinâmica dos nutrientes. O modelo SWAT é utilizado na gestão de recursos hídricos para estimar a produção de água, sedimentos e nutrientes, bem como identificar fontes difusas de poluição. O objetivo deste estudo foi avaliar a variabilidade espacial e temporal na dinâmica dos nutrientes nitrogênio e fósforo derivados de atividades agrícolas, em nível de sub-bacia, na bacia hidrográfica do Rio Poxim-Açu. O modelo foi submetido a testes de sensibilidade, calibração e validação quanto à descarga e ao comportamento dos nutrientes. A análise estatística mostrou que o desempenho do modelo foi satisfeito. Verificou-se que mais de 40% das áreas das principais sub-bacias que produziram sedimentos e nutrientes foram ocupadas por pastagens, e que os tipos de solo predominantes foram Argissolos Vermelho-Amarelos e Gleissolos. Essas sub-bacias corresponderam a 30% da bacia hidrográfica estudada e produziram 65% dos sedimentos, 84% do nitrogênio total, 93% do fosfato e 86% do fósforo total.
Palavras-chave: SWAT; Produção de água; Recursos hídricos; Nutrientes.

Resumen
Los modelos hidrológicos pueden ayudar a predecir el comportamiento de los sistemas acuáticos en las cuencas y son capaces de simular tanto los procesos hidrológicos como la dinámica de los nutrientes. El modelo SWAT se utiliza en la gestión de recursos hídricos para estimar la producción de agua, sedimentos y nutrientes, así como para identificar fuentes difusas de contaminación. El objetivo de este estudio fue evaluar la variabilidad espacial y temporal en la dinámica de los nutrientes nitrógeno y fósforo derivados de las actividades agrícolas, a nivel de subcuenca, en la cuenca del río Poxim-Açu. El modelo fue sometido a pruebas de sensibilidad, calibración y validación respecto al caudal y comportamiento de nutrientes. El análisis estadístico mostró que el rendimiento del modelo estaba satisfecho. Se verificó que más del 40% de las áreas de las principales subcuencas productoras de sedimentos y nutrientes estaban ocupadas por pastos, y que los tipos de suelo predominantes eran Argissolos Vermelho- amarelos y Gleissolos. Estas subcuencas correspondieron al 30% de la cuenca hidrográfica estudiada y produjeron el 65% de los sedimentos, 84% del nitrógeno total, 93% del fosfato y 86% del fósforo total.
Palabras clave: SWAT; Producción de agua; Recursos hídricos; Nutrientes.

1. Introduction

Water contamination by agricultural activities can compromise water availability, especially in regions that already have water deficits, such as the northeast region of Brazil. For this reason, it is necessary to understand the dynamics of hydrological processes and assess the impacts of agricultural activities on water resources in a watershed. This information can be used for planning and management purposes, identifying and quantifying the main sources of pollution.

Pollutants can be classified as point and non-point sources (diffuse pollution). Point source pollution is relatively easy to adjust and control as it is easy to monitor its concentration and flow (Rissman & Carpenter, 2015). Pollution from non-point sources has become one of the greatest threats to water quality in agricultural areas, with nitrogen, phosphorus, and sediments standing out as the primary pollutants since the use and occupation of the land are directly related to the nature of the substances transported in the runoff (Li, 2020; Liu et al., 2020; Zhenyao et al., 2014). These sources of pollution are difficult to control due to the difficulty of establishing causal connections between pollutants and emission sources.

It is also noteworthy that the process of diffuse pollution in watersheds is complex and difficult to control (Chen et al., 2022), as it involves aspects related to agriculture, meteorology, hydrology, among others, and due to the complex mechanism and uncertain characteristics of non-pollution sources. punctual, its assessment presents challenges for water resource managers (Li, 2020).

Water quality modeling is a strategy to assess the current condition of the water body, which also allows the simulation of different scenarios depending on land use and occupation (Lima et al., 2018). It has become an essential tool to support the planning and management of water resources, thus ensuring the multiple uses of water (Volk & Bosch, 2017, Souza et al., 2021).

In this sense, the spatially distributed soil and water assessment tool, such as the Soil and Water Assessment (SWAT), assist in the adoption of different agricultural practices and the models of non-point sources of use (SWAT) (Andrade et al., 2017, Almeida & Aguiar Netto, 2022, Sales et al., 2022).

This model stands out for its ability to directly simulate surface runoff, erosion and sediment production, and nutrient transport in agricultural basins subjected to different managements (Abu-Zreig & Hani, 2021). The model can be used to simulate sources of surface pollution, assessment and management of water resources; soil and water conservation; forecast the influence of climate change; and soil management measures in hydrology, nutrient production, and sediment in complex watersheds (Liu et al., 2020). The model was developed by the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA) in the 1990s, and since its creation, the tool has undergone continuous inspections and expanding their capabilities (Neitsch et al., 2011).

Hydrographic models are able to simulate many different scenarios of the management of hydrographic basins, and therefore offer a low-cost method of assisting in the control and reduction of nutrient transport and losses of nitrogen and phosphorus from agricultural areas (Green & Van Griensven, 2007). The SWAT2005 model is a tool used to evaluate the availability of hydric resources and the presence of nonpoint sources of pollution in large hydrographic basins, enabling the simulation, analysis, and quantification of sediment and nutrient transport (Bossa et al., 2012).

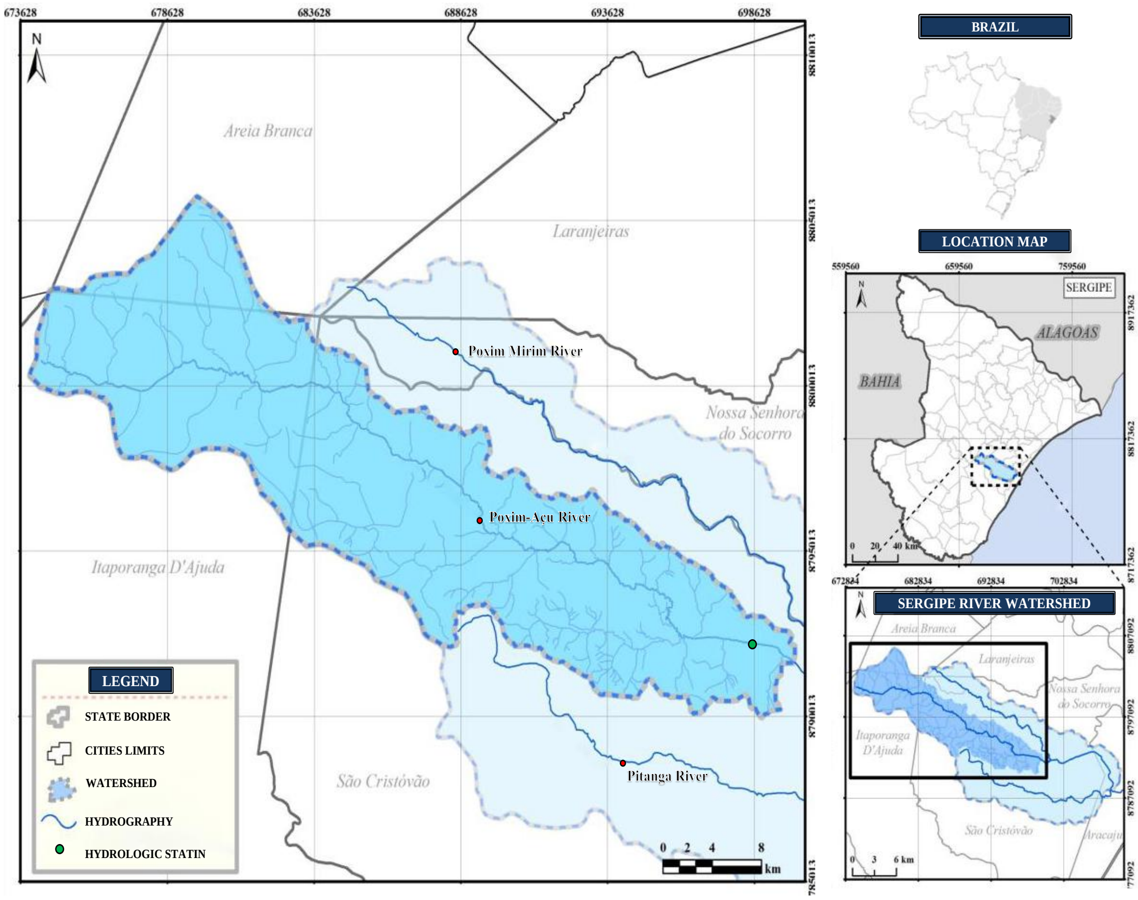
The objective of this study was evaluate the spatial and temporal variability in the dynamics of nitrogen and phosphorus nutrients, at a sub-basin level, in the Poxim-Açu River basin. The procedure adopted was to first perform a sensitivity analysis and then calibrate the SWAT model for the hydrological process and nutrients, using monthly time intervals. That allowed them to evaluate variability in water production, sediments and nutrients.

2. Methodology

2.1 Study area

The study was carried out in the Poxim River basin, an area of 116.11 km² that is part of the Sergipe River basin, one of the most important rivers in the State of Sergipe (Figure 1). It lies between latitudes 10°55'S and 10°45'S and longitudes 37°05'W and 37°22'W and has a total area of 397.87 km². The main tributaries are the Poxim- Mirim, Poxim-Açu and Pitanga rivers (Aguiar Netto et al., 2013).

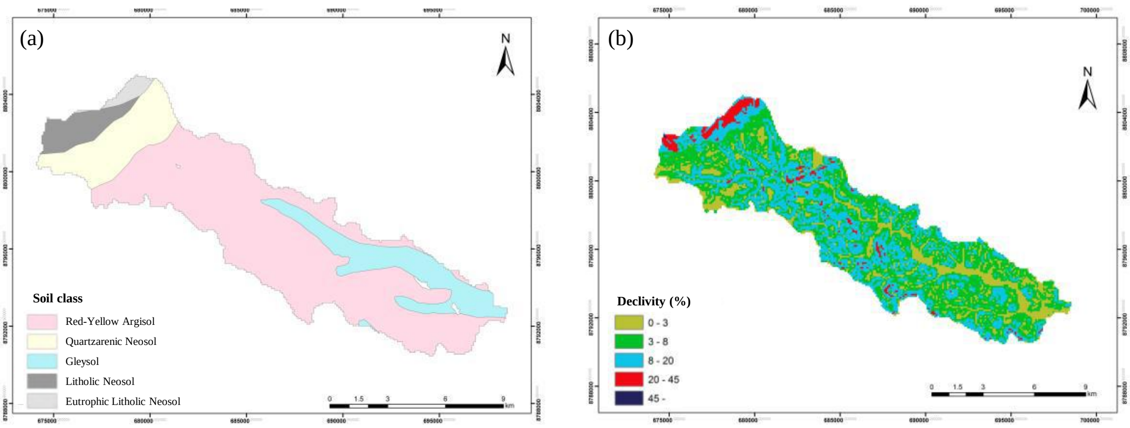
Figure 1 - Location of the watershed of the Poxim River.



Source: Authors (2022).

The region is characterized by a humid tropical climate, with a dry season between September and March and a rainy season between April and August. The average annual rainfall varies between 1,600 mm and 1,900 mm. Average temperatures are around 23 °C during the coldest months (June-August) and around 31°C during the warmer months (December-February). Precipitation is the greatest near the river mouth and may be scarce in some headwaters. The soils are classified as Eutrophic Litholic Neosol (7.02 %), Quartzarenic Neosol (11.78 %), Litholic Neosol (16.67 %), Gleysol (10.11 %), and Red-Yellow Argisol (54.40%) (Figure 2a). The slope of the land was described in five categories established by Embrapa (2006), flat (0-3 % angle), gently undulating (3-8 %), undulating (8-20%), heavily undulating (20-45%) and mountainous (> 45%) (Figure 2b). The land use in the watershed is: degraded areas (1.60 %), water bodies (0.15%), sugarcane cultivation (18.37%), forest (23.80 %), riparian forest (2.21 %), pasture (50.23 %), area (0.54 %), restinga vegetation (3.3 %) and fish farming/saline (0.09 %) (Sergipe, 2015).

Figure 2 - Soil classes (a) and declivity (b) in the watershed of the Poxim River.



Source: Authors (2022).

2.2 Description of the model

The SWAT Model (Soil and Water Assessment Tool) was developed by the USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research (Vasco et al., 2022, Arnold & Fohrer, 2000). In order to predict the impacts of soil management practices on water quality, sediment production, and pollutants in complex watersheds with or without data availability for an extensive period of time (Neitsch et al., 2011). It is considered a physical-based model, in which instead of incorporating regression equations to describe the relationships between input and output variables, the processes associated with the hydrological cycle, sediment movement, plant growth, and nutrient cycle, among others, are modeled using available input data.

Another important feature is its temporal continuity which allows the simulation of physical processes sequentially in a time interval determined by the user in order to provide time series as output data. Such characteristics allow long-term impacts on the components of the natural environment to be simulated, such as the gradual increase in pollutants in the soil and changes in their use and impacts on water bodies.

2.3 Input data

The data needed for simulation in SWAT are topography, soil type, land use, and meteorology. A digital elevation model (DEM) was used to provide topographic data with a resolution of 90x90 m (Figure 3a). The DEM used was generated from radar data obtained during the Shuttle Radar Topography Mission (SRTM) project (Miranda, 2005). The demarcation of the watershed, considering the drainage network and the size of the sub-basins, used a minimum channel area of 150 ha (Galvan et al., 2009). The convergence point of the sub-basins was -10.92 (latitude) and -37.19 (longitude), and the average daily flow

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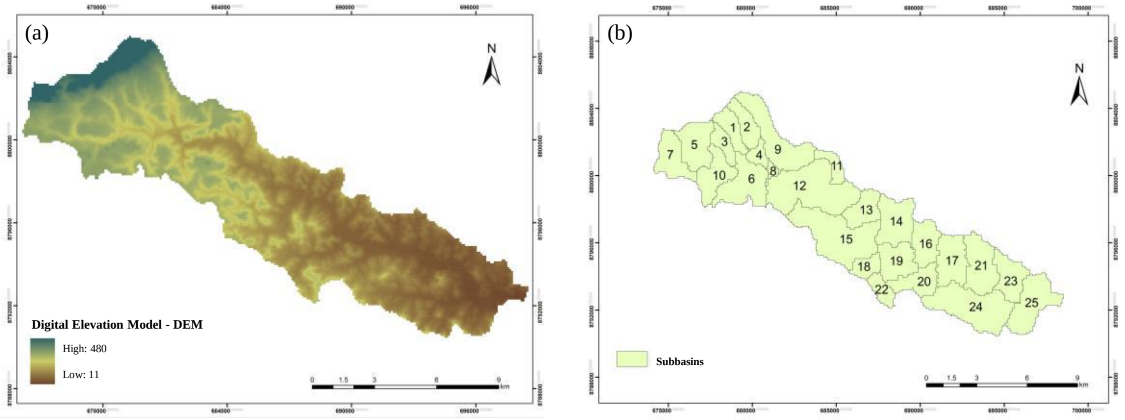
for the period from July 2011 to January 2012 was 1.20 m³ s^{-1}, with minimum and maximum values of 0.02 and 9.17 m³ s^{-1}, respectively. Twenty-five sub-basins were identified in a total area of 113.12 km² (Figure 3b).

Figure 3 - Digital elevation model (a) and subbasins (b) of the watershed of the Poxim River.



Source: Authors (2022).

To simulate the area and hydrological parameters within each sub-basin, SWAT requires data concerning soil type and land use (Arnold et al., 2012). The maps of the Poxim river basin containing this information were obtained from the Sergipe Water Resources Atlas (Sergipe, 2015). As the water balance is one of the physical processes considered by SWAT, the model requires soil parameterization (Romanowicz et al., 2005). Thus, samples were collected and analyzed to determine the physical characteristics of the soil (Table 1).

Table 1 - Characteristics of the soil in the watershed of the Poxim River.

Variable	Parameter in SWAT	Value	Source
Porosity (%)	ANION_EXCL	0.45 – 0.50	Measured
Depth of soil (mm)	SOL_Z	150 – 500	Measured
Density of soil (g cm^{-3})	SOL_BD	1.52 – 1.75	Measured
Available soil water content (mm H_2O mm^{-1} soil)	SOL_AWC	0.03 – 0.42	Measured
Organic carbon (%)	SOL_CBN	0.50 – 2.56	Estimated[a]
Saturated hydraulic conductivity (mm h^{-1})	SOL_K	24.03 – 57.80	Estimated[a]
Clay (%)	CLAY	0.31 – 13.78	Measured
Silt (%)	SILT	12.80 – 22.17	Measured
Sand (%)	SAND	66.01 – 86.89	Measured

Source: Authors (2022).

To define the Hydrological Response Units - UHs, limits of 10, 20, and 10 % were established for land use, soil type, and slope, respectively. These values were previously used by Boskidis et al. (2012). The final number of HRUs was 209. After defining the HRUs, the land uses and slopes in the studied area were reclassified by the model.

The climatic data (daily measurements of precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed) were obtained from the Aracaju meteorological station, operated by the National Institute of

Meteorology (INMET) (latitude -10.95, longitude -37.04, altitude 4.72 m). The data used were from 01/01/1991 to 06/30/2012. Precipitation data were obtained from the measurement stations of Itabaiana (latitude -10.70, longitude -37.42, altitude 200 m), São Cristóvão (latitude -10.92, longitude -37.20, altitude 30 m), and Laranjeiras (latitude -10.81, longitude -37.17, altitude 13 m), operated by the Weather Forecast and Climate Studies Center of the National Institute for Space Research (CPTEC/INPE), from 01/01/2000 to 06/30/2012.

2.4 Collection and analysis of water samples

Water quality monitoring was carried out monthly, from February 2011 to March 2012, totaling 14 collections at the outflow of the delineated watershed. All sample collection, preservation, and analysis procedures followed the methodology described by APHA (2005). In the same place, the flow monitoring and water depths (quota) were carried out through bathymetry and determination of the technique by windlass.

For the analysis of nitrate, nitrite, ammonia, and total nitrogen, the ion chromatography methodology was used. Phosphate and total phosphorus were determined by ascorbic acid and persulfate digestion methods, respectively. Total nitrogen, total phosphorus, and orthophosphate loads were calculated using water volume and mean concentrations (Hesse & Krysanova, 2012).

2.5 Sensitivity analysis, calibration and validation

Sensitivity analysis consists of evaluating the responses generated due to changes in the parameters and input values used, allowing the rationalization of the calibration step, as well as, the setting of parameters for which the model is not sensitive (Durães et al., 2011). This step is very relevant as it is possible to identify the most sensitive parameters and quantify their influence, particularly on the hydrological component, in addition to contributing to modeling studies in similar watersheds (Lelis & Calijuri, 2010).

Hydrological models such as SWAT use a large number of input parameters, requiring calibration to adjust them to the outputs and obtain the best possible agreement between simulated data and real measurements. Manual model calibration consists of changing one parameter at a time (using the parameters previously selected in the sensitivity analysis) and running the model to identify changes in the output variables. The fit obtained between observed and simulated data is evaluated visually and through statistical analysis.

The adjustment obtained between observed and simulated data was evaluated visually and by comparing the statistical indicators Nash-Sutcliffe (NSE), the coefficient of determination (R^2), the percentage of bias (PBIAS), the root means square error (RMSE), and the normalized standard error (NRS), described by the following mathematical expressions:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (1)$$

$$R^2 = \frac{(\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S}))^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(S_i - \bar{S})^2} \quad (2)$$

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - S_i) \cdot 100}{\sum_{i=1}^{n}(O_i)} \quad (3)$$

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$$RMSE = \sqrt{\frac{\left(\sum_{i=1}^{n}(S_i - O_i\right)^2}{n}} \tag{4}$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2}\right]} \tag{5}$$

In the equations above, i represents the time series of measured and simulated data pairs, n is the number of measured and simulated variable pairs, O_i is the observed data, S_i is the simulated data and $\bar{O}$ is the mean of the observed data.

After the calibration procedure, validation was performed by running the model with the set of input parameters defined during calibration without any further modification. The simulated and observed data were then visually and statistically compared to verify the performance of the model (Santhi et al., 2001). In this case, the model was run for a period different from that used for calibration. The calibration used the period from January to June 2012, while the validation used the period from July to December 2011.

Table 2 - Criteria used to evaluate the performance of hydrological models, and the corresponding classifications.

Performance Rating	RSR	R^2	NSE	PBIAS (%)	
				Streamflow	**Nutrients**
Very good	0.00 < RSR < 0.50	---	0.75 < NSE < 1.00	PBIAS < ± 10	PBIAS <± 25
Good	0.50 < RSR < 0.60	---	0.60 < NSE < 0.75	± 10 < PBIAS < ± 15	± 25 < PBIAS < ± 40
Satisfactory	0.60 < RSR < 0.70	---	0.50 < NSE < 0.65	± 15 < PBIAS < ± 25	± 40 < PBIAS < ± 70
Unsatisfactory	RSR > 0.70	---	NSE < 0.50	PBIAS > ± 25	PBIAS > ± 70
Acceptable	---	> 0.50	---	---	---

Source: Authors (2022).

3. Results and Discussion

The initial model sensitivity analysis for the discharge and the nutrients was performed using standard values for the selected parameters. The analysis employed monthly data for the period from 1991 to 2012. The changes in the parameter values used during the manual calibration are shown in Table 3. The parameter values were changed one by one, according to their importance as defined in the sensitivity analysis and their effect on the model output. The model was then executed until a satisfactory fit was obtained between the measured and simulated values.

The results of the sensitivity analysis showed that many hydrological parameters were important for the prediction of water quality. The parameters Sol_AWC, CN, and ESCO reflect the response of surface water, SURLAG, reflect the response of basin, while ALPHA_BF, GW_DELAY, and GW_REVAP reflect the response of subsurface water (Van Liew et al., 2007).

The parameters of the model that were adjusted in the process of calibration of nutrient transport included the biological mixing efficiency (BIOMIX), the nitrogen percolation coefficient (NPERCO), the phosphorus percolation coefficient (PPERCO), and the coefficient of partitioning of phosphorus in the soil (PHOSKD).

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Table 3 - Changes and final values of the model parameters for the manual calibration process.

Parameters	Default	Change	Final calibration value
ALPHA_BF	0.048	+0.95	0.998
BIOMIX	0.2	+0.80	1.0
CANMX	0	+2.00	2
CN2	55-77	*1.05	Various
ESCO	0	+0.95	0.95
GW_DELAY	31	Substituted by 75	75
GW_REVAP	0.02	Substituted by 0.03	0.03
NPERCO	0.2	+0.80	1.0
PHOSKD	175	Substituted by 100	100
PPERCO	10	+7.50	17.5
SOL_AWC	Various	*1.10	Various
SOL_Z	Various	*1.05	Various
SURLAG	4	Substituted by 1	1

Source: Authors (2022).

The simulated discharges were compared with the corresponding data obtained from measurements at the point of discharge of the hydrographic basin (July 2011 to June 2012), for both the calibration and the validation procedures. It can be seen that the hydrograph shows a good fit between the simulated and measured data. The values obtained for the total flows, average flows, and standard deviations are provided in Table 4.

A value of NSE equal to 0.99 indicated the excellent performance of the model, as can be seen from Table 4, which shows an almost perfect fit between the simulated and observed data. Similarly, the coefficient of determination ($R^2 = 0.95$) indicated excellent agreement between the two sets of data. The values obtained for PBIAS, which is a test recommended for identification of poor model performance, and for RMSE, which measures the global dispersion of the residuals in relation to the average value, both indicated that the model provided precise simulation. Values of these parameters closer to zero are indicative of better performance. The RSR value was also indicative of a good fit between the simulated and observed data for the calibration procedure. Overall, the performance of the model was highly satisfactory for simulation of the discharges using monthly time intervals, indicating that it could be used to assist in the management of the hydrographic basin of the Poxim-Açu River, evaluating different soil use scenarios (Leite et al., 2022).

The values of the statistical parameters obtained for the performance of the model during the validation process were also satisfactory (NSE = 0.83; $R^2 = 0.90$; PBIAS = -12.75; RMSE = 0.27; RSR = 0.42). The greatest difference between the calibration and validation processes was obtained for the PBIAS parameter. The value found for the validation period was considered satisfactory, although negative PBIAS values are indicative of overestimation by the model as can be seen from Figure 4 and Table 4 (Gupta et al., 1999). Overall, the statistical results indicated that the SWAT model performed well when it was used to simulate processes in the hydrographic basin of the Poxim-Açu River using monthly time intervals.

Table 4 - Descriptive statistics and performance criteria values for the monthly flows obtained during the calibration (January to June 2012), and validation (July to December 2011) periods.

Statistical parameters	Calibration		Validation	
	Measured	Simulated	Measured	Simulated
Total ($m^3\ s^{-1}$)	5.49	5.45	9.71	10.95
Average ($m^3\ s^{-1}$)	0.92	0.91	1.62	1.82
Standard deviation ($m^3\ s^{-1}$)	0.41	0.42	1.02	0.81
NSE	0.99		0.83	
R^2	0.95		0.9	
PBIAS	0.75		-12.75	
RMSE	0.06		0.27	
RSR	0.11		0.42	

Source: Authors (2022).

The average, minimum, maximum, and standard deviation values for the concentrations of total nitrogen (N_{total}), total phosphorus (P_{total}), and orthophosphate (PO_4^{3-}) are shown in Table 5. The water quality of the Poxim-Açu River improved nearer to its source, and became progressively poorer towards its point of discharge (Silva, 2014). This provided clear evidence that changes in land use resulted in deterioration of water quality, since the lower reaches of the Poxim-Açu River were affected by discharges from urban and industrial sources, in addition to agricultural emissions.

Table 5 - Descriptive statistics and performance criteria values for water quality parameters measured in the hydrographic basin of the Poxim-Açu River during the period from February 2011 to March 2012

Water quality parameter	Statistical parameter (mg L^{-1})				Statistical criteria				
	Average	Standard deviation	Minimum	Maximum	NSE	R^2	PBIAS	RMSE	RSR
N_{total}	0.85	0.68	0.28	1.96	0.79	0.21	-11.3	0.42	0.46
P_{total}	0.06	0.17	0	0.62	0.76	0.97	33.26	0.08	0.49
PO_4^{3-}	0.04	0.07	0	0.17	0.85	0.96	-24.81	0.02	0.38

Source: Authors (2022).

According to Vasco et al. (2011), the nitrogen content of the water in the hydrographic basin of the Poxim-Açu River is predominantly controlled by inputs from point sources (urban and industrial effluents), while phosphorus is mainly derived from diffuse sources (drainage from agricultural areas). Found concentrations of Ptotal that exceeded the statutory limit during the rainy period, which was attributed to surface runoff. Aguiar Netto et al. (2013) reported that nutrients were an important factor influencing the quality of water in the hydrographic basin of the Poxim-Açu River, and attributed their presence in the water to diffuse agricultural sources.

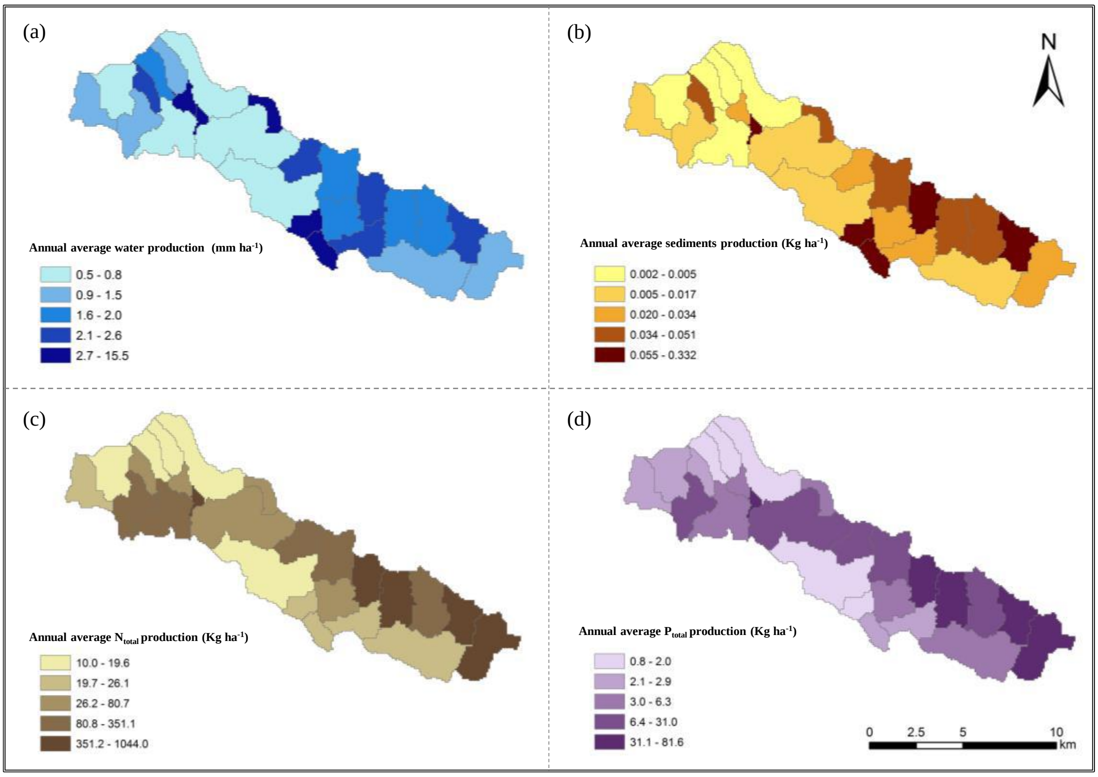
The measured and simulated values of N_{total}, P_{total}, and PO_4^{3-} are illustrated in Figures 5 (a, b and c) , where good fits can be seen for the two forms of phosphorus, in contrast to N_{total}. The values of the statistical criteria used to evaluate the performance of the model for the nutrients are provided in Table 5. In the case of the nutrients, the values of NSE and RSR were classified as very good, since they were all either greater than 0.75, or smaller than 0.5, respectively (Moriasi et al., 2007). The PBIAS values were classified as very good for N_{total} and PO_4^{3-} (PBIAS < ±25), and good for P_{total} (±25 ≤ PBIAS < ±40). The negative values of PBIAS indicated that the model overestimated N_{total} and PO_4^{3-}, as can be seen in Figures 5a and 5c, respectively. In the case of P_{total}, the simulated values were underestimated, compared to the observed values (Figure 5b).

Considering the coefficients of determination, only N_{total} showed an unsatisfactory value, with $R^2 = 0.21$, which was well below the acceptable range ($R^2 > 0.5$), so the simulation of N_{total} was considered to be poor (Santhi et al., 2001). Similarly, the RMSE value obtained for N_{total} (RMSE = 0.42) was considered unsatisfactory, since it exceeded half the standard deviation of the measured data (SD = 0.68) (Singh et al., 2005).

Overall, better values of the statistical parameters were obtained for P_{total} and PO_4^{3-}, compared to N_{total}. White and Chaubey (2005) obtained similar results for simulation of nitrate/nitrite, which appeared to be related to the nature of the input data used. Due to a particular interest in the production of phosphorus at the exits of the hydrographic basins studied, the input data set focused on all the possible sources of phosphorus, with less attention to all possible sources of nitrogen. An additional consideration is that the better results for phosphorus could have been related to the fact that this element was the limiting nutrient in the aquatic environments.

The average annual production of water (mm H_2O ha^{-1} y^{-1}) and sediments (Mg ha^{-1} y^{-1}), together with the loads of total nitrogen (kg ha^{-1} y^{-1}) and total phosphorus (kg ha^{-1} y^{-1}) in the hydrographic basin of the Poxim-Açu River are shown in Figure 4. It should be noted that the production of sediments was not calibrated (due to a lack of data), but this did not hinder the evaluation of spatial variability. According to the developers of SWAT, the model can be applied to river basins for which instrumental data are not available and in the present case it was used to provide an indication of the main sediment production areas (Neitsch et al., 2011, Uzeika et al., 2012). It can be seen that there was a degree of coincidence between the results for the production of water, sediment, and nutrients, with a tendency towards an increase in the eastern part of the hydrographic basin.

Figure 4 - Production of water, sediments, total nitrogen, and total phosphorus in the hydrographic basin of the Poxim-Açu River.



Source: Authors (2022).

The greatest losses of N_{total} and P_{total} showed correspondence with the areas where there was greatest surface runoff. For P_{total}, the highest losses were due to surface runoff in areas occupied by cultivations, where the phosphorus was associated with sediment particles (Ghebremichael et al., 2010, Marques et al., 2022).

The average values for water production, in the subbasins during the period 2000 to 2012, varied between 0.50 and 15.46 mm ha^{-1} y^{-1}. Subbasins 5, 6, 9, 10, 12, 15, and 24 showed the smallest water production, of between 0.50 and 0.90 mm ha^{-1} y^{-1}. In these subbasins, with the exception of subbasins 5 and 24, the main soil use was forest, which explains the low values obtained in the simulations. In subbasin 5, only 14.8% of the area consisted of riparian forest, with the remainder being occupied by pasture (46.5%) and sugarcane (39%). Here, the low water production can be explained by the predominant soil types, Litholic Neosols and Quartzarenic Neosols, whose high infiltration capacities reduce surface runoff (Silva et al., 2005).

The values obtained for sediment production varied between 0.00 and 0.060 t ha^{-1} y^{-1}. The subbasins that showed the smallest losses of soil (0.00-0.01 t ha^{-1} y^{-1}) were subbasins 1, 2, 5, 6, 7, 9, 10, 12, and 15. In subbasins 1, 2, 5, 7, and 9, the main soil types were Litholic Neosols and Quartzarenic Neosols whose high infiltration capacities act to reduce the transport of sediments, while in subbasins 6, 10, 12, and 15, forest cover exceeded 45%. In earlier work using simulations of different scenarios, Machado et al. (2003). reported that losses of soil were reduced when pasture was replaced by forests. Other work has also reported smaller losses of soil in areas where forest predominates, due to protection of the soil by greater interception of raindrops by the forest canopy. Furthermore, the presence of plant litter increases the organic matter content of the soil and improves its structure and permeability.

Subbasins 8, 13, 14, 16, 17, 21, 23, and 25, which accounted for only 30% of the hydrographic basin studied, produced 65% of the sediment, 84% of the total nitrogen, 93% of the phosphate, and 86% of the total phosphorus. The soils of these subbasins were Red-Yellow Argisols and Gleysols, and the areas occupied by pasture exceeded 40% in all cases. In subbasin 21, the area occupied by pasture exceeded 90%. An important point is that in the hydrographic basin of the Poxim-Açu River, the area occupied by pasture and sugarcane includes flat terrain as well as areas with greater declivity.

In subbasins 13 and 25, although over 50% of the areas were occupied by forest, the areas occupied by pasture exceeded 40%. Increased runoff could therefore be explained by factors including soil compaction, the small leaf area of the vegetation, and the shallow depth of the root systems in the pastures (Rocha et al., 2012).

These factors (land use, soil type, and declivity) were therefore associated with greater simulated production of water (25%), sediment (34%), N_{total} (24%), and P_{total} (22%) per hectare in these subbasins. Subbasin 8 could be described as a critical pollution source, since this small area generated disproportionately high amounts of surface runoff and nutrients.

The findings provide clear evidence that anthropogenic activity in the hydrographic basin, including changes in land use, has increased the potential for pollutant emissions due to improper soil management, removal of natural vegetation, and use of fertilizers. On the other hand, the results also show that the implementation of conservation practices, such as the recovery of degraded areas and restoration of riparian vegetation, could help to improve water quality following reduction in the losses of soil and nutrients, as observed for the subbasins with greater forest cover. The months with greatest precipitation (April to July) coincided with the periods of greatest production of sediment, N_{total}, and P_{total}, as well as discharge. The peak production of sediments, N_{total}, and P_{total} occurred in May.

4. Conclusion

Statistical results indicate a very good performance of the SWAT model in monthly simulation of flow and suitable one for the simulation of nutrients for the River Poxim's watershed, these results support the use of this model for the simulation of change scenarios of land use as a form of contributing to the management and handling watershed of the river Poxim.

The main producing areas of water, sediments and nutrients have as the predominant land use pasture and as soil types: Alfissol and Gleysol. These areas are places that require greater attention due to the combination of soils susceptible to erosion and steep relief.

It is evident that human actions related to changes of land use in the river Poxim's watershed promote changes in water quality by increasing sediment and nutrients.

We highlight the importance of implementing a continuous monitoring of the environmental conditions of the Poxim river basin with the objective of subsidizing public policies by the responsible government bodies.

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