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Influence of the integrity of the riparian zone on the Capão Comprido Stream Water Basin (DF) by simulating different spatial discretizations with the SWAT+ model

Influência da integridade da zona ripária na Bacia Hidrográfica do Córrego Capão Comprido (DF) por meio da simulação de diferentes discretizações espaciais com o modelo SWAT+

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ABSTRACT

Riparian zones are areas bordering waterbodies that provide various environmental services. However, the inappropriate use of these spaces, with conversion for urban expansion and agricultural frontiers, has compromised their ecological integrity. The objective of this work was to verify a new perspective for analyzing the influence of the integrity of the riparian zone in river basins based on different possibilities of spatial discretization and landscape representation, of the terrestrial phase of the water balance, from the perspectives of the landscape units available in the Soil and Water Assessment Tool (SWAT+) model. The Capão Comprido Stream basin in the Federal District (DF) was defined as a case study. There were difficulties in calibrating and verifying the model using SWAT Toolbox software, with Nash-Sutcliffe Efficiency (NSE) and logarithm (log)NSE values below 0.5; percent bias (PBIAS) above ±15, and coefficient of determination (R^2) below 0.6. These results, although better than those of the initial simulation, are still unsatisfactory acording to the metrics and values adopted as reference. Despite that, based on the determination of landscape units available in SWAT+, hydrological modeling of river basins has the potential to improve the representation of river basins by differentiating the characteristics of the higher parts of the relief (uplands) from the lower riparian zone (floodplains). Riparian zones proved to be relevant for the conservation of water resources. The simulations confirmed that the increase in these areas contributed to the reduction in surface runoff and sediment load in the river basin. However, it contributed to an increase in lateral flow, percolation, return flow, and deep aquifer recharge.

Keywords: landscape units; hydrological modeling; riparian corridors; permanent preservation areas.

RESUMO

As zonas ripárias são áreas lindeiras aos corpos hídricos e prestam diversos serviços ambientais. Contudo, a utilização inapropriada desses espaços, com conversão para fins de expansão urbana e de fronteiras agrícolas, tem comprometido a sua integridade ecológica. O objetivo deste trabalho foi verificar uma nova perspectiva de análise da influência da integridade da zona ripária em bacias hidrográficas com base em diferentes possibilidades de discretização espacial e representação da paisagem, da fase terrestre do balanço hídrico, sob as perspectivas das unidades de paisagem disponíveis no modelo *Soil and Water Assessment Tool* (SWAT+). Como estudo de caso, definiu-se a bacia do córrego Capão Comprido, no Distrito Federal. Houve dificuldades na calibração e verificação do modelo com o uso do *software* SWAT Toolbox, com valores de Nash-Sutcliffe Efficiency (NSE) e de logaritimo (log)NSE abaixo de 0,5; percent bias (PBIAS) acima de ±15; e coeficiente de determinação (R^2) abaixo de 0,6. Resultados esses que, embora melhores que a simulação inicial, são ainda insatisfatórios, conforme as métricas e valores adotados como referência. Contudo, constatou-se que a modelagem hidrológica de bacias hidrográficas por meio da determinação das unidades de paisagem, disponível no SWAT+, possui potencial para uma representação aprimorada das bacias hidrográficas, por diferenciar as características das partes mais elevadas do relevo (*uplands*) das partes mais baixas, a zona ripária (*floodplains)*. As simulações confirmaram que o incremento das zonas ripárias contribuiu para a redução do escoamento superficial e da carga de sedimentos na bacia hidrográfica. Por outro lado, contribuiu para o aumento do escoamento subsuperficial, da percolação, do fluxo de retorno e da recarga de aquífero profundo.

Palavras-chave: unidades de paisagem; modelagem hidrológica; corredores ripários; área de preservação permanente.

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Introduction

Riparian zones are narrow areas that border water bodies and perform various environmental services such as regulating water flow, maintaining water quality, reducing surface runoff, filtering pollutants, and retaining sediments. They also provide suitable conditions for the development of aquatic communities and serve as corridors for the flow of local biota, significantly contributing to biodiversity (Sirabahenda et al., 2020).

In the Brazilian Forest Code (Law 12.651 of May 25, 2012) (Brasil, 2012), riparian zones are treated as permanent preservation areas (PPAs), legally protected territorial spaces, which have different widths depending on the width of the rivers and the size of the property, with the environmental function of preserving water resources, the landscape, geological stability, and biodiversity, facilitating the gene flow of fauna and flora, protecting the soil, and ensuring the well-being of human populations.

However, despite the importance of riparian zones, their ecological integrity, or even the existence of these areas, is threatened by changes in land use, especially due to urbanization and the expansion of the agricultural frontier. Such changes pose risks to ecosystem conservation and water quality (Miserendino et al., 2011).

From this perspective, with a view toward effective management and the need to mitigate the negative impacts of such transformations, some studies, like those by Gomes et al. (2019), Guidotti et al. (2020), Ikematsu et al. (2020) and Sirabahenda et al. (2020) were conducted to analyze the influence of riparian zones in the face of disturbances caused by these changes, especially related to adequate width of riparian zone strips for the maintenance of environmental services.

The results of these studies show that the integrity of riparian zones plays an important role in the modulation of the hydrological cycle and in the conservation and regulation of water resources. For example, Guidotti et al. (2020) found that in scenarios with riparian zone widths of less than or equal to 8 m, there was significant soil loss, serving as a source of sediment for watercourses, whereas, in scenarios with widths of more than 15 m, the net loss of soil was not evident. Despite the positive evidence presented in the studies, there is a need to broaden our understanding of the impacts of the riparian zone on water resources, especially its different dimensions to improve hydroenvironmental management in urban and rural areas.

Research that analyzes riparian zones and focuses on hydrological modeling uses several computer programs, including the Soil and Water Assessment Tool (SWAT) model, which has wide applicability, mainly because it allows analyses to be conducted in monitored or non-instrumented basins. Recently, the newest version of the model SWAT+ was launched, which has improved runoff propagation resources and allows subbasins to be divided into landscape units (LSUs), uplands, and floodplains (Bieger et al., 2019). This provides more realistic results in the physiographic representation of watersheds, with favorable prospects for this improvement to have a positive impact on hydrological process simulations.

As pointed out by Wagner et al. (2022), when comparing the last version of SWAT+ with the previous one, the more realistic results are due to the strong spatial heterogeneity related to landscape characteristics, as evidenced by the differentiation of upland and floodplain flows in SWAT+, which improves the representation of hydrological processes.

This study was conducted in the Capão Comprido Stream watershed in the Federal District (DF), Brazil. The Capão Comprido Stream, the main channel of the watershed under study, is one of the tributaries and contributors of the Descoberto Reservoir, which in turn, is responsible for supplying water to approximately 60% of the population of the DF. For this reason, the Descoberto Basin, notably the Capão Comprido sub-basin, is constantly monitored and the focus of many academic studies, which contributes to the generation of data and information, especially on hydrological processes.

This study aimed to verify a new perspective for analyzing the influence of riparian zone integrity in watersheds based on different possibilities for spatial discretization and landscape representation of the land phase of the water balance, from the perspectives of the LSUs available in the SWAT+ model, on the components of the water balance, flow, and sediment load production, using the Capão Comprido stream basin in the DF as a case study.

Materials and Methods

Caracterization of the study area

The watershed of the Capão Comprido stream is a sub-basin of the Descoberto River Basin and is located in the western part of the DF, in the Administrative Region of Brazlândia, between 15°43'42" and 15°45'41", as shown in Figure 1. The Capão Comprido watershed covers an area of 16.6 km² and has elevations ranging from 1,033 to 1,273 m. It has two well-defined seasons: the dry season from May to September and the rainy season from October to April. According to data from the Brazilian National Water and Basic Sanitation Agency (ANA, 2023) and the Brazilian National Institute of Meteorology (INMET, 2023), the average annual rainfall is 1,496 mm, and the average monthly temperature in the region varies between 19.3 and 23.0°C. The average monthly humidity ranges from 43 to 76% and the average annual flow of the Capão Comprido Stream is 0.23 m^3/s.

The predominant soil class in the Capão Comprido Stream basin is latosol, both red and yellow-red (Reatto et al., 2004). Most watersheds have a gently undulating slope (58%), with small portions undulating (25%) and flat slopes (16%), and only a fraction with a strongly undulating slope (1%) (Silva, 2022). From an environmental point of view, the Capão Comprido watershed is located in the Descoberto River Environmental Protection Area (EPA). The PPAs are well preserved, covered by gallery forests and Cerrado, with a grassland phytophysiognomy for most of its length. In terms of use and occupation, the region has rural characteristics, mainly fruit and vegetable production (Governo do Distrito Federal, 2023b).

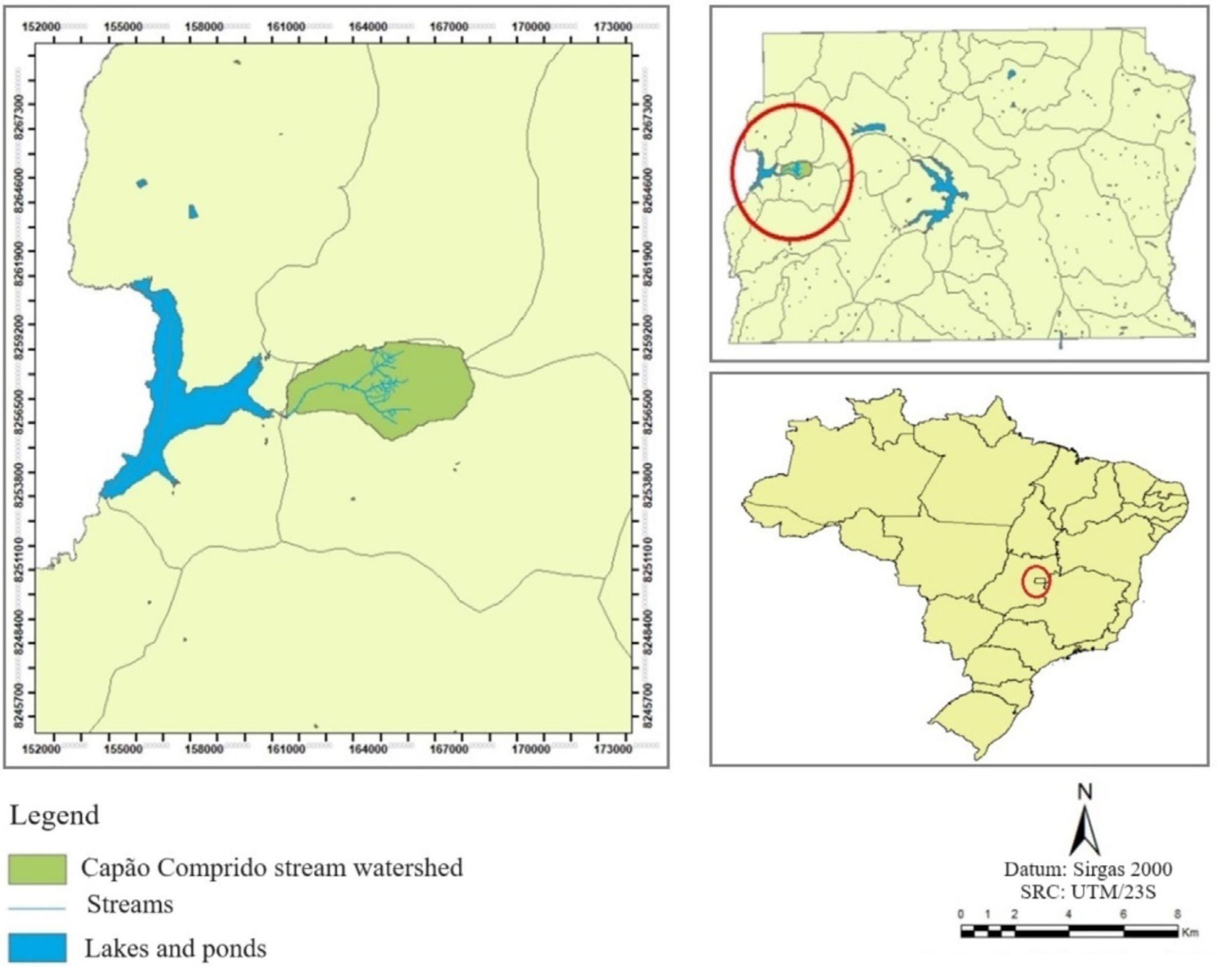

Figure 1 – Location of the Capão Comprido Stream watershed in the Federal District (DF, Brazil).
Source: Adapted from Governo do Distrito Federal (2023a).

Initial modeling

Similar to Silva (2022) and Jovino et al. (2022), who applied SWAT+ to assess the impact of land cover on sediment production and hydrological behavior, hydrosedimentological modeling of the Capão Comprido watershed was performed using SWAT+, rev. 60.5.4, in its geoprocessing interface, QSWAT+. In this study, the initial flow simulation was conducted between January 2001 and December 2015 in monthly steps. The first five years of the series were used to warm up the model.

To simulate the sediment load, we first obtained the observed data using the key curve $Qss=0.6049 \times Q1.329$ ([coefficient of determination] $R^2=0.577$), which in turn, is the result of applying the equation $Qss=0.0864 \times Css \times Q$. Where: *Qss* is the daily sediment discharge (ton/day); 0.0864 is the unit correction constant; *Css* is the concentration of suspended material (mg/L); and *Q* is the daily flow (m^3/s). For this analysis, it was decided to simulate the period from 2013 to 2020, using suspended sediment concentration and flow data.

After the simulation, a sensitivity analysis of the parameters was performed using the Sobol method, available in the SWAT Toolbox, version 1.0. The list of parameters used is presented in Table 1.After the sensitivity analysis stage, the most relevant parameters were calibrated, and the model was verified using the SWAT+ Toolbox. To do this, the Dynamically Dimensioned Search (DDS) calibration algorithm and the Nash-Sutcliffe coefficient (NSE) were used. Calibration was performed for the 300 interactions.

Data series used for calibration and verification followed the proportion 2/3 (two-thirds) by 1/3 (one-third), which are already used in hydrological modeling work, such as Ferrigo (2014), Nunes et al. (2020), and Silva (2022). The flow calibration period was the same as that used in the simulation (10 years), starting on January 1, 2006, and ending on December 31, 2015. The last five years of the series (2016–2020) were considered for verification. Due to the lack of data available for sediment discharge calibration, the period defined was from 2013 to 2017, and for verification, the period was from 2018 to 2020.

Table 1 – Parameters of Soil and Water Assessment Tool model, range of values, and alteration methods used in the sensitivity analysis.

Parameters	Description	Parameters	Description
Flow			
alpha	Base flow recession constant	*cn3_swf*	Evaporation coefficient
revap_co	Groundwater movement coefficient	*latq_co*	Lateral flow coefficient
revap_min	Minimum revap limit for percolation into the deep aquifer	*Awc*	Water storage capacity in soil layers
flo_min	Minimum aquifer storage to allow return flow	*K*	Saturated hydraulic conductivity of the soil
cn2	Number curve in condition II	*Bd*	Apparent soil density
Esco	Soil evaporation compensation factor	*Z*	Depth from shallow aquifer to deep aquifer
Epco	Plant absorption compensation factor	*anion_excl*	Fraction of porosity from which anions are excluded
Perco	Percolation coefficient	-	-
Sediment discharge			
Prf	Coefficient of sediment movement in the main channel	*lat_sed*	Sediment concentration in lateral and subsurface flow
Adj_pkr	Coefficient of sediment movement in the sub-basin	*usle_p*	Compensation factor of the Universal Soil Loss Equation (USLE)
Spexp	Exponent parameter for calculating the sediment retracted in the channel flow	*Slope*	Average slope.
Spcon	Linear parameter for calculating the maximum amount of sediment that can be reintroduced during sediment flow into the channel	*usle_k*	Soil erodibility factor from the Universal Soil Loss Equation (USLE)
Surlag	Sediment concentration lag time	*Bedldcoef*	Percentage of sediment entering the channel that is bed material
slope_len	Average length of slope for erosion to occur	*Cov*	Ground cover factor

Source: adapted from Ferrigo (2014), Pontes et al. (2021), and Tumsa (2023).

To assess the performance of simulations, calibrations, and verifications, the statistical variables suggested by Moriasi et al. (2015) were used: NSE; trend percentage bias (PBIAS), and R^2. In addition, the NSE coefficient was also used for the logarithm of the flow (logNSE), which is more suitable for low flows.

Results and Discussions

Initial simulation

The initial modeling was carried out according to the current land use and occupation scenario of the Capão Comprido Stream basin, both with the determination of LSUs and without this spatial distribution component, in order to analyze the performance of this new functionality brought about by SWAT+. Figure 2 shows a hydrograph comparing the simulated monthly flow data with the observed monthly flow data in the Capão Comprido catchment for the period 2006–2015.

It can be seen from the graphical analysis in Figure 2 that the model without the LSU represented peak flows better in most years. The recurring water saturation in the floodplains may have influenced the lower peak flow values in the simulation with LSUs, which was noticeable in the simulation because the configuration with LSUs can represent the processes that occur specifically in these areas, the floodplains. However, in both configurations, there was an underestimation of flows during dry periods in the Capão Comprido Stream basin.

According to Moriasi et al. (2015), the results of the flow simulation are considered satisfactory when the NSE and logNSE values are above 0.5 and below 0.7, the PBIAS is below ±15, and the R^2 is above 0.6. In this study, with regard to the simulated flow, the responses of all the objective functions used statistically showed that the initial results simulated from the uncalibrated model showed unsatisfactory performance for modeling in both situations, indicating the need to improve the calibration of the model. Table 2 summarizes the results of the performance evaluation.

As for the simulation of the sediment load, Figure 3 shows a comparison between the simulated monthly sediment discharge data and the observed monthly data in the Capão Comprido Stream basin for the period from 2013 to 2020.

Figure 3 shows that the observed and simulated sediment discharge values differed considerably, both in the simulation with LSUs and in the simulation without spatial configuration. The simulated sediment discharge showed overestimated results, with an order of magnitude much higher than the observed values, especially in 2016, which recorded a sediment discharge of over 7,000 tons/month, while the observed value was no more than 5 tons/month.

The objective functions used also showed that the results of the sediment discharge simulation were unsatisfactory for modeling in both situations, starting from the initial model without calibration. According to Moriasi et al. (2015), for sediment discharge, a result considered satisfactory should have NSE above 0.45 and below 0.7; PBIAS below ±20 and above ±15, and R^2 above 1.5. Table 3 summarizes the results of the performance evaluation.

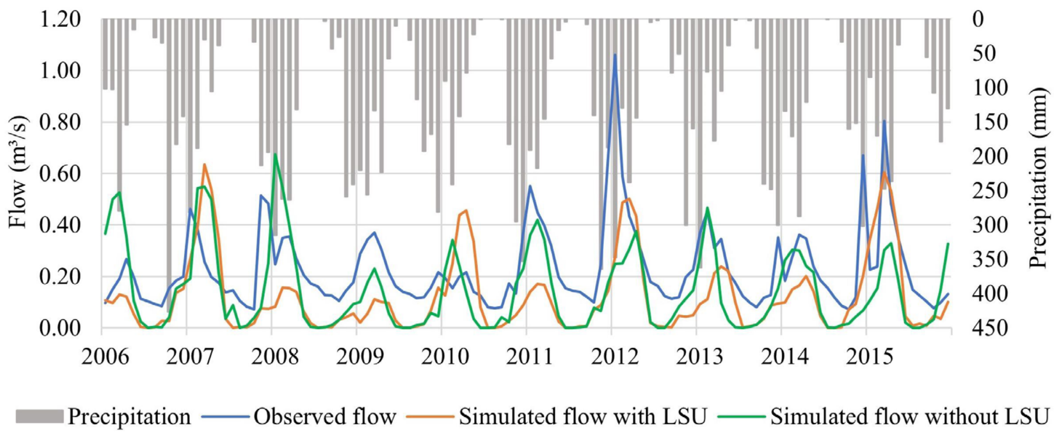

Figure 2 – Observed and simulated flows without calibration in the Capão Comprido Stream Basin (DF, Brazil).
Source: CAESB (2023).
LSU: landscape units.

Table 2 – Performance evaluation of initial simulation of the flow of Capão Comprido Stream (DF).

Objective function	without LSU	Performance	with LSU	Performance
NSE	-0.34	Unsatisfactory	-0.37	Unsatisfactory
PBIAS	37,650	Unsatisfactory	47,864	Unsatisfactory
R^2	0.22	Unsatisfactory	0.27	Unsatisfactory
LogNSE	-21.38	Unsatisfactory	-19.90	Unsatisfactory

LSU: landscape units: NSE: Nash-Sutcliffe Efficiency; PBIAS: percentage bias: R^2: coefficient of determination; log: logarithm.

The results of the initial simulation converge with those of Nunes et al. (2020), who also obtained unsatisfactory initial results when applying the SWAT model to simulate the tributary basins of Lake Paranoá in the Federal District, which revealed the need to adjust the model.

Sensitivity analysis

The most sensitive parameters with the greatest effect on the model responses are listed in Table 4.

Although the results of the sensitivity analysis showed little influence of some of the parameters selected in the modeling of the basin, based on studies carried out in watersheds in the Federal District, which indicate that they are relevant in the hydrological cycle, such as Ferrigo (2014) and Nunes et al. (2020), it was decided to use the parameters described above in the calibration, with the exception of the parameter *anion_excl*, which showed a more discrepant result than the others.

Calibration

Once we had the most relevant parameters, we performed the automatic calibration of the observed flow and sediment data separately, with manual adjustments, until we achieved the best result for the NSE objective function. Table 5 shows the parameters used and the final values obtained from the calibration of both flow and sediment discharges.

After calibrating the parameters, the simulation generally performed better compared to the initial simulation without calibration, particularly for sediment, regarding simulated and observed data as shown in Figures 4 and 5. The evaluation criteria presented in Table 6 also show a better performance, although they are still far from satisfactory.

From the analysis of Figures 4 and 5, similar to the initial simulation, it is evident that the model calibration was also unable to represent the observed peaks in flow and sediment discharge, with records sometimes overestimated and sometimes underestimated, although more discreetly. In the flow calibration, this behavior was especially noticeable in the rainy seasons of 2011 and 2012 (January and February), when the model underestimated the maximum flows. In addition, the recession periods were overestimated in almost all years in the series, although the transition from the dry to the rainy season was more accurately simulated. In the case of sediment calibration, concerning the observed data, solid discharge was underestimated almost every year, especially during the rainy period from December 2014 to March 2015. Only at the beginning of 2016 was there a slight overestimation of the solid discharge, which corresponded to years of low rainfall.

However, even with unsatisfactory results, the performance of this calibration does not differ greatly from other studies carried out in the Capão Comprido Stream basin. Ferrigo (2014), when performing the simulation and calibration in the Descoberto Basin and subsequent verification in the Capão Comprido Stream basin, obtained an NSE of 0.4. Similarly, Silva (2022), using the SWAT Toolbox for calibration and verification with daily stepping, obtained an NSE of 0.5.

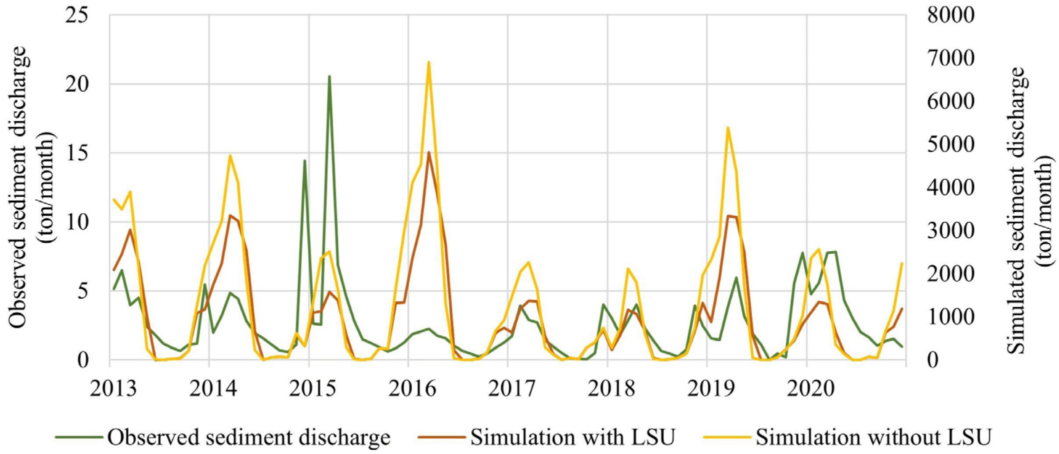

Figure 3 – Observed and simulated sediment discharge without calibration in the Capão Comprido Stream Basin (DF, Brazil).
Source: ANA (2023) (original data).

Table 3 – Performance evaluation of the initial simulation of sediment discharge from the Capão Comprido Stream.

Objective function	Without LSU	Performance	With LSU	Performance
NSE	-4,50E+05	Unsatisfactory	-2,35E+05	Unsatisfactory
PBIAS	-4,73E+04	Unsatisfactory	-2,35E+05	Unsatisfactory
R^2	0.094	Unsatisfactory	0.088	Unsatisfactory

LSU: landscape units: NSE: Nash-Sutcliffe Efficiency; PBIAS: percentage bias: R^2: coefficient of determination.

Table 4 – Parameters and respective values of sensitivity analysis.

	Parameters	Sensitivity		Parameters	Sensitivity
Flow					
1º	*cn2*	0.1797	9º	*revap_co*	0.0157
2º	*cn3_swf*	0.1796	10º	*alpha*	0.0106
3º	*Esco*	0.1570	11º	*latq_co*	0.0053
4º	*Epco*	0.1022	12º	*bd*	0
5º	*Perco*	0.0371	13º	*revap_min*	-0.0045
6º	*flo_min*	0.0367	14º	*z*	-0.0185
7º	*K*	0.0237	15º	*anion_excl*	-8.5100
8º	*Awc*	0.0205	-	-	-
Sediment Discharge					
1º	*Usle_k*	5.7700	3º	*bedldcoef*	0.7200
2º	*Prf*	2.4900	4º	*slope*	0.0055

Table 5 – Parameters, ranges, and values resulting from the calibration of the flow rate in the Capão Comprido Stream Basin.

Parameter	Unit	Type of change	Interval		Value at calibration
			Max	Min	
cn2	-	Percentage	-30	20	12,870
esco	-	Replacement	0	1	0,020
epco	-	Replacement	0	1	0,070
cn3_swf	-	Replacement	0	1	1,000
latq_co	-	Replacement	0	1	0,009
perco	fraction	Replacement	0	1	0,337
alpha	days	Replacement	0	1	0,720
revap_co	-	Replacement	0.01	0.20	0,020
flo_min	m	Replacement	0	20	10,607
revap_mim	m	Replacement	0	20	10,972
z	mm	Percentage	-30	60	4,000
k	mm/h	Percentage	-195	80	-46,728
awc	mm_H20/mm	Percentage	-20	50	-40,864
bd	mg/m³	Percentage	-93	-60	-67,181
prf	-	Replacement	0	2	0,550
bedldcoef	-	Replacement	0	1	0,950
usle_k	-	Replacement	0	0.65	0,270
slope	mm	Percentage	-60	70	-59,466

Max: maximum; Min: minimum.

Verification

This stage also showed unsatisfactory performance for most criteria, as shown in Table 7. The only statistical variable that performed well was the PBIAS obtained in the flow verification. These results indicated that the SWAT+ model was, to some extent, unable to reproduce a good fit between the observed and simulated values outside the calibration period.

Figures 6 and 7 show graphs comparing the observed and simulated flows and sediment discharge during the verification period. Figure 6 shows the difference between the observed and simulated flows for the verification period, particularly in relation to the minimum flows, which were overestimated in the simulation. As shown in Figure 7, the simulated solid discharge for the verification period did not reproduce the observed peaks, especially in relation to 2020, where the difference was more pronounced.

In this study, it was noted that the use of the SWAT Toolbox, a tool that is still being developed and improved, was not appropriate for calibrating and verifying the model in the Capão Comprido Stream basin. Many of the parameters presented in the previous version that were crucial for better results have not yet been replicated in the SWAT Toolbox, such as groundwater delay time (days) (GW_DELAY), initial depth of water in the shallow aquifer (mm H2O) (SHALLST), initial depth of water in the deep aquifer (mm H2O) (DEEPST), initial groundwater height (m) (GWHT), and deep aquifer percolation fraction (RCHRG_DP), which control the groundwater module and may have contributed to poor calibration and verification, highlighting the limits of the current version of the tool.

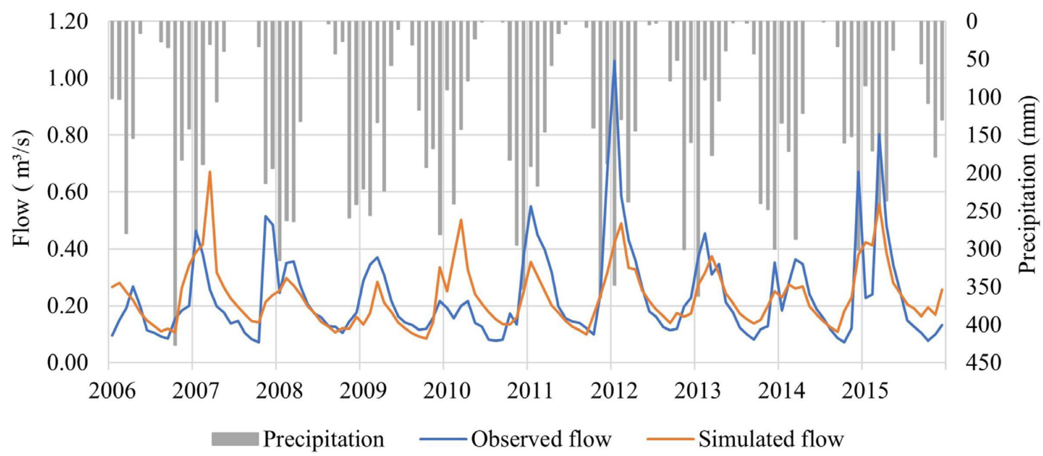

Figure 4 – Observed and simulated flows after the calibration process for the Capão Comprido Stream (DF, Brazil).
Source: CAESB (2023).

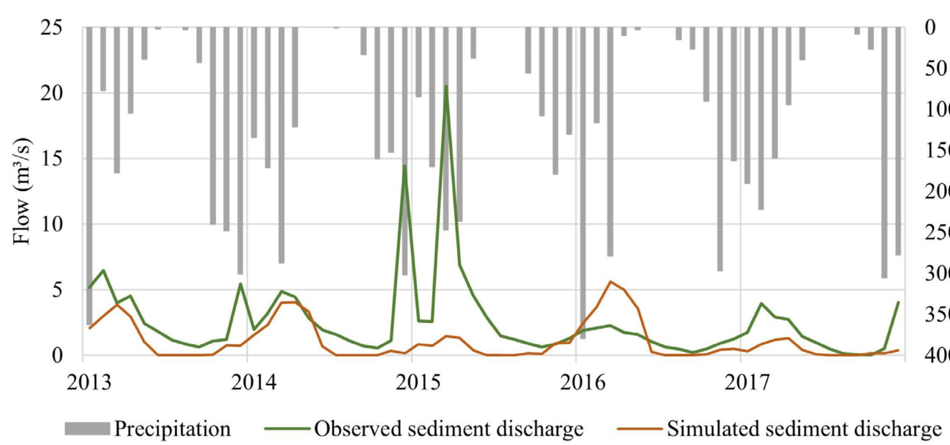

Figure 5 – Observed and simulated sediment discharges after calibration for the Capão Comprido Stream (DF, Brazil).
Source: CAESB (2023).

Table 6 – Criteria for evaluating the performance of the simulation with calibrated parameters for the Soil and Water Assessment Tool model.

Criteria		Values	Performance		Values	Performance
NSE	Flow	0.410	Unsatisfactory	Sediment discharge	-0.198	Unsatisfactory
PBIAS		1,634	Very good		58,150	Unsatisfactory
R^2		0.410	Unsatisfactory		0.050	Unsatisfactory
LogNSE		0.460	Unsatisfactory		-	-

NSE: Nash-Sutcliffe Efficiency; PBIAS: percentage bias: R^2: coefficient of determination; log: logarithm.

Table 7 – Performance evaluation criteria for verifying the flow and sediment discharge of the Capão Comprido Stream.

Criteria		Values	Performance		Values	Performance
NSE	Flow	0.413	Unsatisfactory	Sediment discharge	-0.563	Unsatisfactory
PBIAS		18,215	Good		62,542	Unsatisfactory
R^2		0.470	Unsatisfactory		0.100	Unsatisfactory
LogNSE		0.060	Unsatisfactory		-	

NSE: Nash-Sutcliffe Efficiency; PBIAS: percentage bias: R^2: coefficient of determination; log: logarithm.

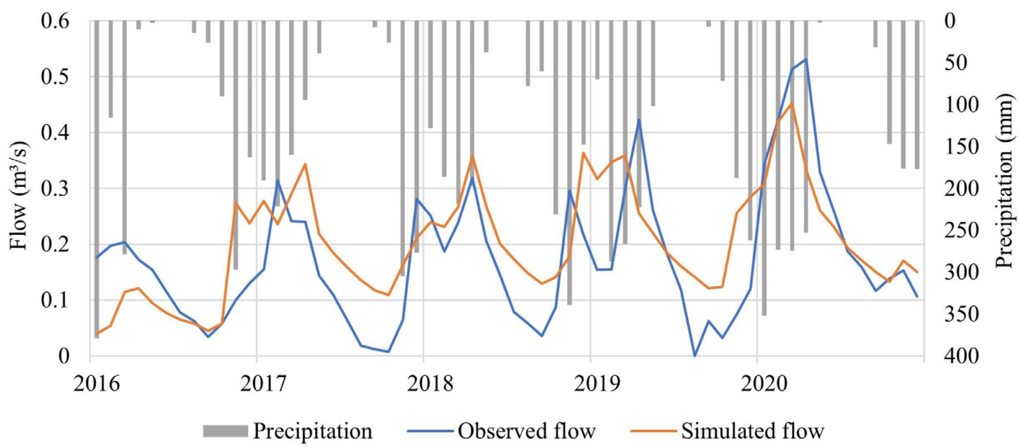

Figure 6 – Observed and simulated flow for verification in the Capão Comprido Stream Basin (DF, Brazil).
Source: CAESB (2023).

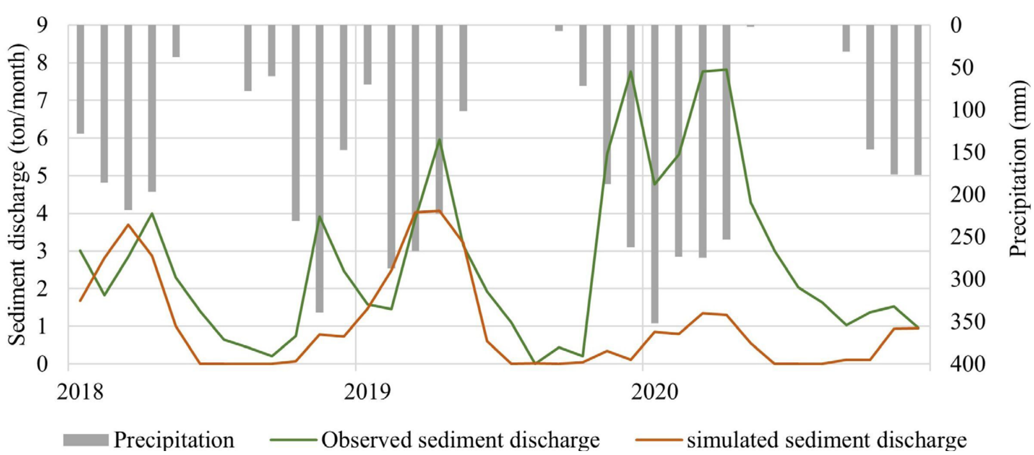

Figure 7 – Observed and simulated solid discharge for verification in the Capão Comprido Stream Basin (DF, Brazil).
Source: CAESB (2023).

Wagner et al. (2022) found that better performance of the SWAT+ model for low and very low flows can be obtained if the groundwater parameters are calibrated more accurately. In the same vein, Silva (2022) believes that choosing more sensitive parameters and checking the amplitude of their respective values, as well as the use of more adapted sensitivity analysis and automatic calibration software, can contribute to more satisfactory results.

Simulating scenarios

Analysis of the impact of landscape units on the water balance and sediment production

The SWAT+ simulation results, among other things, are used in the estimation of values relating to the components of the hydrological cycle and sediment production. For this study, initially, a comparison of these SWAT+ outputs were carried out in the simulation of the Capão Comprido Stream basin, from the perspective of the LSUs.

Figure 8 represents the simulated hydrological cycle for the two possible configurations of SWAT+ (with and without the delimitation of LSUs), from 2006 to 2015, based on the calibrated model. Table 8 summarizes the components values of the hydrologic cycle in millimeters (mm).

In general, the average annual quantity of the components of the hydrological cycle was very different between the two model configurations. The model simulated using LSUs showed higher values for almost all components, except for lateral flow, percolation, and capillarity, which were reduced by 18.80, 0.70, and 4.82%, respectively. This is because each LSU has its own hydrological response units (HRU); the predicted quantities of the water balance components at the HRU level were added together at the landscape unit level.

For surface runoff, the difference between the two configurations was 39.15%, but both results were consistent with the values obtained for the region. Ferrigo (2014) found, using SWAT, that the Capão Comprido Stream basin has a runoff value of less than 300 mm in the drainage area, mainly because of the basin's low impermeability.

However, in both situations, the results of percolation, capillarity, and return flow differ considerably from the values obtained in previous studies carried out in the Capão Comprido Stream basin, such as those obtained by Ferrigo (2014). Considering that Ferrigo (2014) used a previous version of the SWAT model, the differences in these components can be explained by the poor performance of SWAT+ in representing groundwater processes. Bailey et al. (2020) attributed this limitation, among others, to the fact that groundwater flow in SWAT+ is simulated only if water storage exceeds the user-specified limit and not due to hydraulic gradients. Furthermore, in SWAT+, each aquifer is treated as a homogeneous system in which properties such as hydraulic conductivity does not vary in space.

Regarding sediment production, although the calibration did not achieve satisfactory results and the absence of observed data contributed to it, the results of this output, for an initial analysis, are representative for understanding the behavior of this factor in the Capão Comprido Stream basin. Table 9 shows the simulated sediment production for both scenarios from 2006 to 2015.

From the analysis presented in Table 9, the simulation with LSU, in terms of maximum value, produced more sediment during the analyzed period, while there was an increase of 83.33% in sediment deposition in the channel, which indicates the possible interference of lowland areas in the sediment contribution. However, as this was the first comparative study of the hydrosedimentological simulation with the LSUs in the Capão Comprido Stream basin, it is recommended to conduct further research to ascertain the results and behavior of each LSU.

Table 8 – Components values of the hydrological cycle (in millimeters) of the Capão Comprido Stream Basin for the simulations with different spatial discretizations (with and without landscape units).

Components of the hydrologic cycle	Simulation without LSU	Simulation with LSU	Variation
Precipitation	1,431.99	1,431.99	-
Evapotranspiration	710.85	723.68	1.77%
Surface runoff	56.63	93.08	39.15%
Lateral flow	162.02	136.38	-18.80%
Percolation	445.72	442.61	- 0.70%
Capillarity	20.22	19.29	-4.82%
Return flow	445.17	886.10	48.60%
Deep aquifer recharge	15.31	17.40	12.01%

LSU: landscape units.

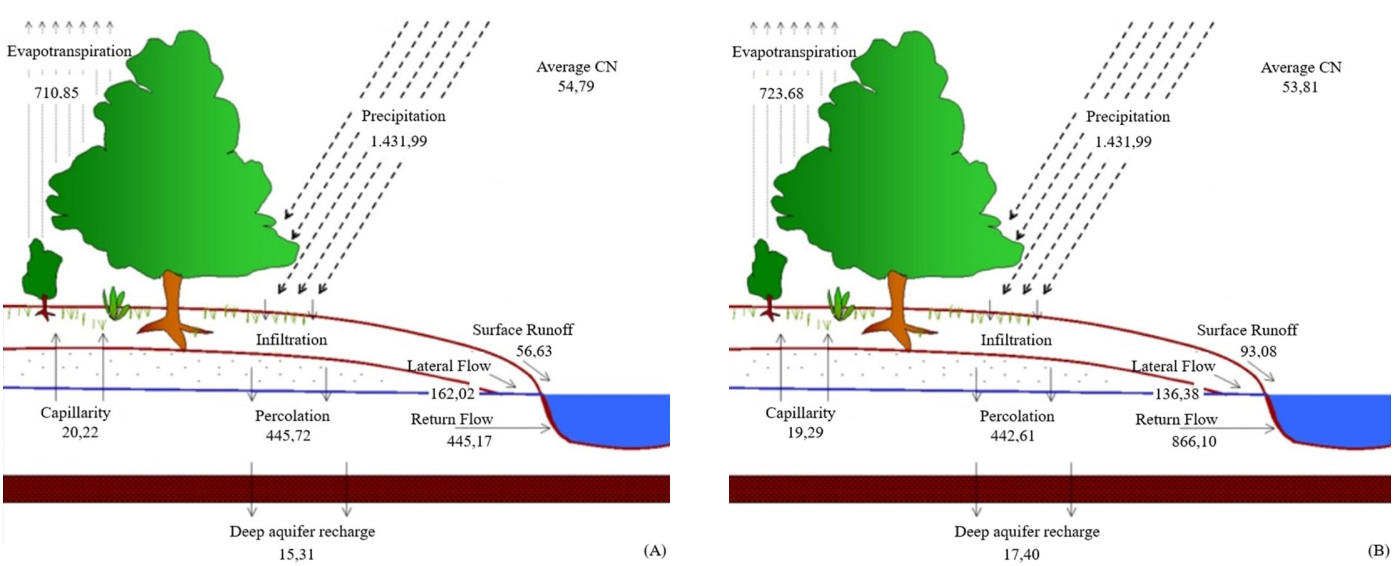

Figure 8 – (A) Simulated hydrological cycle in the Capão Comprido Stream Basin (DF, Brazil), without discretization in landscape units, with the Soil and Water Assessment Tool model, from 2006 to 2015. (B) Simulated hydrological cycle in the Capão Comprido Stream Basin (DF, Brazil), with discretization into landscape units, with the Soil and Water Assessment Tool model, from 2006 to 2015.

Table 9 – Values for sediment production in the Capão Comprido Stream watershed (DF) for the Soil and Water Assessment Tool model simulations with and without landscape units.

Components	Simulation without LSU	Simulation with LSU	Variation
Annual surface runoff (mm/year)	56.63	93.08	39.15%
Average upland sediment yield (ton/ha)	0.43	0.57	24.56%
Maximum sediment yield value (ton/ha)	7.86	38.30	79.47%
Sediment deposition in the channel (ton/ha)	0.01	0.06	83.33%

LSU: landscape units.

Analysis of the influence of an increase in riparian zones on water balance

To analyze the impact of the integrality of the riparian zones on the water balance, on the production of sediment loads, and, by extension, on water quality, the simulation of land use and occupation scenarios was carried out, with variations in the dimensions of the riparian zones, here referred to as PPAs. The dimensions of the PPAs for the scenarios were based on Articles 4 and 61-A of the Brazilian Forest Code (Brasil, 2012) and an extrapolation to a more anthropized scenario. Figure 9 illustrates the scenarios with PPAs of 15, 30, 50, and 100 m, and the scenario with the conversion of preserved PPAs to exposed soil.

The hydrosedimentological simulation was carried out with the determination of the LSU and for the same period as the flow calibration (2006–2015) using the calibrated model. Table 10 summarizes the values in millimeters (mm) of the components of the hydrological cycle in the Capão Comprido Stream basin for each scenario analyzed.

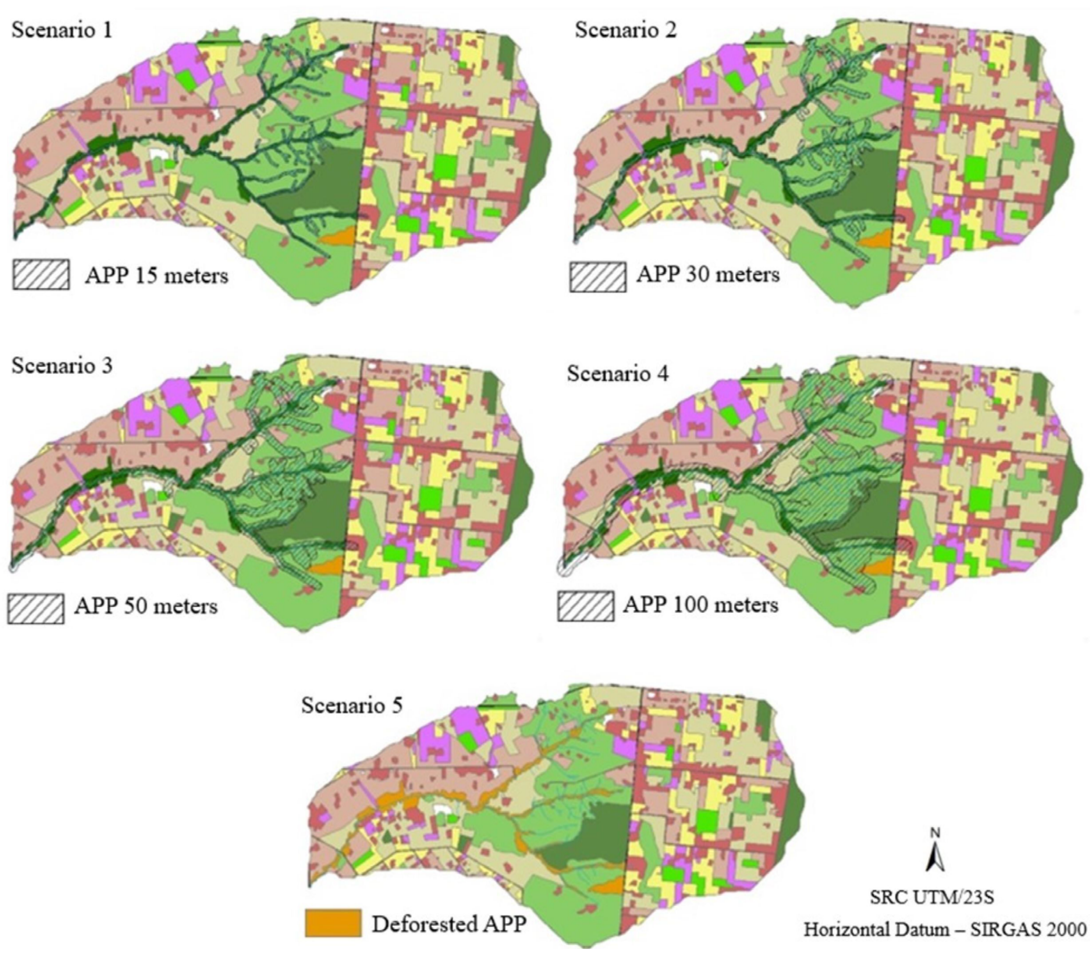

Figure 9 – Scenarios with permanent preservation areas of 15, 30, 50, and 100 m in length and a scenario with conversion of preserved permanent preservation areas to exposed soil in the Capão Comprido Stream watershed (DF, Brazil).

Table 10 – Components of the hydrological cycle for each permanent preservation area scenario.

Components of the hydrologic cycle	Deforested PPA	PPA 15 m	PPA 30 m	PPA 50 m	PPA 100 m
Precipitation	1,431.99	1,431.99	1,431.99	1,431.99	1,431.99
Evapotranspiration	714.16	722.35	722.42	731.71	747.83
Surface runoff	116.61	96.37	94.39	85.36	72.64
Lateral flow	127.44	135.62	136.13	136.02	133.70
Percolating	437.89	441.46	442.82	442.98	442.32
Capillarity	19.29	19.29	19.29	19.30	19.30
Return Flow	861.40	864.95	866.31	866.69	865.60
Deep Aquifer Recharge	17.37	17.39	17.40	17.41	17.43

PPA: permanent preservation area.

Table 10 shows that evapotranspiration increased as the PPA increased. The highest record was in the PPA 100 m simulation, followed by the PPA 50 m scenario, suggesting a strong influence of riparian vegetation on this process. Compared to the PPA 30 m scenario, the evapotranspiration in the PPA 15 m scenario was practically unchanged. In addition, in all the simulated scenarios, return flow was the main component contributing to the hydrological cycle, followed by evapotranspiration and percolation.

As the length of the PPA increased, there was a reduction in surface runoff in the basin and an increase in lateral flow, percolation, return flow, and deep aquifer recharge, indicating a relevant effect of the presence of riparian vegetation on the infiltration of water into the soil. These results are in line with the bibliographic studies by Gomes et al. (2019) and Silva (2022), which emphasize the importance of riparian zones for the conservation and regulation of water resources.

Gomes et al. (2019), in a study conducted in the Barrocão watershed (SP), indicated that the total volume of runoff generated in riparian forest areas was three times lower than in areas cultivated with sugarcane. The authors attributed this difference to the fact that riparian forests have higher soil porosity, a consequence of the greater concentration of organic matter and number of roots, which contributes to a higher capacity for water infiltration and percolation.

Silva (2022), when simulating a conservation land use scenario in the Capão Comprido Stream basin, whose characteristics included the preservation of PPAs and conservation of native vegetation, verified a 2% increase in percolation/infiltration rates and aquifer recharge rates, as well as a 30% reduction in surface runoff compared to the conventional scenario.

From the perspective of LSUs, the watershed behaves differently in higher areas (uplands) and floodplains. Thus, to understand the dynamics of these areas in relation to the hydrological cycle, variations in surface runoff, evapotranspiration, and percolation were analyzed in each scenario and LSU. Table 11 shows the average annual values in millimeters (mm) of these components.

In all scenarios, the surface runoff in the floodplains was higher than that recorded in the uplands. This is because, in the higher areas of the watershed, the soil moisture deficit between rainfall events is greater, which contributes to the surface runoff generated by evaporation or infiltration into the soil more easily, as shown by the upland percolation data, which indicates higher values than floodplains. In addition, residual runoff is carried to floodplains, impacting, as a consequence, the increase in the volume of surface runoff and saturation of these areas. At this point, Rathjens et al. (2022) explained that the saturation of floodplains, especially in the rainy season, decreases the infiltration capacity of both precipitation and surface runoff derived from the uplands. Thus, precipitation falling in these areas results in greater surface runoff.

In the floodplains, the surface runoff reduces to the scenario with a PPA of 50 m, after which there is a 25% increase. This can be explained by the increase in drainage areas in the plains to the detriment of the plateau areas. Similarly, but in the opposite direction, it occurs with percolation, with a 3.5% reduction in floodplains.

Evapotranspiration rates were also higher in floodplains in almost all scenarios, with the sole exception of the deforested PPA scenario, possibly due to the reduction in the area of gallery forest vegetation present in the lowland areas and the greater influence of exposed soil moisture.

Analysis of the influence of permanent preservation areas on sediment production

Following the same pattern as surface runoff, sediment production in the Capão Comprido Stream basin decreased considerably as there was an increase in PPA coverage, as shown in Table 12.

From the analysis presented in the table above, one can observe that the lowest sediment production was recorded in the PPA 10 m scenario. Compared to the deforested PPA scenario, there was a 96.5% reduction in the average upland sediment yield and a 95.3% reduction in the maximum value produced per hectare, demonstrating the importance of preserving and increasing this protection range in attenuating the sediment load.

However, it should be noted that increasing the PPA by 15 m has a positive effect on sediment production, as observed based on the sharp reduction in the values of this scenario in relation to the deforested PPA. Compared to this area, PPA 15 m reduced the average upland sediment yield by 51.7% and the maximum sediment production value by 82.5%, which means a difference of -44.8 and -12.8% of the respective items in relation to the best scenario (PPA 100 m).

Table 11 – Simulated annual average values in millimeters of surface runoff, evapotranspiration, and percolation (Capão Comprido Stream watershed, DF).

Scenarios	Surface runoff		Evapotranspiration		Percolating	
	Uplands	Floodplains	Uplands	Floodplains	Uplands	Floodplains
Deforested PPA	144.26	404.72	692.19	672.95	409.68	277.82
PPA 15 m	106.76	139.52	701.38	755.15	415.60	311.17
PPA 30 m	106.64	131.92	705.30	757.23	415.14	316.47
PPA 50 m	98.74	116.43	714.83	775.72	414.90	314.15
PPA 100 m	73.64	155.24	743.96	774.93	414.36	303.06

PPA: permanent preservation areas.

Table 12 – Simulated sediment production data for each permanent preservation area scenario (Capão Comprido Stream watershed, DF).

Components	Deforested PPA	PPA 15 m	PPA 30 m	PPA 50 m	PPA 100 m
Annual surface runoff (mm/year)	116.61	96.37	94.39	85.36	72.64
Average upland sediment yield (ton/ha)	1.47	0.57	0.54	0.20	0.05
Maximum sediment yield value (ton/ha)	72.51	12.68	12.68	6.99	3.35
Sediment deposition in the channel (ton/ha)	-0.30	0.06	0.06	0.12	0.12

PPA: permanent preservation areas.

These results were consistent with those reported by Távora (2017). In a study of the Cerrado riparian zone in the Capetinga stream basin, the author stated that lateral protection strips, as narrow as 5 m, exhibited a significant improvement in water quality in terms of the average concentration of suspended solids, which was also noted in the significant reduction in surface runoff and sediment production in the PPA 15 m scenario.

In addition, it can be identified that there were no considerable differences between the 15 m and 30 m PPA scenarios. The PPA 30 m reduced surface runoff by only 2% and average sediment production by 5.2%. These results demonstrate, at least in terms of the quantitative aspects of sediment input, that reducing the width of the PPA by 15 m, as allowed by the Brazilian Forest Code for rural properties with an area greater than two and up to four fiscal modules, does not result in significant losses in the conservation of the integrity of the water resources in the Capão Comprido Stream basin. However, an evaluation based on parameterized management data is recommended at a later date.

As for sediment deposition in the channel, the values showed increasing variation in the width of PPA. The 15 m and 30 m PPA scenarios had similar values, whereas the scenarios with deforested PPA had a lower rate of sediment deposition in the channel. A possible explanation for this behavior is the contribution of the sediments generated in the PPAs themselves, thus acting as a source of sediment for the streams. In addition, it should be noted that the edaphoclimatic characteristics and management of the watershed also played a significant role in this process and may have stood out in this simulation.

Conclusions

The main objective of this study was to analyze the impact of the integrality of riparian zones in the Capão Comprido Stream basin, based on scenarios generated from different spatial discretizations, using the SWAT+ tool, from the perspective of configuration in LSUs.

After calibration with SWAT Toolbox software, the graphical and statistical results of the hydrosedimentological simulation showed significant improvements. Thus, in this study, SWAT+ modeling showed promise for the new perspective of watershed representation, coming closer to the physical reality of the landscape, which can contribute, among other aspects, to define the transition points of the landscape and better target field monitoring sites.

From the simulations based on the differences in the configuration of the model in LSUs, it can be seen that the spatialization available in SWAT + significantly influenced the behavior of the components of the water balance and sediment load, with a notable distinction between the aspects analyzed. However, for a better representation of the processes and a more realistic comparison, it is recommended: 1. adjustments to the calibration of parameters; 2. parameterization of floodplains and upland data, in order to differentiate these LSUs and better represent the processes that occur in the watershed; and 3. conducting field research to obtain data that can confirm whether the spatial discretization perspective of the SWAT+ model is, in fact, a real improvement in simulating the water balance of watersheds in its terrestrial phase.

The SWAT+ model responded well to variations in the extent of the riparian zone, with results that probably indicate what would happen in reality, both regarding the behavior of the hydrological components and sediment discharge. The increase in riparian zones indicated a strong influence of vegetation on the infiltration of water into the soil and containment of sediment loads. In addition, the presence of riparian vegetation had a significant effect on the evapotranspiration process.

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Authors' Contributions:

Nogueira, M.P.: conceptualization, data curation, investigation, methodology, software, validation, writing – original draft. Silva, P.R.: data curation, investigation, methodology, software, writing – review & editing. Minoti, R.T.: conceptualization, formal analysis, investigation, methodology, supervision, visualization, writing – review & editing.

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