O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 159–183, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96597

Simulation of hydrological scenarios in the Jaguari/RS river water basin using the SWAT model

Simulação de cenários hidrológicos na bacia hidrográfica do rio Jaguari/RS com a utilização do modelo SWAT

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http://dx.doi.org/10.5380/raega.v60i0.96597

Abstract

Hydrological models are computational tools that can assist in river basin management through the modeling of the water balance. This modeling allows for the prediction of impacts driven by the uncertainty of future climate scenarios that affect socioeconomic activities and environmental conditions. In this context, this study applied the Soil and Water Assessment Tool (SWAT) model to simulate hydrological scenarios in the Jaguari River Basin. The simulation period was determined based on data availability for modeling and validation. Thus, in this data-scarce context, the calibration period was from 2013 to 2016, and the validation period was from 2017 to 2019. The manual calibration method used ensured a coherent water balance across all simulated hydrological processes, achieving good results for streamflow, with an efficiency coefficient of 0.74 and a correlation coefficient of 0.86 during calibration, and coefficients of 0.72 and 0.85 during validation. After model adjustment, an alternative scenario was introduced, preserving riparian forests in the Jaguari River Basin's hydrographic network, resulting in notable changes, such as increased groundwater storage and higher streamflow due to a greater proportion of water in base flow. The hydrological simulation proved successful, highlighting the model's capability even with limitations in national data acquisition. Future work is recommended to apply alternative land use or climate change scenarios, leveraging the adjusted calibration obtained.

Keywords:
Hydrological modeling, Altered surfaces, Environmental studies.

Resumo

Os modelos hidrológicos são ferramentas computacionais que podem auxiliar na gestão de bacias hidrográficas através da modelagem do balanço hídrico. Essa modelagem permite a predição de impactos proporcionado pela incerteza do futuro quadro climático que afeta as atividades socioeconômicas e as condições do ambiente. Nesse sentido, esse estudo aplicou o modelo *Soil and Water Assessment Tool* (SWAT) para simular cenários hidrológicos na Bacia Hidrográfica do Rio

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Jaguari. O período de simulação realizado foi determinado a partir da disponibilidade de dados para a modelagem e sua validação. Assim, nesse contexto de escassez de dados, o período de calibração foi 2013 a 2016 e o período de validação foi de 2017 a 2019. O método de calibração manual utilizado garantiu um balanço hídrico coerente em todos os processos hidrológicos simulados, alcançando bons resultados para a vazão, com coeficiente de eficiência de 0,74 e correlação de 0,86 durante a calibração, e coeficientes de 0,72 e 0,85 durante a validação. Após o ajuste do modelo, um cenário alternativo foi inserido, preservando as matas ciliares da rede hidrográfica da Bacia do Rio Jaguari, resultando em mudanças notáveis, como maior armazenamento de água subterrânea e aumento na vazão devido à maior fração de água no fluxo de base. A simulação hidrológica demonstrou êxito, evidenciando a capacidade da modelagem mesmo diante de limitações na aquisição de dados a nível nacional. Recomenda-se, em trabalhos futuros, a aplicação de cenários alternativos de uso da terra ou mudanças climáticas, aproveitando a calibração ajustada obtida.
Palavras-chave:
Modelagem hidrológica, Ambientes alterados, Estudos ambientais.

I. INTRODUCTION

The cyclical movement of water across the Earth's surface can vary according to environmental characteristics, being influenced primarily during the terrestrial phase of the hydrological cycle as it is replenished by precipitation. According to Ferket et al. (2003), precipitation is one of the most important climatic variables for determining the water balance, as it is the predominant source of water in the cycle.

Studies indicate that the hydrological cycle, at least on a regional scale, is being affected due to spatial transformations, as hydrological processes directly respond to changes in land use (COHEN, 2007; FRITZEN, 2011; STERLING, 2013). Anthropogenic interferences such as vegetation suppression, soil degradation, morphological changes in topography, water contamination, and irregular waste deposition are some of the alterations in environments that reshape hydrological processes (PINHEIRO, 2009; BOTELHO & SILVA, 2004; SPERA, 2016; ANACHE, 2017).

In addition to impacts on land use and occupancy, climate change is a precursor to transformations in the water cycle. Research (PBMC, 2013b; GROISMAN et al., 2005; MARENGO et al., 2008) provides data indicating a future propensity for occurrences of meteorological phenomena and extreme events (related to increased precipitation) with greater frequency and intensity in the Southern region of Brazil.

The response of the hydrological cycle to climate change or land use is crucial for planning mitigation actions to prevent losses and damage to the natural environment and society. Therefore, monitoring hydrological variables using hydrological models is a tool that can aid in basin management by modeling

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hydrological processes and predicting impacts due to the uncertainty of future climatic scenarios, which affect socioeconomic activities and environmental conditions.

One of the well-established and widely used models is the SWAT (Soil and Water Assessment Tool) model, developed for the Agricultural Research Service (ARS/USDA) of the United States. It has eight main components: hydrology, climate, sedimentation, soil temperature, plant growth, nutrients, pesticides, and agricultural management.

Applications of SWAT are frequent and primarily used for simulating the water balance of a particular basin (SETEGN, 2008; PISINARAS, 2010; ANDRADE, 2013). However, the modeling potential for simulating synthetic scenarios makes it possible to analyze hydrological behavior under alternative types of land use and land cover (MACHADO, 2003; GHAFARI, 2010; BLAINSKI, 2017; TRENTIN, 2023), or even within the context of climate change (VALÉRIO, 2015; SOUSA, 2019).

The Jaguari River Basin (BHRJ) is located in the Central-West region of Rio Grande do Sul and covers an area of 5,141.62 km², situated about 450 kilometers from the capital, Porto Alegre. As shown in Figure 1, the BHRJ is part of the Uruguay River Basin (RHU); the Jaguari River is located on the right bank of the Ibicuí River, which is one of the main tributaries of the Uruguay River. The main channel of the Jaguari River extends 539 km, flowing in a northeast to southwest direction until it reaches its mouth.

Due to its geolocation in the central region of Rio Grande do Sul, the Jaguari River Basin (BHRJ) is situated in a transitional environment of physiographic aspects. This is evident from the diverse relief of the study area and the predominant vegetation, which includes both Atlantic Forest and Pampas grasslands. These factors influence variations in land use practices, with a primary focus on agricultural activities (SANTOS, 2018). These spatial dynamics also lead to differences among sub-basins within the study area, consequently affecting the hydrological processes occurring there.

In this way, the present work aims to calibrate and simulate two hydrological scenarios for the Jaguari River Basin - RS. The first scenario involves evaluating the water balance based on recent land use mapping, while the second scenario considers an alternative where the conservation of riparian forests in the study area is implemented.

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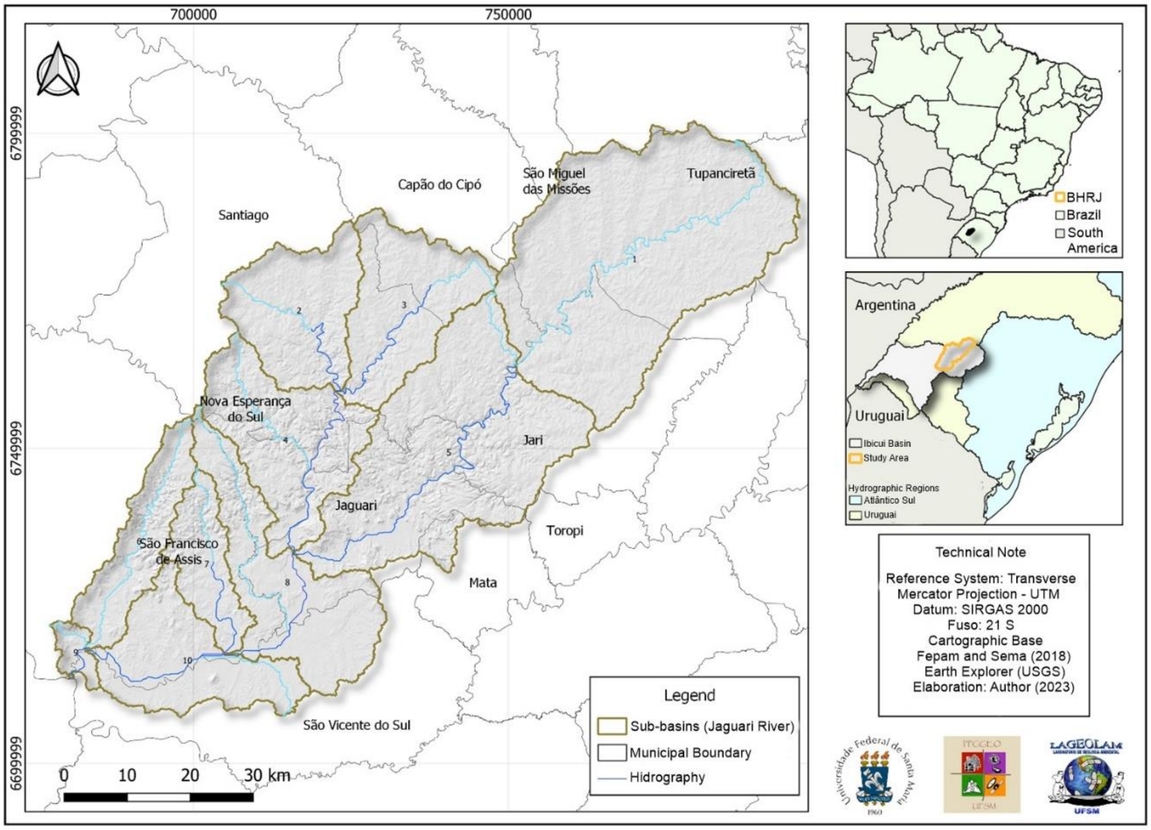

Figure 1 - Location map of the study area. (Authors, 2024)

II. MATERIALS AND METHODS

To carry out hydrological modeling effectively, database organization is a fundamental step. The SWAT model requires complex tabular and cartographic input data. Tabular data includes information on climate and soil properties, while cartographic data consists of maps related to slope, soils, and land use. Table 1 presents a summary of the information required for input into the model and their respective sources.

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Table 1 - Details of the source and description of the data requested by the model

Data type	Information	Description	Source
Cartographic	Digital Elevation Model	Spatial Resolution 30m	SRTM (USGS)
Cartographic	Soils	Scale 1:250.000	IBGE (2002)
Cartographic	Land and Cover Use	Spatial Resolution 30m	Adapted form MapBiomas – Colection 7
Tabular	Pedological profile	Granulometry, depth, density, hydraulic conductivity, etc.	Levantamento de Reconhecimento de Solos do Rio Grande do Sul (1973).
Tabular	Daily Precipitation	Reanalysis Data	W3S - Water
Tabular	Minimum and Maximum Temperatures	Reanalysis Data	Global Wheater Data
Tabular	Solar radiation, relative humidity and wind speed	Reanalysis Data	WXGEN

Figure: Authors (2024).

The spatial delineation of the study area begins with the automated delineation of sub-basins using flow direction and accumulated area of the Digital Elevation Model (DEM) cells. The choice of a consistent DEM, along with the validation of generated data through existing cartographic bases and satellite images, allowed for the most accurate possible definition. This was achieved by selecting specific and previously known outlet points of the basin to ensure that the model performed a delineation with minimal "noise." Subsequently, Hydrological Response Units (HRUs) are defined, which originate from the intersection of cartographic data: soil type, land use, and slope. According to Neitsch et al. (2005), after delineating the HRUs, the model calculates the flows for each unit; the results of each HRU are then aggregated to compute the output of the sub-basin; and finally, the responses generated by sub-basins are directed to the river channels according to the existing drainage network in the river basin to estimate the final flow.

To generate the slope map, the Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 1 arc-second (30 meters), acquired from the United States Geological Survey (USGS) website, was used. The choice of this model is associated with its consistency, particularly due to the filters and processing performed by the USGS on water masks, which allows for a better representation of the river basin compared to other digital elevation models, including newer ones. This is essential for this type of analysis.

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For the soil information in the study area, the soil map provided at a scale of 1:250,000 by IBGE and the National Soil Program of Brazil (Pronassolos) was used. Tabular information related to pedological profiles is required, including parameters such as the number of horizons, hydrological group, granulometry, saturated hydraulic conductivity, etc. To obtain these listed parameters, the Soil Reconnaissance Survey of the State of Rio Grande do Sul, produced by the Ministry of Agriculture in Technical Bulletin No. 30 (MINISTRY OF AGRICULTURE, 1973), was used, which describes the information based on soil profiles.

Land use and land cover for the Jaguari River Basin (BHRJ) was obtained from Collection 7 of the 2019 Land Cover and Land Use Maps for Brazil in GeoTiff format from MapBiomas Brazil (https://brasil.mapbiomas.org/colecoes-mapbiomas/). With MapBiomas mapping, land use classes were grouped into: fields, forest, water, agriculture, and urban areas. Only one cartographic dataset related to land use in 2019 was included because the changes in vegetation cover during the simulated period were not significant. The main objective of the work was, in addition to calibrating the model, to analyze a scenario related to land use changes in order to identify the impacts on the water balance.

Due to the presence of other anthropogenic activities with significant extent and impact on the territory, classes related to forestry and rice cultivation were added. The delineation and refinement of these new units were established through satellite image analysis using interpretation keys and manual vectorization.

Regarding climatic information, minimum and maximum temperature data were obtained using the Global Weather Data for SWAT platform (https://globalweather.tamu.edu/), which provides data from the Climate Forecast System Reanalysis (CFSR). Additional tabular data required for the model include information on solar radiation, relative humidity, and wind speed, which were obtained from the WXGEN atmospheric conditions generator of SWAT (SHARPLEY and WILLIAMS, 1990). This generator was originally developed for the EPIC model. The WXGEN climate generator uses available precipitation and temperature data to estimate these variables, with a particular focus on precipitation, as it is sensitive to the number of dry or wet days in a given month for calculating solar radiation.

There is no precipitation data from rain gauge stations that are representative for the entire Jaguari River Basin, and the available stations have continuity issues. Therefore, the precipitation data used were from the World Weather for Water Data Service (W3S) platform, recommended by SWAT developers and hosted on a server at the University of Guelph (https://www.uoguelph.ca/watershed/w3s/). This platform uses the Integrated Multi-satellitE Retrievals for GPM (IMERG) algorithm, which combines information from the GPM satellite constellation to estimate precipitation across most of Earth's surface with high spatial resolution (0.1°)

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and temporal resolution of 30 minutes (HUFFMAN et al. 2020). By selecting a specific region, meteorological data can be downloaded in various formats compatible with hydrological models, such as SWAT and generic CSV format. According to Ghimire et al. (2022), IMERG provides satisfactory to good precipitation simulations in most regions of the world.

For handling geospatial data, the ArcGIS 10.7.1 software provided by ESRI (Redlands, USA) was used. With the installation of the ArcSWAT extension in the GIS system, a tool tab is added to the main layout, which allows for the creation of a project to follow the modeling processes.

The calibration phase during modeling involves systematically adjusting the SWAT model parameters until the simulated results are statistically similar to the observed data. The precipitation data from W3S-Water are available up to 2019, and the observed streamflow data from the fluviometric station used—the Jaguari station (code: 76440000; geographic coordinates: 29°30'10.28" S and 54°41'15.70" W), managed by the National Water Agency (ANA)—have significant continuity gaps in the historical series from 2020 onwards. Thus, given the data availability, the years 2013 to 2016 were chosen for model calibration and the years 2017 to 2019 for model validation, both on a daily scale, with 2010 to 2012 considered the warming-up period.

Thus, the adopted calibration method was direct manual adjustment based on the modification of selected parameters with reference to the literature. Studies by Baltokoski et al. (2010), Salles (2012), Marcon (2013), Silva (2014), and Medeiros (2014) are cited as examples where the manual method was used to calibrate the hydrological model, achieving good results. For parameter sensitivity assessment, consulted works include Lelis et al. (2012), Souza et al. (2015), Nunes et al. (2022), and Brighenti et al. (2017).

After calibration, a hydrological simulation was carried out based on a synthetic scenario of the river basin under study with conservation of its riparian forests to evaluation the water balance in altered environments. This is relevant to the study area due to the conflict between land use and preservation areas. The mapping of riparian forests was conducted based on the delineation of Permanent Preservation Areas (APPs) according to Art. 4 of Federal Law 12,651/2012 (BRAZIL, 1965), which defines as permanent preservation areas the forests and other forms of natural vegetation located: along watercourses and around springs/intermittent or perennial water sources. APPs were generated using the cartographic base of hydrography organized by FEPAM and SEMA, at a scale of 1:25,000, with a 30-meter buffer added to river lines and a 50-meter buffer added to spring points.

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To evaluate the modeling performance, three statistical indicators were used: Correlation Coefficient (r), Efficiency Coefficient (COE) and Percentage of Bias (PBIAS). The performance classification and the mathematical equations applied for each indicator can be seen in Figure 2.

	COE	r	PBIAS
Very good	0,75 < COE < 1	0,80 < r ≤ 1	PBIAS < ± 10
Good	0,65 < COE < 0,75	0,70 < r ≤ 0,80	± 10 < PBIAS < ± 15
Satisfactory	0, 50 < COE < 0,65	0,60 < r ≤ 0,70	± 15 < PBIAS < ± 25
Unsatisfactory	COE < 0,50	r ≤ 0,60	PBIAS < ± 25

$$COE = 1 - \frac{\sum_{i=1}^{n}(E_{obs} - E_{sim})^2}{\sum_{i=1}^{n}(E_{obs} - \bar{E})^2} \quad r = \frac{\sum_{i=1}^{n}(x_1 - \bar{x})(y_1 - \bar{y})}{\sqrt{\left[\sum_{i=1}^{n} x_1 - \bar{x}\right]^2 \left[\sum_{i=1}^{n}(y_1 - \bar{y})^2\right]}} \quad P_{BIAS} = \left(\frac{\sum_{i=1}^{n} Q_{ci} - \sum_{i=1}^{n} Q_{oi}}{\sum_{i=1}^{n} Q_{oi}}\right) \cdot 100$$

Figure 2 - Performance classification for the statistical indicators used: Correlation Coefficient - r, Efficiency Coefficient - COE and Percentage of Bias – PBIAS. (Source: Adapted from Moriasi et al., 2007).

III. Discussion and Results

Definition of Hydrological Response Units

From the combination of slope, land use, and soil type, the software generated a total of 659 Hydrological Response Units for the Jaguari River Basin. The slope map was classified into 3 distinct ranges: < 5%, 5 – 15%, and > 15%. The slope class between 5% and 15% is well-distributed across the basin and represents the largest land area of all the classes. These slopes are characterized by rolling hill forms that significantly influence agricultural and livestock activities.

The slopes that make up the topography are of extreme importance as a pedogenetic factor because they control the dynamics of water flow in the landscape, such as leaching of solutes, erosive processes, and drainage conditions. Thus, the soil cover in the study area is defined by 8 soil types from the Pronassolos cartographic base. Additional quantitative information about the soils can be found in Table 2.

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Table 2 – Information about soils in the Jaguari River Basin.

Soil	Number of Horizons	Hydrological Group	Profile Depth (cm)	Area (km²)
Gleissolo Háplico	3	D	85	53,2
Latossolo Vermelho	5	B	300	860,8
Argissolo Bruno Acinzentado	5	C	150	292,3
Argissolo Vermelho	6	B	300	2144,2
Argissolo Vermelho Amarelo	6	B	210	21,7
Planossolo Háplico Eutrófico	6	D	200	227,6
Neossolo Litólico	1	C	15	876,8
Neossolo Chernossólico	1	C	20	660,3

Source: The authors (2024)

The last cartographic information layer used is the land use and land cover mapping (adapted from MapBiomas). The soil capabilities related to landforms influence the different land uses and land covers in the territorial space. In the Jaguari River Basin (BHRJ), the identified classes are: Soybean, Fields, Native Forest, Forestry, Rice, Water, and Urban Area. The predominant class for land use and cover is Fields, which are distributed throughout all regions of the basin and are primarily used for livestock farming. The significant presence of soybean cultivation across the BHRJ territory and the greater amount of native forest on steep slope are noteworthy. In the mosaic of Figure 3, the maps used for defining the HRUs and the distribution of sub-basins are identified.

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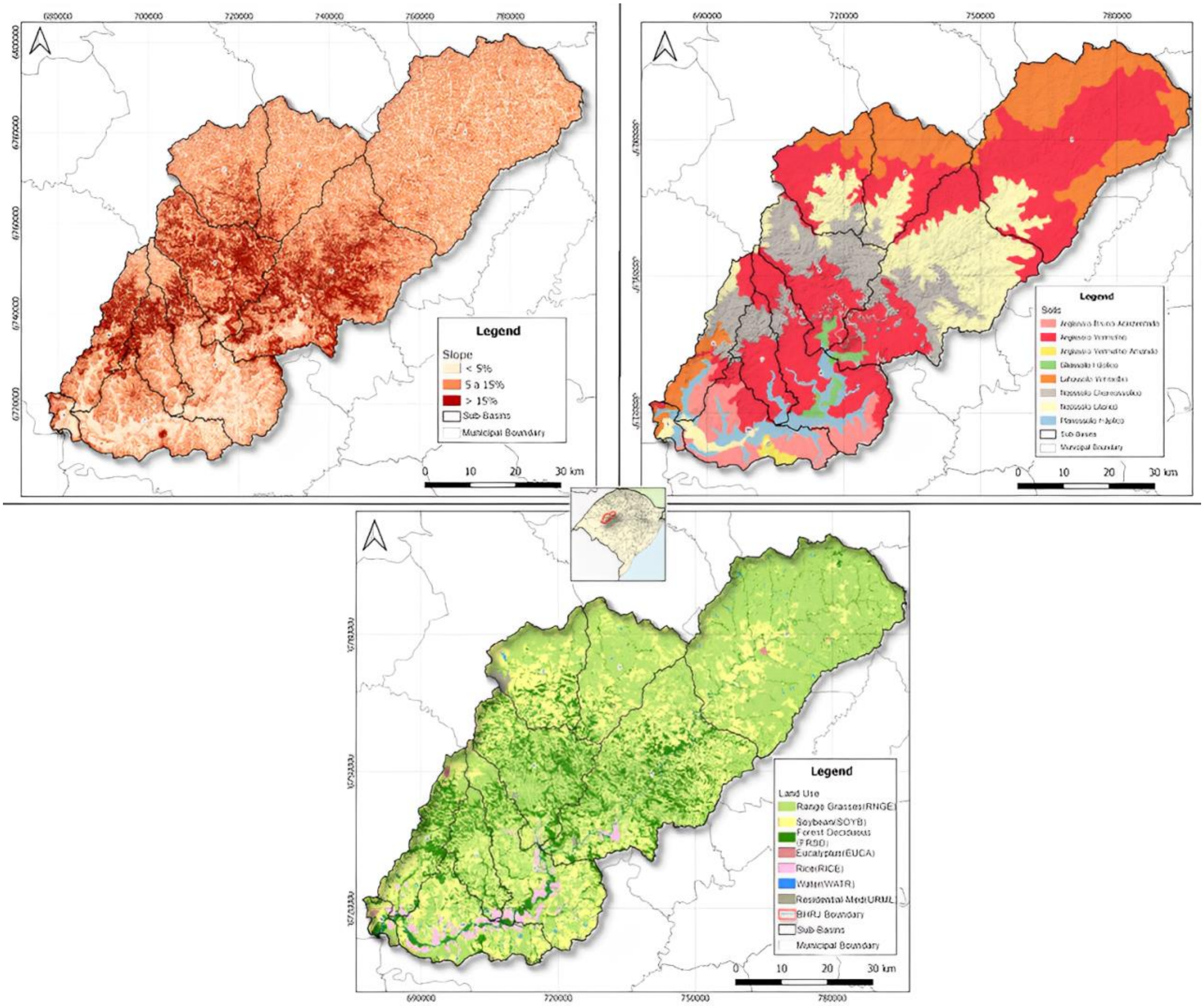

Figure 3 - Mosaic of maps used to define URHs in the Jaguari River Basin. Slope: < 5%; 5 – 15%; > 15%. Soils: Argissolo Bruno Acinzentado, Argissolo Vermelho, Argissolo Vermelho Amarelo, Gleissolo Háplico, Latossolo Vermelho, Neossolo Chernossólico, Neossolo Litólico and Planossolo Háplico. Land Use: Range-Grasses, Soybean, Forest Deciduos, Eucalyptus, Rice, Water, Residential. (Source: Authors)

It is emphasized that the use of fixed land use information for modeling does not significantly interfere with the results achieved, since the simulated period is short and the changes in the surface are not of a large proportion, affecting the scale of the mapping used (30m) . Therefore, the use of updated data for continuous and historical simulation is widely adopted in modeling work (SOUZA, 2013; MARTINS, 2020; PASSOS, 2021).

Calibration on a daily scale

During the model calibration using daily streamflow data, the consistency of the entire water balance was considered, along with modifications to parameters that would reduce streamflow, given the overestimated

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results of the initial simulation without calibration. Table 2 includes the selected parameters for calibration and their adjustments made from 2013 to 2016.

The change in the CH_K2 value from 0 to 30 mm/h indicates a moderate rate of water loss in the main flow, attributed to the presence of materials such as sand and gravel in the river course. The CANMX parameter, which represents the maximum water storage capacity in a plant canopy, was adjusted to 5 to achieve an appropriate evapotranspiration response. This value was determined based on the work of Van Griensven et al. (2006) and Leta et al. (2015), which established that the maximum possible variation for this parameter ranges between 0 and 10 mm.

According to Chow (1959), there are no exact methods for determining Manning's roughness coefficient for surface runoff (OV_N). Therefore, this coefficient was increased to enhance resistance to runoff and reduce flow, as roughness increases resistance to flow and a rougher surface result in lower flow for a given channel slope and cross-sectional area.

The delay time between the water leaving the soil profile and entering a shallow aquifer (GW_DELAY) was increased because a higher value for this parameter reduces the recharge of the shallow aquifer, as more of the water flow remains in the vadose zone. Consequently, this can result in a reduction in the contribution of groundwater to the total flow.

The soil evaporation compensation coefficient (ESCO) was reduced to 0.75, allowing the model to extract more water from lower soil levels. With this change, at least 75% of the soil's evaporative demand is met by the upper centimeters of the layer, with the remaining portion provided by the lower soil layers.

The reduction of SURLAG was made to store more water, delaying the entry of some surface runoff into the main channel. This adjustment was necessary because, in large basins, the time of concentration is greater than one day, and only a portion of the surface runoff will reach the main channel on the day it was generated.

Table 3 - Parameters selected for model calibration.

Extension	***Paramater***	***Default Value***	***Final Value***	***Unity***
URH	CANMX	0	5	mm
URH	ESCO	0,95	0,75	adim
URH	OV_N	0,15	2	adim
Routing	CH_K2	0	30	mm/h
Groundwater	REVAPMN	750	900	mm
Groundwater	GW_DELAY	31	60	dias
Groundwater	GWQMN	1000	2000	mm

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Groundwater	ALPHA_BF	0,01	0,7	dias
Groundwater	SURLAG	4	2	adim

Source: Authors (2024).

The GWQMN parameter represents the minimum depth of the shallow aquifer required for groundwater flow to occur. Groundwater reaches the surface only when the depth in the shallow aquifer is equal to or greater than the GWQMN value. Reducing this parameter results in increased base flow, but is accompanied by increased capillarity, as observed by Salles (2012).

Another relevant parameter is ALPHA_BF, an index that quantifies the response of groundwater flow to changes in recharge. Its values range from 0.1 to 0.3 for slow-response terrains and from 0.9 to 1.0 for fast-response terrains. In the Jaguari River Basin (BHRJ), features such as high altitudinal range, rolling slopes, and permeable soils indicate a rapid response to recharge, leading to a base flow recession constant value of 0.7 days.

These adjustments aim to improve the representation of the basin's hydrological behavior in the SWAT model, as calibration is considered the most important and labor-intensive stage of modeling according to Adriolo (2008). Green and Griesven (2008) suggest that when Efficiency Coefficient values exceed 0.4 and Correlation Coefficient values exceed 0.5 in a daily-scale simulation, the performance can be considered satisfactory.

Simulation Analysis

With the final parameterization, all the years of the calibration period (2013-2016), except for 2014, achieved very good simulated results according to the main statistical indicators used. There is a very strong correlation for the analyzed years with a slight tendency to underestimate the results.

Analyzing the rainfall regime of the following hydrographs, it is evident the alternation between dry and wet periods in the study area. This variation is caused by anomalies in the Tropical Pacific Sea Surface Temperature pattern. These anomalies affect atmospheric circulation, altering air temperature and, more importantly, precipitation. The warm phase (El Niño) of this phenomenon is associated with dry periods in tropical regions and wet periods in extratropical regions, while the cold phase (La Niña) is marked by the opposite: wet periods in the tropics and dry and cold conditions outside the tropics (FONTANA AND BERLATO, 1997).

During 2013, the model's efficiency was very good (COE = 0.77) with a very strong correlation (r = 0.87). However, it can be stated that from May to October 2013, the simulation was unsatisfactory as it did not model

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the peak flows resulting from precipitation (Figure 4), with an emphasis on base flow simulation represented by the linearity of low flow during these months, even when there were rainy periods.

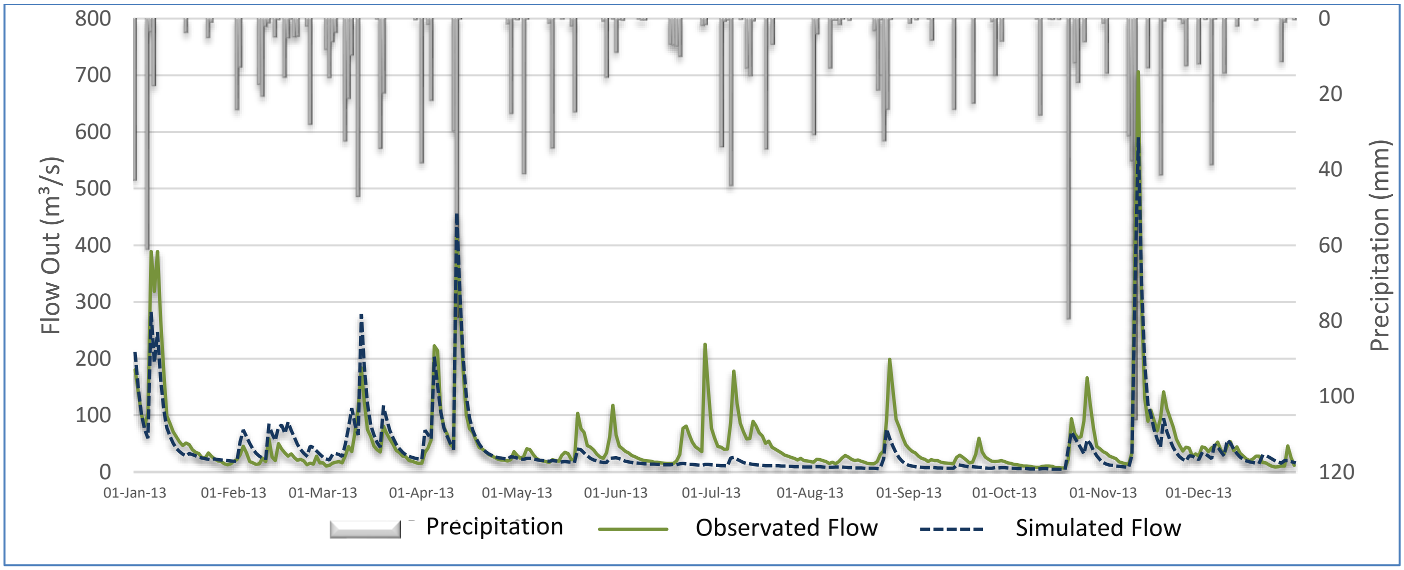

Figure 4 - Comparison of observed and simulated data for the year 2013. (Source: Authors, 2024)

In the following years, climatic influences from El Niño resulted in high rainfall indices. In 2014, a year with high precipitation (2444 mm) and a COE of 0.53, there were difficulties in modeling, making it the year with the worst performance during calibration. However, it was still considered satisfactory according to the literature (GREEN and GRIESVEN, 2008). In 2015, also with high precipitation (annual average of 2383 mm), the model showed greater consistency (COE = 0.83) and better performance compared to other periods. The discrepancy between the years, despite a difference of only 61 mm, can be attributed to the distribution of the rainfall regime. In 2014, rainfall was more diffuse throughout the year, resulting in numerous peak flows (about 15 events exceeding 200 m³/s), while in 2015, peaks were concentrated in the final months, which were well simulated. Figure 5 highlights this disparity.

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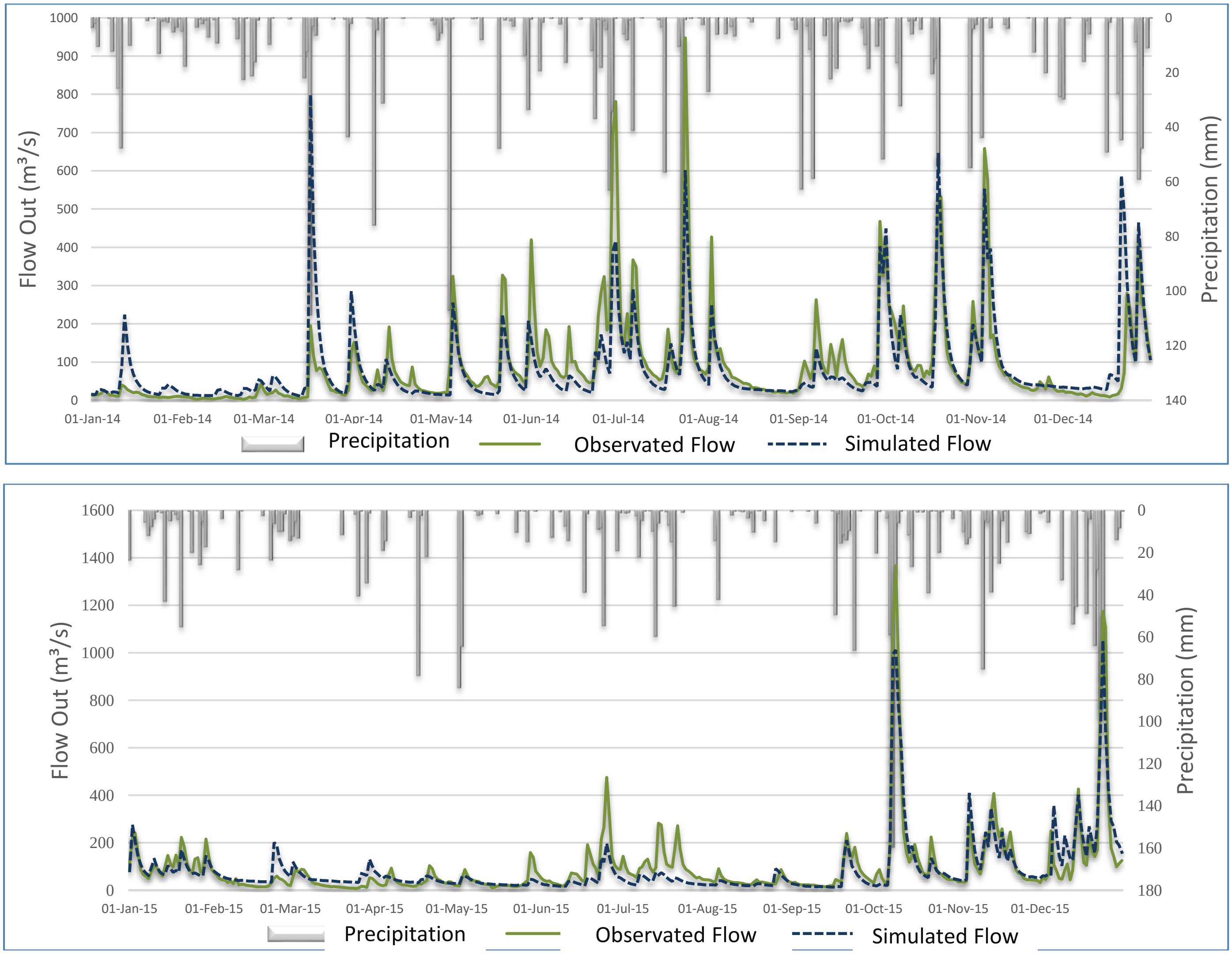

Figure 5 - Comparison of observed and simulated data for 2014 and 2015. (Source: Authors, 2024)

For the year 2016 (Figure 6), it is interesting to analyze the model's performance based on time frames. The first half of this year overestimated the base flow and underestimated the peak flow. However, the second semester performed excellently from October onwards. There is a COE = 0.23 and 0.88 for the first and second semesters, respectively. But in its entirety, 2016 had a COE = 0.78 and r = 0.7.

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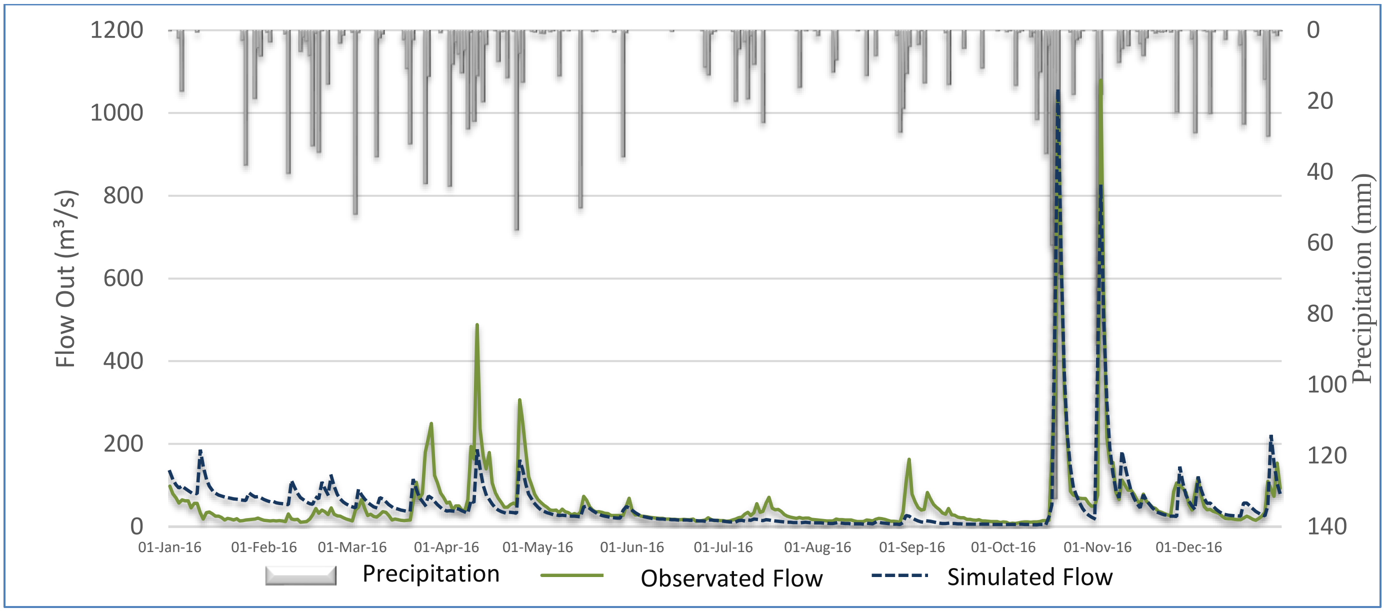

Figure 6 - Comparison of observed and simulated data for the year 2016. (Source: Authors, 2024)

After calibrating the SWAT model, validation was carried out for the years 2017 to 2019. The simulation for the year 2017 (Figure 7), with a PBIAS very close to zero, indicates that the model's predictions are not significantly biased compared to the observed values, which is reflected in the similar means of simulated and observed data.

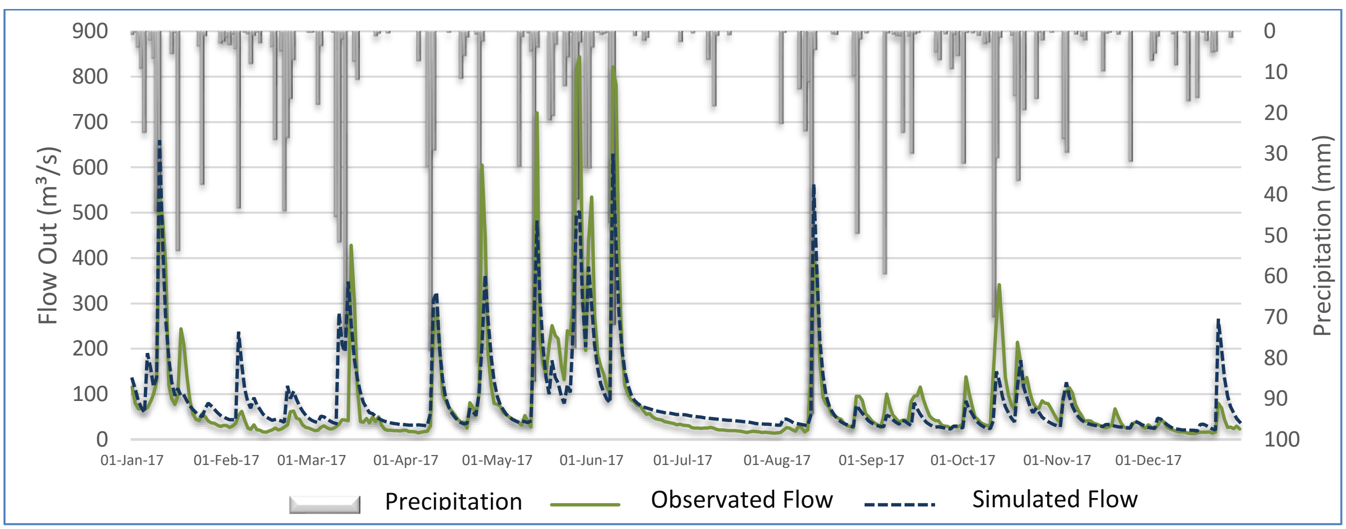

Figure 7 - Comparison of observed and simulated data for the year 2017. (Source: Authors, 2024)

The worst year of simulation during the validation period (2017 to 2019) was 2018 (Figure 8), with a COE of 0.53 and r = 0.77. The results were considered unsatisfactory, particularly for the less intense flows occurring between April and July, which were underestimated.

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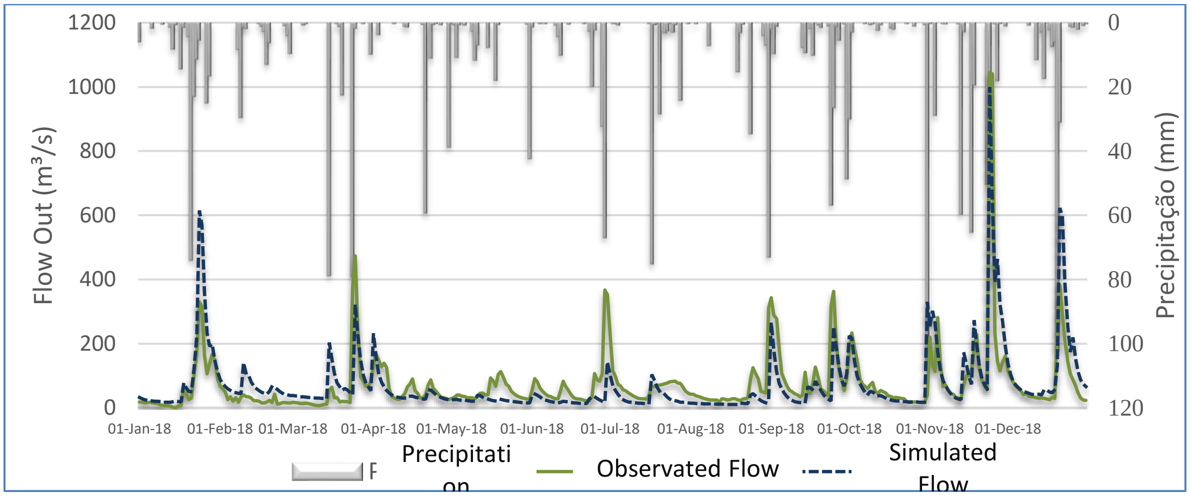

Figure 8 - Comparison of observed and simulated data for the year 2018. (Source: Authors, 2024)

The last simulated year with the possibility of validation, 2019, had the best performance throughout the entire simulation period, with a COE of 0.85 and a very strong correlation (r = 0.92). The rainfall regime, with few extreme events, may have also influenced this performance. As shown in Figure 9, from November onwards, there was a low-flow regime where the model overestimated this event. This occurred because this period was characterized by the influence of La Niña, which intensified in the years 2020 and 2021.

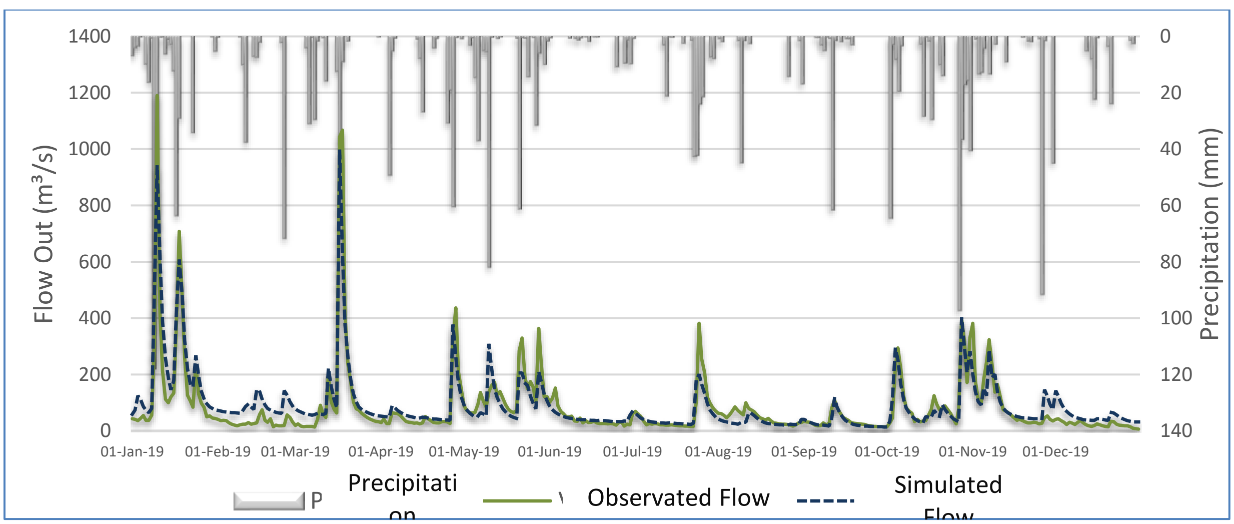

Figure 9 - Comparison of observed and simulated data for the year 2019. (Source: Authors, 2024)

Water Balance of Scenario I

The first scenario represents the current land use and land cover conditions. The analysis of the components of the water balance simulated by the SWAT model on an annual scale indicates that 47% of the total precipitation (an average of 2,050 mm annually) is converted into streamflow in the rivers, while 45% of the precipitation is allocated to evapotranspiration, which includes surface water evaporation and plant

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transpiration. Of the total flow, 35% comes from baseflow, which is the contribution of groundwater to rivers such as subsurface flow, while 65% of the total flow is composed of surface runoff. The fraction of precipitation that infiltrates into the soil (percolation), contributing to groundwater recharge, is 21% of the rainfall. There is a very small proportion, about 1%, of precipitation contributing to the deep recharge of the aquifer, represented by the Guarani Aquifer System (SAG). The illustration representing the hydrological processes of the water balance simulated by SWAT is shown in Figure 10.

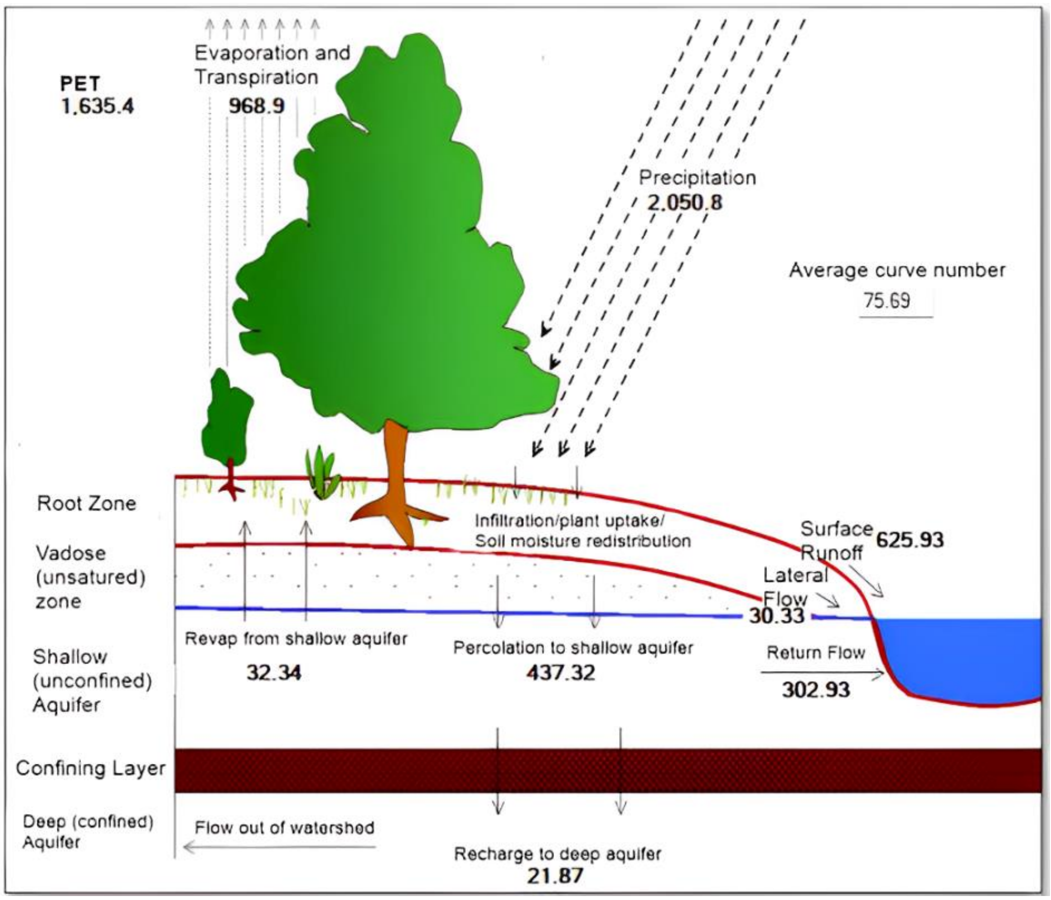

Figure 10 - Annual Water Balance of Scenario I in millimeters. (Source: Adapted from SWAT)

To estimate the surface runoff for the Jaguari River Basin (BHRJ), the Curve Number (CN) method developed by the Soil Conservation Service (SCS, 1957) was used, which is based on precipitation, soil hydrological class, and land use and land cover. With these parameters already input into the model, a Curve Number of 75.7 was obtained. CN values can range from 1 to 100, and the higher the value, the greater the area's impermeability, which enhances surface runoff. The estimated CN value of 75 for the BHRJ can be defined as a curve number representing vegetation cover of the grassland type (fields/pastures) in deep soils with low

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infiltration rates, such as Red Argisol (TUCCI, 2000; SARTORI, 2005). These definitions reflect the predominant soil and land use conditions in the basin, which brings coherence to the calculated CN results.

Water Balance of Scenario II

With the inclusion of reforestation in the land use and land cover mapping for areas designated as Permanent Preservation Areas (APPs) along riverbanks, the native forest class increased by 3.3%, leading to an overall increase in the basin's total flow. The comparison of the average simulated discharge between the current land use and land cover conditions (Scenario I) and the alternative scenario of riparian forest preservation (Scenario II) is observed in Table 4.

Table 4 - Comparison of simulated flow results (m³/s) in two hydrological scenarios

YEAR	FLOW SCENARIO I	FLOW SCENARIO II
2013	39,5	53,4
2014	83,7	103
2015	87,1	100
2016	55,6	64,7
2017	84,3	94,6
2018	72,2	79,2
2019	89,6	100,3

Source: Authors, 2024.

The flow of the Jaguari River increased with the inclusion of riparian forests (Figure 11). This result may be confusing because an increase in flow is often attributed to areas with lower vegetation density and without soil conservation practices, which lead to increased surface runoff. However, in this case, there was a decrease in such runoff. Therefore, when analyzing only the simulated flow, it may seem that the effect of riparian forest conservation is similar to what occurs when vegetation cover is removed. This highlights the importance of a comprehensive evaluation of the hydrological balance results provided by the modeling. Oliveira (2023) achieved similar results to this study, with increases in average simulated flows in reforestation scenarios due to a decrease in surface runoff and an increase in base (subsurface) runoff.

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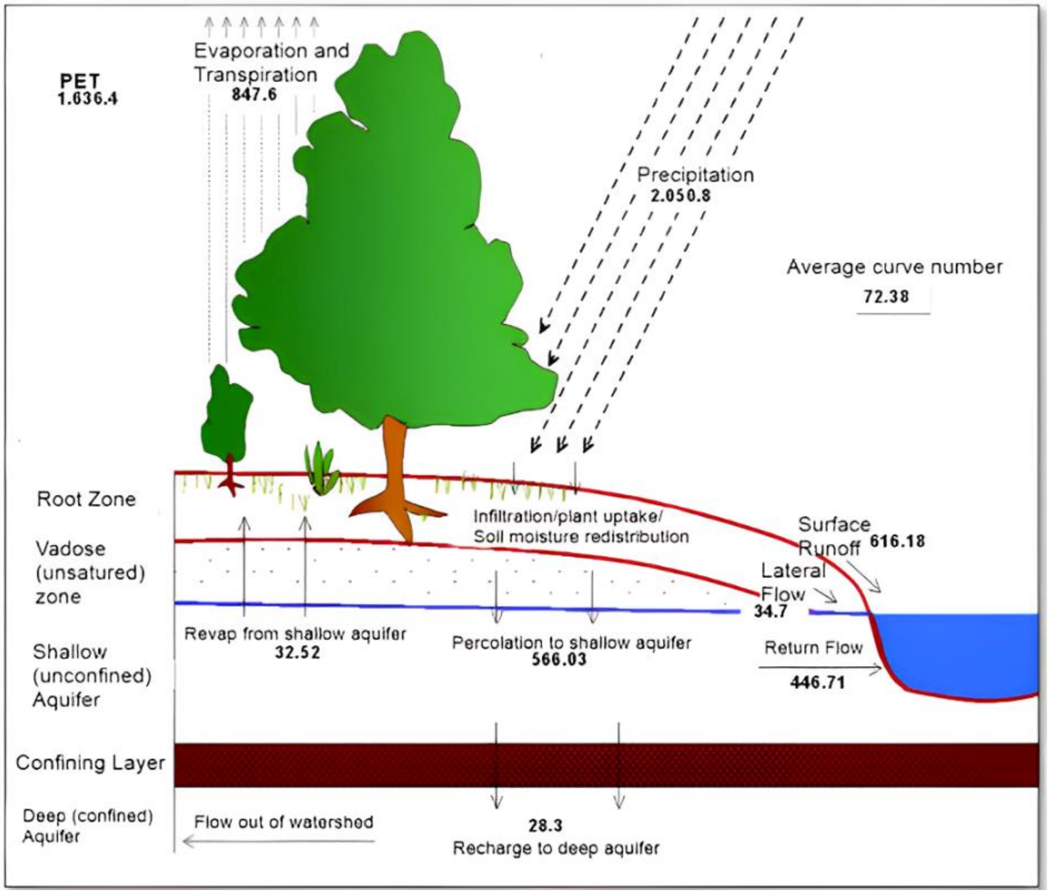

Figure 11 - Annual Water Balance of Scenario II in millimeters. (Source: Adapted from SWAT)

A set of changes in the water balance of the basin is observed in contrast to scenario I of land use and occupation under current conditions. There was a reduction in surface runoff, but with an increase in subsurface runoff and base runoff, with emphasis on the latter, which increased by 9 percentage points, resulting in the highest simulated flow. Groundwater storage was higher than scenario I, with an increase in aquifer recharge from greater percolation in relation to precipitation (7 percentage points). The reduction in the average CN for the basin by 72 already indicates the higher infiltration coefficient.

that the average annual evapotranspiration decreased by 5 percentage points. In principle, the expected result was that the reverse would occur, due to the greater presence of vegetation that contributes to water transpiration. However, many areas where there is conflict over land use in APPs are places where rice crops were cultivated where irrigation is required, forming sheets of water in the crops, contributing to evapotranspiration. When inserting riparian forests to model the alternative scenario, the reduction in rice farming may have contributed to the reduction in evapotranspiration values. Scariot (2022) corroborates this by noting, through modeling, that regions where systematized irrigated rice plantings occur are those that most contribute to the release of water from the surface into the atmosphere.

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In simulating alternative scenarios, Rodrigues (2015) also observed a reduction in evapotranspiration in the native forest preservation scenario compared to current land use in a basin of the Pará River. Evapotranspiration values only increased when simulating an intense reforestation scenario, which was also the case for Oliveira (2023).

In summary, the alternative scenario for the BHRJ, despite the minor differences in the inserted cartographic information, was sufficient to reveal changes in the hydrological balance, particularly highlighting the increased groundwater storage that flows into rivers. This is essential for long-term water supply, as it maintains base flow levels in watercourses during drought periods, mainly caused by the La Niña phenomenon. This underscores the importance of maintaining and preserving riparian forests as stipulated by current legislation.

IV. Conclusions

The development of studies related to water resources is crucial for analyzing the socio-environmental impacts of climate change and inadequate land use practices. In this context, hydrological models play a significant role by providing valuable insights for river basins management through the simulation of hydrological balance components.

The hydrological simulation with manual calibration achieved good results, as reflected in the literature: a calibration performance of COE = 0.74 and r = 0.86 and a validation period performance of COE = 0.72 and r = 0.85. This demonstrates that the application of the SWAT model in study areas with limited monitoring and/or scarce reliable hydrometeorological data can be effectively supported by utilizing alternative sources, such as reanalysis meteorological data.

When evaluating the hydrological modeling with a synthetic land use scenario focused on riparian forest conservation, the average flow of the Jaguari River increased due to enhanced groundwater storage and base flow. This underscores the significant role of environmental services, demonstrating that even minor changes in areas associated with Permanent Preservation Areas (APPs) can lead to substantial alterations in the hydrological balance of a river basin.

Finally, it is recommended to promote research and practices that apply hydrological models, as these can be effective tools for understanding and predicting socio-environmental impacts, particularly with respect to extreme events that are becoming increasingly frequent in river basins. For this to be effective, it is necessary for the responsible agencies to improve monitoring and data collection methods.

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ACKNOWLEDGEMENTS

Special thanks to the Coordination for the Improvement of Higher Education Personnel (CAPES) for the financial support.

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RA'EGA, Curitiba, PR, V.60, n.1, p. 159–183, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96597