Calibration of SWAT model in the Pernambuco state watersheds to support the SUPer system

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ABSTRACT
Water governance in Brazil is a major challenge. To cope with this complexity, increasing the monitoring capacity, constituting a solid database, in addition to developing methodologies and technologies for understanding processes at the basin level is essential. The SUPer (Hydrological Response Units System for Pernambuco State, Brazil) was developed through a great partnership between universities and public agencies to support economic and political decisions, based on real-time simulations, and short, medium and long term, with the Soil and Water Assessment Tool (SWAT). For the SUPer system to work effectively, it needs a wider range of calibrated basins, in order to cover the hydrological behavior of the entire state of Pernambuco, including physical, hydrological, relief, and water use characteristics. In this research we build and calibrate an integrated hydrological model of Pernambuco State using the Soil and Water Assessment Tool (SWAT) program, in order to subsidize the SUPer system and make it an active tool for the Pernambuco Water and Climate Agency (APAC), contributing to the process of planning and management of water resources in the state. For that, we selected eight Pernambuco State basins: Brígida, Capibaribe, Goiana, Ipanema, Mundaú, Pajeú, Sirinhaém and Una. Different components of water resources were simulated and reservoir characteristics were considered at the Hydrological Response Unit (HRU) level. The water resources were quantified at subbasin level with monthly time intervals. In addition, SWAT-CUP was used with a semi-automated approach (SUFI2) for sensitivity analysis, and for the calibration and validation procedures. In a general analysis, satisfactory adjustments and statistical performance were observed between the measured and simulated values of streamflow during the calibration and validation processes in most of the basins analyzed, where the Brígida River basin presented the worst performance and the Goiana River basin presented the best performance among the eight analyzed basins. It is important to highlight that the SUPer system is constantly updating and improving hydrological simulations, whether in the calibration of new basins in the Pernambuco State, or in basins that have already been worked on, such as the eight presented in this study. The findings of this study reinforce the importance of hydrological modeling and systems such as SUPer as valuable tools for analysis and governance of water resources at the regional level, capable of assisting in making informed and sustainable decisions.

Keywords: streamflow, watershed, water resources management, SWAT model, SWAT-CUP, SUPer

Calibração do modelo SWAT em bacias hidrográficas do estado de Pernambuco para subsidiar o sistema SUPer

RESUMO
A governança da água no Brasil é um grande desafio. Para lidar com essa complexidade, aumentar a capacidade de monitoramento, constituir um banco de dados sólido, além de desenvolver metodologias e tecnologias para o entendimento dos processos a nível da bacia é fundamental. O SUPer (Sistema de Unidades de Resposta Hidrológica do Estado de Pernambuco, Brasil) foi desenvolvido através de uma grande parceria entre...
universidades e órgãos públicos para apoiar decisões econômicas e políticas, baseadas em simulações em tempo real, e de curto, médio e longo prazos, com a Ferramenta de Avaliação de Solo e Água (SWAT). Para que o sistema SUPer funcione efetivamente, ele precisa de uma grande quantidade de bacias calibradas, de forma a abranger o comportamento hidrológico de todo o estado de Pernambuco, incluindo características físicas, hidrológicas, de relevo e uso da água. Nesta pesquisa, construímos e calibramos um modelo hidrológico integrado do Estado de Pernambuco utilizando o programa Soil and Water Assessment Tool (SWAT), a fim de subsidiar o sistema SUPer e torná-lo uma ferramenta ativa para a Agência Pernambucana de Águas e Clima (APAC), contribuindo para o processo de planejamento e gestão dos recursos hídricos do estado. Para isso, selecionamos oito bacias do Estado de Pernambuco: Goiana, Sirinhaém, Capibaribe, Una, Mundaú, Pajeú e Brígida. Diferentes componentes dos recursos hídricos foram simulados e as características dos reservatórios foram consideradas a nível da Unidade de Resposta Hidrológica (HRU). Os recursos hídricos foram quantificados a nível de sub-bacia com intervalos de tempo mensais. Além disso, o SWAT-CUP foi usado com uma abordagem semiautomática (SUFI2) para análise de sensibilidade e para os procedimentos de calibração e validação. Em uma análise geral, foram observados ajustes e desempenho estatístico satisfatórios entre os valores medidos e simulados de vazão durante os processos de calibração e validação na maioria das bacias analisadas, onde a bacia do Rio Brígida apresentou o pior desempenho e a bacia do Rio Goiana apresentou o melhor desempenho entre as oito bacias analisadas. É importante destacar que o sistema SUPer está em constante atualização e aprimoramento das simulações hidrológicas, seja na calibração de novas bacias no Estado de Pernambuco, seja em bacias já trabalhadas, como as oito apresentadas neste estudo. Os achados deste estudo reforçam a importância da modelagem hidrológica e de sistemas como o SUPer como valiosas ferramentas de análise e governança dos recursos hídricos em nível regional, capazes de auxiliar na tomada de decisões informadas e sustentáveis.

Palavras-chave: vazão, bacia hidrográfica, gestão dos recursos hídricos, modelo SWAT, SWAT-CUP, SUPer

Introduction

The multiple demands for water in Brazil generate conflicts, especially between irrigation, domestic supply and industrial demand. This “water crisis” are caused mainly by intense urbanization, water stress and scarcity in many regions, poor infrastructure in many urban areas, excessive withdrawals of river flows, pollution, eutrophication, salinization, extreme hydrological events, and lack of articulation and consistent actions of governability of water resources. This situation therefore requires a serious and scientifically based water management policy. Thus, it becomes essential to identify the water potential of the regions, expand the availability, make the uses compatible and manage conflicts. In addition, increase the monitoring capacity with the preparation of a database and develop methods, technologies and the production of software suitable to optimize water use and conservation are also important (Braga et al., 1999; Tundisi et al., 2008; Loucks and Beek, 2017).

Concerning the governance of water in Brazil, the National Water Resources Policy - PNRH (BRASIL, 1997) was created with the objective of ensuring the availability of water through rational and integrated management, in order to prevent extreme hydrological events resulting from the inappropriate use of natural resources. In the state of Pernambuco, Northeast of Brazil, the Pernambuco State Water Resources Plan – PERH was created as a fundamental objective to plan the use of water resources for guarantee its quality, availability, conservation and use in a rational manner, in benefit of current and future generations, enabling sustainable development (PERH | PE, 2020). In relation to the water resources management, the Pernambuco state is divided by 29 planning units (UPs), being 13 watersheds, 6 groups of small coastal basins (GL), 9 groups of small inland basins (GI) and the Fernando de Noronha archipelago (PERH | PE, 2020). These UPs are distributed in five mesoregions: Metropolitan Region of Recife, Mata Pernambucana, Agreste, Sertão of São Francisco and Sertão Pernambucano, which give UPs a great variability in climate, land use, soil types, topography, economic activities and multiple uses of water. According to Souza et al. (2018), Metropolitan Region of Recife, and Mata Pernambucana have the largest economic and demographic potential. The Agreste is a transition zone between the humid tropical climate (Mata) and the semiarid climate (Sertão). The Sertão, which is cut in part by the São Francisco basin, has the presence of irrigated agriculture and potential for food production. At the same time, this region has great rainfall irregularity, high rates of evapotranspiration, presence of extreme drought events and intermittent rivers.
In order to understand the hydrological processes that occur in different watersheds with a large heterogeneity, the development of hydrological models has been revolutionary, and these tools have been used by water resource managers for planning and decision making. One model available for the water resources managers is the Soil and Water Assessment Tool (SWAT), a distributed parameter model developed by the United States Department of Agriculture to analyze the impacts of land use changes on discharge, erosion, sedimentation, and water quality in gauged and ungauged watersheds (Arnold et al., 1998). SWAT has been applied for many purposes, as studies analyzing water availability (Andrade et al., 2017a; Viana et al., 2018), sediment yield (Viana et al., 2019), soil moisture dynamics (Andrade et al., 2018; Magalhães et al., 2018), climate change impacts (Oliveira et al., 2017; Andrade et al., 2020), land use change (Andrade et al., 2017b; Fontes Júnior and Montenegro, 2019), and in analyses of uncertainty, sensibility, calibration and validation (Arnold et al., 2012b; Moriasi et al., 2012; Abbaspour et al. 2015; Andrade et al., 2017c; Miranda et al., 2017; Miranda, 2017). Distributed parameter models, like the SWAT, have more accurate representation of the hydrologic system, and associated with Geographic Information System (GIS), have been essential in several academic studies. Although there are several studies and different applications involving the SWAT model, there is still a gap on the application of this model through a single system that can be used by government agencies of Brazil states to understand the dynamics of hydrological processes under different scenarios of land use and climate, and thus make decisions about planning, regulation and management of water resources.

To overcome this gap in the Pernambuco State, Brazil, the SUPer (Hydrological Response Units System for Pernambuco State, Brazil) (http://super.swat.tamu.edu/) was developed, funded by the National Council for Scientific and Technological Development (CNPq), involving a great partnership between the Federal University of Pernambuco (UFPE), Federal Rural University of Pernambuco (UFPRPE), Campina Grande Federal University (UFCG), Technology Institute of Pernambuco (ITEP) and Texas A&M University to support economic and political decisions, based on real-time simulations, and short, medium and long term, with the SWAT model. This system is very similar to HUMUS (Hydrologic Unit Modeling for the United States), that nowadays is called HAWQS (Hydrologic and Water Quality System), and can be applied worldwide. SUPer provides input data for modeling, provides results obtained in watersheds simulations in Pernambuco, and presents modeling projects in development. Such a system substantially increases the usability of the SWAT model to simulate the effects of management practices under different types of crops, soils, vegetation cover, uses and scenarios of climate change in hydrology, water quality and sediment production in watersheds of Pernambuco.

In the partnership, researchers from UFPE and UFRPE were responsible for popularizing SUPer with properly calibrated and validated SWAT projects. For a hydrological model to be representative of real conditions, calibration and validation procedures are essential, and according to Moriasi et al. (2012), are necessary before applying in research and/or real-world simulations. The procedure of hydrological models’ calibration consists in to estimate the model parameter values that offer the best possible hydrological results of interest, by adjustment of these parameters (Almeida et al., 2018; Huang et al., 2020). The validation procedure consists in apply the calibrated model in a different database so that the applicability of the model can be assessed (Pereira et al., 2014; Arnold et al., 2012b).

For the SUPer system to work effectively, it needs a wider range of calibrated basins, in order to cover the hydrological characteristics of the entire state of Pernambuco, including physical, hydrological, relief, and water use characteristics at the level of the ecosystem (watershed).

Therefore, in this research we seek to calibrate and validate different watersheds of Pernambuco state using the Soil and Water Assessment Tool (SWAT) program, in order to subsidize the SUPer system and make it an active tool for the Pernambuco State Water and Climate Agency (APAC), Brazil, contributing to the process of planning and management of water resources in the state. In addition, the SUPer system may represent a “showcase” to be replicated in other Brazilian states.

**Material and Methods**

**Study area**

The study was conducted in eight of thirteen biggest watersheds at the Pernambuco State,
Northeast of Brazil. Pernambuco has an area of 98,149.1 km², with 185 municipalities, including the Fernando de Noronha archipelago. Pernambuco was the first economic nucleus in Brazil, since it excelled in the extraction of Pau-Brazil and was the first part of the country where the sugarcane culture developed effectively. The Captaincy of Pernambuco, the richest captaincy during the sugarcane cycle, reached the position of the largest sugar producer in the world. Pernambuco is the seventh most populous state in Brazil. Its capital, Recife, is home to the most populous urban concentration in the North-Northeast and the fourth most populous in the country.

The State Water Resources Plan (1998) divided the State into 29 Planning Units (UP), thus characterizing the State Hydrographic Division, composed of 13 watersheds, 6 groups of small coastal rivers basins, 9 groups of small interior rivers basins and a small river basin that make up the drainage network of the Fernando de Noronha archipelago. The biggest watershed of Pernambuco has two aspects: The São Francisco River and the Atlantic Ocean. The basins that flow into the São Francisco River form the so-called inland rivers, the main ones being: Pontal, Garças, Brígida, Terra Nova, Pajeú, Moxotó, Ipanema, in addition to groups of small inland rivers. The basins that flow into the Atlantic Ocean, constitute the so-called coastal rivers, and the main ones are: Goiana, Capibaribe, Ipojuca, Sirinhaém, Una and Mundaú and groups of small coastal rivers (Figure 1). Most of the biggest watersheds in Pernambuco are located entirely within the limits of the State, except the basins of the rivers Una, Mundaú, Ipanema and Moxotó, which have part of their drainage area in the State of Alagoas. In addition to these, there are small basins shared with the States of Ceará, Paraíba and Alagoas states. The basins selected for the present study were Brígida and Pajeú (inland rivers); and Goiana, Capibaribe, Sirinhaém, Una and Mundaú (coastal rivers).

The relief of the State is mostly linear, consisting of coastal plain in some points, especially in Recife, reaching, in some areas, to be below sea level. As you go inland, there are peaks that exceed 1,000 meters in altitude, mainly on the Borborema Plateau. It is understood as being part of this “plateau”, the entire sector of highlands, above 200 meters, located north of the São Francisco River, structured in the various crystalline lithotypes, corresponding to the remobilized Archean massifs, Brazilian folding systems and igneous intrusions syn tardi and post-orogenic Neoproterozoic (Corrêa et al., 1998).
al., 2010). It is also possible to observe high-altitude swamp areas outside the Borborema plateau.

Regarding the soils of Pernambuco, those with greater representation stand out, occupying about 61% of the area, belonging to the classes of Argisols (25%), Lithic Neosols (20%) and Planosols (16%). Soils belong to the classes of Oxisols (9%), Luvisols (9%) and Quartzarenic Neosols (5%) occupying about 23% of the State's area. Regolithic Neosols (5%) and Flúvic Neosols (2%) classes represent about 7% of the area. About 4% of the area is occupied by diverse soils, including Cambisols, Gleissolos, Spodosols, Vertisols, Indiscriminate Mangrove Soils, Chernosols, Nitosols and Plinthosols. Terrain types, mainly rock outcrops, occupy a surface around 3% of the area. About 2% of the State's surface corresponds to internal waters (Santos et al., 2018).

The State of Pernambuco is strongly influenced by three rainfall regimes: in the far west, close to Petrolina city, there is the southern regime – frontal systems (SF) and upper air cyclonic vortices (VCAS). A large part of the Sertão, in the courses of the Pajeú and Moxotó rivers, and the eastern Agreste, presents a typical regime of the north of the Northeast – Intertropical Convergence Zone (ITCZ). In the Zona da Mata there is an influence of the northeast trade winds, waves from the east, clusters of cumulonimbus associated with the sea breeze (ACB) and the subtropical high of the North Atlantic (ASAN) and South Atlantic (ASAS). Based on the Köppen-Geiger climate classification, Pernambuco is characterized by two types of climates: the humid tropical predominant on the coast and the semiarid predominant inland, respectively As' and BSh. However, microclimate is observed in swamp points, whose altitude factor favors a characteristic of tropical climate of altitude Cwa, being able to reach minimum temperatures of 10 °C.

Regarding land use/land cover (LULC), according to Brazilian Institute of Geography and Statistics (IBGE), the most abundant type is “natural pasture”, occupying 43.4% of the State of Pernambuco. The following uses, in descending order, are grassland vegetation mosaics, with agricultural areas (38.95%) and agriculture mosaic, with forest remnants (12.89%). Other remaining uses account for only 4.76% of the state's territory. The State is also endowed with a very diversified vegetation, with forests and mangroves, in addition to the great presence of caatinga.

**SWAT model**

The Soil and Water Assessment Tool (SWAT), freely available at (http://swat.tamu.edu/), is a physically based and semi-distributed, continuous-time, long term, hydrological simulation model developed by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research to simulate different physical processes within the study area, such as climate, hydrology (surface runoff, percolation, interception, infiltration, subsurface flow, baseflow and evapotranspiration), soil moisture, plant growth, nutrients, pesticides, bacteria and pathogens, and soil management (Arnold et al., 2012a).

The hydrological cycle in SWAT is based on the water balance equation (Arnold et al. 1998):

\[
SW_t = SW + \sum_{i=1}^{n} (R_i - Q_i - ET_i - P_i - QR_i)
\]

where SW is the soil water content minus the 15-bar water content, t is time in days, and R, Q, ET, P, and QR are the daily amounts of precipitation, surface runoff, evapotranspiration, percolation, and return flow; all units are in mm.

For the hydrological modeling with SWAT, the watershed is previously divided into several sub-basins, which amount depends on the minimum drainage area. Afterwards, the model carries out combinations among the land use, soil types and slope layers, producing the Hydrological Response Units (HRUs). Evapotranspiration estimation, as well as surface runoff, is predicted separately for each HRU, to enable a better physical representation of hydrological processes (Strauch et al., 2012).

**Input data**

The SWAT model requires four main types of input data, including geospatial information about relief, land use and soil type and a tabular series of meteorological data. The spatial data of the relief were obtained from the database of the TOPODATA project of INPE (Brazilian Space Research Institute) (http://www.dsr.inpe.br/topodata/), which provides corrected products from the NASA SRTM mission (Shuttle Radar Topography Mission), which aims to map the topography of the Earth's surface. The data of this model is in image format, whose pixels have a spatial resolution of 30 m, and altitude values (m). The land use data were obtained in a map format with a 1: 100,000 scale from the IBGE (https://downloads.ibge.gov.br/) for the year 2014.

The spatial data of the soil classification were obtained through three databases, (1) IBGE, which provides data in map format with scale 1: 250,000, on the website https://downloads.ibge.gov.br/; (2) FAO / UNESCO, which has a global mapping with a spatial resolution of 1: 5,000,000; and (3) Brazilian Agricultural Research Corporation (EMBRAPA), which has data from the Agroecological Zoning of the State of Pernambuco (ZAPE) project, with a resolution of 1: 100,000. In addition, georeferenced data regarding the physical-chemical characteristics (i.e. initial parameters) of each type of soil were obtained through a partnership with EMBRAPA researchers: maximum soil depth (SOL_ZMX; mm), clay (<0.002 mm; SOL_CLAY; %), silt (>0.002 and <0.05 mm; SOL_SILT; %), sand (> 0.05 and <2 mm; SOL_SAND; %), stone (> 2 mm; SOL_ROCK; %), and organic carbon (SOL_CBN; %). The distribution map of slope classes, soils, and land use is presented in the Figure 2.

Figure 2. Distribution map of slope classes, soils, and land use of the Pernambuco State basins

The climatic data for the series from 1961 to 2016 were obtained through two databases, (i) daily rainfall data (i.e., precipitation) through the APAC website, and then (ii) complete meteorological data (precipitation, global radiation, relative air humidity or dew point temperature, average air temperature, maximum and minimum air temperatures, and wind speed) through the National Institute of Meteorology (INMET); http://www.inmet.gov.br/projetos/rede/pesquisa/inic. Additionally, 109 reservoirs were filtered based on the availability of the following data, obtained through the APAC website: volume and area of the water depth in the main and emergency spillways, and year of construction; resulting in 44 reservoirs distributed in 12 of the 13 basins of Pernambuco. The distribution map of rainfall gauges, reservoirs, climate and streamflow stations are presented in the Figure 3.

Figure 3. Distribution map of rainfall gauges, reservoirs, climate and streamflow stations

Calibration and validation procedures

The calibration procedure of SWAT model was performed in the SWAT Calibration and Uncertainty Programs (SWAT-CUP). The SWAT-CUP is an independent software developed for sensitivity analyses, calibration and validation, and uncertainty analyses based on SWAT simulations. The program comprises 5 calibration procedures (i.e., SUFI2, GLUE, ParaSol, MCMC, and PSO), 11

goal functions (e.g., $R^2$, NS, PBIAS) and includes applications such as visualization of the study area (Abbaspour et al., 2018). In this study, the calibration procedure was performed in the SWAT-CUP using the Sequential Uncertainty Fitting algorithm (SUFI-2). Additionally, the Nash–Sutcliffe model efficiency (NS) coefficient was used as goal function.

SUFI-2 is an algorithm that reads all parameters of the SWAT model and the amplitude of their values, verifying that the flow data are inserted in 95% of uncertainty compared to the initial values. The degree to which all uncertainties are accounted for is quantified by measures referred to by the p-factor and r-factor (Abbaspour, 2015). The p-factor and the r-factor assess the reliability of the adjustment and the degree of efficiency of the calibrated model for uncertainties, in which the p-factor varies between 0 and 100% and the r-factor between 0 and infinity. A p-factor of 100% and an r-factor of 0 indicate a simulation that corresponds exactly to the measured data, and the distances represented by them are used to evaluate the effectiveness of the calibration. Andrade et al. (2018) analyzed the uncertainties of the hydrological simulation performed by SWAT, taking as threshold values p-factor above 70% and r-factor close to 1, for the flow variable.

According to Arnold et al. (2012b), it is recommended to allocate between 2 and 3 years of the total series used in the simulation to warm-up the model. Furthermore, the total series, as well as the subdivision of periods for calibration and validation, must consider all the hydrological characteristics of the basin, that is, consider normal, wet and dry periods in the studied area. In the present study, considering that the data series is between the period of 1961 and 2016 (i.e., 55 years of flow data, being sufficiently long), the first 5 years was destined for warm-up the SWAT model. The monthly flow data were downloaded from the website http://hidroweb.ana.gov.br/, hydrological database of ANA (National Water and Basic Sanitation Agency of Brazil).

To evaluate the calibration and validation performance, we used the determination coefficient ($R^2$), the Nash–Sutcliffe model efficiency (NS) and the percent bias (PBIAS) (Table 1). The NS varies between negative infinite and 1 (the optimal value). Values between 0 and 1 are generally regarded as acceptable performance levels and values < 0 indicate that it is better to use the mean observed data than the predicted value of the model (Nash and Sutcliffe, 1970). In relation to PBIAS, its optimal value is 0, with low magnitudes indicating good precision in the model simulation. Positive values indicate underestimation by the model and negative values indicate overestimation (Gupta et al., 1999).

Table 1 - Objective functions used to evaluate model performance for flow simulation

<table>
<thead>
<tr>
<th>Objective function</th>
<th>Unit</th>
<th>Equation</th>
<th>Perfect value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Percent Bias</td>
<td>%</td>
<td>$PBIAS = \frac{\sum_{i=1}^{n}(Q^{obs} - Q^{sim})^2}{\sum_{i=1}^{n}(Q^{obs})^2} \times 100$</td>
<td>0</td>
</tr>
<tr>
<td>(2) Nash-Sutcliffe</td>
<td></td>
<td>$NS = 1 - \left( \frac{\sum_{i=1}^{n}(Q^{obs} - Q^{sim})^2}{\sum_{i=1}^{n}(Q^{obs} - Q^{obs})^2} \right) \times 100$</td>
<td>1</td>
</tr>
<tr>
<td>(3) Coeficiente de</td>
<td></td>
<td>$R^2 = \left( \frac{\sum_{i=1}^{n}(Y_i - Y_m) \times (X_i - X_m)}{\sum_{i=1}^{n}(Y_i - Y_m)^2 \times (X_i - X_m)^2} \right)^2$</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: $Q^{obs}$ is the observed flow, $Q^{sim}$ is the average observed flow, $Q^{sim}$ is the simulated flow and $n$ is the total number of observations; $X_i$ the observed values and $X_m$ the mean of these values, $Y_i$ the values calculated by the model and $Y_m$ its mean.

Table 2 presents the recommended performance evaluation criteria for hydrological models, considering the flow component and the monthly time scale and also considering in general terms the component and time scale, in the calibration and validation process, according to

In this study, the statistical evaluation rating criteria used are based on Moriasi et al. (2015).

Table 2. Recommended performance evaluation criteria for hydrological models, considering the flow component and the monthly time scale in the calibration and validation processes

<table>
<thead>
<tr>
<th>Statistical parameter</th>
<th>Component</th>
<th>Very good</th>
<th>Good</th>
<th>Satisfactory</th>
<th>Unsatisfactory</th>
</tr>
</thead>
<tbody>
<tr>
<td>R²</td>
<td>Streamflow (monthly)</td>
<td>&gt; 0.85</td>
<td>0.80 ≤ R² ≤ 0.85</td>
<td>0.70 ≤ R² ≤ 0.80</td>
<td>≤ 0.70</td>
</tr>
<tr>
<td></td>
<td>General</td>
<td>&gt; 0.80</td>
<td>0.70 ≤ R² ≤ 0.80</td>
<td>0.50 ≤ R² ≤ 0.70</td>
<td>≤ 0.50</td>
</tr>
<tr>
<td>NS</td>
<td>Streamflow (monthly)</td>
<td>&gt; 0.85</td>
<td>0.70 ≤ NS ≤ 0.85</td>
<td>0.55 ≤ NS ≤ 0.70</td>
<td>≤ 0.55</td>
</tr>
<tr>
<td></td>
<td>General</td>
<td>&gt; 0.80</td>
<td>0.60 ≤ NS ≤ 0.80</td>
<td>0.50 ≤ NS ≤ 0.60</td>
<td>≤ 0.50</td>
</tr>
<tr>
<td>PBIAS (%)</td>
<td>Streamflow (monthly)</td>
<td>≤± 3</td>
<td>±3 &lt; PBIAS &lt; ±10</td>
<td>±10 &lt; PBIAS &lt; ±15</td>
<td>≥±15</td>
</tr>
<tr>
<td></td>
<td>General</td>
<td>≤± 5</td>
<td>±5 &lt; PBIAS &lt; ±10</td>
<td>±10 &lt; PBIAS ≤ ±25</td>
<td>≥±25</td>
</tr>
</tbody>
</table>

Regarding the division of the monthly flow historical series for the different basins, the split-sample test was used. The split-sample test is a model calibration and validation approach that consists on equally splitting the available data, when the record is sufficiently long to represent different climate conditions (Her and Chaubey, 2015; Klemes, 1986). However, when the amount of data available is not sufficient for 50/50 splitting, these should be split into two different forms, e.g., 70/30 and/or 30/70, so that the calibration interval is sufficiently far away. For this research, the 70/30 calibration and validation method were used. Although in the present study the series is sufficiently long, the choice of the 70/30 division was due to the fact that there is great rainfall variability in the state of Pernambuco. According to Lopes et al. (2017), maximum and minimum extreme events in the backlands, countryside and coast of the state occurred throughout this period, and while in the countryside and on the coast the maximum and minimum extreme events, respectively, marked the years 2010 and 2016 (countryside); and 2004 and 1998 (coastal), in the backlands, these events occurred in 1985 and 1993, respectively. Therefore, seeking to obtain greater representation of extreme years during the calibration process, 70% of the data were used in this stage. It is worth noting that for each basin, the period used in calibration and validation varied (between 1961 and 2016), since the series of observed data often presented missing or inconsistent data. Further details of the calibration procedure for each basin analyzed in the present study will be given below.

The calibration process in the Mundaú River basin took place in a monthly time step, considering flow data (m³/s) from the year 1990 to the year 2016. Among the parameters tested during the calibration process in this basin, 16 were selected for the process, since initial tests (i.e., an iteration with around 50 simulations) pointed to satisfactory results. Once the parameters were defined, the SWAT model was calibrated and validated, considering 70% of the data for calibration (1990-2008) and 30% (2009-2016) of the data for validation. The calibration process involved 4 iterations with 500 simulations each, totaling 2,000 simulations. The validation process considered only 1 iteration with 500 simulations (with the parameter ranges obtained in the last calibration iteration). In this basin, 4 fluviometric stations were calibrated (multi-site calibration). For the station presented in this study, the calibration period, that is, 70% of the data used, comprised the year 1990 until 2008; while the 30% allocated to the validation period consisted of 2009 until 2016.

For the Capibaribe River basin, the calibration process was carried out considering nine fluviometric stations. The monthly flow series presented different observation periods between the stations, covering, in general, the period between the years 1966 and 2016. Due to the heterogeneity of this region (e.g., topography, vegetation and soils) and, consequently, the difficulty to obtain satisfactory results during the first simulations, the basin was divided into areas contributing to the main reservoirs. Therefore, four regions were considered in the basin calibration and validation stage. The regions were

composed of the set of sub-basins located upstream of each reservoir, including Poço Fundo (7 sub-basins), Jucázinho (19 sub-basins), Carpina (13 sub-basins) and another region in the east of the basin, where the Tapacurá and Goitá reservoirs are located (13 subbasins). In the simulations, around 12 parameters were adopted in each contribution area. The number of data series resulting from the calibration and validation processes differed between stations. At the station presented in this study, for example, the calibration period, which covers 70% of the data, corresponded to the years 1974 to 1994, while validation comprised the period between 1995 and 2007.

For the Ipanema River basin, the model was calibrated and validated at two fluvimetric stations, using monthly flow data (m³/s) from 1977 to 2016. In this context, a set of 12 parameters was used during the calibration process. As observed in previously mentioned river basins, in order to standardize the calibrations, the procedure involved four iterations, each comprising 500 simulations, totaling 2,000 simulations. The validation stage, in turn, included a single iteration with 500 simulations, using the parameter ranges obtained in the last calibration iteration. It is important to highlight that, despite the presence of two fluvimetric stations in the Ipanema River basin, this study focuses on presenting calibration and validation results for only one of these stations. The data distribution for these phases was established at 70% for calibration (1977-2004) and 30% for validation (2005-2014).

The calibration process in the Sirinhaém River basin also occurred in a monthly time step, considering flow data (m³/s) from the year 1989 to the year 2016. A total of 12 parameters were used to verify good fits between the data observed and simulated by the model. The calibration process involved 4 iterations with 500 simulations each, totaling 2,000 simulations. The validation process considered only 1 iteration with 500 simulations (with the parameter ranges obtained in the last calibration iteration). In this basin, 3 fluvimetric stations were calibrated (multi-site calibration). For the station presented in this study, the calibration period, that is, 70% of the data used, comprised the year 1989 until 2008; while the 30% allocated to the validation period consisted of 2009 until 2016.

Calibration in the Pajeú River basin occurred in a monthly time step, considering flow data (m³/s) from five fluvimetric stations. However, for this research only one will be presented. Each station covered different calibration and validation periods, covering the period from 1966 to 2016. Calibration corresponded to the period from 1967 to 2000 and validation from 2001 to 2016, considering 70% of the data for calibration and 30% for validation. Due to the heterogeneity of the basin, 19 parameters were initially tested for subsequent application of the aforementioned processes. After testing, 10 parameters were defined for basin calibration. For this, 4 iterations were adopted with 500 simulations each, making a total of 2,000 simulations. As in the other basins, only one iteration of 500 was considered for validation, with fixed intervals from the last calibration.

To carry out the calibration process of the Una River basin, flow data (m³/s) from five fluvimetric stations on a monthly scale were considered. The data series presented different temporal scales between the stations, comprising data observed in the period between 1967 and 2016. Similar to what was carried out in the calibration of the Capibaribe river basin, the Una River basin was divided into 2 regions different settings for calibration. These regions correspond to the areas upstream (15 sub-basins) and downstream (33 sub-basins) of the Prata reservoir. In this process, 10 parameters were calibrated. For the station presented in this study, observing the methodology of using 70% of the data series for calibration and 30% for validation, the calibrated data relates to the years 1989 to 2008, and the validated period was from 2009 to 2016. The number of iterations and simulations applied in the calibration and validation processes were the same as those used in the other basins included in this study.

SUPer system and water resources management

The Hydrological Response Units System for Pernambuco – SUPer – is an interactive hydrological and water quality modeling platform that uses the Soil and Water Assessment Tool (SWAT) as a modeling engine to carry out assessments and simulations at the watershed level to the State of Pernambuco, under different land use/land cover and climate change scenarios.

The main purpose of SUPer is to serve not only academic research linked to the subject, but also to serve as a management tool and decision support for water resources in the State of Pernambuco, through the Pernambuco Water and Climate Agency (APAC), taking based on Law 9,433, of January 8, 1997, which governs the instruments of the National...
Water Resources Policy, whose vision is to ensure good quality water for current and future generations. The Pernambuco Water and Climate Agency (APAC) has currently been using the SUPer to obtain the water balance of the state's watersheds, with the aim of monitoring and managing the hydro-environmental plans of the basins. However, the agency also intends to use the tool as a management tool for water allocation.

With regard to its operation, SUPer allows users to create their projects, based on the basins available for the State of Pernambuco, for different temporal and spatial scales, offering an interactive web interface, maps, pre-entry data -uploaded, user guide and results comprising tables, graphs and output data. In addition, it allows users to develop, execute and store their projects online. It also generates simulations, through SWAT, of the effects of management practices based on crop varieties, soils, natural vegetation types, land use/land cover and climate change scenarios for hydrology and water quality parameters (sediments, pathogens, nutrients, biological oxygen demand, dissolved oxygen, pesticides and water temperature). More details about this system can be found at https://super.hawqs.tamu.edu/#/

Results and Discussion

Parameters used in the calibration and validation processes

Table 3 shows the parameters adopted in the calibration and validation processes for each watershed, as well as methods, adjustment values and minimum and maximum values. The parameters used as a basis for the calibration process were determined from the researchers' knowledge of the area of each basin and from literature (Abbaspour et al., 2015; Andrade et al., 2018; Carvalho Neto, 2018; Fernandes, 2015; Miranda et al., 2018; Paz et al., 2018; Santos et al., 2015; Srinivasan et al., 2010).

Of the twenty parameters considered most relevant for the calibration of the streamflow of the surveyed basins, eight are related to the hydrological response units (hrus) and five to the shallow and deep aquifers (gw), which influence the base flow; four to the physical characteristics of the soil, which influences the generation of surface runoff together with CN2; and two related to the effective hydraulic conductivity of the channel and the Manning coefficient for the main channel (rte). More details and definition of the parameters adopted in this research can be found in Abbaspour et al. (2015).

It is important to highlight that due to the uniqueness of each river basin, not all parameters used in this research were common to all basins, except for CN2 and SOL_AWC, which are present in all of them, which may be an indication that these parameters have a strong influence on the hydrological processes of the basins in the state of Pernambuco. SLSUBBSN and SOL_BD were used only in the Capibaribe and Sirinhaém basins, respectively. Additionally, the parameters HRU_SLP, OV_N and LAT_TTIME were only adopted in the calibration of the Mundaú River basin.

Simões et al. (2022) applied the SWAT model in flow and solid discharge simulation of the Indaia River Basin, Alto São Francisco, Minas Gerais and found that the five parameters (of the 26 analyzed) that most influenced the flow estimate results were GW_REVAP, SOL_K, GWQMN, SHALLST, and CN2. With the exception of SHALLST, all four parameters considered sensitive by the authors were also used in the present study, and such parameters were present either in all eight watersheds analyzed or at least in six of them.

Table 3. Parameters used in model calibration for different watersheds, intervals and alteration methods employed

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Standard range</th>
<th>Brigida</th>
<th>Capibaribe</th>
<th>Goiana</th>
<th>Ipanema</th>
<th>Mundaú</th>
<th>Pajeú</th>
<th>Sirinhaém</th>
<th>Una</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:R_CN2.mgt</td>
<td>Initial SCS runoff curve number for moisture condition II.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:V_ALPHA_BF.gw</td>
<td>Baseflow alpha factor (1/days).</td>
<td>0</td>
<td>0.85</td>
<td>0.37</td>
<td>0.11</td>
<td>0.3</td>
<td>0.38</td>
<td>0.48</td>
<td>0.69</td>
<td>0.06</td>
</tr>
<tr>
<td>3:V_ESCO.hru</td>
<td>Soil evaporation compensation factor.</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>0.6</td>
<td>0.27</td>
<td>-</td>
<td>0.25</td>
<td>-</td>
<td>0.44</td>
</tr>
<tr>
<td>4:V_EPCO.hru</td>
<td>Plant uptake compensation factor.</td>
<td>0.25</td>
<td>1</td>
<td>-</td>
<td>0.56</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.26</td>
</tr>
<tr>
<td>5:V_CANMX.hru</td>
<td>Maximum canopy storage (mm H₂O).</td>
<td>20</td>
<td>70</td>
<td>-</td>
<td>48.35</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20.15</td>
</tr>
<tr>
<td>6:R_SOL_AWC(..).sol</td>
<td>Available water capacity of the soil layer (mm H₂O/ mm soil).</td>
<td>-0.25</td>
<td>2.5</td>
<td>0.19</td>
<td>0.15</td>
<td>0.42</td>
<td>0.71</td>
<td>0.42</td>
<td>2.24</td>
<td>0.45</td>
</tr>
<tr>
<td>7:R_SOL_K(..).sol</td>
<td>Saturated hydraulic conductivity (mm/h).</td>
<td>-2.43</td>
<td>0.7</td>
<td>-</td>
<td>0.18</td>
<td>-0.29</td>
<td>-0.98</td>
<td>-0.74</td>
<td>0.01</td>
<td>-2.43</td>
</tr>
<tr>
<td>8:R_SOL_Z(..).sol</td>
<td>Depth from soil surface to bottom of layer (mm).</td>
<td>-0.93</td>
<td>1.16</td>
<td>-</td>
<td>0.06</td>
<td>1.02</td>
<td>0.24</td>
<td>0.26</td>
<td>0.17</td>
<td>-0.88</td>
</tr>
<tr>
<td>9:R_SOL_BD(..).sol</td>
<td>Moist bulk density (Mg/m³ or g/cm³).</td>
<td>-0.12</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.01</td>
<td>-</td>
</tr>
<tr>
<td>10:V_GW_DELAY.gw</td>
<td>Groundwater delay time (days). Threshold depth of water in the shallow aquifer required for return flow to occur (mm H₂O).</td>
<td>0</td>
<td>500</td>
<td>6.78</td>
<td>5.1</td>
<td>83.79</td>
<td>-</td>
<td>103</td>
<td>92.32</td>
<td>491.53</td>
</tr>
<tr>
<td>11:V_GWQMN.gw</td>
<td>Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm H₂O).</td>
<td>573.2</td>
<td>4500</td>
<td>3675</td>
<td>-</td>
<td>3682.27</td>
<td>3484.83</td>
<td>934.44</td>
<td>2431.57</td>
<td>621.94</td>
</tr>
<tr>
<td>12:V_REVAPMN.gw</td>
<td>Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm H₂O).</td>
<td>280.93</td>
<td>500</td>
<td>-</td>
<td>-</td>
<td>321.16</td>
<td>-</td>
<td>47.7</td>
<td>399.75</td>
<td>-</td>
</tr>
<tr>
<td>ID</td>
<td>Description</td>
<td>Units</td>
<td>Value 1</td>
<td>Value 2</td>
<td>Value 3</td>
<td>Value 4</td>
<td>Value 5</td>
<td>Value 6</td>
<td>Value 7</td>
<td>Value 8</td>
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<tr>
<td>----------</td>
<td>------------------------------------------------------------------------------</td>
<td>-------</td>
<td>---------</td>
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<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>13:V_GW_REVAP.gw</td>
<td>Groundwater “revap” coefficient.</td>
<td></td>
<td>0.02</td>
<td>0.2</td>
<td>-</td>
<td>0.18</td>
<td>0.16</td>
<td>0.07</td>
<td>1482.91</td>
<td>0.38</td>
</tr>
<tr>
<td>14:V_CH_N2.rte</td>
<td>Manning’s “n” value for the main channel.</td>
<td></td>
<td>0</td>
<td>0.3</td>
<td>-</td>
<td>0.16</td>
<td>0.08</td>
<td>0.32</td>
<td>0.22</td>
<td>0.1</td>
</tr>
<tr>
<td>15:V_CH_K2.rte</td>
<td>Effective hydraulic conductivity in main channel alluvium (mm/h).</td>
<td></td>
<td>25.2</td>
<td>160.68</td>
<td>-</td>
<td>28.84</td>
<td>-</td>
<td>0.02</td>
<td>-</td>
<td>159.05</td>
</tr>
<tr>
<td>16:V_SURLAG.hru</td>
<td>Surface runoff lag coefficient.</td>
<td></td>
<td>0.05</td>
<td>24</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>17:V_SLSUBBSN.hru</td>
<td>Average slope length (m).</td>
<td></td>
<td>10</td>
<td>150</td>
<td>-</td>
<td>73.42</td>
<td>-</td>
<td>-</td>
<td>0.16</td>
<td>-</td>
</tr>
<tr>
<td>18: R__HRU_SLP.hru</td>
<td>Average slope steepness.</td>
<td></td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.07</td>
<td>-</td>
</tr>
<tr>
<td>19: R__OV_N.hru</td>
<td>Manning's &quot;n&quot; value for overland flow.</td>
<td></td>
<td>0.01</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>20 a__CANMX.hru</td>
<td>Plant interception</td>
<td></td>
<td>-</td>
<td>-</td>
<td>1.59</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>21: V__LAT_TTIME.hru</td>
<td>Lateral flow travel time</td>
<td></td>
<td>0</td>
<td>180</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.03</td>
<td>-</td>
</tr>
</tbody>
</table>

*AV: adjustment value; R: Relative; V: Replace*
Calibration and validation analyses

Comparison between simulated and observed hydrographs is an important procedure to verify model calibration results (Blainski et al., 2017). The Figure 4 presents the hydrographs observed and simulated by the SWAT model for the calibration and validation phases for the eight basins analyzed (Brígida, Capibaribe, Goiana, Ipanema, Mundaú, Pajeú, Sirinhaém and Una) in the monthly time intervals. For both stages, satisfactory adjustments were observed between the measured and simulated values in the eight basins, except for some flow peaks, observed in Capibaribe, Ipanema, Una, Mundaú and Pajeú basins, in which the model was not able to represent the highest measured values well in comparison to the rest of the series. In the Capibaribe, in 1985 (calibration) and in 2003 (validation), the peaks were not well represented (e.g., the model underestimates the streamflow in almost 60% in April 1985 when compared to the observed data of the same date). The same can be observed in the calibration and validation of the Una River basin, between 2004 and 2005, 2009 and 2011, respectively. In the Ipanema, Mundaú and Pajeú basins these underestimations are also observed, both in calibration and validation, however in a few months of the historical series. According to Silva and Medeiros (2014), these differences must be associated with the difficulty of simulation or uncertainties of the input data.

Overall, comparisons between simulated and observed discharge values in the eight surveyed basins were considered good. The recession periods were well simulated by the SWAT model, under all proposed conditions, confirming the adequate representation and applicability of the SWAT model for the study regions. According to Andrade et al. (2013), the SWAT model fitting during the recession periods, both in calibration and validation periods, indicates good model performance in simulating low flows. In general, good calibrations and validations are achieved when the data series used to calibrate and validate the model included both dry and wet years within the region. In addition, good correspondence between other model outputs and measured data (soil moisture, evapotranspiration, etc.) might increase confidence in model calibration (Arnold et al., 2012b; Zhang et al., 2015; Andrade et al., 2018).

The streamflow calibration performed by Farias et al. (2023) in the São Francisco River basin, corroborate the results found in this research, with satisfactory results, despite the heterogeneity of the basin, its different uses, soil types and different climatic conditions. The statistics analyzed at three different fluviometric stations of the São Francisco River basin had R² ranging from 0.60 to 0.70, NS 0.55 to 0.69 and PBIAS from -8.2 to -16.1%.

Table 4 shows the results of the model's performance in simulating the streamflows of the eight SUnPer basins in the calibration and validation processes, as well as the uncertainties. With regard to the p_factor and r_factor values for the basins in the calibration, the results indicate some uncertainties, especially in the Brígida and Una basins. The values of R² and NS are considered good and satisfactory in practically all basins, except for Brígida, whose R² was 0.47 and NS was 0.45, values considered unsatisfactory, according to the recommendation of Moriasi et al. (2015). The PBIAS values for almost all basins indicated satisfactory results, with values between ±25%, with the exception of the Pajeú River basin in the validation period, which presented a PBIAS of -64.9% (overestimating the observed data).

Alves et al. (2021) used reanalysis meteorological data for streamflow simulation in the Ribeirão do Pinhal River Basin, São Paulo State, Brazil, and found satisfactory statistics in the calibration with SWAT, with NS of 0.51 and PBIAS of -7%. However, the authors also verified overestimations of the flow data simulated by the model, according to the PBIAS value. In the validation, the greatest uncertainties were pointed out in the estimates of the Brígida basin, when analyzing the r_factor value (3.55). The results of R² and NS in validation had a greater variation than in calibration, indicating unsatisfactory estimates for the Brígida and Una basins, with values below 0.50. However, for the Ipanema and Mundaú basins, the NS was also below 0.50, being 0.49 for both basins. The results found by Andrade et al. (2018) in the Mundaú River basin, with a database different from that of the SUnPer project, showed satisfactory values in the annual calibration of the streamflow with the SWAT model, with NS ranging from 0.71 to 0.92 and between 0.55 and 0.78 in intervals of monthly time. In validation, NS values ranged from 0.53 to 0.76 in both time intervals.
Figure 4. Monthly hydrograph with data observed and simulated by the SWAT model for the calibration and validation phases for the eight basins analyzed (Brígida, Capibaribe, Goiana, Ipanema Mundaú, Pajeú, Sirinhaém and Una) in the State of Pernambuco.
Table 4. Result of the statistical performance of the SWAT model in estimating the streamflow (calibration and validation) for the SUPER basins

<table>
<thead>
<tr>
<th>Watersheds</th>
<th>Objective functions for calibration</th>
<th>p-factor</th>
<th>r-factor</th>
<th>r²</th>
<th>NS</th>
<th>PBIAS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brigida</td>
<td>Calibration</td>
<td>0.29</td>
<td>3.55</td>
<td>0.71</td>
<td>0.61</td>
<td>-3.3</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.01</td>
<td>0.01</td>
<td>0.44</td>
<td>0.59</td>
<td>-29.7</td>
</tr>
<tr>
<td>Capibaribe</td>
<td>Calibration</td>
<td>0.09</td>
<td>0.05</td>
<td>0.71</td>
<td>0.66</td>
<td>-19.5</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.09</td>
<td>0.06</td>
<td>0.62</td>
<td>0.55</td>
<td>2.5</td>
</tr>
<tr>
<td>Goiana</td>
<td>Calibration</td>
<td>0.77</td>
<td>2.35</td>
<td>0.55</td>
<td>0.40</td>
<td>24.3</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.14</td>
<td>0.06</td>
<td>0.96</td>
<td>0.82</td>
<td>6.6</td>
</tr>
<tr>
<td>Ipanema</td>
<td>Calibration</td>
<td>0.69</td>
<td>0.58</td>
<td>0.76</td>
<td>0.76</td>
<td>-2.3</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.61</td>
<td>0.82</td>
<td>0.50</td>
<td>0.49</td>
<td>9.2</td>
</tr>
<tr>
<td>Mundaú</td>
<td>Calibration</td>
<td>0.44</td>
<td>0.42</td>
<td>0.75</td>
<td>0.64</td>
<td>31.2</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.60</td>
<td>1.02</td>
<td>0.65</td>
<td>0.64</td>
<td>5.8</td>
</tr>
<tr>
<td>Pajeú</td>
<td>Calibration</td>
<td>0.19</td>
<td>0.23</td>
<td>0.82</td>
<td>0.68</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.07</td>
<td>0.40</td>
<td>0.71</td>
<td>0.64</td>
<td>-64.9</td>
</tr>
<tr>
<td>Sirinhaém</td>
<td>Calibration</td>
<td>0.69</td>
<td>0.95</td>
<td>0.66</td>
<td>0.62</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.60</td>
<td>0.82</td>
<td>0.68</td>
<td>0.67</td>
<td>-5.7</td>
</tr>
<tr>
<td>Una</td>
<td>Calibration</td>
<td>0.19</td>
<td>0.01</td>
<td>0.71</td>
<td>0.70</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.19</td>
<td>0.02</td>
<td>0.52</td>
<td>0.50</td>
<td>-7.6</td>
</tr>
</tbody>
</table>

The results found by Viana et al. (2021) with monthly satellite data and observed data showed good adjustments between estimated and measured flows, with satisfactory R², NS and PBIAS, both in the calibration and validation of a watershed in the Metropolitan Region of Recife, Brazil. The authors found that the results with measured data were better than those obtained by satellite, however they highlighted the importance of using data from satellite to subsidize areas with scarce rainfall data, considering the advances in remote sensing with environmental satellites. The research carried out by Santos et al. (2021) in the Tapacurá River basin, Northeastern Brazil, also showed good results for NS, R² and PBIAS in the calibration and validation of streamflow for the study area. The authors analyzed the effects of future changes in land use and climate in the basin on streamflow and sediment production. Estimates showed an increase in streamflow in some of the analyzed scenarios, as well as an increase in sediment production, which could have serious implications for the local reservoir, reducing water storage and causing siltation.

In a general analysis, it is noticed that both the calibration and the validation, presented from satisfactory to very good statistical performance in most of the basins analyzed, with values consistent with the literature. The basins that performed below the recommended level (e.g., Brigida River basin) presented values close to these, being subject to future adjustments. In this context, it is important to highlight that the SUPer system is constantly updating and improving hydrological simulations, whether in basins that have already been worked on, such as the eight presented in this study, or in new basins in the Pernambuco State, such as, for example, the Ipojuca River basin, where Silva et al. (2023) used the SUPer platform to evaluate four different runoff generation scenarios under precipitation modifications.

Luz et al. (2023) also used the SUPer platform in their research, with the aim of verifying the effect of the hydrological cycle on the quality of vegetation, and how the hydrological system can affect society, as well as helping to reduce water inequalities. Furthermore, the authors also evaluated how climate change can affect environmental changes and quality of life on a local scale. Galvício (2021) used the SUPer system to obtain the water balance of basins in Pernambuco and, subsequently, raise a joint discussion with an assessment of the impacts that atmospheric CO₂ can have on precipitation in the state of Pernambuco. The research carried out by Tibúrcio et al. (2023) sought to analyze climate change scenarios and their impacts in a small river basin in the semiarid region of Pernambuco.
Pernambuco. To this end, the authors used SUPer to carry out scenario simulations, which showed a significant reduction in water availability in the basin, with a reduction in base flow and an increase in loss through evapotranspiration in all scenarios analyzed.

Thus, it is understood that the development of the SUPer platform, based on the calibrations carried out in the present study, represents a major advance for hydrosedimentological studies with SWAT, since the basins calibrated in this system can support scenario analyses, as presented in the first studies mentioned above. Furthermore, the creation of the SUPer system represented the starting point for the development of another system in Brazil, called the Brazilian Ecohydrological Simulation Tool (BEST), with a similar objective to SUPer, but covering the entire Brazilian territory, based on an effort national team of researchers and government agencies to help calibrate Brazilian watersheds.

Conclusions

The results obtained in the calibration and validation of the streamflow of the eight basins analyzed in this study were considered good and satisfactory, in view of the heterogeneity of each basin and the large amount of data involved in carrying out the hydrological modeling of part of the basins in the Pernambuco State.

Regarding the parameterization of the SWAT model, the analyzed watersheds presented different sets of parameters, which corroborates the singularities of each region, with different climate, relief, soil type, land use and cover, and other physiographic characteristics. Still, even for equal parameters in different watersheds, with the same minimum and maximum interval adopted, the adjustment values were different for each one of them, evidencing the space-time heterogeneity.

The analyzed hydrographs well represented the streamflow variability in the basins, both in calibration and validation. The greatest uncertainties were pointed out in the modeling of the Una, Capibaribe and Brígida watersheds, which presented a shorter series within the period analyzed.

Although some statistical indices were not satisfactory in some basins, whether in calibration or validation (e.g., Brígida River basin), most basins presented indices ranging from satisfactory to very good, where Goiana River basin presented the best performance among the eight analyzed basins. It is important to highlight that the SUPer system is constantly updating and improving hydrological simulations, whether in the calibration of new basins in the Pernambuco State, or in basins that have already been worked on, such as the eight presented in this study (i.e., the basins that performed below the recommended statistical level are subject to future adjustments).

Finally, the findings of this study reinforce the importance of hydrological modeling and systems such as SUPer as valuable tools for analysis and governance of water resources at the regional level, capable of assisting in making informed and sustainable decisions. Additionally, the possibility of expanding the SUPer platform to other states in Brazil is being studied, based on the experience already implemented in Pernambuco and in the United States of America.

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