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Hydrosedimentological modeling in a headwater basin in Southeast Brazil

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ABSTRACT: Hydrosedimentological modeling is a useful tool to predict the water dynamic in a basin and for water resources management. This study aimed to i) evaluate the ability of Soil and Water Assessment Tool (SWAT) to model sediment load and continuous monthly streamflow in the Mortes River Basin (MRB) in Southeastern Brazil; ii) estimate the sediment yield spatially distributed by sub-basins; iii) estimate the sediment load export to the Funil Hydroelectric Power Plant reservoir (FHPP), located in the MRB outlet. For the sensitivity analysis, calibration, and uncertainty analysis of the model, a semi-automatic calibration in SWAT-CUP version 5.1.6 software with the "Sequential Uncertainty Fitting" algorithm was used. To evaluate the ability of SWAT to reproduce the continuous MRB monthly streamflow and sediment load, statistical indexes, and graphical analyses were used to compare the simulated and observed data. For the sediment evaluation, a spatial and temporal comparison of sediment yield maps was used as well as the sediment yield observed in sub-basins, aiming to identify the areas with a more significant contribution to the sediment generation in the basin. The results demonstrated that SWAT performed satisfactorily in simulating both monthly sediment load and streamflow. For discharge calibration, 99 % of the measured data were bracketed by the 95 % prediction uncertainty (95PPU), and for validation, 97 % of the data were bracketed by the 95PPU, which indicates proper bracketing of the measured data within model prediction uncertainty. Uncertainty analysis indicated that 95PPU could capture 78 % of the sediment loads measured during the calibration and 72 % of the measured data during the validation period at MRB. The hydrologic response unit with pasture and *Argissolos* (Ultisols), *Neossolos Litólicos* (Entisols), and *Cambissolos* (Inceptisols) combined with undulated relief were the main areas responsible for the highest sediment contributions. The sediment load delivered to the reservoir from its filling 2002 to 2015 was estimated in 6,682,704 m^3 (16,706,761 Mg) (density of 2.5-Mg m^{-3}) which value corresponded to 2.6 % of storage capacity (water plus sediment) in 14 years. These results are strategic since to become feasible identifying priority areas for soil and water conservation practices as well as useful information for water resources planning and management in the studied basin.

Keywords: SWAT model, soil erosion, environmental management, sediment delivered.

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INTRODUCTION

For a more environmentally sustainable occupation of a given basin, a better assessment of the hydrological processes and soil erosion is required (Setegn et al., 2009), and such management practices depend directly on information related to the estimates and mapping of the soil loss (Ganasri and Ramesh, 2016).

In this sense, hydrosedimentological models arise as the most useful tool for predicting soil losses, allowing quantification of the detachment processes, sediment transport, and deposition of eroded soil. Also, the use of hydrologic models has been a widely useful tool to support decision-makers in the management of the hydrographic basins. The application of these tools is based on the understanding of the hydrological cycle and their capabilities for prediction (Mello et al., 2016). One of the hydrosedimentological models most applied around the world is the Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012a).

Soil and Water Assessment Tool is a semi-distributed and time-continuous hydrosedimentological model that was developed to predict daily streamflow and soil and nutrient losses in a basin. Several studies have demonstrated the robustness of SWAT to sediment transport prediction at different basins' scale (Setegn et al., 2009; Pinto et al., 2013; Santos et al., 2013; Almendinger et al., 2014; Duru, 2015; Zuo et al., 2016; Nguyen et al., 2019; Pulighe et al., 2020). In SWAT, a basin is split into multiple sub-basins, which are then further subdivided into hydrologic response units (HRU) that consist of homogeneous land use, topographical, and soil properties (Arnold et al., 2012a). Streamflow and sediment yield are summed per HRU and then routed to the basin outlet (Neitsch et al., 2011). SWAT calculates the surface erosion caused by rainfall and runoff within each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). To calculate the coverage factor and soil management, SWAT uses the equation proposed by Wischmeier and Smith (1978). In MUSLE, the rainfall energy factor is replaced with a runoff factor to simulate erosion and sediment yield. The current version of the model routes the maximum amount of sediment as a function of the peak channel velocity and sediment yield estimates for each HRU using MUSLE (Williams, 1975; Neitsch et al., 2011). The modeling method is applicable for temporal and spatial analysis of sediment yields, of which the results are essential for agriculture and reservoir management strategies (Duru, 2015). In addition, controlling sediment production requires knowledge of soil erosion and sedimentation processes.

Soil erosion is one of the main problems in the Mortes River Basin (MRB), located at the Upper Grande River basin, southeast Brazil, with high amounts of sediment yield and transportation (Beskow et al., 2009; Batista et al., 2017) (1.45 million Mg yr^{-1}). High water erosion rate (16.81 Mg ha^{-1} yr^{-1}) in the basin and sediment transport in the drainage network increase in the sedimentation problems in the reservoirs as well as in downstream areas (Batista et al., 2017). The MRB drains directly to the Funil Hydroelectric Power Plant reservoir (FHPP), an important power facility of Minas Gerais State, in southeastern Brazil. Although this reservoir is relatively new (it was filled with water in 2002/2003), it already has presented troubles with sediment loading that is generated mainly from MRB (Batista et al., 2017). This sediment loading can affect both the Plant's capacity and increase the ponding areas in the extended backwater areas.

The Mortes River basin is located in areas with a predominance of granitic and gneiss crystalline basement rocks, covered by a thick layer of regolith, which is very susceptible to gully erosion (Morais et al., 2004). A significant portion of the basin is compromised by inadequate agricultural management and by roads improperly constructed, from mining activities with the presence of gullies and rills, which present a greater potential for sediment production (Curi et al., 1994; Sampaio et al., 2015). Once the sediments are delivered to watercourses, they are responsible for

the siltation of rivers, lakes, and reservoirs. Therefore, the identification of the places with the highest specific sediment yield is essential for the conservation planning of this basin (Silva and Curi, 2001).

Within this context, this study aimed to evaluate the ability of the SWAT model to predict continuous monthly streamflow and sediment loads in the MRB. SWAT was used to estimate the sediment yield spatially distributed by sub-basins and identify the areas with more significant contributions of sediments in the basin. Also, it was evaluated the sediment load delivered to the Funil Hydroelectricity Power Plant reservoir, located at the MRB outlet.

MATERIALS AND METHODS

Study area

The study was conducted in Mortes River Basin (MRB), in the Upper Grande River basin, Southeast Brazil (Figure 1a), with a drainage area of 6,070 km^2 with an estimated erosion rate of 16.81 Mg ha^{-1} yr^{-1} (Batista et al., 2017).

The MRB lies upstream to the Funil Hydroelectric Power Plant reservoir (FHPP), covering approximately 40 % of the total drainage area to the FHPP reservoir.

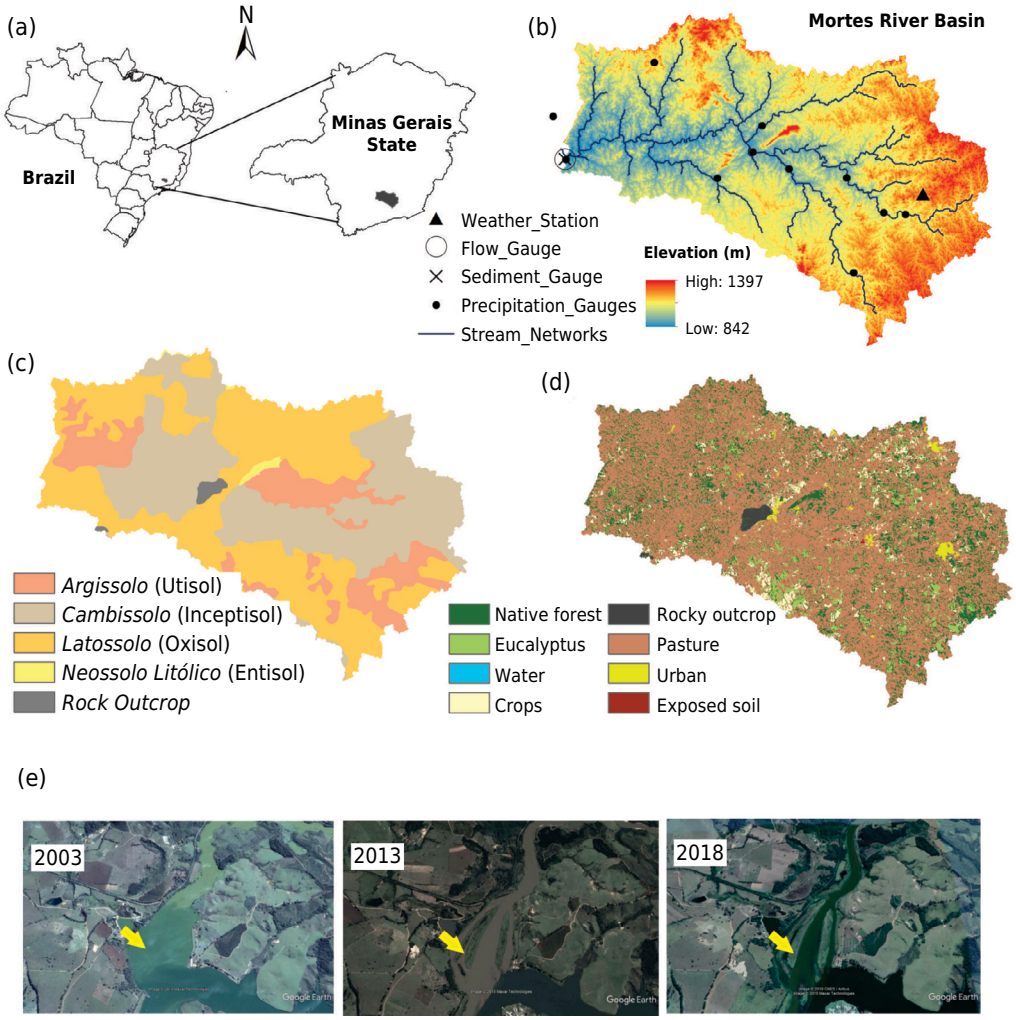

Figure 1. Map of Mortes River Basin (MRB) location (a), hydro-climatological gauging stations and digital elevation model (DEM) (b), soil types (c), land use and soil cover map (d) of the MRB for the application with the SWAT model, and temporal images of the sedimentation of the Mortes river delta in FHPP (e).

This area is marked by mild and humid summers and cold and dry winters (Cwb and Cwa climate type) according to the Köppen climate classification system, characterized, with an annual average temperature of 18 °C and an annual average rainfall of 1500 mm (Mello et al., 2012).

SWAT model input data

Three maps are needed as SWAT input data, i.e., maps of topography, soil type, and land use of the basin, as described below. Vector topographic maps of the Systematic Mapping at the scale of 1:50,000 provided by the Brazilian Institute of Geography and Statistics (IBGE) were used for the generation of the DEM. Such maps were interpolated to generate the DEM allowing generating a regular grid of elevations with a spatial resolution of 30 m. The interpolation procedures (Topo to Raster command) were performed through the ArcGIS 10.1 software interface. The elevations in the basin ranged from 842 to 1,387 m (Figure 1b).

The tabular soil data were obtained from bibliographic research (Hudson, 1982; Marques et al., 1997; Silva et al., 2009; Bertoni and Lombardi Neto, 2010; Castro et al., 2011), and from some soil samples collected in the watershed. These data are presented in Eduardo (2016). The soils were classified according to Brazilian Soil Classification System - SiBCS (Santos et al., 2018).

In the basin, the classes of *Latossolo* (Oxisol) (45.1 % of the area), *Cambissolo* (Inceptisol) (38.2 %), and *Argissolo* (Ultisol) (15.4 %) are predominant; rock outcrop and *Neossolo Litólico* (Entisol) occupy, respectively, 0.7 and 0.6 % of the area (Figure 1c). The *Latossolos* (Oxisols) present in MRB are formed in intensely weathered parent material with a physically well-structured soil, which confers a high permeability and thus greater resistance to water erosion (Curi et al., 1994; Skorupa et al., 2016). This soil has low soil erodibility, and Silva et al. (2009) suggested a value of 0.0032 Mg h (MJ mm)$^{-1}$ for this parameter. Sub-basin "9" is composed only of *Latossolo* (Oxisol) and has shown the least sediment yield. *Argissolos* (Ultisols) and *Cambissolos* (Inceptisols), on the other hand, are soils with a greater tendency for water erosion. *Argissolos* (Ultisols) have a sub-surface clayed layer, with lower permeability than the surface layer (Curi et al., 1994), and moderate to high soil erodibility, 0.033 Mg h (MJ mm)$^{-1}$ (Marques et al., 1997). *Cambissolos* (Inceptisols) have a low water storage capacity as they are shallow soils and present greater susceptibility to crusting (Curi et al., 1994; Pinto et al., 2015). Thus, these soils have high soil erodibility, 0.0355 Mg h (MJ mm)$^{-1}$ (Silva et al., 2009).

The land-use map was generated based on satellite imagery obtained by the OLI sensor (Operational Land Imager) aboard the Landsat 8 satellite from 2013, with a spatial resolution of 30 m (Figure 1d) using object-oriented classification. The classification image method aimed to split the image into homogeneous regions through its spectral and spatial attributes, followed by classification of these objects split into established land cover classes. The tabular crop data were obtained from the land-use map, images.

The model setup for MRB was constructed using the ArcSWAT interface within the ArcGIS 10.1 platform (ESRI, 2011). The first step in constructing the SWAT simulations was to delineate the sub-basins. As a result, a total of 62 sub-basins were delineated, and 882 HRU's were generated according to the basin's land use, soil types, and slope characteristics.

Other essential input parameters of the SWAT model are hydro-climatic data. For the application of the model, a hydro-meteorological database with a monthly time step was developed using daily rainfall and discharge from the Hydrological Information System of the Brazil National Water Agency (ANA). Besides, the meteorological elements from the National Institute Brazilian Weather (INMET) station (13 stations) were also used in the model calibration and validation (Figure 1a; Table 1).

Table 1. Basic information about the utilized stations

Code	Name	Type of station	Observation period
83689	Barbacena	Weather	1990-2005
2044050	São Tiago	Pluviometric	1993-2005
2143005	Campolide	Pluviometric	1993-2005
2143006	Barroso	Pluviometric	1993-2005
2143008	Ibertioga	Pluviometric	1993-2005
2143009	Usina Barbacena	Pluviometric	1993-2005
2144000	Bom Sucesso	Pluviometric	1993-2005
2144002	Porto Tiradentes	Pluviometric	1993-2005
2144009	Porto do Elvas	Pluviometric	1993-2005
2144020	Usina de São João Del Rei (SJDR)	Pluviometric	1993-2005
2144023	Ibituruna	Pluviometric	1993-2005
2144024	Vila do Rio das Mortes	Pluviometric	1993-2005
61135000	Ibituruna	Fluviometric	1993-2005

Model sensitivity, uncertainty analysis, calibration, and validation

The semi-automatic calibration in SWAT-CUP version 5.1.6 software with the "Sequential Uncertainty Fitting" algorithm (SUFI-2; Abbaspour et al., 2004, 2007) was used for the sensitivity analysis, calibration, and uncertainty analysis of the model.

The first step in the calibration and validation processes in SWAT is the determination of the most sensitive parameters for a given basin (Arnold et al., 2012a). For sensitivity analysis, SWAT uses the combination of the Latin-Hypercube and the One-factor-At-a-Time (LH-OAT) method (van Griensven et al., 2006) provided by the SWAT model. The sensitivity analysis establishes which are the parameters most important for the basin, allowing rationalization of the calibration step, and fixing those parameters that are insensitive.

As recommended by Neitsch et al. (2011) and Abbaspour (2015), streamflow was first calibrated, and then, the sediment yield and transport. For that, two data sets of monthly average streamflow, one from 1993 to 2000, and another from 2001 to 2005 were, respectively, used for performed a model parameter calibration and validation considering data from the Ibituruna gauging station (Figure 1). The years 1993 and 1994 were used for the warming up of the model (von Stackelberg et al., 2007; Zhang et al., 2007).

Table 2 presents the most sensitivity parameters in the streamflow simulation through SWAT and their lower and upper bounds, original values, and final calibrated values. The calibration procedure used six fluviometric stations: Vila do Rio das Mortes (272 km^2), Campolide (569 km^2), Usina (SJDR) (643 km^2), Porto do Elvas (828 km^2), Barroso (1040 km^2), and Ibituruna (6070 km^2). The 16 parameters used are considered by the literature as the most sensitive for streamflow simulation (Abbaspour et al., 2007; Duraes et al., 2011; Lelis et al., 2012; Andrade et al., 2013; Melo Neto et al., 2014; Mello et al., 2016). In all interactions, the parameters CN2, GW_REVAP, CH_K2, CH_N2, and GWQMN were the most sensitive. We performed four iterations with 600 simulations each. After each iteration, the sensitivity parameters were determined (Table 2), having as criterion parameters presenting the $p<0.05$. Then, these parameters were selected and had their ranges reduced for the next iteration. This procedure is supported by the fact that such parameters present greater sensitivity since values close to 0 indicate a high significance (Abbaspour, 2015).

For sediments parameters, we used the seven parameters (Table 3) that were considered by the literature as the most sensitive for sediment yield simulation in several papers around the world (Abbaspour et al., 2007; Setegn et al., 2009; Pinto et al., 2013;

Table 2. Influential parameters for the streamflow simulation by SWAT and their lower and upper bounds, original values, and final calibrated ones

Parameter	Lower and upper bounds	Initial value	Calibrated value
v__ESCO.hru	0.5 to 0.95	0.80	0.648875
r__CN2.mgt	-0.1 to 0.1	Variable	- 0.09958
v__ALPHA_BF.gw	0.004 to 0.005	0.004	0.004269
a__GW_DELAY.gw	-30 to 60	31	- 27.375
a__GWQMN.gw	-1000 to 1000	1000	- 890.16925
v__CANMX.hru	0 to 30	0	12.167521
v__CH_K2.rte	0 to 10	0	4.356992
v__CH_N2.rte	-0.01 to 0.2	0.014	0.110644
v__EPCO.bsn	0.01 to 1	1	0.994885
v__GW_REVAP.gw	0.02 to 0.2	0.02	0.146377
a__REVAPMN.gw	-1000 to 1000	750	78.333305
r__SOL_AWC().sol	-0.05 to 0.05	0.142 to 0.175	+ 0.01125
r__SOL_K().sol	-0.1 to 0.1	5.18 to 67.32	+ 0.059833
v__SURLAG.bsn	0.01 to 24	2	3.628492
v__CH_N1.sub	0.01 to 0.2	0.014	0.084575
v__CH_K1.sub	0 to 5	0	3.104167

v__ means the existing parameter value is to be replaced by a given value; a__ means a given value is added to the existing parameter value; and r__ means an existing parameter value is multiplied by (1 ± a given value) (Abbaspour, 2015). Description of the parameters – ESCO: soil water evaporation compensation coefficient; CN2: initial curve-number for moisture conditions II; ALPHA_BF: baseflow recession coefficient (days); GW_DELAY: time interval for aquifer recharge (days); GWQMN: water limit in the shallow aquifer for the occurrence of base flow (mmH_20); CANMX: maximum amount of water intercepted by vegetation (mmH_20); CH_K2: effective hydraulic conductivity in the main channel (mm h^{-1}); CH_N2: Manning's "n" value for the main channel; EPCO: water absorption coefficient by plants; GW_REVAP: water rise coefficient to the saturated zone; REVAPMN: soil water limit for occurrence of a capillary rise to the saturated zone (mmH_20); SOL_AWC: available water capacity of the soil (mm H_2O mm $soil^{-1}$); SOL_K: soil saturated hydraulic conductivity; SURLAG: surface runoff delay coefficient (day); CH_N1: Manning's "n" value for the secondary channel; CH_K1: effective hydraulic conductivity in the tributary channel (mm h^{-1}) (Arnold et al., 2012b).

Table 3. Influential parameters in the sediment simulation process by the SWAT and their lower and upper bounds, initial values and calibrated value

Parameter	Lower and upper bounds	Initial value	Calibrated value
v__SPCON().bsn	0.0001 to 0.01	0.0001	0.002948
v__SPEXP().bsn	1 to 1.5	1.0	1.472083
v__PRF_BSN.bsn	0 to 2	1	1.548333
v__ADJ_PKR.bsn	0.5 to 2.0	1.0	0.77875
v__LAT_SED.hru	0 to 100	0	29.416668
v__CH_EROD .rte[1]	_	0	0.6
v__CH_EQN.rte[2]	_	0	1.0

v__ means the existing parameter value is to be replaced by a given value; a__ means a given value is added to the existing parameter value; and r__ means an existing parameter value is multiplied by (1 ± a given value) (Abbaspour, 2015). Description of the parameters – SPCON: linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing; SPEXP: exponent parameter for calculating sediment re-entrained in channel sediment routing; PRF_BSN: peak rate adjustment factor for sediment routing in the main channel; (ADJ_PKR): peak rate adjustment factor for sediment routing in the sub-basin (tributary channels); LAT_SED: sediment concentration in lateral flow and groundwater flow (Arnold et al., 2012a). [1] We changed the channel resistance to erosion (CH_EROD.rte) setting it to 0 for the dry season and 0.6 for the rainy season in SWAT manually. [2] We used the Simplified Bagnold Equation as sediment routing method (CH_EQN.rte) (Monteiro et al., 2016).

Monteiro et al., 2016; Zuo et al., 2016). In all interactions, the parameters SPCON and SPEXP were the most sensitive. The calibration procedure was the same that we used for hydrological parameters. The SWAT performs for sediment calibration was good, how we were using less parameter for and they were selected by previous studies, these steps optimized the calibration step.

The stage-discharge sediment curve adopted in this study was fitted by Batista et al. (2017). The datasets used in the fitting of the sediment stage-discharge were obtained at the Ibituruna gauging station in the Mortes River, upstream from the FHPP (6019.2 km^2 of the drainage area). The total sediment concentration (SC) and correspondent discharge (Q) were taken once per month with field campaigning using as equipment, pleasure boat with a fluviometric winch, sampler type "US D-49" for suspended sediment concentration collection and sampler type "USBM-60" for collection of bottom sediment concentration, evaluated from March 2008 to April 2012.

This data was used to generate a discharge curve, which related total sediment concentration in the water to river discharge (Equation 1). The database used to generate the discharge curve covers a wide range of discharge values, including some flood events, allowing its application for the generation of our data sets for SWAT model calibration and validation. Overall, in Brazil, there is a very scarce sediment load monitoring in basins. Even if these datasets are available from some Government Environmental Agencies, these are obtained only 3 or 4 times per year, in Brazil, and most had not sampled peak discharges, which lead to underestimates of the sediment load and transport. Thus, equation 1 accounts for the necessary robustness for the estimation of sediment amounts throughout time with consistent quality.

$$SC = 0.5058 \times Q^{1.212} \quad \text{Eq. 1}$$

in which, SC is the total sediment concentration (mg L^{-1}), and Q corresponds to discharge (m^3 s^{-1}); $R^2 = 0.7598$.

Equation 1 was applied to estimate the daily value corresponding to the discharge that comes from the observed hydrograph. Daily sediment discharge data were determined from the product of the total sediment concentration and the respective discharge, using a correction factor as a function of the units (0.0864). Afterward, these data sets were used to generate the monthly sediment discharge data, which were used for the sediment calibration and validation in SWAT-CUP.

Model evaluation

To evaluate the ability of SWAT to reproduce the continuous MRB monthly streamflow and sediment load, statistical indexes, and graphical analyses were used to compare the simulated and observed data. The following statistical indexes were used for the calibration and validation phases: Nash–Sutcliffe coefficient (C_{NS}) (Nash and Sutcliffe, 1970), and Percent Bias (PBIAS) (Gupta et al., 1999), both recommended by Moriasi et al. (2007) to evaluate the performance of SWAT. The C_{NS} coefficient can be evaluated considering a monthly time step as follows: C_{NS} >0.75, the model is considered as "very good"; 0.65< C_{NS} ≤0.75, "good"; and between 0.50 and 0.65, "satisfactory". For the PBIAS: |PBIAS| ≤10 %, "very good"; 10 % ≤ |PBIAS| ≤ 15 %, "good"; 15 % ≤ |PBIAS| < 25 %, "satisfactory". For sediment yield, |PBIAS| <15 %, "very good"; 15 % < |PBIAS| < 30 %, "good"; 30 % < |PBIAS| < 55 %, "satisfactory". Positive values of PBIAS indicate model underestimation bias, and negative, overestimation bias (Gupta et al., 1999).

In the SUFI-2 algorithm, calibration uncertainties on the combined parameter range to capture most of the measured data within the 95 % prediction uncertainty (95 PPU). These are calculated at the 2.5 and 97.5 % levels of the cumulative distribution of output variables obtained by the propagation of the uncertainties of the parameters using Latin Hypercube sampling (LH). The LH is known as the 95 % prediction uncertainty (95PPU), which is the model's outputs in a stochastic calibration (Abbaspour et al., 2004, 2007).

To assess the goodness of fit and the degree in which the calibrated model accounts for the uncertainties, we used P-factor and R-factor statistics. The P-factor is the

fraction of observed data (plus its error) within the 95 PPU interval and varies from 0 to 1. The R-factor is the average width of the 95PPU interval divided by the standard deviation of the observed variable. For streamflow, values of P-factor >0.7 and of R-factor <1.5 are recommended for an adequate calibration (Abbaspour et al., 2004, 2007; Abbaspour, 2015).

Sediment transport in MRB

For the sediment evaluation, a spatial and temporal comparison of sediment yield maps was used as well as the sediment yield observed in sub-basins, aiming to identify the areas with a more significant contribution to the sediment generation in the basin. It was done through an output file generated by the ArcSWAT interface at the end of the simulation period.

For the practical application of the simulations, after the model's calibration, we used a new weather database from 2006 to 2015 to determine the sediment load delivered to the reservoir from its filling from 2002 up to 2015.

The sediment load refers to the total estimated amount of sediment transported out from each reach, cumulative from all drainage areas upstream, as a result of the channel phase. The sediment yield refers to the total amount of sediment that is delivered to one reach by that local sub-basins over a given period as a result of its subbasin of the landscaping phase.

Lastly, from the results of sediment yield simulated by SWAT, it was possible to evaluate spatial behavior of the sediment load along the basin through the propagation of the sediments in the stream network at the MRB from 2002 to 2015. It was done through the output file generated by the ArcSWAT interface at the end of the simulation period (Arnold et al., 2012a). This analysis was carried out by the relationship between SED_OUT and SED_IN results (Equation 2). This relationship describes the sediment fraction (SF) that each stream network section transports to a section subsequent based on sediment load input (SED_IN), in which values near 1.0 indicate little or practically no deposition of sediments. On the other hand, values near 0 indicate that the deposition process of sediments is predominant at the channel segment, and values >1.0 indicate that the erosion process is predominant.

$$SF = SED_{OUT}/SED_{IN} \quad \text{Eq. 2}$$

RESULTS

SWAT calibration for streamflow and sediment load

Figure 2 presents both the simulated and observed hydrographs and the monthly hyetographs for the MRB's outlet during calibration and validation periods, respectively. From this, we can see that the model managed to capture the oscillations of observed streamflow, showing an acceptable performance, with proper adherence between simulated and observed values.

Figure 2 also presents the results of the precision statistics applied to evaluate the performance of SWAT for hydrological simulation in MRB. The monthly river discharge simulation showed good results. Figure 3 shows both the simulated and observed monthly sediment load and respective hyetograph for MRB during calibration and validation periods.

In figure 3, it is also presented the results of the precision statistics applied to evaluate the performance of SWAT in the sediment load simulation for MRB. The C_{NS} values were 0.78 ("very good" performance) and 0.63 ("satisfactory" performance), respectively for

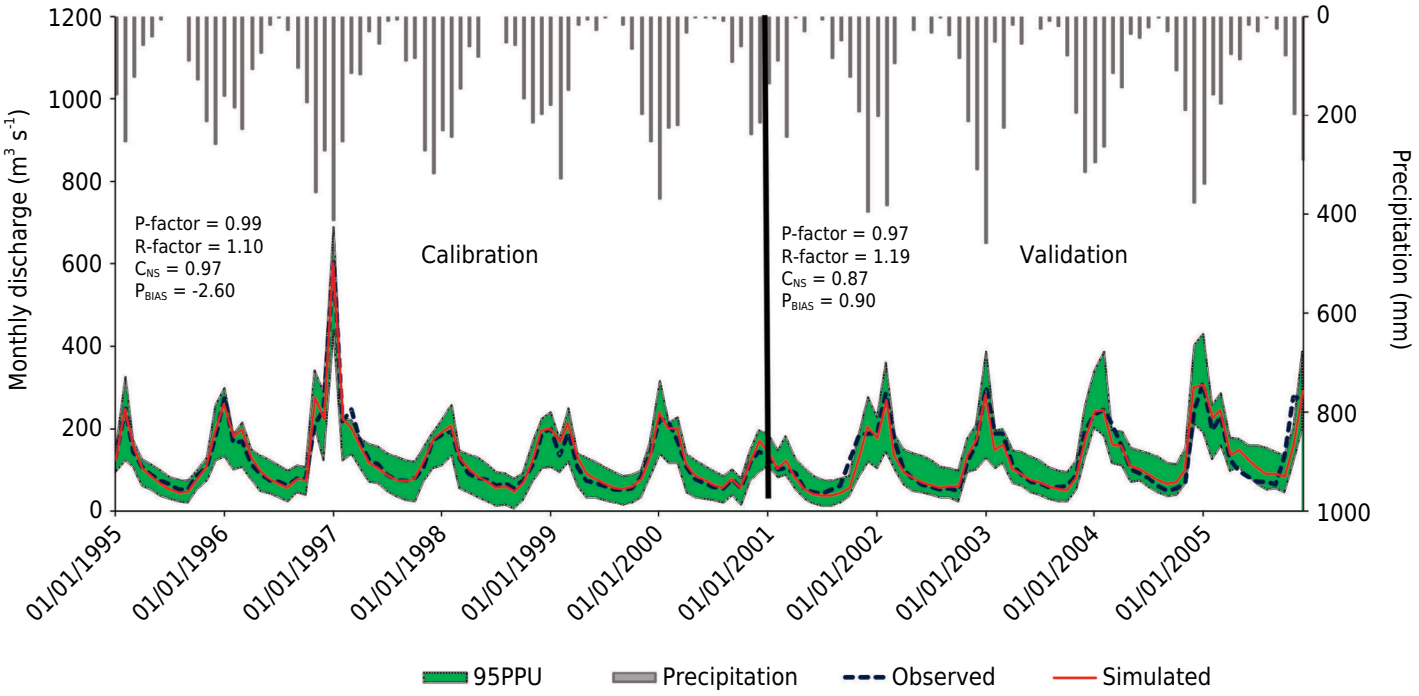

Figure 2. Monthly observed and best-simulated hydrographs and respective hyetographs, precision statistics from SWAT calibration and validation, 95 % prediction uncertainty (95PPU – P-factor), and R-factor.

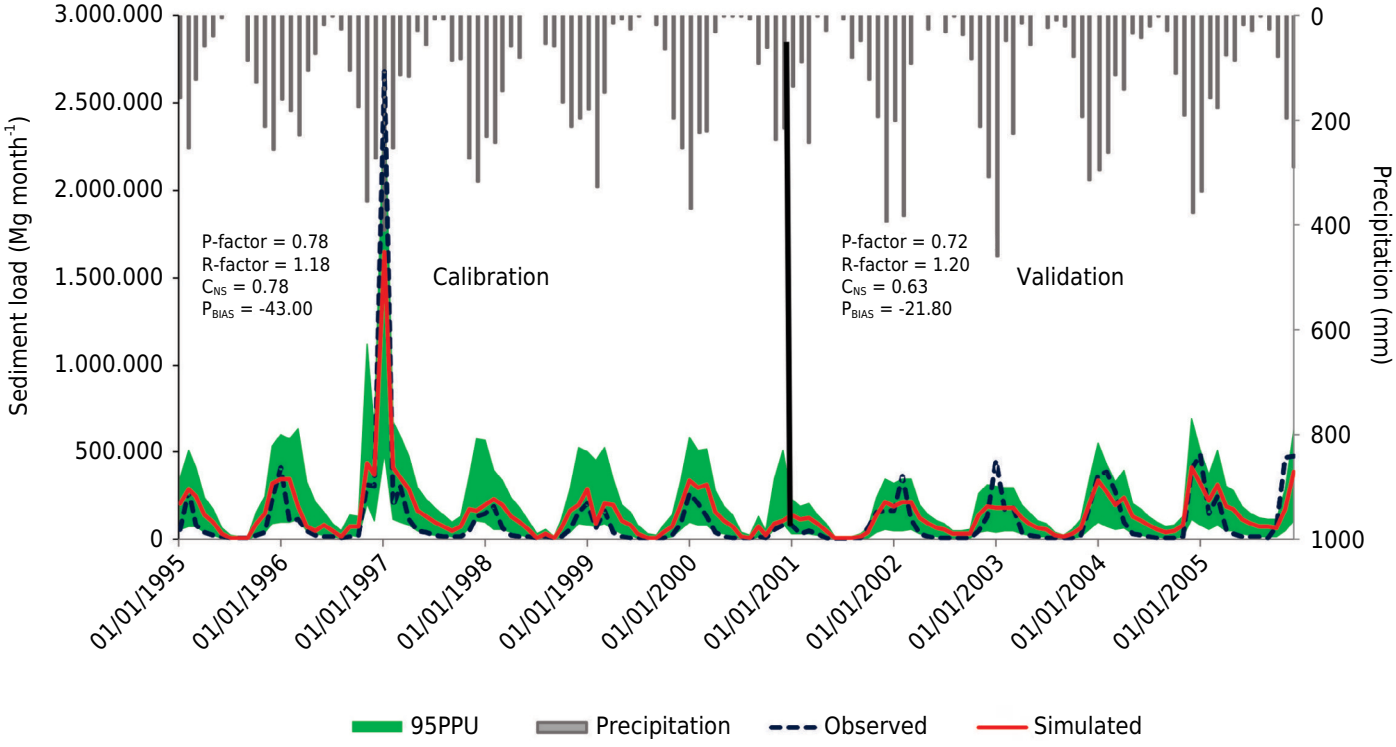

Figure 3. Observed and best simulated monthly sediment load and respective hyetograph results of the precision statistics resulting from SWAT calibration and validation, and 95 % prediction uncertainty (95PPU – P-factor) and R-factor.

calibration and validation (Moriasi et al., 2007). Analyzing the performance of the model based on P_{BIAS}, the values indicated an average overestimation of 43.0 and 21.8 % of the sediment load, respectively, in the calibration and validation phases. These values are understood as "satisfactory" for the calibration, and "good" for the validation (Moriasi et al., 2007).

To evaluate the ability of the SWAT model to predict continuous monthly streamflow and sediment loads in the MRB, permanence curves of simulated and observed streamflow and sediment for the MRB were developed (Figure 4).

The permanence curves show that the overestimation for sediment yield occurred for low and high sediment yield and streamflow. It is important to emphasize that erosion simulation is more complex than runoff; if the ground is partially or fully discovered, it will get much erosion due to lack of vegetation covers the land. In this sense, the model may be overestimating the production of sediments in areas without vegetation. In this study, the parameters SPCON and SPEXP that affect the movement and separation of the sediment fractions in the channel were the most sensitive, it shows that the simulation stages of the channel phase require more attention for the simulation of sediment yield. Santos et al. (2020) evaluating the performance of the SWAT model in the streamflow and sediment simulation concluded that the streamflow simulation was better than the sediment simulation and that the quality of the simulation decreased when estimating daily streamflow and sediment yield. In this way, future studies are recommended to improve the sediment module of the SWAT.

Sediment yield spatial distribution at MRB

For a better understanding of the predicted sediment yield in each sub-basin and to support the identification of areas more prone to water erosion, figure 5 presents maps that show spatial and temporal predicted sediment yield for the period from 1995 to 2000 simulated by SWAT.

Further understanding of the behavior of the sediment yield in MRB, three sub-basins were selected; sub-basin "29" with the highest values in both spatial and time (average value of 12.1 Mg ha^{-1} yr^{-1}); sub-basin "9" with lesser value (0.08 Mg ha^{-1} yr^{-1}); and sub-basin "1" with intermediary value (3.61 Mg ha^{-1} yr^{-1}) (Figure 6). One can be seen that the three sub-basins present significant differences concerning land use and cover soil, the soil types, and slope class (Table 4).

Since the HRU represents the smallest hydrologic unit in the model, reflecting a unique land cover, soil type, and topographic characteristics, it can be seen that for the sub-basin "9", the dominant HRU was Pasture/*Latossolo* (Oxisol)/(8-20 %); for sub-basin "1" was Pasture/*Cambissolo* (Inceptisol)/(8-20 %), and for sub-basin "29", Pasture/*Argissolo* (Ultisol)/(8-20 %) (Table 4).

Sediment delivered to the FHPP reservoir

Table 5 presents the results of the sediment load delivered to the FHPP reservoir from 2002 (its filling) to 2015 and the results of the monthly average sediment load delivered to the reservoir from January to December in the studied period (2002-2015), and

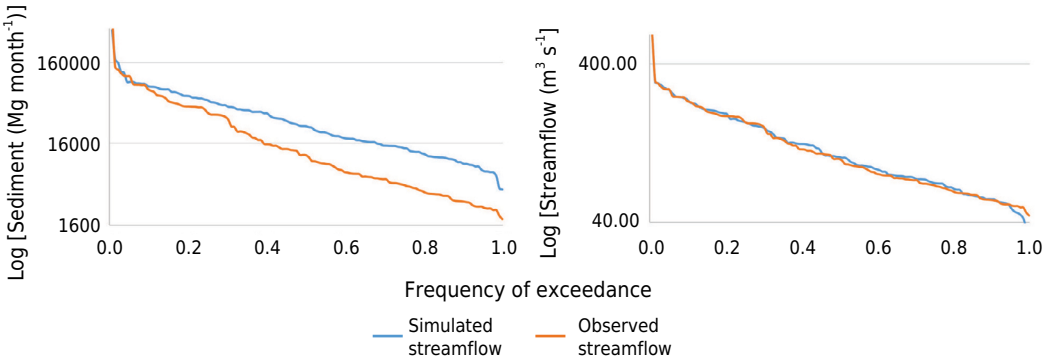

Figure 4. Permanence curves of simulated and observed sediment and streamflow for the Mortes River Basin (MRB).

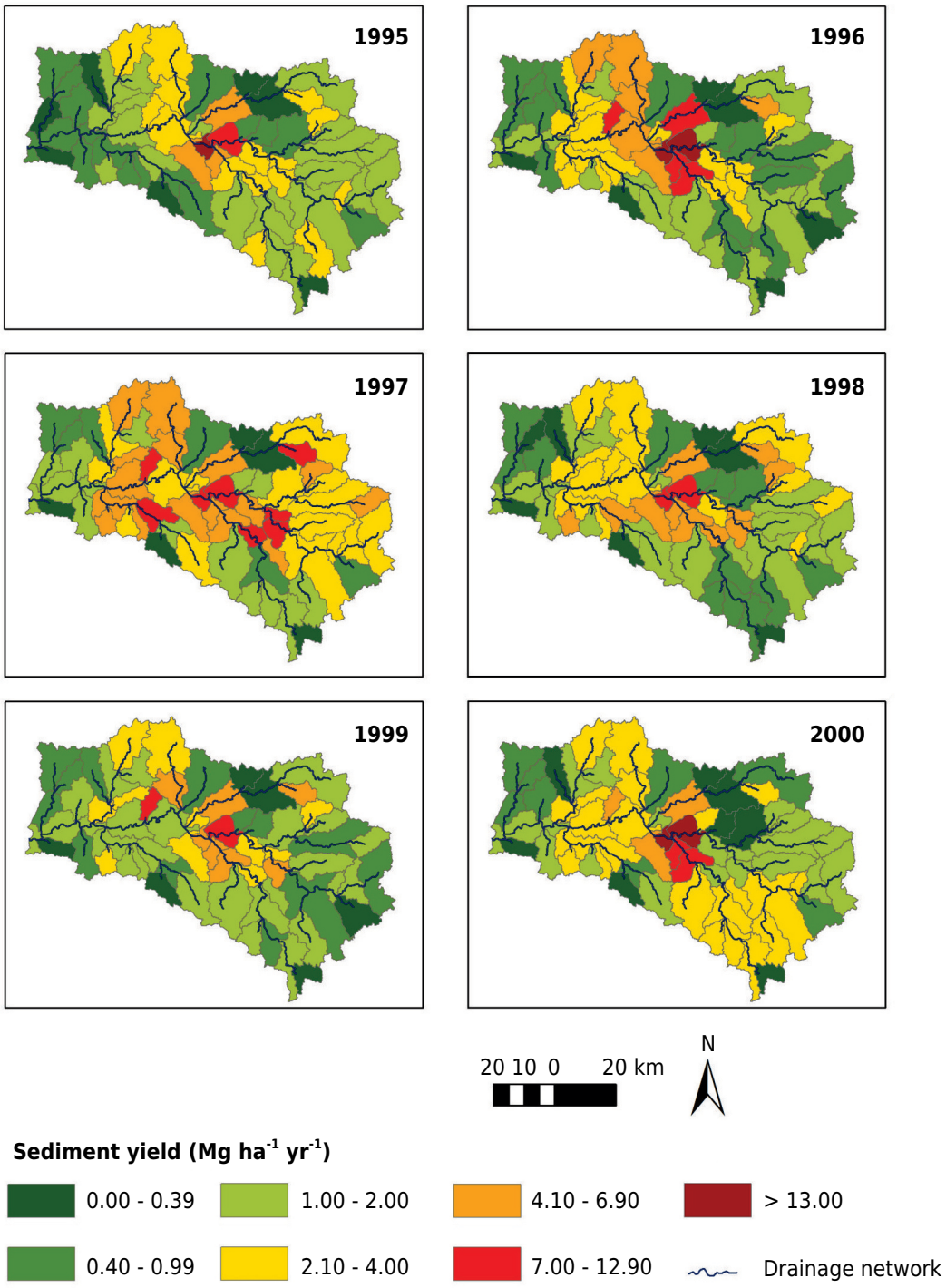

Figure 5. Spatial and temporal distribution of predicted sediment yield in each sub-basin of Mortes River Basin (MRB) in the period from 1995 to 2000 simulated by SWAT.

respective standard deviation. Analyzing this table, one can be seen that during this period, a total sediment load of 6,682,704 m^3 (16,706,761 Mg) (particle density of 2.5 Mg m^{-3}) was delivered, considering that the FHPP reservoir has a storage capacity of 259.4 Mm^3 (Soares, 2015). This value corresponded to 2.6 % of storage capacity (water plus sediment) in 14 years. The highest value was observed in the year 2012, with a volume of 638,528 m^3 (1,596,320 Mg), and the lowest value in the year 2014 equal to 193,878 m^3 (484,695 Mg).

The months between November and April presented the most significant values of sediment load because this period coincides with the rainy season for the region. Both

December and January have shown the highest standard deviation due to greater temporal variability of rainfall observed in the studied period (Table 5). The other months presented lesser standard deviations showing that, in general, the values of sediment load presented fluctuations that are small if compared to the average.

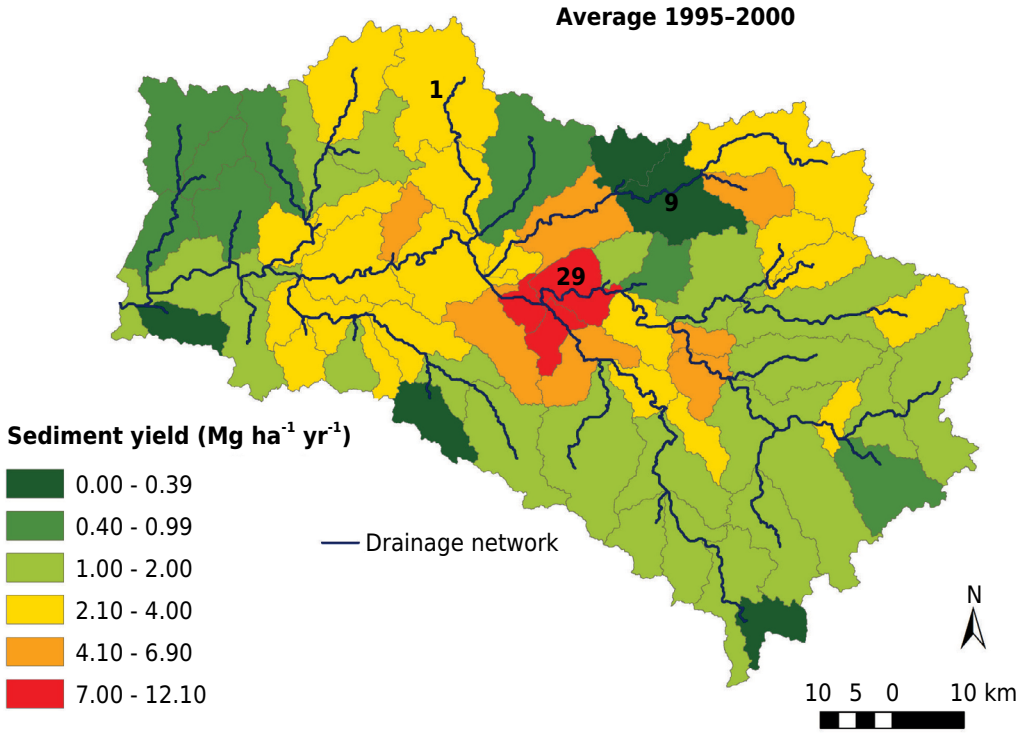

Figure 6. Average sediment yield from 1995 to 2000 and three sub-basins in highlighted of the MRB at the end of the simulation period.

Table 4. Class and percentage values for land use and soil cover, soil types, slope class, and dominant HRU for the three sub-basins selected at MRB

Sub-basin	9		1		29	
	Class	Percent	Class	Percent	Class	Percent
		%		%		%
Land use and Soil cover	Native forest	16.9	Native forest	19.1	Native forest	34.7
	Eucalyptus	8.5	Eucalyptus	5.0	Eucalyptus	0.1
	Water	0.1	Water	0	Water	1.0
	Crops	7.1	Crops	1.9	Crops	0.1
	Pasture	66.3	Pasture	73.1	Pasture	61.3
	Exposed soil	1.1	Urban	0.1	Urban	2.6
			Exposed soil	0.8	Exposed soil	0.1
Soil class	*Latossolo* (Oxisol)	100	*Cambissolo* (Inceptisol)	59.0	*Cambissolo* (Inceptisol)	0.4
			Latossolo (Oxisol)	40.0	*Argissolo* (Ultisol)	84.6
			Neossolo Litólico (Entisol)	1.0	*Neossolo Litólico* (Entisol)	15.0
Slope class	0–8 %	25.0	0–8 %	17.1	0–8 %	20.0
	8-20 %	62.1	8–20 %	55.4	8-20 %	41.6
	20-45 %	12.9	20-45 %	26.9	20-45 %	35.6
	> 45 %	0	> 45 %	0.6	>45 %	2.7
Dominant HRU	Pasture/*Latossolo* (Oxisol)/ 8 - 20 %	40.8	Pasture/*Cambissolo* (Inceptisol)/ 8 - 20 %	25.0	Pasture/*Argissolo* (Ultisol)/ 8 - 20 %	24.1

For understanding the spatial behavior of the sediment load throughout the basin, we evaluated the propagation of sediments through stream networks obtained by SWAT from 2002 to 2015, analyzing the sediment fraction (SF) (Figure 7).

Table 5. Sediment load delivered to the FHPP reservoir from 2002 (its filling) to 2015 and monthly average sediment load delivered to the reservoir from January to December in the studied period (2002-2015), and respective standard deviation

Year	m^3	Month	Average	Standard deviation
			m^3	
2014	193.878	January	76.130	48.435
2015	344.454	February	54.067	15.088
2003	379.436	March	59.187	15.078
2013	408.344	April	47.734	13.513
2002	425.412	May	33.542	11.346
2006	463.308	June	23.960	9.039
2010	470.136	July	18.536	7.026
2007	475.636	August	14.574	5.755
2011	526.760	September	14.529	5.628
2009	551.864	October	19.379	10.615
2008	572.588	November	40.200	13.619
2004	606.072	December	75.497	31.988
2005	626.288			
2012	638.528			

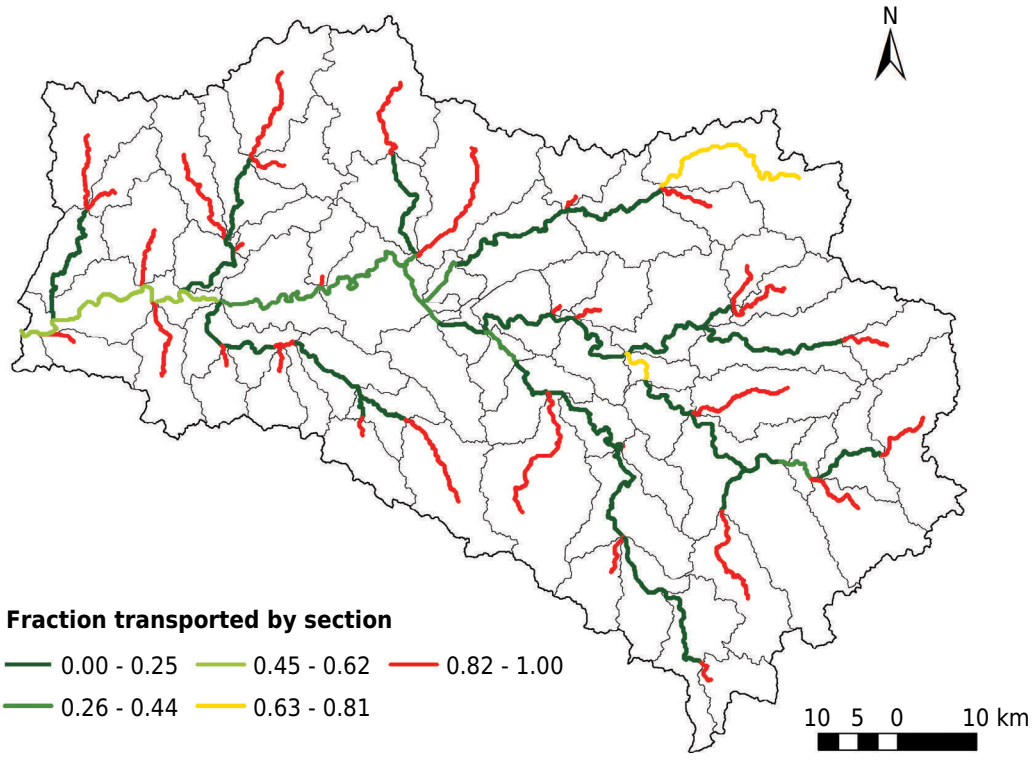

Figure 7. Sediment fraction (SF) routed through the stream network for each channel segment of the Mortes River Basin (MRB) at the end of the simulation.

DISCUSSION

SWAT calibration for streamflow

The values of CNS for the calibration (Figure 2) was of 0.97, and for the validation, 0.87, both classified as "very good" (Moriasi et al., 2007). Analyzing the performance of the model based on PBIAS, the values found in this study indicate an average overestimation of 2.6 % of the streamflow in the calibration and underestimation of 0.9 % in the validation, both values classified as "very good" (Moriasi et al., 2007). These effects can be explained by the spatial variation of precipitation along the basin, which directly influences the flow response and in the basin, there is only one season monitoring such variable, a fact that can hinder the simulation process of the model and cause the observed effects of overestimation and underestimation for the streamflow.

For discharge calibration (Figure 2), 99 % of the measured data were bracketed by the 95PPU (P-factor of 0.99), while R-factor was equal to 1.10. The validation results were also quite "very good", with 97 % of the data bracketed by the 95PPU, with an R-factor equal to 1.19 (Figure 2). That set of values indicates good bracketing of the measured data, within model prediction uncertainty bounds, which means that most of the observed streamflow values were bracketed by the 95PPU (Abbaspour et al., 2007; Abbaspour, 2015).

SWAT calibration for sediment load

It can be seen that, in general, the amount of sediment transported by the river follows the precipitation peaks (Figure 3). Pinto et al. (2013) applied SWAT for sediment simulation at a daily time step in a basin located in the Mantiqueira Range region, Minas Gerais State, Brazil, with a drainage area of 6.88 km². They obtained C_{NS} of 0.68 and 0.75 for calibration and validation, respectively. Setegn et al. (2009) found C_{NS} of 0.81 and P_{BIAS} equal to 28 % for calibration, and C_{NS} of 0.79 and P_{BIAS} of 30 % for validation, simulating the sediment load in a monthly time step with SWAT, in the Lake Tana basin, Ethiopia, that has a drainage area of 15,096 km^2. Zuo et al. (2016) obtained C_{NS} values of 0.98 and 0.61 for calibration and validation, respectively, for sediment load at a daily time step, also using SWAT in a basin in the Loess Plateau of China, which covers an area of 3246 km^2. Oliveira et al. (2019) applied SWAT to investigate the climate change impacts on hydrology and sediment load in a headwater basin of the Paranaíba river, with a total drainage area of 3,754 km². They obtained C_{NS} of 0.89 and 0.93 for calibration and validation, respectively, and percent bias (PBIAS) of −4.5 and −3.5 %, respectively, for calibration and validation. Thus, we can see that the results obtained in this study are following results found in other studies that used SWAT for sediment load simulation.

The 95PPU indicates the propagation of uncertainty in the parameters related to rainfall, soil properties, water use, and discharge (Abbaspour, 2015). During the calibration of sediment loads, approximately 78 % of the measured data and during the validation period, 72 % of the measured ones were bracketed by the 95PPU (R-factor = 1.18 for calibration and R-factor = 1.20 for validation). The prediction uncertainty of sediment load was relatively small as indicated by the p>0.7 and R-factor <1.5 (Figure 3), which indicates that the model showed an adequate behavior in terms of prediction uncertainty (Abbaspour et al., 2004, 2007; Abbaspour, 2015).

Sediment yield spatial distribution at MRB

It is observed that 1997 was the year that showed higher sediment yield for most of the sub-basins (Figure 5), while 1999 was a year with lesser values. This behavior can be explained because MUSLE model, which is embedded at SWAT, uses the amount of runoff to simulate water erosion and sediment load, and the year of 1997 had higher values of

streamflow as a response of greater rainfall, with a monthly average of 168 $m^3 s^{-1}$, and in 1999, 110 $m^3 s^{-1}$. In general, for all the years analyzed, the areas with the highest and least sediment load were usually the same.

The sub-basin "29" has its area with 84.6 % covered with *Argissolos* (Ultisols), which showed the greatest sediment yield, followed by the sub-basin "1", which had 59 % of the area with *Cambissolos* (Inceptisols). Further, sub-basin "29" has 15 % of its area with a *Neossolo Litólico* (Entisol) and 35.6 % under strongly undulated relief. This soil is also shallow and has a low water retention capacity (Curi et al., 1994), thus, a very high soil erodibility, 0.053 Mg h $(MJ\ mm)^{-1}$ (Bertoni and Lombardi Neto, 2010).

The differences found for the sediment yield by analyzing the three sub-basins are associated with the particularities of each soil type. The HRU formed by pasture, *Argissolo* (Ultisol) and undulated relief, along with the association of *Neossolo Litólico* (Entisol) having strongly undulated relief resulted in the greatest sediment yield in the sub-basin. However, the HRUs formed by an association with pasture, *Cambissolo* (Inceptisol), and undulated relief are the most vulnerable areas to soil erosion in MRB.

The identification of areas more prone to erosion in a basin is important for the implementation of management actions more appropriate aiming to reduce the sediment yield. SWAT is a powerful tool for spatial visualization at the sub-basin level so that one can see which areas produce higher sediment amounts.

Sediment delivered to the FHPP reservoir

The results of the sediment load delivered to the reservoir (Table 5) show that MRB is an important source of sediments for this reservoir, corroborating the results found by Soares (2015) and Batista et al. (2017). According to these authors, Mortes River delta is the main sedimentation zone in the FHPP (Figure 1e) and this river is the primary source of sediment into this reservoir.

The average annual sediment load estimated by SWAT was 2.0 Mg $ha^{-1}\ yr^{-1}$. This result was near to that presented by Batista et al. (2017), who evaluated the average annual Specific Sediment Yield (SSY) in the MRB from March 2008 to April 2012. Their results showed that the average annual SSY in the basin was 1.60 Mg $ha^{-1}\ yr^{-1}$. In the cited study, it was also evaluated the sediment yield using the Revised Universal Soil Loss Equation (RUSLE) and the Sediment Delivery Distributed model (SEDD), obtaining a mean SSY value of 1.58 Mg $ha^{-1}\ yr^{-1}$. Based on the results found in the present study, we consider that the SWAT model can sufficiently predict the sediment load at the MRB.

Some results of table 5 showed a high delivered sediment load to this reservoir, leading to a reduction in its storage capacity, and then, reducing its "useful life", as well as affecting the amount of hydroelectric energy production.

Another important consideration is that the sediment from erosion may contain, in specific local conditions, substantial concentrations of agricultural inputs and other elements of industrial origin, absorbed by the soil and transported during the erosion process, causing pollution in watercourses (Guilherme et al., 2000). Besides, sediments, with organic and inorganic fertilizers from the agricultural fields that enter the river by runoff, may result in eutrophication (Setegn et al., 2009).

It can be observed in figure 7 that the stream network belonging to the headwater sub-basins, which offer higher slopes, there occurs little or practically no deposition, i.e., the SF values were near to 1. On the other hand, in the region positioned immediately downstream after the headwaters of sub-basins occurs a reduction in land slope along a streamflow path decreases the sediment transport capacity of flows, thereby leading to sedimentation, i.e., the SF values were near to 0. According to Santos et al. (2013), it is possible to state that the sediment deposition is promoted primarily by

the rapid reduction of steepness since this configuration leads to a reduction in the river transport capacity.

Therefore, it is important to consider the sediment dynamics at the watersheds' scale. Almendinger et al. (2014) pointed out that fundamentally, sediment is detained, whether temporarily or permanently, wherever runoff velocity decreases enough to deposit the suspended sediments. Studies show that the larger the watershed size, the higher the deposition process (Williams, 1975; Almendinger et al., 2014). Basically, the higher the ramp length, the greater the possibility of deposition of sediments. However, this behavior does not follow a linear trend (Lane et al., 1997; Kirkby, 2001), showing the complexity involved with this kind of modeling.

The main limitations in studies that involved sediment transport are related to the number of gauge-stations (sediment concentration and streamflow) over the basin for both temporal and spatial scales representation and their interactions with the environment. Also, SWAT model presents limitations for sediment transport simulation associated with the model's structure as it uses the Modified-USLE, which is a simple model, as well as in the modeling of the sediment propagation over the drainage network (Lelis et al., 2012). The uncertainties that are involved with these hydrosedimentological simulations using SWAT are also related to errors from the input variables and notably in the estimated parameters.

This kind of study requires a long-term data set of sediment loads that allow the spatial and temporal representation of this variable. In the present study, some limitations can be highlighted: i) database for fitting the stage-discharge-sediment curve (data scarcity); and ii) calibration of the model taking a monthly time step, which does not let the model capture the peak discharges and respective sediment load; thus, the model trends typically to underestimate the sediment loads.

Although the limitations of the sediment-discharge stations in the basin for a more robust validation process, our study is a preliminary effort for this basin, allowing a long-term simulation of sediment delivery rate. It brings a relevant contribution to basin management and subsequent future investigations related to soil erosion and sediment transport in sub-basins, upstream from the FHPP reservoir.

In light of this, SWAT can be adopted by engineers and hydrologists in MRB as a decision support tool to help the different personnel that works in the basin to assist in achieving sustainable water management at the basin level.

CONCLUSIONS

Despite the complexity of processes influencing sediment in the basin, this research demonstrates that SWAT performed satisfactorily in simulating sediment and streamflow.

For discharge calibration, 99 % of the measured data were bracketed by the 95PPU, and for validation, 97 % of the data were bracketed by the 95PPU indicating proper bracketing of the measured data within model prediction uncertainty. Uncertainty analysis in SUFI-2 indicated that 95PPU could capture about 78 % of the sediment loads measured during the calibration and about 72 % of the measured data during the validation period at MRB.

The HRU's having pasture, with *Argissolo* (Ultisol), *Neossolo Litólico* (Entisol), *Cambissolo* (Inceptisol) soils with undulated relief, are the main areas with higher sediment contributions. These results are essential to identify high priority areas for soil and water conservation measures.

The sediment load delivered to the reservoir from its filling 2002 to 2015 was estimated in 6,682,704 m^3 (16,706,761 Mg) (density of 2.5-Mg m^{-3}) which value corresponded to 2.6 % of storage capacity (water plus sediment) in 14 years.

Finally, the results obtained in this study provide useful information for water resource planning and management at the Mortes River Basin region.

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Validation: Eliete Nazaré Eduardo Mauri (equal), Phillip Ray Owens (supporting), Marcelo Ribeiro Viola (equal), Nilton Curi (supporting), Lloyd Darrell Norton (supporting), and Carlos Rogério de Mello (lead).

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