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Assessing sediment yield and streamflow with SWAT model in a small sub-basin of the Cantareira System

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ABSTRACT: Hydro-sedimentological models might be useful tools for investigating the effectiveness of soil and water conservation practices. However, evaluating the usefulness of such models requires that predictions are tested against observational data and that uncertainty from model parameterization is addressed. Here we aimed to evaluate the capacity of the SWAT model to simulate monthly streamflow and sediment load in the Posses creek catchment (12 km²), Southeast Brazil. The SUFI-2 algorithm from SWAT-CUP was applied for calibration, testing, uncertainty, and sensitivity analysis. The model was calibrated and initially tested using discharge and sediment load data, which were measured at the catchment outlet. Additionally, we used soil loss measurements from erosion plots within the catchment as independent data for model evaluation. Average monthly streamflow simulations obtained satisfactory results, with Nash-Sutcliffe coefficient (NSE) values of 0.75 and 0.51 for the calibration and testing periods, respectively. Sediment load simulations also displayed satisfactory results for calibration (NSE = 0.65) and testing (NSE = 0.52). However, the comparison with independent plot data revealed that SWAT severely overestimated hillslope erosion rates and compensated it with high sediment channel deposition. Moreover, the model was not sensitive to the parameters used for calculating hillslope sediment yields. Therefore, it should be used with caution for evaluating the interactions between land use, soil erosion, and sediment delivery. We found that the commonly used outlet-based approach for model calibration and testing can lead to internal misrepresentations, and models can reproduce the right answer for the wrong reasons.

Keywords: sediment yields, sediment transport models, soil erosion models, model testing, model invalidation.



INTRODUCTION

Soil erosion is the main cause of land degradation in agricultural catchments in tropical countries (Lal, 2001). Negative on-site erosion effects include the loss of nutrients, seeds, organic matter, and biodiversity. Moreover, soil erosion compromises water quality and leads to reservoir sedimentation, reducing storage capacity and threatening water security in urban centers (Telles et al., 2011). However, greater emphasis has been given to on-site erosion model-based assessments, to the detriment of sediment transport and deposition and its effects on water supply. In Brazil, hydro-sedimentological modeling studies are scarce, particularly due to the lack of hydro-meteorological and -sedimentological data (Bonumá et al., 2014; Bressiani et al., 2015). This difficulty is particularly relevant for small headwater catchments (e.g., $<10 \text{ km}^2$), for which historical streamflow and sediment discharge data are rarely available.

Headwater catchments are responsible for maintaining the flow of the main sources of water supply in the Brazilian Southeast, the most populated region of the country, and which concentrates most of the national GDP. These small mountainous catchments have a complex relief, a high drainage density, and many areas of water upwelling (springs), which compound watercourses downstream. Because of the importance of these catchments, they are prioritized for soil and water conservation projects focusing on water security.

The *Conservador das Águas* (Water Conserver) program, in the municipality of Extrema, Minas Gerais, is a pilot payment for environmental services program in Brazil (Richards et al., 2015). The program focuses on increasing forest cover in sub-catchments that drain into the Cantareira System, which is responsible for the water supply of the 4.5 million inhabitants of the São Paulo Metropolitan Region. Therefore, the program aims to control the impacts of soil erosion on water quality, increase water infiltration, and promote aquifer recharge. These actions will ultimately provide water security downstream.

The values paid for environmental services should be based on the effectiveness of the adopted practices (Richards et al., 2015), which can be assessed by dynamic hydro-sedimentological models. These models are an important tool to understand and simulate the effects of land-use change, the use of support practices, and the influence of climate change on soil erosion and the water cycle (Bonumá et al., 2015; Bressiani et al., 2015; Zuo et al., 2016).

One of the most widely used hydrological models is the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). SWAT is a time-continuous, semi-distributed, process-based hydrological model, which has reportedly provided satisfactory streamflow simulations for diverse conditions and different regions of the world (Abbaspour et al., 2015; Bressiani et al., 2015; Zuo et al., 2016). SWAT was developed to assess the impact of management and climate on water supply, sediment production, and agricultural chemical yields for large river basins. However, the model has also been applied in small catchments, mainly to estimate average monthly streamflow (Spruill et al., 2000; Fukunaga et al., 2015; Roth et al., 2016). Usually, SWAT model calibration is carried out with outlet streamflow and sediment load data, even in the studies that calibrate parameters related to hillslope soil losses (Arnold et al., 2012; Roth et al., 2016; Zuo et al., 2016).

There are few studies that evaluate the SWAT sediment component in Brazil, particularly in small headwater catchments. The lack of sediment load and sediment yield data is the main limitation to setup reliable hydro-sedimentological models (Bressiani et al., 2015; Monteiro et al., 2015). Besides the lack of data, another problem in studying headwater catchments is that most of the currently established and tested models were developed for large basins. Hence there is a need for studies such as the one presented here, which

tests model suitability at smaller scales. This will potentially enable us to identify which adaptations are necessary to improve the performance of these models in situations they were not developed for.

This study aimed to evaluate the capability of the SWAT model to estimate monthly streamflow and sediment load for a headwater catchment in Southeast Brazil, which is part of the Water Conserver program. The SWAT was calibrated and tested following the commonly employed outlet-based temporal split-off test, using average monthly streamflow and sediment load data. The model was further evaluated by the use of uncertainty and sensitivity analyses and by incorporating hillslope soil loss data from erosion plots installed within the catchment.

MATERIALS AND METHODS

Study area

The Posses creek catchment is located between coordinates 22.83° and 22.90° South latitude and, 46.22° and 46.26° West longitude. The catchment has 12 km² of drainage area, with altitudes between 1050 and 1350 m. According to Köppen's classification system, the catchment has Dry-winter sub-tropical highland climate (Cwb) (Alvares et al., 2013). The annual mean temperature is 18 °C, with average annual precipitation of 1652 mm. The Posses catchment is within the Mantiqueira mountain range, in Southeast Brazil, where Atlantic Forest is the original biome. Land use consists predominately of minimally managed pastures, and Ultisols are the dominant soils (Soil Survey Staff, 2014). These soils correspond to *Argissolos*, according to the Brazilian Soil Classification System (Santos et al., 2018). The input maps used to parameterize SWAT, with rainfall gauges and fluviometric stations are presented in figure 1.

SWAT model

SWAT divides the modeled catchment into multiple sub-catchments connected by a stream network. Each sub-catchment is fractioned into hydrological response units (HRUs), consisting of unique combinations of land cover, slope, and soil type (Arnold et al., 1998). The model computes the water balance for each HRU, all of which drain into the channel network.

SWAT estimates surface runoff with the SCS curve number approach, and the peak runoff is obtained with a modified rational method equation (Equation 1):

$$q_{peak} = \alpha_{tc} \times Q_{surf} \times Area / (3.6 \times t_{conc}) \quad \text{Eq. 1}$$

in which q_{peak} is the peak runoff rate (m³ s⁻¹), α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff (mm), Area is the sub-catchment area (km²), t_{conc} is the time of concentration for the sub-catchment (hour), and 3.6 is a unit conversion factor. Peak runoff is used for the erosion and sediment transport components of the model.

Sediment transport is computed as a function of two components: hillslope and channel routing. Hillslope erosion and sediment yield are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) (Equation 2):

$$sed = a(Q_{surf} \times q_{peak} \times area_{hru})^b \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG \quad \text{Eq. 2}$$

in which sed is the sediment yield on a given day (Mg), a and b are the adjustable coefficients, $area_{hru}$ is the HRU area (ha), K_{USLE} is the soil erodibility factor (Mg h MJ⁻¹ mm⁻¹), C_{USLE} is the cover and management factor, P_{USLE} is the support practice factor, LS_{USLE} is the topographic factor, and CFRG is the coarse fragment factor.

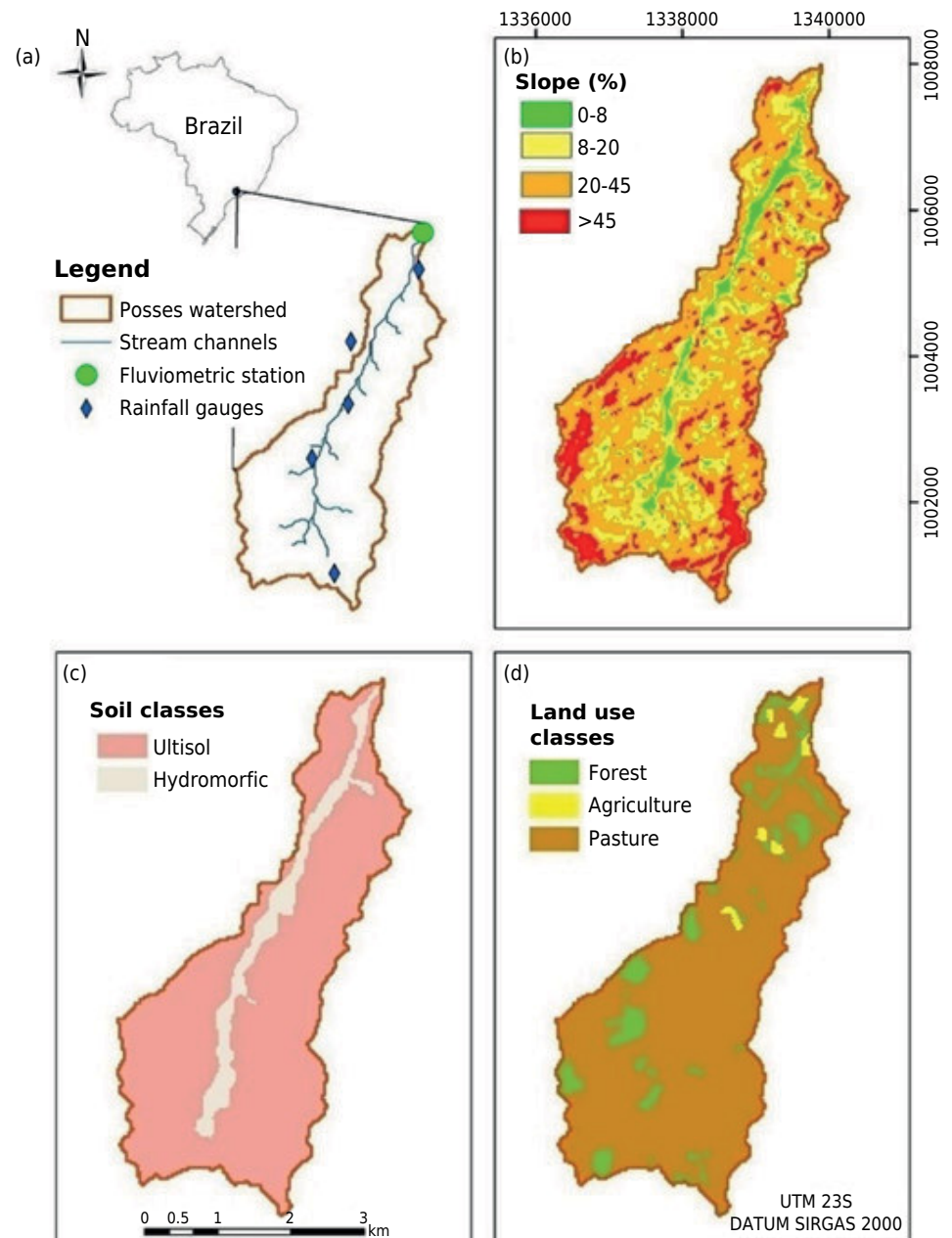


Figure 1. Input maps used in SWAT modeling for PosSES watershed (a), slope classes (b), soil classes (c), and land use (d).

Sediment yield that reaches the stream channel is given by the sum of total sediment yield calculated by MUSLE minus a lag, which is calculated by considering temporary retentions of sediments in the landscape. Each sub-catchment has a main routing reach, in which upland sediment is routed and then added to downstream reaches.

The default channel routing component uses a simplified version of the Bagnold (1977) equation to estimate the maximum amount of sediment that can be transported from a reach segment (Equations 3):

$$conc_{sed,ch,mx} = SPCON \times v_{ch,pk}^{SPEXP} \quad \text{Eq. 3}$$

in which $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water ($Mg\ m^{-3}$), $SPCON$ and $SPEXP$ are the linear and exponent coefficients, and $v_{ch,pk}$ is the peak channel velocity ($m\ s^{-1}$), which is given by q_{peak} divided by the cross-sectional area of flow in the channel.

Input data and model setup

Daily rainfall and climate records from 2008 to 2014 were used as input data. Five rainfall gauge stations within Posses watershed were provided by the National Water Agency (ANA): Bela Vista (2246170), Nascente Principal (2246167), Ratinho (2246171), Siriema (2246169), and Sítio São José (2246168). Climate data was taken from Monte Verde (A509) station, available in the Meteorological Database for Teaching and Research (BDMEP) of the National Weather Institute (INMET). Land-use and soil classification data were retrieved from previous studies in the catchment (Bispo et al., 2017a; Silva et al., 2019).

SWAT uses the hydrological response unit (HRU) concept to discretize and spatialize the water budget. The HRUs for this study were delineated with slope classes of 0 to 10 %, 10 to 20 %, 20 to 45 %, and higher than 45 %. Thresholds for soil type and land-use were set at 10 % area coverage. Sub-catchments were delineated with a 2 % threshold of the total Posses catchment area.

Calibration, testing, and sensitivity analysis

The model was applied in a monthly time-step and with a temporal split-off for calibration (Jan 2009 – Dec 2011) and testing (Jan 2012 – Dec 2014). Discharge data of the Posses creek outlet gauging station (62584600) was used for model calibration and testing. Once calibrated, the streamflow parameters were fixed. Subsequently, the erosion and sediment transport parameters were optimized.

The observed sediment load data was obtained by applying a rating curve for sediment discharge adjusted for the Posses stream to the continuously measured flow data (Figure 2). A rating curve was developed based on measurements of suspended solids concentration (g dm^{-3}) retrieved from the Posses stream according to the method 2540D from the *Standard Methods for the Examination of Water and Wastewater* (Rice et al., 2012). Suspended solids were measured on 80 occasions, between July 2015 and June 2016.

The fitted power equation presented statistically significant parameters and the adjusted coefficient of determination (R^2). Although this high R^2 is due to the large number of low streamflow and low sediment load observations, in this study, the maximum daily streamflow observed was less than $3.81 \text{ m}^3 \text{ s}^{-1}$. Therefore, the sediment load was calculated with a representative range of discharge/sediment concentration values.

Calibration, testing, sensitivity, and uncertainty analysis were carried out with the SUFI-2 algorithm (Abbaspour et al., 2007) from the SWAT-CUP program. This algorithm allows for a stochastic application of the SWAT model, which is then evaluated by the P-factor and R-factor statistics and by the 95 % prediction uncertainties (95PPU). The

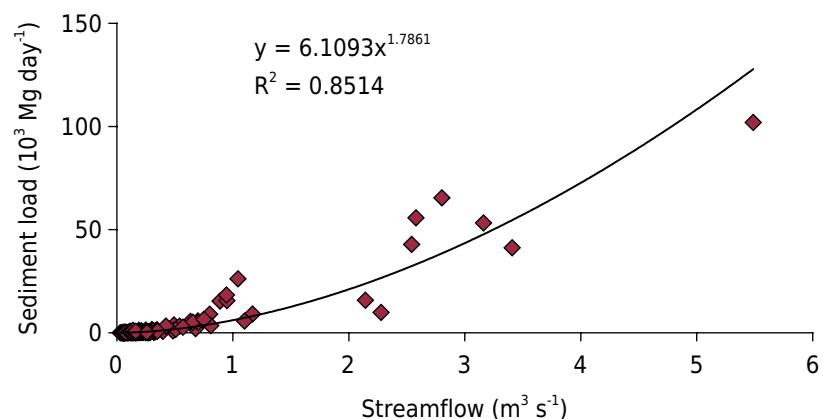


Figure 2. Rating curve for sediment load for the Posses stream.

95PPU is calculated at the 2.5 and 97.5 % levels of the cumulative distribution of the simulation results, which are calculated with Latin hypercube sampling. The P-factor represents the fraction of the measured data encompassed by the 95PPU band. The R-factor is the ratio of the average width of the 95PPU band and the standard deviation of the measured variable. Threshold values of the P-factor, R-factor, PBIAS, and NSE are shown in table 1.

During model calibration, we performed five model iterations with 500 simulations each. For each iteration, the parameters with $p < 0.05$ in the Global Sensitivity Analysis (GSA) had their range narrowed by half. New maxima and minima were kept within the initial range of parameter values (Table 2).

Table 1. Performance evaluation and uncertainty analysis criteria used to classify SWAT model results

Measure	Output response	Performance evaluation			
		Very good	Good	Satisfactory	Not Satisfactory
NSE ⁽¹⁾	Flow	NSE > 0.80	0.70 < NSE ≤ 0.80	0.50 < NSE ≤ 0.70	NSE ≤ 0.50
	Sediment	NSE > 0.80	0.70 < NSE ≤ 0.80	0.45 < NSE ≤ 0.70	NSE ≤ 0.45
PBIAS (%) ⁽¹⁾	Flow	PBIAS < ±5	±5 ≤ PBIAS < ±10	±10 ≤ PBIAS < ±15	PBIAS ≥ ±15
	Sediment	PBIAS < ±10	±10 ≤ PBIAS < ±15	±15 ≤ PBIAS < ±20	PBIAS ≥ ±20
R-factor ⁽²⁾	Flow and sediment	-	-	R-factor ≤ 1.5	R-factor > 1.5
P-factor ⁽²⁾	Flow and sediment	-	-	P-factor ≥ 0.7	P-factor < 0.7

⁽¹⁾ Moriasi et al. (2015). ⁽²⁾ Abbaspour et al. (2015). “-”: not applicable.

Table 2. List of parameters adjusted during the calibration process, their description, and results

Parameter	Description	Initial range		Final range		Best simulation
		Minimum	Maximum	Minimum	Maximum	Fitted
v_ESCO.hru	Plant uptake compensation factor	0.5	0.95	0.594	0.878	0.771
r_CN2.mgt	SCS runoff curve number factor	-0.1	0.1	-0.1	-0.0592	-0.0954
v_ALPHA_BF.gw	Base flow alpha factor (days)	0	0.1	0	0.00146	0.00045
a_GW_DELAY.gw	Groundwater delay time (days)	-30	60	-30	-18.75	-26.276
a_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mmH ₂ O)	-1000	1000	-775.521	197.045	-350.510
v_CANMX.hru	Maximum amount of water trapped in the canopy (mm H ₂ O)	0	30	8.435	30	20.921
v_CH_K2.rte	Effective hydraulic conductivity in main channel (mm h ⁻¹)	0	10	4.415	8.681	7.619
v_CH_N2.rte	Manning's n value for the main channel	-0.01	0.2	0.0564	0.2	0.112
v_EPCO.bsn	Plant uptake compensation factor	0.01	1	0.01	1	0.460
v_GW_REVAP.gw	Revap coefficient	0.02	0.2	0.0569	0.177	0.0739
a_REVAPMN.gw	Threshold water level in shallow aquifer revap (mm H ₂ O)	-1000	1000	-1000	1000	174
r_SOL_AWC().sol	Available water capacity of the soil layer	-0.05	0.05	-0.05	0.05	0.0301
r_SOL_K().sol	Saturated hydraulic conductivity (mm h ⁻¹)	-0.10	0.10	-0.10	0.085	-0.0946
v_SURLAG.bsn	Surface runoff lag coefficient (days)	0.01	24	0.01	24	17.691

The ten parameters of the erosion and sediment transport model component (ADJ_PKR, CH_COV1, CH_ERODMO, LAT_SED, PRF_BSN, USLE_C, USLE_K, SPEXP, SPCON, and CH_COV2) were tested with a One-at-Time (OAT) sensitivity analysis. Sensitive parameters were then used to calibrate the model component.

Erosion plot data were used to evaluate modeled hillslope erosion rates. The plot experiments and erosion monitoring are described in detail by Bispo et al. (2017b). In short, the erosion plots (24 × 4 m) were made of 0.40 m high galvanized plates (0.20 m buried in the soil). After each erosive rainfall, three samples were taken from sedimentation tanks at the drainage flume in the lower part of the plots. The samples were oven-dried and weighed to calculate erosion rates. For evaluating model results, we used data from two plots installed in Ultisols with permanent pasture and 32 % slope. The comparison was made for HRUs composed of the same soil and soil cover type and a slope range of 20 to 45 %, which provide equivalent conditions to the plots. The soil loss rate, in $\text{Mg ha}^{-1} \text{ yr}^{-1}$, was obtained by the average of the selected HRUs within the sub-basin where the plots were located. The period used for the comparison was between November 2013 and December 2014, which provide an overlap between the model simulations and the erosion measurements. Of note, we did not use the erosion plot data for calibration to evaluate the model's internal performance, considering the common approach for calibration and testing, which relies entirely on outlet measurements.

RESULTS

Streamflow simulations

The Posses catchment was sub-divided into 25 sub-catchments and 138 HRUs during the SWAT model setup. For the studied period, the average annual rainfall was 1,554 mm, while the estimated annual average evapotranspiration was 597 mm (38 % of the annual rainfall). Surface runoff was estimated at 159 mm yr^{-1} , and water recharge at 543 mm yr^{-1} .

The results display a good agreement between estimated and observed monthly streamflow for the calibration period, which should be expected considering the number of parameters available for optimization. However, for the testing period, streamflow was overestimated for the entire year of 2014. Overall, results were still considered satisfactory ($\text{NSE} > 0.5$) (Figure 3).

The Nash-Sutcliffe (NSE) index and PBIAS were classified as good for calibration and satisfactory for the testing period (Moriassi et al., 2015). The uncertainty analysis indicated an adequate balance of the 95PPU width (R-factor) and the envelopment of the observed data by the 99PPU (P-factor) (Abbaspour et al., 2015). However, the R-factor of the testing period was higher than 1.5. This means that the range of calibrated parameters produced a 95PPU range wider than recommended during the testing period.

During calibration, the parameters with the lowest p-value, i.e., the highest global sensitivity, were ALPHA_BF, GWQMN, CH_N2, CH_K2, CN2, and ESCO (the final range of calibrated parameters are shown in table 1). Other studies have also reported that SWAT displayed high sensitivity to these parameters, which have been frequently used for calibration (Aragão et al., 2013; Fukunaga et al., 2015; Melaku et al., 2017).

Sediment load simulations

The One-at-time (OAT) sensitivity analysis was applied to ten parameters of the erosion and sediment transport model component. Modeled sediment loads were sensitive to variations in parameters SPEXP, SPCON, and CH_COV2. These parameters were therefore used for calibration (Table 3).

For the global sensitivity analysis (GSA), the CH_COV2 parameter had $p > 0.05$ in all iterations. This means that the model outputs are not sensitive to this parameter, which therefore did not have its range narrowed. On the other hand, the SPEXP and SPCON parameters presented $p < 0.05$, and, therefore, they had their ranges narrowed. The best simulation results occurred when these parameters were closest to their lowest possible values. Parameters SPEXP and SPCON refer to the Bagnold equation 3, which determines the maximum amount of sediment transported by the streamflow.

Modeled sediment loads estimated that the Posses watershed contributes with 291 Mg yr^{-1} of sediment to the Jaguarí River, while the rating curve estimated that the sediment load is 274 Mg yr^{-1} . This corresponds to specific discharges of $24.28 \text{ Mg km}^{-2} \text{ yr}^{-1}$ for the simulations and $22.87 \text{ Mg km}^{-2} \text{ yr}^{-1}$ for the fluviometric data. Sediment loads and streamflow were larger during the calibration period than for the testing period (Figure 4).

In general, there is an acceptable correspondence between values estimated by SWAT and the observed data, which can be visualized in the dispersion charts and the efficiency

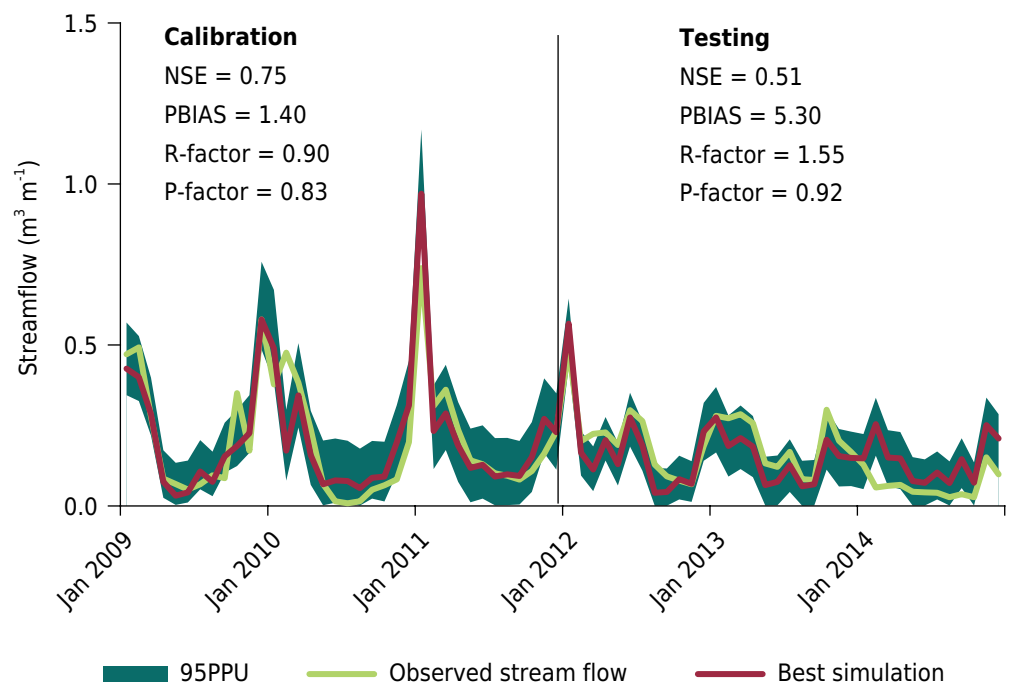


Figure 3. Observed and simulated monthly streamflow for calibration and testing periods with the evaluation indexes. Calibration period: January of 2009 to December of 2011; testing period: January of 2012 to December of 2014.

Table 3. Parameters used to calibrate the sediment load in Posses stream

Parameter ⁽¹⁾	Description	Initial range		Final range		Best simulation
		Minimum	Maximum	Minimum	Maximum	Fitted
v_SPEXP.bsn	Exponential parameter for calculating the sediment in channel routing.	1.0000	1.5	1.0000	1.111	1.012
v_SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	0.0001	0.0	0.0001	0.00083	0.000165
v_CH_COV2.rte	Channel cover factor	0.0001	1.0	0.0001	1.000	0.733

indexes (Figure 5). The largest discrepancies occurred in October 2009, December 2009, and October 2013, which correspond to the points highlighted in the scatter plot (Figure 5b). These points represent model underestimations, and, except for December 2009, it corresponds to underestimations of the streamflow.

Compared to the streamflow, there was less agreement between estimated and observed sediment loads. Nevertheless, the calibration and testing results were classified as satisfactory, with an R^2 of 0.59 for the whole period, a NSE of 0.65 for calibration, and 0.52 for testing. The PBIAS values also allowed us to classify the model as acceptable. It is classified as very good for calibration and satisfactory for testing, which means that the model had no tendency to overestimate or underestimate the predicted values.

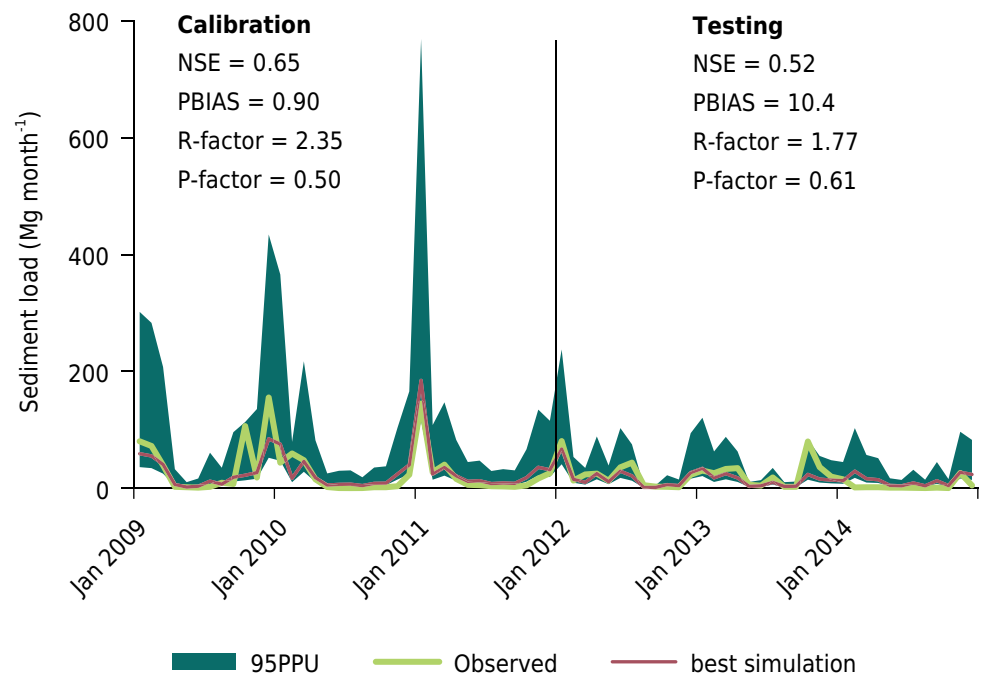


Figure 4. Observed and simulated sediment load for calibration and testing periods with the evaluation indexes. Calibration period: January of 2009 to December 2011; testing period: January 2012 to December 2014.

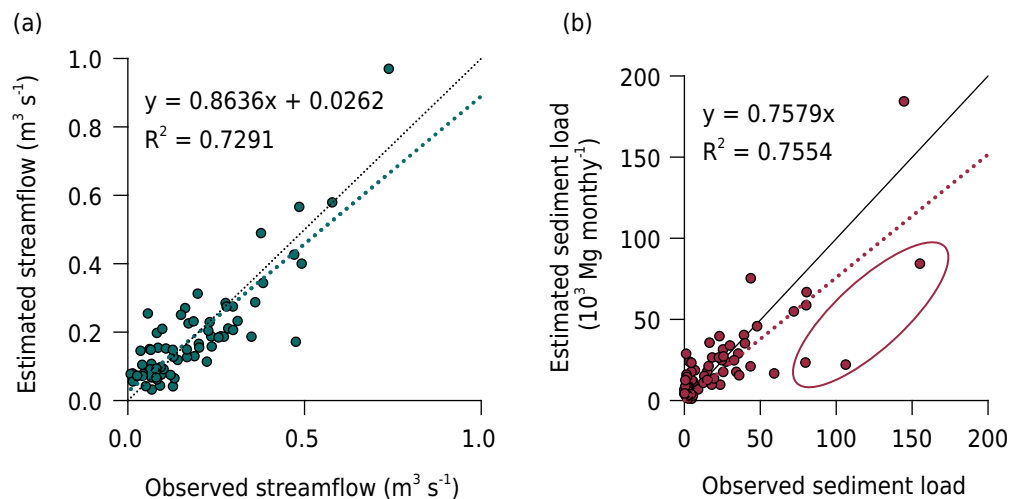


Figure 5. Observed and simulated monthly streamflow discharge (a) and sediment load (b) from Jan 2009 to Dec 2014. Circles highlight the points in which there was greater underestimation from the model simulations.

For the uncertainty analysis, the R-factor was above the recommended value (<1.5) (Abbaspour et al., 2015). The P-factor was also outside the desired range (>0.70). For the calibration period, the 95PPU, represented by the green band in the hydrograph, is quite wide. This means that the range of values of the parameters SP_EXP, SP_CON, and CH_COV2 resulted in a wide variation in the estimated sediment load. Nevertheless, the 95PPU encompassed only 50 % of the observed data (P-factor = 0.50). This result is mainly due to the minimum values of sediment load, for which the lower limit of the 95PPU was higher than the observed values.

Model evaluation against independent erosion plot data

Despite the satisfactory NSE results for the sediment loads simulations, the mean annual channel deposition in the PosSES creek was 7.625 Mg yr^{-1} , which corresponds to 97 % of the catchment sediment yield. By comparing the estimated specific sediment yield in HRUs with soil class, slope, and land use comparable to the erosion plots installed in the field, we observed that the model overestimated the soil losses by about 22 times. In the erosion plots, between November 2013 and December 2014, a total loss of $0.0818 \text{ Mg ha}^{-1}$ was measured. For the same period, the SWAT estimated a total loss of 1.832 Mg ha^{-1} . Further information about measured soil losses can be found in Bispo et al. (2017b), who observed an average annual soil loss of $0.058 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for the erosion plots in Ultisols with pastures and slope of 32 % in the PosSES catchment during two years of monitoring (2013-2015). For the same period, the soil losses in HRUs composed of Ultisols under pastures and slope between 20 and 45 % was $12 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, i.e., 200 times more than the observed in the field.

DISCUSSION

The SWAT model displayed satisfactory results for the monthly streamflow estimations in the PosSES creek catchment, although the performance was lower in the testing period. In 2014, southeastern Brazil experienced a severe drought, which may explain the overestimations obtained by the model. That is, the total annual rainfall in 2014 for the PosSES catchment was approximately 450 mm or 28 % lower than the long-term average (1652 mm). The decrease in model accuracy for the testing period indicates the model had difficulties providing adequate responses to climatic patterns not covered in the calibration period, which is a well-known issue for calibrated models (Oreskes and Belitz, 2001). The R-factor above the limit considered satisfactory in the testing period is likely explained by the small variation of the streamflow during the 2013/2014 drought, which is contrasting to streamflow behavior during the calibration period. This climatic anomaly might also be related to the NSE results for the testing period, which is at the limit of acceptability (0.5) (Moriassi et al., 2015).

Despite the high uncertainty associated with modeled sediment loads, these were still considered satisfactory. Higher R-factor and lower P-factor values are considered acceptable for modeling sediments due to the high complexity of erosion processes (Abbaspour et al., 2015). Moreover, modeling of erosion processes with SWAT tends to have worse results in small basins, as with monthly flow. In the study by Uzeika et al. (2012), the NSE values for sediment load were always negative; the same was true for a basin of 4.8 km^2 in southern Brazil (Bonumá et al., 2014). In both cases, SWAT overestimated sediment loads. One of the limitations of using the model in small catchments is that the time step of the simulations is often much larger than the catchment time of concentration. For the PosSES watershed, the time of concentration is about 3.5 hours, which limits the response of the model to the maximum flows (Viola et al., 2009). In this case, to obtain satisfactory NSE for sediment load simulations with SWAT, the SPCON parameter was minimized during calibration, which resulted in high values of channel sediment deposition.

Despite the satisfactory NSE results for the sediment load simulations, the SWAT model greatly overestimated erosion rates in the hillslopes and compensated them with high channel deposition rates, as revealed by the comparison between modeled and observed plot data. That is, while modeled sediment yields were much higher than the observed erosion rates, outlet sediment loads were not. Moreover, a 97 % channel deposition rate seems unrealistic considering the Posses catchment is characterized by steep channels with high transport capacity. In particular, we observed no signs of excessive channel or even floodplain deposition in the catchment during multiple field assessments. Hence, the high soil loss values in HRUs are possibly related to the overestimation of runoff peaks and the USLE parameters: USLE_K, USLE_C, USLE_P, and LS_USLE. Therefore, the modeled erosion rates could theoretically be improved with the adjustment of the USLE factors. However, varying the values of the USLE parameters had little impact on estimated sediment load, as showed by the OAT sensitivity analysis. Importantly, we used a wide range of possible USLE_K values, which were selected considering the specificities of the erodibility of tropical soils (Salvador Sanchis et al., 2009; Borselli et al., 2012; Avalos et al., 2018).

Since the landscape and routing sediment components are computed separately, landscape soil loss overestimations were compensated during calibration with a minimization of the SPCON Bagnold equation parameter, which lowered channel transport capacity. This meant that the amount of sediments that enter the stream from the hillslopes were always higher than the streamflow sediment transport capacity. Even the lowest hillslope sediment parameters values within the tested range did not affect the SWAT OAT sensitivity analysis. For this reason, we understood that SWAT was not able to represent the interaction between land cover (here represented by the USLE_C parameter) and erosion processes in our study area. Therefore, the model should not be used to simulate the impacts of reforestation in the context of the payment for environmental services program in the Posses catchment. As similar situations might arise elsewhere, we recommend that model users should be careful when using SWAT to simulate the effect of land cover on soil erosion and sediment transport, as the channel routing component will often compensate mispredictions of hillslope erosion rates.

To achieve more accurate estimation of erosion rates, an alternative would be to carry out the calibration in steps: first calibrating the parameters related to hillslope sediment yield and then the channel routing component, as performed by Vigiak et al. (2015). To calibrate the hillslope sediment yield component, it would be necessary to include commensurable soil redistribution data, which are uncertain and difficult to obtain (Batista et al., 2019). However, to avoid over-fitted models with poor representation of internal soil redistribution processes, we recommend that model conditioning should be based on multiple sources of data and with explicit representation of the uncertainty in models and observations of system responses (Beven and Binley, 2014; Beven, 2018; Batista et al., 2021).

Although the SWAT model was not able to represent the interaction between land cover and hillslope erosion, the results obtained with the SWAT for the Posses watershed can be used to estimate the sediment delivery to downstream watercourses and their contributions to reservoir sedimentation. This indicates that SWAT might be useful for calculating monthly streamflow and sediment load in small basins with complex relief. However, our results clearly demonstrate how the model can provide adequate estimates of sediment transport rates at catchment outlet while misrepresenting upstream processes. This issue is ultimately a consequence of equifinality (Beven, 2006), which is of course not exclusive to SWAT, and similar misrepresentations have been reported by others (van Oost et al., 2005; Govers, 2011; Batista et al., 2019).

CONCLUSIONS

We presented an evaluation of the SWAT model performance focusing on the sediment load and erosion processes in a southeastern Brazilian headwater catchment, which

hosts a pioneer program of payment for environmental services. Given the relevance of the project, the Posses catchment has been thoroughly monitored for hydrological and climatological studies. This monitoring provided detailed streamflow, rainfall, erosion, and sediment transport data, which enabled us to perform a thorough evaluation of SWAT, particularly of the model hillslope erosion component.

The SWAT model was calibrated and tested to estimate monthly streamflow. Coefficients used to evaluate the model were classified as good for calibration and satisfactory for testing, and the uncertainty width bands were also considered satisfactory.

Sediment load simulations also obtained satisfactory evaluation indexes for the calibration and testing periods. However, the uncertainty analysis revealed large prediction bands, which often failed to encompass the observed data. Moreover, the estimated hillslope sediment yields were excessively high in comparison with erosion plot data. This overestimation was compensated by the model channel routing component with a high deposition rate that minimized the difference between observed and estimated sediment loads. The model showed no sensitivity to the soil loss hillslope parameters and therefore could not represent the interaction between land cover and hillslope erosion catchment on sediment loads.

Hence, we recommend caution when using the SWAT model for estimating the impacts of land-use changes on soil erosion and sediment transport in small catchments. In such cases, the hillslope soil loss parameters should not be calibrated as usual, i.e., using sediment load measurements from catchment outlet and simultaneously with channel routing parameters. For calibrating SWAT, and distributed/semi-distributed soil erosion and sediment transport models in general, it should be necessary to include multiple sources of internal erosion data. If model users continue to rely on the common outlet-based approach for model calibration and testing, models might often provide the right answer for the wrong reasons, as we have shown.



SUPPLEMENTARY DATA



Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-45-e0200140/1806-9657-rbcs-45-e0200140-suppl01.pdf




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REFERENCES

- Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Kløve B. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *J Hydrol.* 2015;524:733-52. <https://doi.org/10.1016/j.jhydrol.2015.03.027>
- Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *J Hydrol.* 2007;333:413-30. <https://doi.org/10.1016/j.jhydrol.2006.09.014>
- Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. Köppen's climate classification map for Brazil. *Meteorol Zeitschrift.* 2013;22:711-28. <https://doi.org/10.1127/0941-2948/2013/0507>
- Aragão R, Cruz MAC, Amorim JRA, Mendonça LC, Figueiredo EE, Srinivasan VS. Análise de sensibilidade dos parâmetros do modelo SWAT e simulação dos processos hidrossedimentológicos em uma bacia no agreste nordestino. *Rev Bras Cienc Solo.* 2013;37:1091-102. <https://doi.org/10.1590/S0100-06832013000400026>
- Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, Santhi C, Harmel RD, van Griensven A, van Liew MW, Kannan N, Jha MK. SWAT: Model use, calibration, and validation. *Trans ASABE.* 2012;55:1491-508. <https://doi.org/10.13031/2013.42256>
- Arnold JG, Srinivasan R, Muttiah RS, Williams JR. Large area hydrologic modeling and assessment part I: Model development. *J Am Water Resour Assoc.* 1998;34:73-89. <https://doi.org/10.1111/j.1752-4991688.1998.tb05961.x>
- Avalos FAP, Silva MLN, Batista PVG, Pontes LM, Oliveira MS. Digital soil erodibility mapping by soilscape trending and kriging. *Land Degrad Dev.* 2018;29:3021-8. <https://doi.org/10.1002/ldr.3057>
- Bagnold RA. Bedload transport in natural rivers. *Water Resour Res.* 1997;13:303-12.
- Batista PVG, Davies J, Silva MLN, Quinton J. On the evaluation of soil erosion models: Are we doing enough? *Earth Sci Rev.* 2019;197:102898. <https://doi.org/10.1016/j.earscirev.2019.102898>
- Batista PVG, Laceby JP, Davies J, Carvalho TS, Tassinari D, Silva MLN, Curi N, Quinton JN. A framework for testing large-scale distributed soil erosion and sediment delivery models: Dealing with uncertainty in models and the observational data. *Environ Model Softw.* 2021;137:104961. <https://doi.org/10.1016/j.envsoft.2021.104961>
- Beven KJ. On hypothesis testing in hydrology: Why falsification of models is still a really good idea. *WIREs Water.* 2018;5:e1278. <https://doi.org/10.1002/wat2.1278>
- Beven KJ. A manifesto for the equifinality thesis. *J Hydrol.* 2006;320:18-36. <https://doi.org/10.1016/j.jhydrol.2005.07.007>
- Beven K, Binley A. GLUE: 20 years on. *Hydrol Process.* 2014;28:5897-918. <https://doi.org/10.1002/hyp.10082>

- Bispo DFA, Silva MLN, Marques JJGSM, Bechmann M, Batista PVG, Curi N. Phosphorus transfer at a small catchment in southeastern Brazil: distributed modelling in different land use scenarios. *Cienc Agrotec*. 2017a;41:565-79. <https://doi.org/10.1590/1413-70542017415012217>
- Bispo DFA, Silva MLN, Pontes LM, Guimarães DV, Marques JJGSM, Curi N. Soil, water, nutrients and soil organic matter losses by water erosion as a function of soil management in the Posses sub-watershed, Extrema, Minas Gerais, Brazil. *Semina*. 2017b;38:1813-24. <https://doi.org/10.5433/1679-0359.2017v38n4p1813>
- Bonumá NB, Reichert JM, Rodrigues MF, Monteiro JAF, Arnold JG, Srinivasan R. Modeling surface hydrology, soil erosion, nutriente transport, and future scenarios with the ecohydrological SWAT model in Brazilian watersheds and river basins. In: Nascimento CWA, Souza Júnior VS, Freire MBGS, Souza ER, editores. *Tópicos em ciência do solo*. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2015. v. 9. p. 241-90.
- Bonumá NB, Rossi CG, Arnold JG, Reichert JM, Minella JP, Allen PM, Volk M. Simulating landscape sediment transport capacity by using a modified SWAT Model. *J Environ Qual*. 2014;43:55-66. <https://doi.org/10.2134/jeq2012.0217>
- Borselli L, Torri D, Poesen J, Jaquinta P. A robust algorithm for estimating soil erodibility in different climates. *Catena*. 2012;97:85-94. <https://doi.org/10.1016/j.catena.2012.05.012>
- Bressiani DA, Gassman PW, Fernandes JG, Garbosa LHP, Srinivasan R, Bonumá NB, Mediondo EM. Review of soil and water assessment tool (SWAT) applications in Brazil: Challenges and prospects. *Int J Agric Biol Eng*. 2015;8:9-35. <https://doi.org/10.3965/j.ijabe.20150803.1765>
- Fukunaga DC, Cecílio RA, Zanetti SS, Oliveira LT, Caiado MAC. Application of the SWAT hydrologic model to a tropical watershed at Brazil. *Catena*. 2015;125:206-13. <https://doi.org/10.1016/j.catena.2014.10.032>
- Govers G. Misapplications and misconceptions of erosion models. In: Morgan RPC, Nearing MA, editors. *Handbook of erosion modeling*. Chichester: Blackwell Publishing Ltd; 2011. p. 117-34.
- Lal R. Soil degradation by erosion. *Land Degrad Develop*. 2001;12:519-39. <https://doi.org/10.1002/ldr.472>
- Melaku ND, Renschler CS, Holzmann H, Strohmeier S, Bayu W, Zucca C, Ziadat F, Klik A. Prediction of soil and water conservation structure impacts on runoff and erosion processes using SWAT model in the northern Ethiopian highlands. *J Soils Sediments*. 2017;18:1743-55. <https://doi.org/10.1007/s11368-017-1901-3>
- Monteiro JAF, Strauch M, Srinivasan R, Abbaspour K, Gücker B. Accuracy of grid precipitation data for Brazil: application in river discharge modelling of the Tocantins catchment. *Hydrol Processes*. 2015;30:1419-30. <https://doi.org/10.1002/hyp.10708>
- Moriasi DN, Gitau MW, Pai N, Daggupati P. Hydrologic and water quality models: performance measures and evaluation criteria. *Trans ASABE*. 2015;58:1763-85. <https://doi.org/10.13031/trans.58.10715>
- Oreskes N, Belitz K. Philosophical issues in model assessment. In: Anderson MG, Bates PD, editors. *Model validation: Perspectives in hydrological science*. Nova Jersey: John Wiley & Sons; 2001. p. 23-41.
- Rice EW, Baird RB, Eaton AD, Clesceri LS. *Standard methods for the examination of water and wastewater*. 2nd ed. Washington, DC: APHA; 2012.
- Richards RC, Rerolle J, Aronson J, Pereira PH, Gonçalves H, Bracalioni, PHS. Governing a pioneer program on payment for watershed services: Stakeholder involvement, legal frameworks and early lessons from the Atlantic forest of Brazil. *Ecosyst Serv*. 2015;16:23-32. <https://doi.org/10.1016/j.ecoser.2015.09.002>
- Roth V, Nigussie TK, Lemann T. Model parameter transfer for streamflow and sediment loss prediction with SWAT in a tropical watershed. *Environ Earth Sci*. 2016;75:1321. <https://doi.org/10.1007/s12665-586 016-6129-9>
- Salvador Sanchis MP, Torri D, Borselli L, Bryan R, Poesen J, Yañez MS, Cremer C. Estimating parameters of the channel width-flow discharge relation using rill and gully channel junction data. *Earth Surf Process Landf*. 2009;34:2023-30. <https://doi.org/10.1002/esp.1887>

- Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbrreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.
- Silva BPC, Silva MLN, Avalos FAP, Menezes MD, Curi N. Digital soil mapping including additional point sampling in Posses ecosystem services pilot watershed, southeastern Brazil. *Sci Rep*. 2019;9:13763. <https://doi.org/10.1038/s41598-019-50376-w>
- Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2014.
- Spruill CA, Workman SR, Taraba JL. Simulation of daily and monthly stream discharge from small watersheds using the SWAT model. *Trans ASABE*. 2000;43:1431-9. <https://doi.org/10.13031/2013.3041>
- Telles TS, Guimarães MF, Dechen SCF. The costs of soil erosion. *Rev Bras Cienc Solo*. 2011;35:287-98. <https://doi.org/10.1590/S0100-06832011000200001>
- Uzeika T, Merten GH, Minella JPG, Moro M. Use of the SWAT model for hydrosedimentologic simulation in a small rural watershed. *Rev Bras Cienc Solo*. 2012;36:557-65. <https://doi.org/10.1590/S0100-59506832012000200025>
- van Oost K, Govers G, Cerdan O, Thauré D, van Rompaey A, Steegen A, Nachtergaele J, Takken I, Poesen J. Spatially distributed data for erosion model calibration and validation: The Ganspoel and Kinderveld datasets. *Catena*. 2005;61:105-21. <https://doi.org/10.1016/j.catena.2005.03.001>
- Vigiak O, Malagó A, Bouraoui F, Vanmaercke M, Poesen J. Adapting SWAT hillslope erosion model to predict sediment concentrations and yields in large Basins. *Sci Total Environ*. 2015;538:855-75. <https://doi.org/10.1016/j.scitotenv.2015.08.095>
- Viola MR, Mello CR, Acerbi FW, Silva AM. Modelagem hidrológica na bacia hidrográfica do Rio Aiuruoca, MG. *Rev Bras Eng Agric Ambient*. 2009;13:581-90. <https://doi.org/10.1590/S1415-60343662009000500011>
- Williams JR. Sediment routing for agricultural watershed. *Water Resour*. 1975;11:965-74. <https://doi.org/10.1111/j.1752-6061688.1975.tb01817.x>
- Zuo D, Xu Z, Yao W, Jin S, Xiao P, Ran D. Assessing the effects of changes in land use and climate on runoff and sediment yields from a watershed in the Loess Plateau of China. *Sci Total Environ*. 2016;544:238-50. <https://doi.org/10.1016/j.scitotenv.2015.11.060>

COMPLEMENTARY MATERIAL

Sediment load data

Between July 2015 and June 2016, 80 water samples were collected from Posses stream. The samples were filtered, the filtered residue was dried and weighed to obtain the suspended solids. This measure was compared with the average streamflow of the respective day to estimate the discharge of solids (sediment load) in tons per day. A further 25 turbidity data provided by National Agency of Water were also used for the period between November 2008 and June 2016. The data set is shown in Fig. 1.

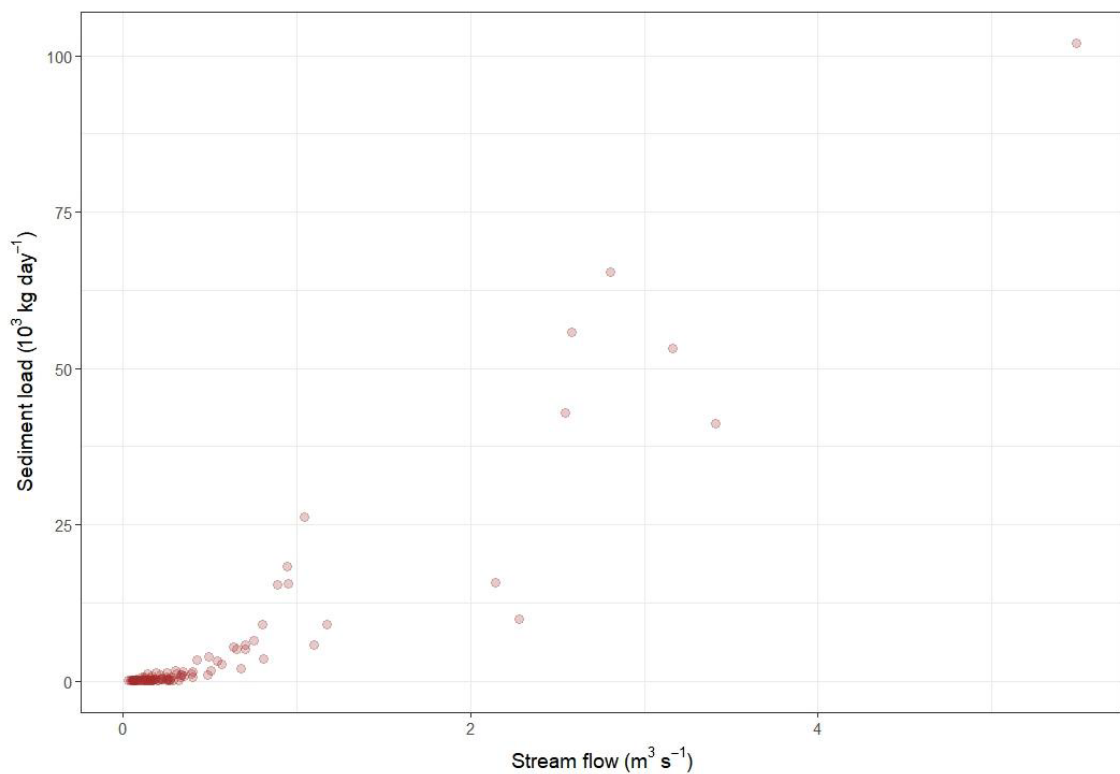


Fig. 1 Sediment load versus streamflow observed at Posses stream for the period of November 2008 to June 2016.

For the period used in the SWAT simulations (2009 to 2015) the average flow rate was $0.17 \text{ m}^3 \text{ s}^{-1}$. The maximum daily flow observed was $3.81 \text{ m}^3 \text{ s}^{-1}$. This is an important information since we can verify that this maximum observed flow is contained in the range of values used to construct the discharge curve. In this way, we have less uncertainty for high values of estimated sediment load. Most data refer to low flow rates and small sediment load. To improve the visualization of the low streamflow data, a graph was plotted only with streamflow less than 1 (Fig. 2).

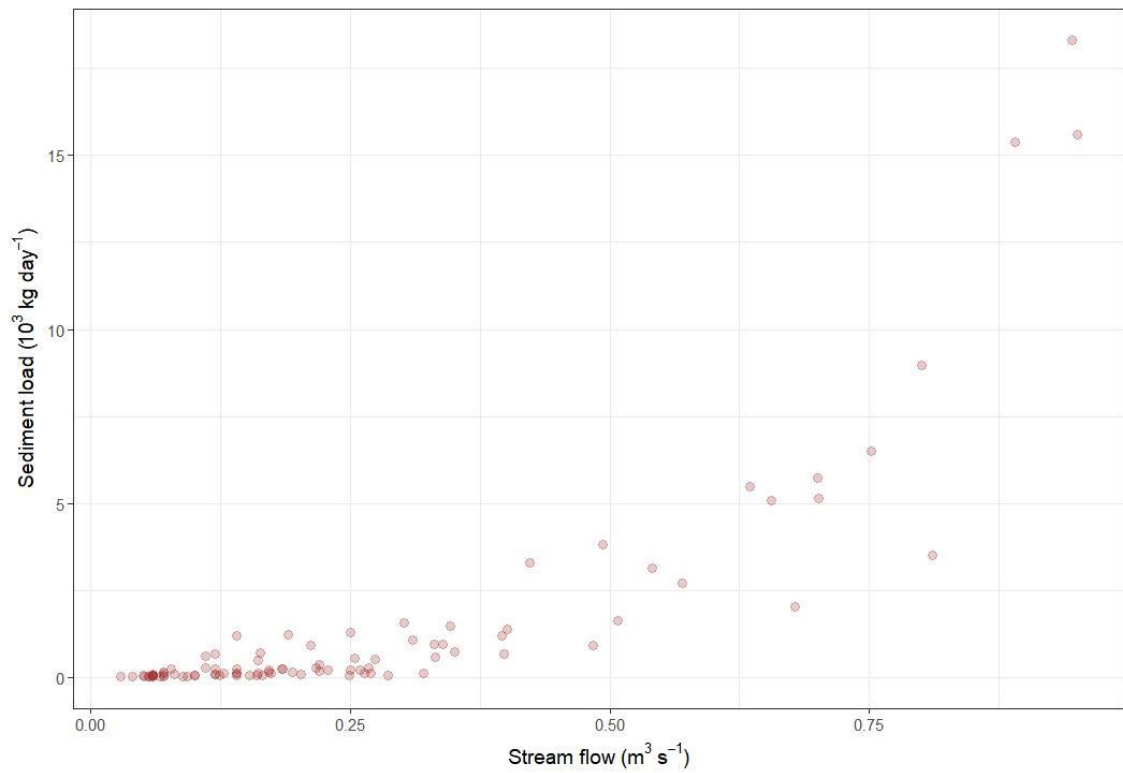


Fig. 2 Sediment load for streamflow less than $1 \text{ m}^3 \text{s}^{-1}$.

In Fig. 2 we also observe the exponential pattern of the data, which is also evident when observing the sediment load histogram (Fig. 3).

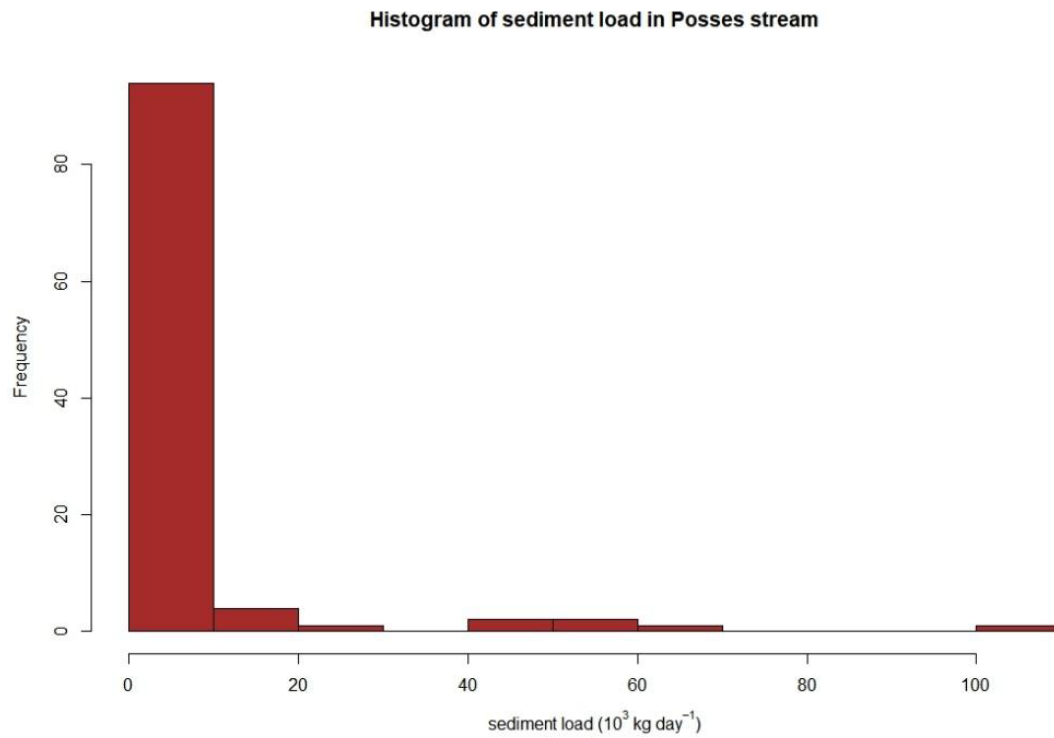


Fig.3 Histogram of the sediment load raw data.

Due to the non-normal distribution of data, the logarithmic transformation was used to linearize the data and adjust a linear regression. In Fig. 4 are presented the histogram of the transformed sediment load data.

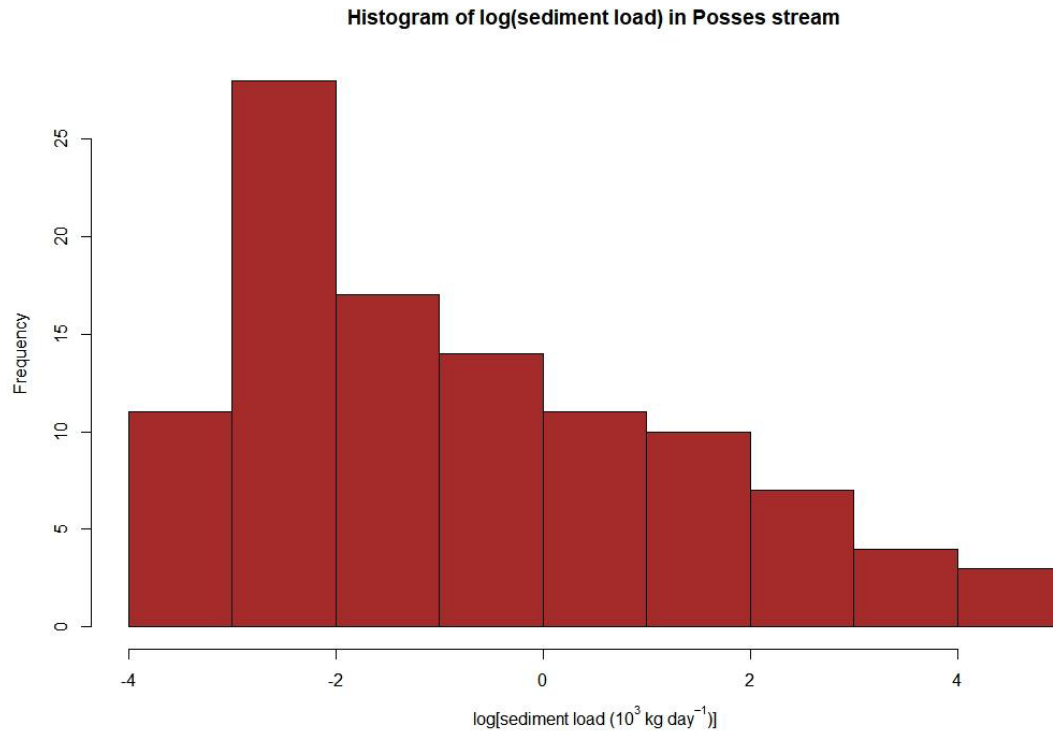


Fig. 4 Histogram of the transformed sediment load data.

Even with the transformation the distribution still presents left skewness. However, the fitted linear regression was satisfactory, as observed in the Fig. 5.

Fitting sediment load curve

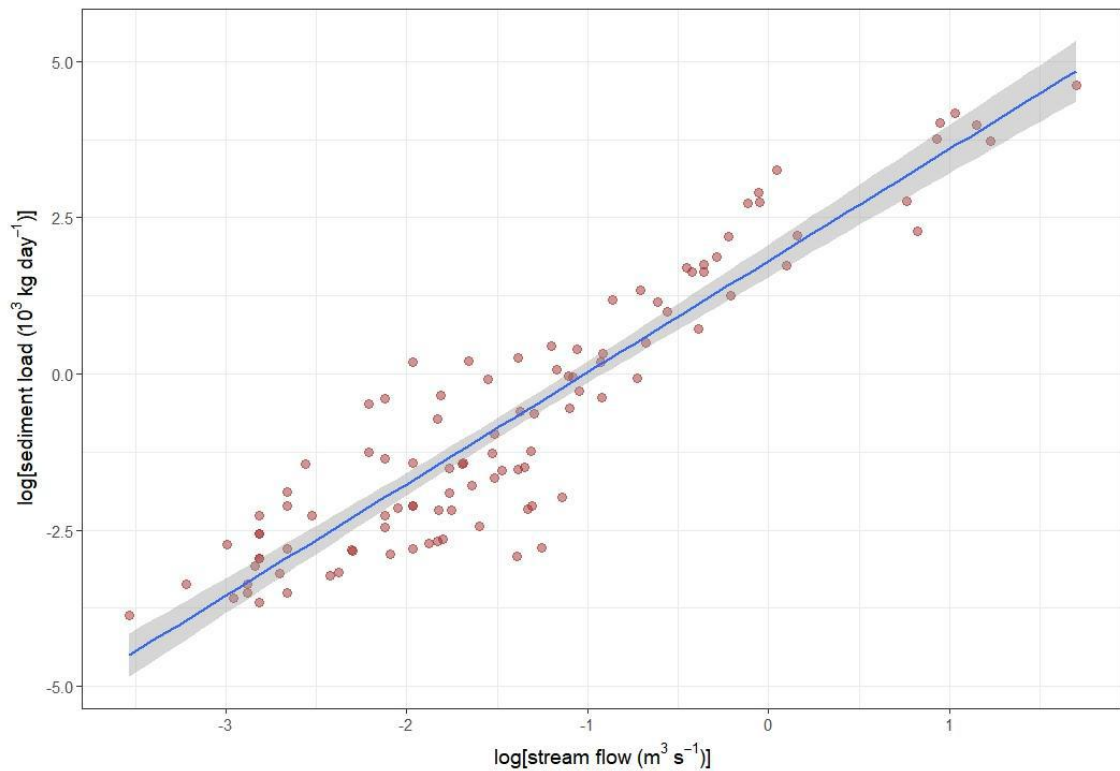


Fig. 5 Linear regression for log transformed streamflow and sediment load data. The grey area represents the confidence interval with 95% around the regression line.

Graphically it is possible to observe a good fit of the regression, which can be proved by the adjusted R-squared coefficient of 0.85. In our manuscript we present the exponential regression curve and the original data, with the same coefficients here presented. The intercept, the angular coefficient and the coefficient of determination were statistically significant, with $p\text{-value} < 2.2\text{e-}16$. Furthermore, model assumptions were test with the gvlma R package function (Table 1).

Table 1. Results of the tests for assessing modeling assumptions.

	Value	p-value	Decision
Global Stat	4.89	0.2987	Assumptions acceptable
Skewness	1.34315	0.2465	Assumptions acceptable
Kurtosis	0.00609	0.9378	Assumptions acceptable
Link Function	3.37756	0.0661	Assumptions acceptable
Heteroscedasticity	0.16359	0.6859	Assumptions acceptable

In Fig. 6 the QQplot of the residues is presented, which support the assumption of normality of the residuals.

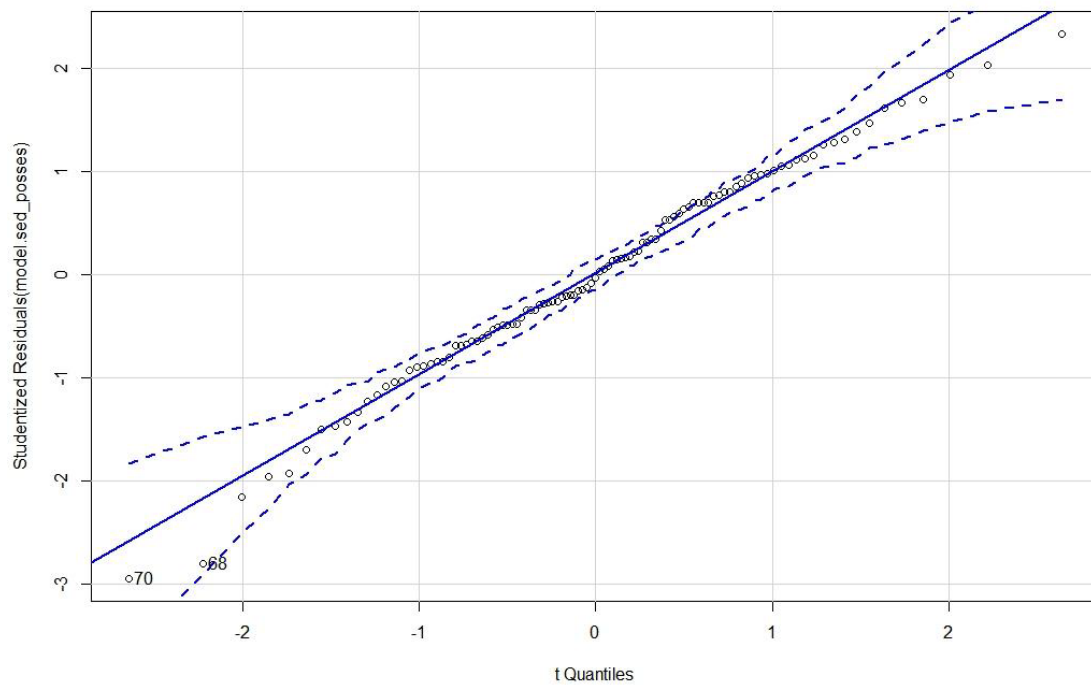


Fig. 6 Quantile-Quantile plot of the residuals.

Fig. 7 shows residues against estimated values. The lack of pattern in the points distribution support the linear regression assumptions.

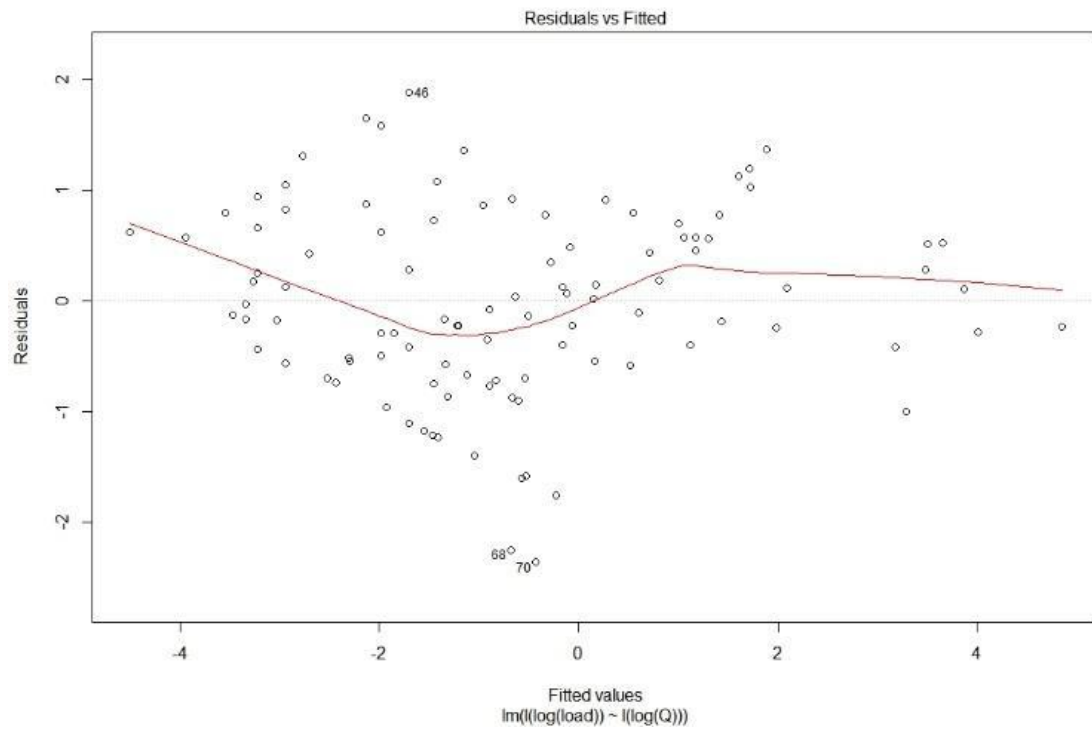


Fig. 7. Plot of the residual versus fitted values.

Thus, we conclude that the fitted sediment load curve obtained with the field data presents a good fit and adequately represents the phenomenon in the study area. This information is crucial to the quality of our work as it provides the data used to calibrate and validate the SWAT model.