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No-tillage implementation: Analyzis on water-based sediment flow in the Marombas River, Brazil[1]

Implantação da semeadura direta: Análise do fluxo de sedimentos na água do Rio Marombas, Brasil

Eder A. S. Sá[2*], Ildegardis Bertol[3], Silvio L. Rafaeli Neto[4] & Daiane T. Schier[2]

[1] Research developed at Canoas River Basin, SC, Brazil
[2] Universidade do Estado de Santa Catarina/Centro de Ciência Agroveterinárias, Lages, SC, Brazil
[3] Universidade do Estado de Santa Catarina/Centro de Ciência Agroveterinárias/Departamento de Solos e Recursos Naturais, Lages, SC, Brazil
[4] Universidade do Estado de Santa Catarina/Centro de Ciência Agroveterinárias/Departamento de Engenharia Ambiental e Sanitária, Lages, SC, Brazil

HIGHLIGHTS:
The Soil Water Assessment Tools was suitable to represent the average daily flow and sediment flow in the Marombas watershed.
The hypothesis of reduced concentration of suspended solids (CSS) with increasing soil crop in the form of no-tillage system was accepted.
The alteration of the cultivation system along the watershed affected the CSS in the watershed outlet.

ABSTRACT: Water erosion is influenced by climate, soil, soil cover and soil conservation practices. These factors can be modified by natural (especially climate) and/or anthropogenic (especially soil, soil cover and conservation practices) actions. The relief factor also influences the water erosion and can also be partially modified by anthropic action. This study aimed to evaluate the impact of anthropogenic action due to the introduction of soil crop in no-tillage system on water erosion, and on the consequent flow of sediments in the water. The study was carried out in the Marombas river basin with an area of 3,939 km², using the Soil Water Assessment Tools (SWAT) model. The calibration and validation of the model for sediment production was carried out with a historical series of synthetic data. The data from this series were estimated by linear regression from sediment value load and the average daily flow obtained punctually in the basin's outlet. The SWAT model was calibrated on a daily scale with data from 1979 to 1989 and was validated with data from 1994 and 1997. The SWAT model was suitable to represent the average daily flow and sediment flow in the Marombas watershed. The hypothesis of reduced sediment production with increasing soil crop in no-tillage system was accepted.

Key words: soil conservation, erosion, hydrological modelling, Nash-Sutcliffe, SWAT model

RESUMO: A erosão hídrica é influenciada pelos fatores clima, solo, cobertura do solo e práticas de conservação do solo. Esses fatores podem ser modificados por ações naturais (especialmente o clima) e/ou antrópicas (especialmente o solo, a cobertura do solo e as práticas conservacionistas). O fator relevo também influencia a erosão hídrica e pode também ser parcialmente modificado pela ação antrópica. Com este estudo objetivou-se avaliar o impacto da ação antrópica devido ao cultivo do solo no sistema de semeadura direta sobre a erosão hídrica, e sobre o consequente fluxo de sedimentos na água. O estudo foi realizado no canal que drena a bacia hidrográfica do rio Marombas com área de 3,668 km², utilizando-se o modelo Soil Water Assessment Tools (SWAT). A calibração e validação do modelo para a produção de sedimentos foi realizada com uma série histórica de dados sintéticos. Os dados dessa série foram estimados por regressão linear a partir de valores da carga de sedimentos e da vazão média diária obtidos pontualmente no exutório da bacia. O modelo SWAT foi calibrado em escala diária com dados de 1979 a 1989 e foi validado com dados de 1994 e 1997. O modelo SWAT foi adequado para representar o fluxo médio diário e o fluxo de sedimentos na bacia hidrográfica do rio Marombas. A hipótese de redução da produção de sedimentos com o aumento do cultivo do solo no sistema de semeadura direta foi aceita.

Palavras-chave: conservação solo, erosão, modelagem hidrológica, Nash-Sutcliffe, modelo SWAT

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* Corresponding author - E-mail: eder.alexandre.ef@gmail.com
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Introduction

Water erosion is the most intense form of soil degradation, reducing its productive capacity and causing serious environmental damage (Dechen et al., 2015; Erkossa et al., 2015; Nigussie et al., 2017). Soil crop increases soil losses (SL) in relation to forest areas and the no-tillage (NT) reduce SL in relation to conventional tillage (CT) (Schick et al., 2017). Soil crop is based on soil mechanic mobilization reduces the ground cover in relation to the forest, with reduced plant biomass (Tiecher, 2015).

The area under NT for annual crops increased from 1,350,000 ha in 1992 to 14,000,000 ha in the year of 2018 (FEBRAPDP, 2021). The NT in 2014 was present around 86% of the Brazilian agricultural area of soy, corn (1st harvest) and beans (1st harvest) reducing the process of erosion and siltation of water resources (EMBRAPA, 2018).

Water erosion is the result of a combination of factors: climate, soil, topography, soil cover and management, and conservation practices (Rodrigues et al., 2017). These factors vary in temporal and spatial scale, which makes water erosion spatially dependent. The scale is important over runoff and erosion. That is why, the definition of scale relationships as well as knowledge of the processes governing water and sediment flows at each scale is critical to water and soil management (Mayor et al., 2011).

This study aimed to test the hypothesis that the implementation of no-tillage (NT) in reduce water erosion in relation to the forest area, reducing impact inherent to the erosion process, due to the reducing impact of anthropic action on the soil in relation to the non-anthropic area.

The present study was carried out to evaluate the effect of the implementation of no-tillage on water-based sediment flow in the Marombas River basin region.

Material and Methods

The study was conducted in the Marombas River Basin (BHM), inserted in the Canoas River Basin, located between the geographic coordinates 26° 45' 20" and 27° 21' 00" south latitude and between 51° 02' 10" and 50° 10' 35" of west longitude in the mountainous region of the Santa Catarina state. According to the Köppen (1918), the climate of the region is of "Cfb" type, humid, subtropical humid, with average annual temperature between 13.4 and 16.4 °C, average annual precipitation of 1,650 mm and annual average relative humidity between 71 and 83%.

The basin's main channel is the Marombas River, one of the main tributaries of the Canoas River, with a length of 109 km and a contribution area of approximately 3,668 km². The main soil types found in the study region are Ultisols (55%) and Inceptisols (28%) (USDA, 1999).

With respect to orography, the slope is higher in the higher areas are located at the highest points in the north and east of the basin near the General Saw escarpment.

The main input hydrological data in the Soil and Water Assessment Tools (SWAT) model are rain, flow and climate, used for the calculation of evapotranspiration (Winchell et al., 2009). Data selection criteria were quality, frequency of failure in the historical series, and number of rain stations with valid data.

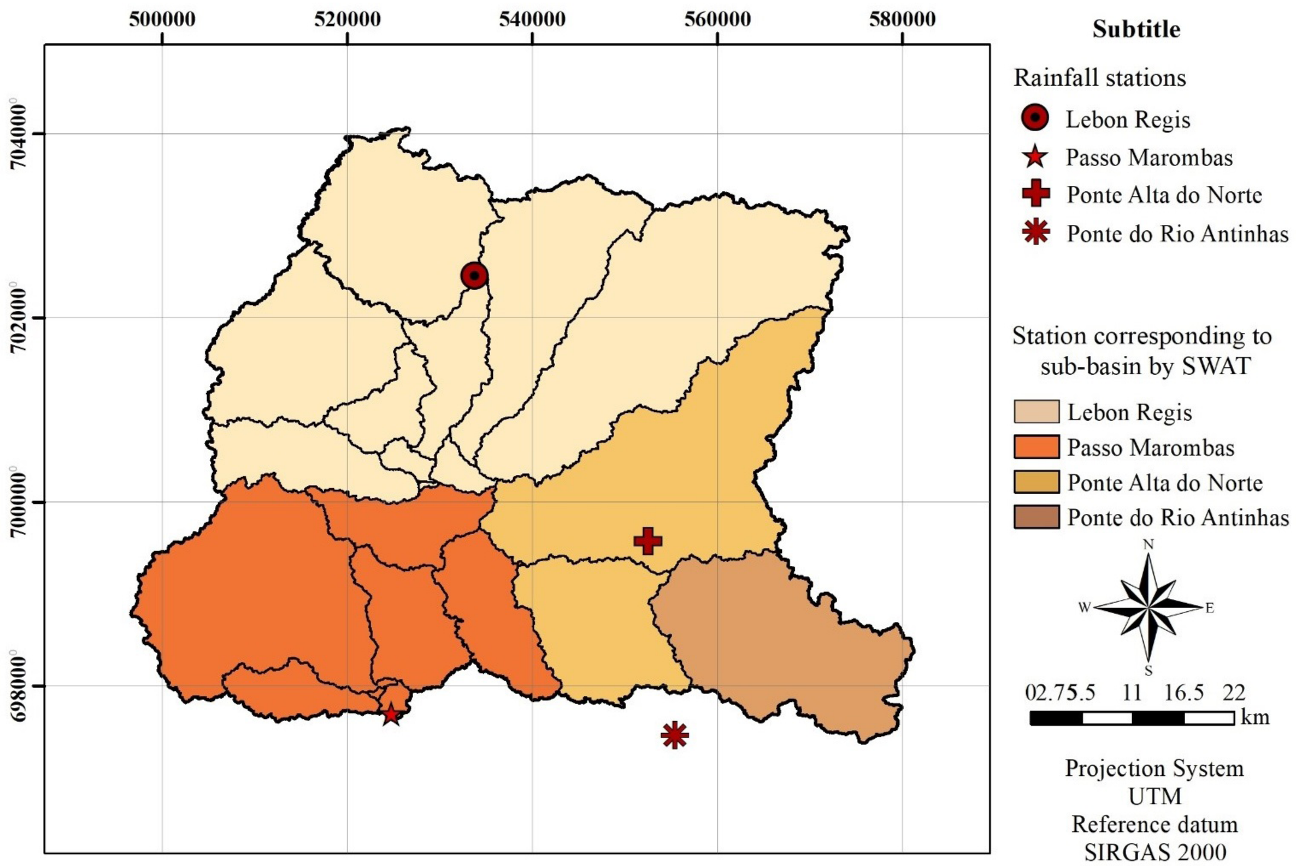


Figure 1. Location of flow rates in BHM

Daily rainfall data for the calibration (1977-1989) and validation (1993-1997) period of the model were obtained from the Passo Marombas, Antinhas River Bridge, Ponte Alta and Lebon Régis Stations and the flow rates of the Passo Marombas Fluviometric Station located in the watershed (Figure 1).

Potential evapotranspiration daily, for the same period, was calculated by the Penman-Monteith method. For the maximum and minimum temperature, relative humidity, solar radiation and wind speed, daily data from Agricultural Research and Rural Extension Company of Santa Catarina (EPAGRI), Santa Catarina Environmental Resources and Hydrometeorology Information Center (CIRAM), National Institute of Meteorology (INMET) of Lages city were used.

The historical series of suspended sediments observed was in the Passo Marombas river station, which had point measurement data. Data from 84 measurements from 1978 up to 2017 were used. These data were converted into mass flow from the Eq. 1:

$$F = 86.4\ Q\ CSS \tag{1}$$

where:

F - mass flow in the section, kg day^{-1};
Q - flow, $m^3\ s^{-1}$; and,
CSS - concentration of suspended solids, mg L^{-1}.

The mass flow data (F) were correlated with the flow data (Q) in order to obtain the regression equation used to construct the estimated sediment values of data series for sediments loss.

Thus, two regression equations were defined. The first was obtained from the historical series from 1978 up to 2017 and was used to estimate sediment flow data for the model calibration period from 1977 up to 1989. The second equation was obtained based on data from 1993 up to 2017 and was used to estimate sediment flow data for the model validation period between 1993 and 1997.

For this study was used the SWAT model, appropriate to assess the impact of land use change on medium and large river basins (Arnold et al., 2012), calibrated and validated at the Passo Marombas river station for the average daily flow and sediment loss variables. SWAT is a continuous-time, semi-distributed, process-based river basin- or watershed-scale model (Melaku et al., 2018), and allows you to divide the basin into sub-basins, which can be parameterized based on the concept of Hydrologic Response Units (HRU's).

The model estimates evapotranspiration, runoff, peak runoff rate, groundwater flow and sediment loss for each URH. The SWAT simulated water balance was obtained by Eq. 2 (Winchell et al., 2009):

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \tag{2}$$

where:

SWt - final amount of soil water (mm);
SW0 - initial soil moisture on day i (mm);
t - time (day);
Rday - amount of rain on day i (mm);
Qsurf - total runoff on day i (mm);
Ea - amount of evapotranspiration on day i (mm);
Wseep - amount of water entering the soil profile aeration zone on day i (mm); and,
Qgw - amount of flow return on day i (mm).

The theoretical documentation describing the wording, input and output data and use of the ArcSWAT interface can be accessed on the SWAT website (Winchell et al., 2009).

For model calibration and validation, SWAT-CUP software was used and SUFI-2 as a method of uncertainty analysis, because, it requires fewer executions to reach a good range of forecasting uncertainties when compared to other available methods in the SWAT (Yang et al., 2008; Nkonge et al., 2014; Hallouz et al., 2018).

The model was calibrated with daily data observed of eleven years, from 1979 to 1989, considering a warming period with data of two years (1977 and 1978) in order to capture the previous soil moisture conditions. The validation period comprised data from 1994 and 1997 considering 1993 data as warming.

The choice of parameters used for model calibration was based on literature review and parameter sensitivity analysis (Santhi, 2001; Yang, 2008; Bueno et al., 2017). The literature review indicated the most commonly used parameters and the sensitivity analysis provided more detailed information about the importance and representativeness of each of these parameters for BHM. Table 1 shows the parameters evaluated for model calibration.

The performance indexes used to measure the accuracy of the model were: Nash and Sutcliffe index (NSE) and bias percentage (Pbias), according to the Eqs. 3 and 4.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \tag{3}$$

Table 1. Parameters used for SWAT model calibration

Parameters evaluated for daily average flow calibration ($m^3\ s^{-1}$)	
ALPHA_BF	Base flow alpha factor (day)
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
GW_REVAP	Groundwater revap coefficient
REVAPMN	Threshold depth of water in the shallow aquifer required for revap to occur (mm)
CH_N2	Manning coeficiente for main channel
CH_K2	Effective channel hydraulic conductivity (mm h^{-1})
ALPHA_BNK	Margin flow recession constant
OV_N	Overland Manning roughness
ESCO	Soil evaporation compensation factor
EPCO	Plant absorption compensation factor
CH_N1	Manning coeficiente for channel tributary
CH_K1	Effective channel tributary hydraulic conductivity (mm h^{-1})
SURLAG	Runoff delay coefficient
SOL_K	Soil saturated hydraulic conductivity (mm h^{-1})
SOL_AWC	Available water capacity of the soil layer (mm mm^{-1})
Parameters evaluated for calibration of sediment production (ton)	
SPEXP	Expoent parameter for calculating the channel sediment routing
SPCON	Linear parameter for calculating the channel sediment routing
CH_ERODMO	Channel erodibility factor
PRF_BSN	Maximun Flow Rate Adjustment Factor
USLE_K	Soil erodability factor

$$P_{bias} = \frac{\sum_{i=1}^{n}(O_i - S_i)}{\sum_{i=1}^{n}(\bar{O})}100 \quad (4)$$

where:

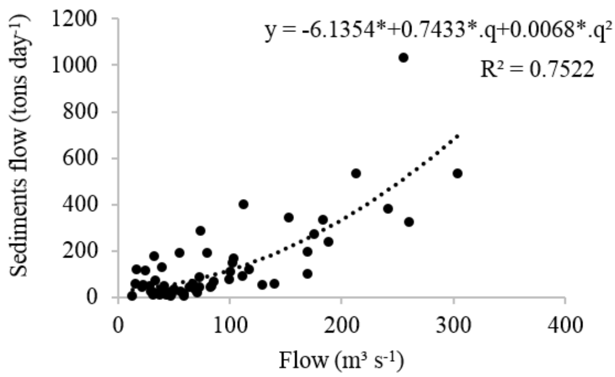
n - number of days of observation;
O_i - observed flow rate of the seventh day;
S_i - simulated flow for the th day;
O - average observed flow i in period n; and,
S - the simulated average flow in period i.

The hypothesis that the implementation of soil crop from the 1990's on increases sediment loss in the BHM was evaluated based on the statistical analysis of the historical sediment flow series available for the Passo Marombas river station and based on the differences found between the calibration period (1977-1989) and validation period (1993-1997) of the model.

Results and Discussion

The linear regression equation adjusted to the observed and estimated sediment used in this study is presented in Figure 2 (R^2 = 0.7522). This means that this model has a high capacity to estimate sediment flow, and that these results justify the use of historical sediment series synthetically obtained by this type of regression equation for SWAT calibration.

The Nash-Sutcliffe (NSE) values found for the calibration and validation periods indicated a good fit between the estimated and observed flow values by the model (Table 2). NSE values in relation to their performance was very good (NSE ≥ 0.65), good (0.65 > NSE ≥ 0.54) and satisfactory (0.54 > NSE ≥ 0.50) according with Santhi et al. (2001). According to this classification, NSE values of 0.91 for calibration and 0.74 for validation indicate a very good modelling performance.



* Significant at p ≤ 0.05 by t test

Figure 2. Correlation between observed flow sediment flow

Table 2. Values of performance indexes in the calibration and validation of the SWAT model for average daily flow and sediments loss

	Flow		Sediments	
	Calibration	Validation	Calibration	Validation
Nash-Sutclife	0.91	0.74	0.71	0.52
Pbias	0.20	-0.80	-23.9	-39.9

*Pbias - Percent Bias

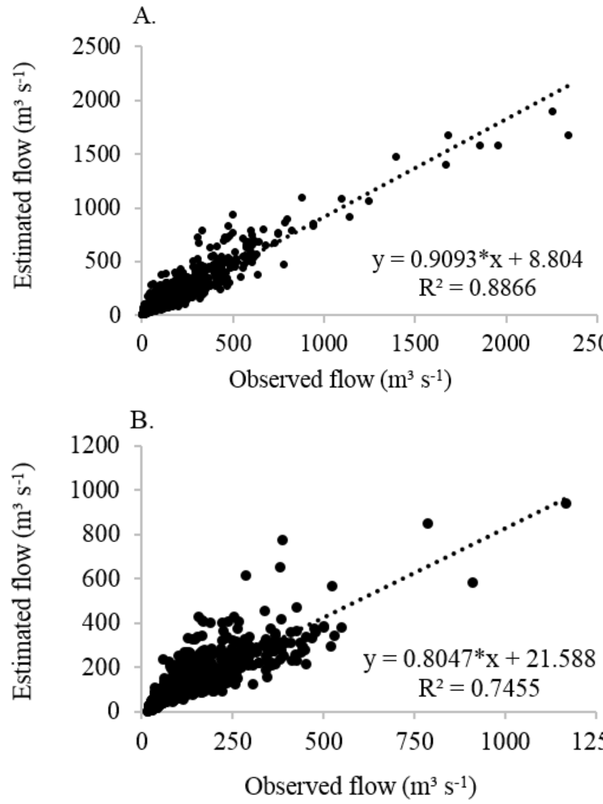
However, the model in some cases showed poor fit between these variables (Blainski et al., 2017), compromising the relationship between estimated and observed values with base in NSE index. In some months it was noted that the peaks of observed flow rates were not well represented. This fact may be associated with key curve extrapolation problems and not exclusively the flow or rain measurements.

Pbias (Percent bias) values also showed good adherence between the estimated and observed data by the model. The ideal value for Pbias is 0 (zero), with negative values indicating that the model underestimates the flow and positive values overestimate the same (Bueno et al., 2017). In the present case, there was a small overestimation of the flow values in the calibration period (0.2%) and a short underestimation in the validation period (-0.8%). According to Blainski et al. (2017), based on the Pbias index the swat model showed good ability to predict the flow rate based on observed data.

Brighenti et al. (2016) obtained NASH OF 0.7 for the calibration and 0.63 for the validation of the flow in the Rio Negrinho hydrographic basin, in the state of Santa Catarina, the authors cite the years with greater training have more efficient calibrations and validations than the years considered to be dry.

In the Figures 3A and B, the data approached the central adjustment trend, with few deviations, especially during the calibration. During the validation, although in most observations the values tended to adjust appropriately, the deviations were greater.

Regarding sediment flow, the model calibration result was considered very good (NSE ≥ 0.65) and of satisfactory validation (0.54 > NSE ≥ 0.50), according to the classification of Santhi et al. (2001).



* Significant at p ≤ 0.05 by t test

Figure 3. Observed and estimated flow simulated by the models in the calibration (A) and validation (B)

In their study Aragão et al. (2013) observed that in the calibration process the SWAT model was able to reproduce both the shape of the hydrographs and the peaks well (NSE = 0.83 and Pbias = 8.50%), making a reservation for the dry periods in which the model underestimates the simulated values.

These values are in line with those obtained in other researches in Brazil to estimate sediment loss with the SWAT model. Paim & Menezes (2009) obtained NSE of 0.60, Lubitz et al. (2013) obtained 0.84 from NSE and Baltokoski et al. (2010) found values of 0.68.

The negative value (-23.9 %) for the Pbias indicates an underestimation of the daily sediment flow, which differs from the results for the mean deviation, which indicated an overestimation of 35.78 tons in the estimated values compared to the observed ones.

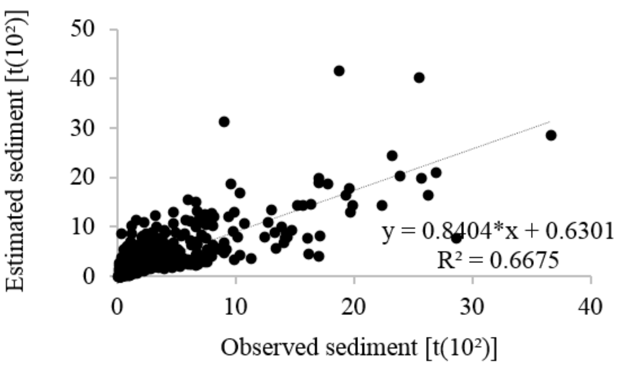
The negative values for the Pbias also occurred during the validation period in which was -39.9% and average deviation of 91.1. This divergence may be due to the instability of the model to represent the sediment flow, because, it sometimes tended to overestimate the sediment flow and sometimes to underestimate it.

The dispersion diagram and the coefficient of determination confirm the hypothesis of variation between underestimation and overestimation of sediment flow by the model (Figure 4). In the validation period, there is a tendency for the model to underestimate the sediment flow on days when the synthetic series presented high flow values, for this period an appropriate adjustment was not possible (R^2 = 0.6675).

The estimated sediment flow behaviour in relation to the observed one during the calibration period confirms the hypothesis of sometimes underestimation and sometimes overestimation of the model. What is observed is that the model tended to overestimate the smallest sediment flow peaks and underestimate the larger peaks.

In the validation, the overestimation pattern of the estimated values for sediment flow in relation to the observed values stands out. This fact is indicative that conditions in the basin have changed over time, resulting in an inadequate adjustment of the model to the observed data.

Though the model presented divergences between the estimated data and observed data, the results found for the objective functions, NSE and Pbias, were considered adequate



* Significant at p ≤ 0.05 by t test

Figure 4. Observed and estimated sediment losses simulated by the models in the calibration

in the sediment flow representation based on the ranges of values used for the satisfactory judgment or not of the SWAT model proposed by Moriasi et al. (2007).

It should be borne in mind that the SWAT was calibrated based on a synthetic series of sediments obtained from regression equations that contained statistical errors. Therefore, the raw values obtained in this research should be analysed taking into account the errors of the model calibration process added to those coming from the regression adjustment.

From the history of the soil crop in Brazil, there is a significant increase of the cultivated area in no-tillage (NT) system in the last decades. In the period there was a considerable annual increase of the annual cultivation areas in NT system (Cassol et al., 2007).

Starting in 1991, a series of actions promoting the NT system took place, aiming to induce farmers to believe that this technique was synonymous with "conservationist agriculture" (Cassol et al., 2007). This promotion further boosted the pressure on farmers to consume available technologies. As a result, there was an exponential increase in cultivation area under NT in Brazil from that time.

In Santa Catarina State, there was increase from 5% in 1987 to 18 and 44% in 1994 and 1997, respectively, of the NT area (Freitas et al., 1998), corresponding to increase from 112,000 ha in 1987 to 793,000 ha in 1997. In 1999 the Santa Catarina State NT area represented 60% in the grain and cereal areas.

The number of enterprises that joined the NT in the municipalities that are part of the Marombas Basin (BHM) increased from 4,157 in 2006 to 5,199 in 2017 (IBGE, 2017). In the last census on this subject, in 2017, the area under NT in BHM totaled 129,166 ha, with emphasis on Campos Novos and Brunópolis municipality which held approximately 40% of their agricultural area being cultivated with this soil management.

The sediment flow data obtained from the point measurements at the Passo Marombas River Station show reduction in sediment production values from the 1990's onwards, coinciding with the period in which there was considerable increase in cultivated area in of NT in BHM (Figure 5).

It is observed that the measurements made in the 1980's had high sediment concentration values, even in periods with low flow. The first collection, as an example, presented sediment concentration of 80.42 mg L^{-1} at a time when the flow rate was 16.8 m^3 s^{-1}.

The ratio between the values of sediment concentration and flow can be observed in Figure 6.

This ratio was performed based on the importance of runoff in sediment loss. It was assumed that the higher the flow of the river, the greater the surface runoff resulting from the days prior to collection. These results demonstrated the presence of higher sediment concentration values during measurements made in the 1980's.

From the 1990's onwards, sediment concentration values decreased, even at higher flow events, as shown in some values throughout the series. On September 19th, 1978, for example, a measurement pointed to sediment concentration of 44.31 mg L^{-1} for a flow rate of 74.3 m^3 s^{-1}. In another flow, similar to

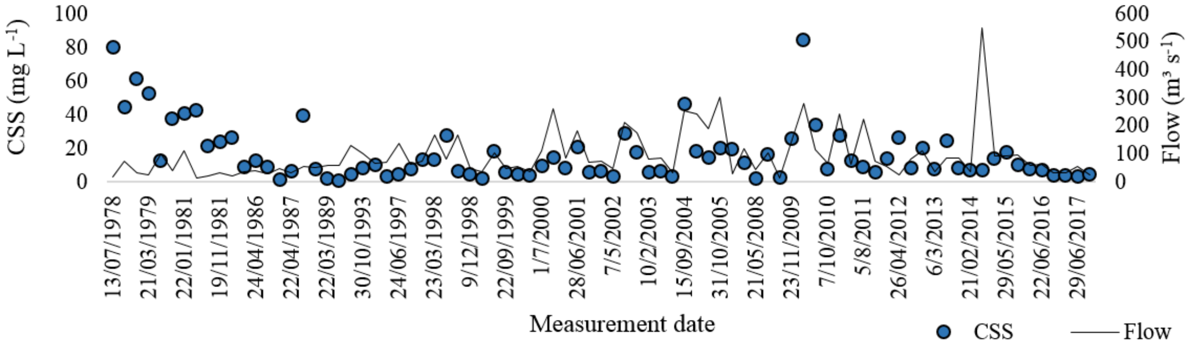


Figure 5. Concentration of suspended solids (CSS) and flow at the Passo Marombas River Station from 1978 to 2017

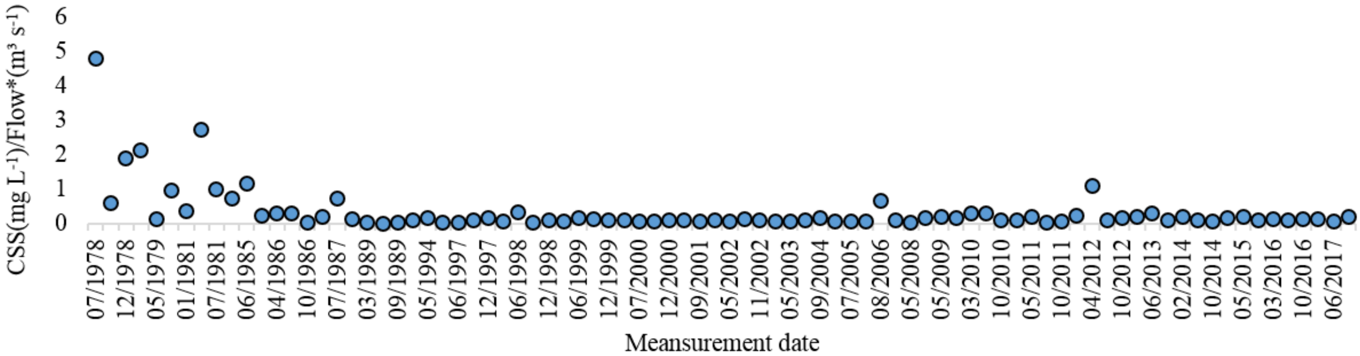


Figure 6. Ratio of concentration of suspended solids (CSS) in relation to flow at the Passo Marombas River Station from 1978 to 2017

this, observed on December 11th, 1997, however, the sediment concentration was 11.15 mg L^{-1}.

Several factors influence sediment concentration, unrelated to river flow. However, the results show that there was a certain systematization, in which the concentration of sediments decreased from the 1990's, from when there was an increase in the cultivation area under NT, even in rain events that resulted in greater flow.

Although the cultivated area under the NT system has increased in BHM, there was increase in the agricultural and forest cultivated area during the 1990's. Table 3 shows that the area under cultivation of Pinnus ssp. and Eucaliptus ssp. has tripled over the last decades at NT, in that 41% of the native forest and 55% of the native field were replaced by agricultural crops.

With this increase of areas under agriculture and reforestations an increase in sediment loss in the basin was expected. Which did not occur based on the observed sediment flow results. It is considered here that this effect was the result of the implementation of NT in the region's agricultural crops. With residual biomass kept on the soil surface that controlled water erosion and the consequent loss of sediment.

Table 3. Evolution of land use and occupation at Marombas River Basin (BHM) between 1986, 2002 and 2017

Land use class	Area (km²)			Area (%)		
	1986	2002	2017	1986	2002	2017
Urban area	13.5	24.5	31.4	0.4	0.7	0.9
Water	13.2	24.2	20.4	0.3	0.7	0.6
Agriculture	364.7	762.1	1016.5	9.9	20.7	27.6
Pasture	1534.8	1197.9	694.4	41.7	32.6	18.9
Native forest	1441.8	1244.3	846.7	39.2	33.8	23.0
Reforestation	308.7	423.6	1067.3	8.4	11.5	29.0

Source: Adapted of Ricardo (2019)

Comparison of the calibration and validation results of the model to each other also indicates that the basin soil has been anthropogenic influenced over the search period. The model tended to overestimate sediment flow during validation.

This means that the SWAT model, calibrated to the conditions of the 1990's, predicted higher than actually observed sediment production. This fact reinforces the idea that the increase in cultivation area under NT changed the dynamics of water erosion mechanics in the basin, so that the observed sediment flow was lower than it would be under pre-1990 cultivation conditions.

The replacement of conventional tillage (CT) by NT management in the late 1980's reflected mainly in the maintenance of residual surface coverage and the minimization of mechanical soil mobilization. The soil cover acts in two ways in the erosive process. It intercepts the rain and dissipates its kinetic energy and, in addition, the surface cover dissipates the kinetic energy of the runoff. This, together, reduces the disintegration and transport of sediments, which would be the result of both rain and runoff.

In addition, it is considered that other land use changes such as the implementation of reforestation, the implementation of livestock activities, among others, may have affected the behavior of the sediment flow in the basin.

In watersheds, the erosive process must be considered spatially. In this case. cultivated areas in the form of NT may act as a filter similarly, but to a much lesser extent than areas under native vegetation, resulting in lower sediment loss compared to under cultivated areas. Additionally, the positioning of land use and occupation along the slope interferes with the deposition or not of sediments.

Conclusions

1. The Soil Water Assessment Tools model is suitable to represent the average daily flow and sediment flow in the Marombas watershed, with Nash-Sutcliffe values of 0.91 and 0.74 for the calibration and validation of the average daily flow respectively and 0.71 and 0.52 for sediment flow calibration and validation.

2. The hypothesis of reduced concentration of suspended solids with increasing soil crop in the form of no-tillage system was accepted.

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