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Land cover and climate change effects on streamflow and sediment yield: a case study of Tapacurá River basin, Brazil

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Abstract. This study assesses the impact of the land use and climate changes between 1967–2008 on the streamflow and sediment yield in Tapacurá River basin (Brazil) using the Soil and Water Assessment Tool (SWAT) model. The model was calibrated and validated by comparing simulated mean monthly streamflow with observed long-term mean monthly streamflow. The obtained R^2 and Nash–Sutcliffe efficiency values to streamflow data were respectively 0.82 and 0.71 for 1967–1974, and 0.84 and 0.82 for 1995–2008. The results show that the land cover and climate change affected the basin hydrology, decreasing the streamflow and sediment yield (227.39 mm and 18.21 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ for 1967–1974 and 182.86 mm and 7.67 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ for 1995–2008). The process changes are arising mainly due to the land cover/use variability, but, mainly due to the decreasing in the rainfall rates during 1995–2008 when compared with the first period analysed, which in turn decreased the streamflow and sediments during the wet seasons and reduced the base flow during the dry seasons.

1 Introduction

Runoff and sediment yield processes in a basin are sensitive to the changes of climate and land uses. Physically based distributed hydrological models, whose parameters have a physical representation for the spatial variability of hydrological processes and land uses are capable of simulating the impact of climate change and human activities on hydrological cycle (Dos Santos et al., 2014). Nowadays, runoff-erosion models are increasingly being used to simulate complex water resource systems including simulation for the impact of land use and climate change on water resources in river basins during past and recent decades. Especially, in areas characterized by strong seasonal variability, as is the case of the Tapacurá River basin. The Tapacurá River basin has far-reaching implications for Pernambuco state (Silva et al., 2012), because this basin is one of the main sub-basins which supplies the Recife Metropolitan Region, one of the water resource management planning units for that region, Pernambuco state. The Tapacurá River basin covers an area of about 470 $\mathrm{km^2}$, and is located in the Zona da Mata region in the state of Pernambuco, north-eastern Brazil, between coordinates 7°58′0′′ S and 8°13′0′′ S, and 35°5′0′′ W and 35°30′0′′ W (Fig. 1).

Studies about the influence of land use change on the streamflow in basin scale have been reported by several authors (e.g. Silva et al., 2013; Braga et al., 2013; Montenegro and Ragab, 2012). This study assesses the impact of the land use and climate changes between 1967–2008 on the streamflow and sediment yield in Tapacurá River basin (Brazil) using the Soil and Water Assessment Tool (SWAT) model.

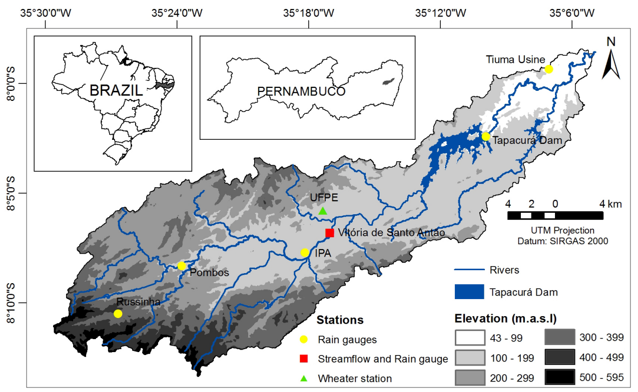

Figure 1. Map showing the location of the study area in Brazil, streamflow gauge and rain gauges.

2 Material and methods

2.1 SWAT model and data description

The Soil and Water Assessment Tool (SWAT) is a comprehensive, semi-distributed river basin model that requires a large number of input parameters. The SWAT is one of the most suitable models for simulating streamflow under land use and management scenarios (Behera and Panda, 2006). It is a physically based, distributed, continuous daily time step parameter model designed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large and complex watersheds with varying soil, land use and management conditions over long periods of time. A great number of SWAT applications have been used to study hydrology in small or large basins (Dos Santos et al., 2014).

The basic datasets that are required by the hydrological model are topographic, climatic, streamflow, soil and land use data. The digital elevation model is one of the essential inputs required by SWAT to delineate the basin into a number of sub-basins. Digital elevation model is used to analyse the drainage pattern of the watershed, slope, stream length and width of channel within the basin. The digital elevation model (DEM) used in this study was obtained from the Brazil National Institute for Space Research (http://www.dsr.inpe.br/topodata), with a spatial resolution of 30 m. Daily precipitation data were collected from six rainfall gauges distributed within the study area (i.e., Tiuma Usine, Russinha, Pombos, IPA, Vitória de Santo Antão and Tapacurá Dam). Daily wind speed and relative humidity, as well as maximum, minimum, and mean air temperature data were collected at UFPE wheater station (Fig. 1).

In this study, calibration efforts focused on improving model performance at the main gauge station. Flow calibration was focused on monthly simulations using the SWAT Calibration Uncertainty Procedures (SWAT-CUP) version 5.1.6.2. In this paper, we apply the calibration using the Sequential Uncertainty Fitting procedure (SUFI-2) (Abbaspour et al., 2007), based on streamflow data from January 1995 to December 2008, using the data from a gauging station at Vitória de Santo Antão.

Calibration was implemented by changing one of the more sensitive parameters in the model and then observing the corresponding changes in simulated stream flow. Once the model parameters were optimized for calibration, model validation was performed based on monthly streamflow data for the period from January 1967 to December 1974.

Although daily sediment load estimation may be available, their uncertainty was higher than the measured flow uncertainty due to reduced sampling frequency. Therefore, sediment yield calibration focused mainly on monthly simulation rather than daily simulation. The calibration objective for each constituent of interest was to maximize the coefficients of determination (R^2) and Nash–Sutcliffe efficiency (NSE). NSE ranges from negative infinity to 1, with 1 denoting a perfect model agreement with observation. Generally, the model is deemed perfect when NSE is higher than 0.75, satisfactory when NSE is between 0.36 and 0.75, and unsatisfactory when NSE is lower than 0.36 (Nash and Sutcliffe, 1970; Moriasi et al., 2007). The model was first calibrated for runoff and then concentrations of sediment in the river were estimated in a monthly scale.

2.2 Land use assessment

The land cover data for the period 1967–1974 were obtained by aerial photos (Dos Santos et al., 2014) and for 1995–2008 from Landsat 5/TM multispectral imagery (Santana et al., 2014). The imagery used to create land cover data for 1967–1974 and 1995–2008 were obtained from spatial resolution of 90 and 30 m, respectively. The dominant land uses in the basin for 1967–1974 were Caatinga (48 %), agriculture (39 %), rain forest (9 %), water (2 %) and urban areas (1 %), and for the period 1995–2008 were agriculture (39 %), livestock (39 %), sugarcane (11 %), rain forest (6 %), urban areas (2 %), water (2 %) and Caatinga (1 %) for the period 1995–2008.

3 Results and discussion

3.1 Land use changes assessment

The spatial distributions of the land use types between 1967–1974 and 1995–2008 are shown in Fig. 4a–b. The area and percentage of total area of land use during the past four decades in the Tapacurá River basin are shown in Table 1. Changes in land use occurred in all parts of the basin and stretches mainly in the south-western region. The results obtained for period 1967–1974 reveals that Caatinga (48 %) and agriculture (39 %) are the most representative land covers in the basin. For the second period, the distribution of land cover shows that most of the basin is covered by agricul-

Table 1. Descriptive statistics of measured and simulated monthly streamflow and sediment in the Tapacurá River basin.

Statistics	Rainfall* (mm)		Streamflow (mm)				Sediment Yield ($t\,ha^{-1}\,yr^{-1}$)	
			Q_{obs}	Q_{sim}	Q_{obs}	Q_{sim}		
	1967/1974	1995/2008	1967/1974		1995/2008		1967/1974	1995/2008
Mean	1126.10	910.65	227.39	325.18	182.86	234.40	18.21	7.67
Standard deviation	145.98	245.51	144.65	148.79	168.64	139.64	8.15	6.25
Maximum	1356.48	1420.33	444.30	527.37	524.56	524.60	30.44	22.99
Minimum	922.87	453.33	64.80	133.67	4.44	40.90	8.11	0.10
NSE	–		0.71		0.82		–	
R^2	–		0.82		0.84		–	
BIAS			−47.88		−27.95			

* Rainfall here refers to the average precipitation all over the basin during the two studied periods, not just over the sub-basins that are upstream the gauge (western portion), which receive less rainfall than the eastern portion.

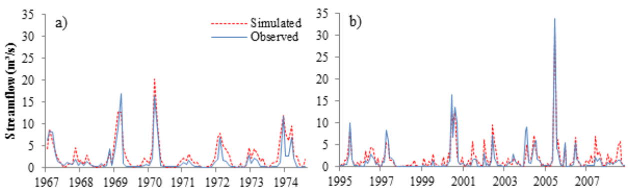

Figure 2. Simulated versus observed monthly streamflow in the Tapacurá River basin: **(a)** 1967–1974, and **(b)** 1995–2008.

Table 2. Land use changes in the Tapacurá River basin.

Land Cover	1967–1974		1995–2008		% of Area
	Area (km^2)	%	Area (km^2)	%	
Agriculture	186	39	182	39	−2
Caatinga	228	48	5	1	−98
Livestock	–	–	185	39	+100
Rain forest	41	9	26	6	−37
Sugarcane	–	–	53	11	+100
Urban areas	7	1	11	2	+57
Water	10	2	11	2	+10

ture (39 %), livestock (39 %) and sugarcane (11 %). Caatinga vegetation and rain forest decreased after 1974, with −98 and −37 %, respectively. Conversely, the area covered by Caatinga decreased due to the change of land use from agricultural to livestock areas after 1974 in south-western part of the basin and change from agriculture and rain forest to sugarcane, i.e., a land use characterized by monoculture. The urban area gradually expanded from 1 % to 2 % during the entire studied period, while the proportion of livestock relatively increased (100 %) from 1967–1974 to 1995–2008. Vegetation cover within the basin has changed considerably due to human activities, mainly through the conversion of natural vegetation to agriculture, livestock and sugarcane. These changes have altered the water resources through biophysical and biogeochemical processes in the soil. Through these land cover changes, the characteristics of the vegetation have been modified and, therefore, these changes have affected the exchange of water between the atmosphere and land surface.

3.2 Climate change effects on streamflow and sediment yield

In order to analyse the impact of climate and land-cover change on hydrology during forty years, SWAT model was used to simulate the scenarios 1967–1974 and 1995–2008. The SWAT receives input daily data, but operates with daily and monthly time output intervals. In this study, the monthly output intervals were used to better graphically represent the results. The consistency of the simulated and measured values is clear. The NSE and R^2 values for the monthly calibration and validation are listed in Table 2. All of the NSE and R^2 values for streamflow data are greater than 0.7, which suggests a good model performance (Moriasi et al., 2007). It is shown that the magnitude and temporal variation of simulated runoff matched closely with the observed runoff values. Thus, it can be noted that the model achieved a satisfactory simulation. Thus, it can be noted that the model achieved a satisfactory simulation. The hydrograph distribution also shows a good fitting between simulated and observed streamflow. The observed mean precipitation is respectively 1126.10 mm in 1967–1974 and 910.65 mm in 1995–2008. It decreased by 215.45 mm in this period. However, the mean runoff is respectively 227.39 mm in 1967–1974 and 182.86 mm in 1995–2008. It decreased by 44.53 mm.

Figure 2a–b compare graphically observed and simulated monthly streamflow values for both periods. The results of statistical tests performed on the agreement between observed and simulated monthly streamflow are presented in Table 2. Although an overestimation of monthly runoff by the

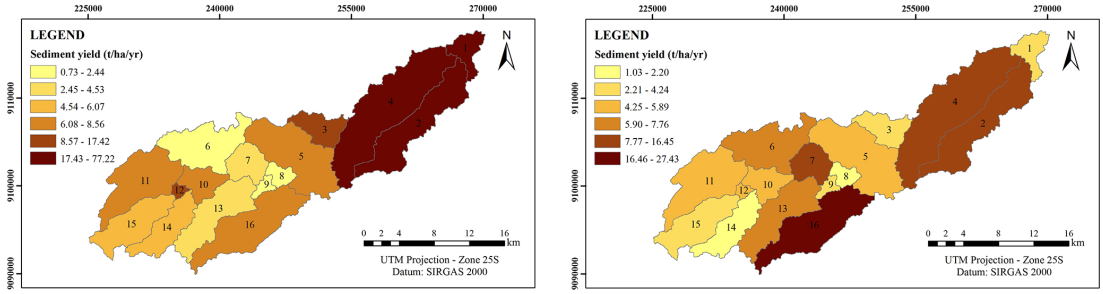

Figure 3. Simulated sediment yield in the Tapacurá River basin: **(a)** 1967–1974, and **(b)** 1995–2008.

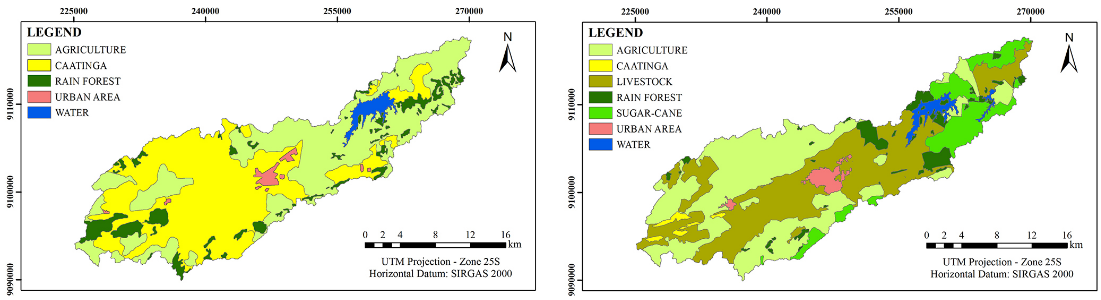

Figure 4. Land use and land cover maps of the Tapacurá River basin for: **(a)** 1967–1974, and **(b)** 1995–2008.

model was beyond the satisfactory level of acceptance, considering the overall statistics, it can be said that the model simulations were relatively satisfactory. The PBIAS values (−47.88 and −27.95) show that the model had a very good performance for both periods, 1967–1974 and 1995–2008, respectively. The good performance of the SWAT for both the periods is corroborated in a more quantitative way by the values of the statistical parameters. The R^2 and NSE values of 0.82 and 0.71 for 1967–1974, and 0.84 and 0.82 for 1995–2008, respectively, indicated close relationships between simulated monthly runoff with the observed ones. Thus, the SWAT model, using the optimal parameters was successfully employed to evaluate the hydrological consequences of the land use changes.

Table 2 also shows the values of statistical test for monthly sediment yield simulated during both periods analyzed. This difference could be due to amount rainfall, which was higher in the first period 1126.10 mm than during 1995–2008 (910.65 mm). It can be seen that the period 1967–1974 receives more precipitation than the period 1995–2008 and generates more runoff and sediments as well. As expected, the streamflow generation showed an upward trend generally following the pattern of the rainfall. For example, in practice, high-intensity and even short duration rainfall can generate more sediment than did the model based on daily rainfall. Based on these indexes and on the simulation results, the spatial distribution for the intensity of soil erosion in the Tapacurá River basin in both periods is given in Fig. 3.

The analysis of the spatial distribution of sediment yield in the periods for each sub-basin showed high variation. Compared to the period 1967–1974, the mean annual rainfall over the basin was 19.13 % lower in 1995–2008. Therefore, the changes in streamflow matched the land use dynamics, particularly due to the increase of livestock and sugarcane within the area. The spatial analysis of areas susceptible to the erosion process emphasizes that a subset of these areas showed a total annual sediment yield of over 77 and 27 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ for 1967–1974, and 1995–2008, respectively, which reveals the importance of timely analysis of the basin sites susceptible to the erosion process.

4 Conclusions

Based on the results obtained, the following conclusions are drawn: (a) the basin experienced a significant land use change between the two analysed periods. It is concluded that the decrease in forest land and grassland is accompanied by the increase in agricultural and built up areas, (b) the hydrological model SWAT adequately simulates the runoff with satisfactory R^2 and NSE, (c) the process changes are arising due to the land cover/use variability, but mainly due to the decreasing in the rainfall depth during 1995–2008 when compared with the first period analysed, which in turn decreased the streamflow and sediments yield during the wet seasons and reduced the base flow during the dry seasons. The model runs for different land uses revealed that the wet season flow increases for the most recent year, while the dry season flow decreases appreciably. This is mainly attributed to the land degradation (conversion of Caatinga and forest into agriculture, livestock and sugarcane), which in turn increased surface runoff during wet seasons and reduced base flow during the dry seasons. The evaluation of the SWAT model response to the land cover and climate changes has shown that the mean monthly flow, during the rainy seasons of the studied period increased, since no significant climatic changes were observed in the basin for the period 1967–2008.

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