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Use of the SWAT model to evaluate the impact of different land use scenarios on discharge and sediment transport in the Apucaraninha River watershed, southern Brazil

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Abstract The SWAT model was used to simulate the production and transport of water and sediment (suspended and bedload) in the Apucaraninha River watershed (504 km^2), southern Brazil. The model was calibrated with daily discharge and sediment transport data, obtained during the period 1988–2005. The model simulation showed a good fit for both discharge and sediment transport when compared to observed values. Using the calibrated SWAT model, the impacts of different land-use and soil management activities on discharge and sediment transport were evaluated under the following scenarios: (1) the present condition without soil conservation practice; (2) the present condition with full riparian vegetation; (3) agriculture with soil conservation practice and full riparian vegetation; (4) 100% forest; (5) agriculture without soil conservation practice and with full riparian vegetation; (6) 100% agriculture without soil conservation practice; and (7) 100% agriculture with soil conservation practice. The mean values of total discharge between the various scenarios had a very small coefficient of variation (1%), while the mean values of surface runoff had a larger value (25%). For sediment transport, the difference between the scenarios was more significant. Compared with the current condition, scenario (4) resulted in a decrease of sediment transport of 89%, while scenario (6) resulted in an increase of 142%.

Key words hydrological monitoring; hydrological modeling; sediment transport; land use scenarios; SWAT; southern Brazil

INTRODUCTION

The sediment load transported by rivers is complex and depends on the erosion occurring on hillslopes and the bed and bank of rivers, and the hydrogeomorphologic connectivity between hillslopes and drainage networks, both of which vary greatly over time and space. With knowledge of the main factors influencing these processes, it is possible to model the erosion and transport of sediment in drainage networks. Since these processes occur at different places within a drainage basin, it is important that they are modelled in a spatially distributed manner.

In this context, the present study presents an evaluation of the impacts of land use on discharge and sediment transport in the Apucaraninha River watershed, located within the Tibagi River basin, Paraná state, Brazil. The distributed modelling of the watershed used the SWAT (Soil and Water Assessment Tool) model developed by Neitsch *et al.* (2002). The sediment transport and yield in the watershed were modelled under seven different land use scenarios, as well as the actual present conditions. Model calibration was carried out with various parameters and available hydrologic and environmental daily data sets.

METHODOLOGY

Study area

The Apucaraninha River watershed is located in the northern state of Paraná (between 23°41′ and 23°55′S and between 50°58′ and 51°15′W), southern Brazil, and has a drainage area of 504 km^2 (Fig. 1). Its outlet is the river gauging station at Montante Fiú. The original vegetation of the region is subtropical rain forest, which currently occupies only 26% of the watershed. The rest of the watershed is occupied with agriculture (60%), pasture (13%), and urban areas (<1%) (Fig. 2). Regional economic activities are mainly based on cattle grazing and mechanized agriculture of soybeans, corn and wheat.

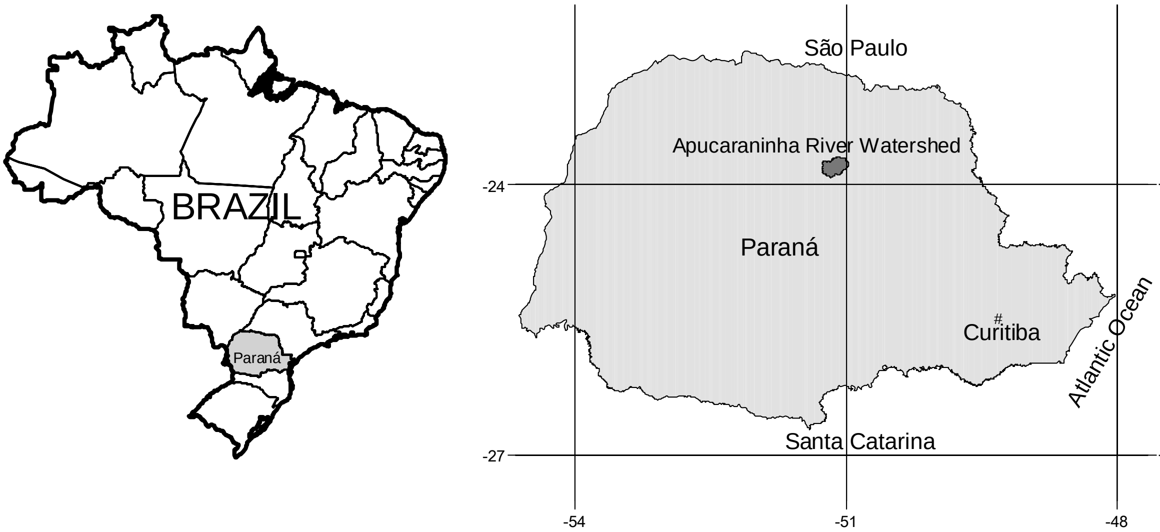

Fig. 1 Location of study area.

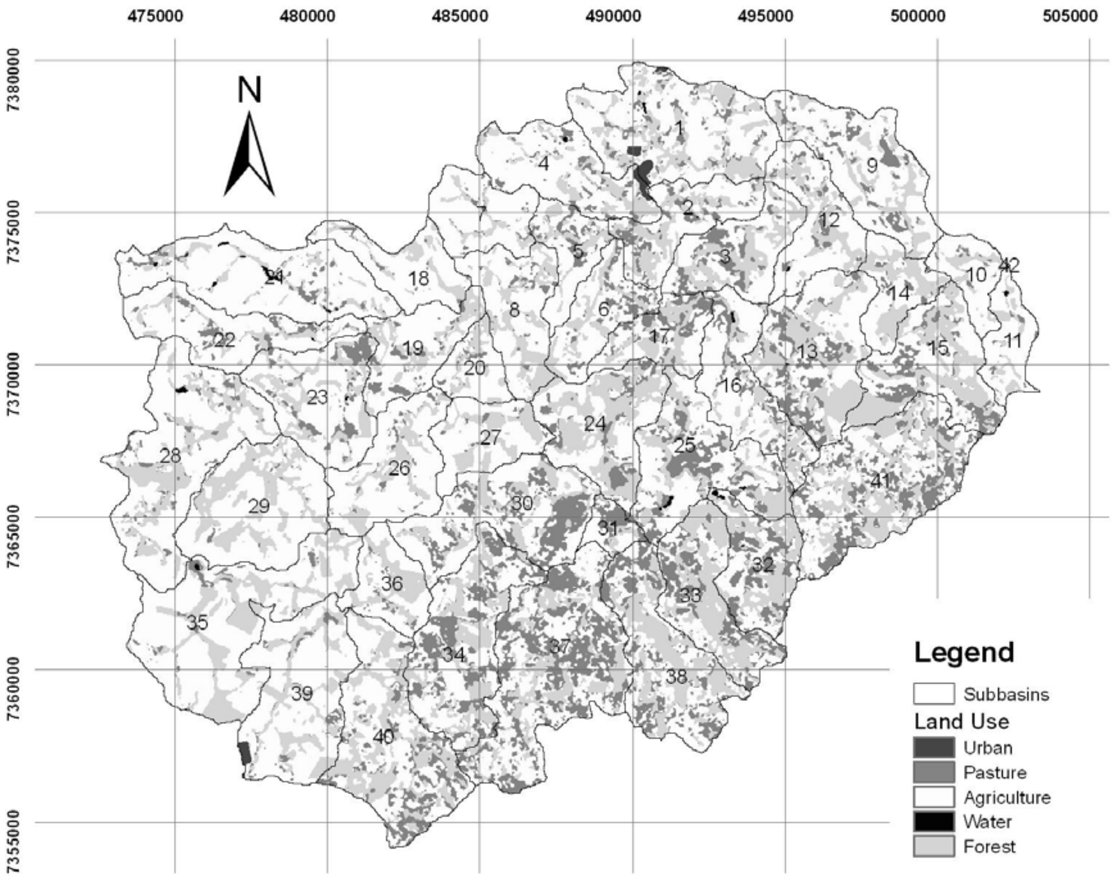

Fig. 2 Land-use of the Apucaraninha River watershed.

Utilized data

For model simulation, the Apucaraninha River watershed was divided into 42 sub-watersheds (Fig. 2). The division procedure was undertaken so that sub-watersheds had relatively uniform topography, soil type and vegetation, and were of a similar size. The spatial data used were: a digital terrain model; river network; soil types (including soil physical and hydraulic characteristics); land use; location of gauging stations; and the map of the sub-watersheds. For the time series, the present study created daily data files which contained maximum and minimum temperatures, solar radiation, wind speed, relative humidity, rainfall, discharge, and sediment transport.

In the present study an intensive monitoring of sediment (suspended and bedload) transport was carried out at the Montante Fiú gauging station. The suspended sediment concentration (SSC) was determined from daily samples collected during the period February 2004 to October 2005. The daily SSC data were used together with daily data on discharge (1988–2005) to determine daily suspended sediment flux. In addition, monthly sediment transport data from 2004 to 2005 was determined through the collection of the suspended load and the direct measurement of bed load (for details on methods see Santos *et al*., 2001).

The relationship between the sediment transport (suspended sediment and bedload) and the water discharge at the Montante Fiú gauging station was determined with 508 measurements and is given by the following equation (Santos *et al*., 2007):

$$Q_{ST} = 0.0798 \cdot Q_L^{2.3428} \qquad (R^2 = 0.89) \tag{1}$$

where Q_{ST} is the total sediment discharge (t day^{-1}), and Q_L is the water discharge ($m^3\ s^{-1}$).

SWAT model application

The SWAT model aims to predict the impact of soil use and management on the hydrological cycle, and associated impacts on sediment transport and water quality, in large and complex watersheds for long periods (Neitsch *et al*., 2002). This model has undergone continuous review, modification and enhancement since its creation in 1996 (Krysanova & Arnold, 2008). The model version used in the present study was the AVSWAT2000, which is fully integrated with ArcView ® GIS and is available at http://swatmodel.tamu.edu/.

Initially, the daily time series was divided into two periods: 1 January 2000 to 31 July 2005 for calibration of the model, and 1 January 1988 to 31 December 1999 for model validation (Andriolo *et al*., 2008). Later, in assessing the impact of different scenarios of land use of the water and sediment yields, the model was applied to the whole period from 1 January 1988 to 31 July 2005.

The performances of the model calibration and validation were evaluated with the Nash Sutcliffe criterion (*COE*), which allowed the comparison of the observed and simulated water discharge and sediment transport:

$$COE = 1 - \left[\sum_{i=1}^{n}\left(E_{obs} - E_s\right)^2\right] / \left[\sum_{i=1}^{n}\left(E_{obs} - \overline{E}\right)^2\right] \tag{2}$$

where E_{obs} is the observed value, E_s is the simulated value and $\overline{E}$ is the mean value of E_s during the simulation period. A *COE* value closer to 1 indicates a better model performance.

RESULTS AND DISCUSSION

Calibration and validation

The model had a good fit for calculating daily discharge, with *COE* values of 0.73 for calibration and 0.78 for validation. The simulation for the whole time period (i.e. 1 January 1988 to 31 July 2005) resulted in a *COE* value of 0.77. In this case, the mean values of the observed and simulated discharges were 11.53 $m^3 s^{-1}$ and 11.61 $m^3 s^{-1}$, respectively; a difference of only 0.75%. From these values of *COE* and the similarity in the plots shown in Fig. 3, it can be seen that the SWAT model performed well for the Apucaraninha River watershed.

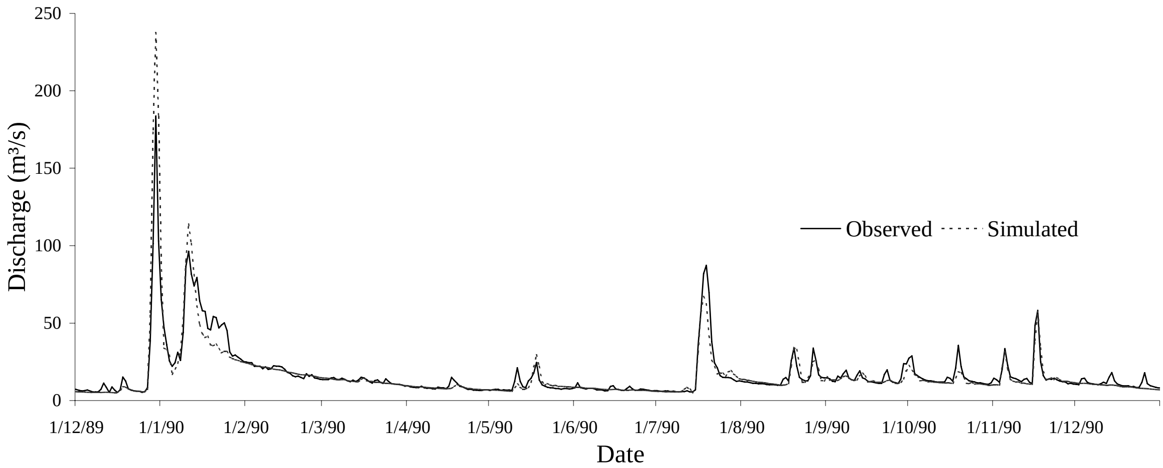

Fig. 3 Observed and simulated discharge of the Apucaraninha River in 1990.

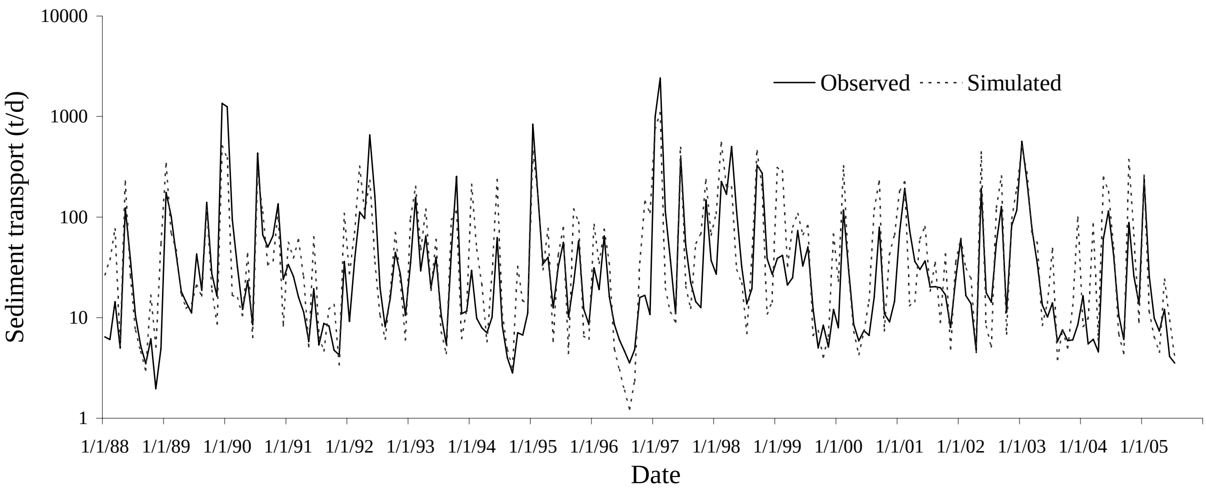

Fig. 4 The observed and simulated monthly sediment transport rate of the Apucaraninha River.

With respect to sediment transport, the *COE* values for the monthly data during the calibration, validation and full period were 0.42, 0.62 and 0.61, respectively. The average sediment transport rates were 83.03 t day^{-1} and 85.22 t day^{-1} for the observed and simulated data, respectively; a difference of 2.6%. Despite the fact that the observed and simulated sediment transport values for the whole period of simulation are very close, and that the SWAT model had a good fit using the monthly values (see Fig. 4), the *COE* values for the daily data were very low: 0.20, –2.36 and –1.86 for the calibration, validation and full period, respectively. Benaman *et al*. (2005) also found that the SWAT model performed better for discharge than for sediment transport.

Simulation scenarios

The objective of the scenario simulations was to evaluate the effect of seven different land use and management options (Table 1) and to compare them with the current condition in terms of

Table 1 Description of simulated scenarios.

Scenario	Description
1	Current condition without the soil conservation practices
2	Current condition with full replacement of riparian vegetation
3	Agricultural use with soil conservation practices and full riparian vegetation
4	100% original forest
5	Agricultural use without soil conservation practices and full riparian vegetation
6	100% agricultural use without soil conservation practices
7	100% agricultural use with soil conservation practices

Table 2 Land use for the simulated scenarios.

Land use	Scenario (% of total area of the watershed)							
	Current	1	2	3	4	5	6	7
Urban	0.19	0.19	0.19					
Pasture	13.17	13.17	11.59					
Agricultural (with con. practices)	60.52		57.91	90.75				100
Agricultural (without con. practices)		60.52				90.75	100	
Water	0.12	0.12	0.05					
Forest	25.99	25.99	30.26	9.25	100	9.25		

Table 3 Discharge, base flow, overland flow and sediment transport in the different scenarios.

Scenario	Discharge ($m^3 s^{-1}$)	Base flow ($m^3 s^{-1}$)	(%)*	Overland flow ($m^3 s^{-1}$)	(%)*	Sediment transport (t day^{-1})	(%)**
Current	11.61	9.17	79.0	2.44	21.0	85.22	–
1	11.72	8.50	72.5	3.22	27.5	115.52	35.6
2	11.64	9.21	79.1	2.43	20.9	80.60	–5.4
3	11.65	8.92	76.6	2.72	23.3	137.72	61.6
4	11.87	9.87	83.2	2.00	16.8	9.47	–88.9
5	11.81	7.94	67.2	3.87	32.8	184.47	116.5
6	11.80	7.75	65.7	4.05	34.3	205.94	141.7
7	11.62	8.83	76.0	2.79	24.0	153.94	80.6

* Percentage in relation to the total discharge
** Percentage change in relation to the current scenario

sediment transport, overland flow and base flow. Table 2 shows the relative areas of land cover for the Apucaraninha River watershed for the current situation and the seven simulated scenarios.

The results for total discharge, base flow and overland flow for each scenario are shown in Table 3. There is little variation in the total discharge amongst the current and simulated scenarios, with a maximum difference of +2.2% between the current situation and scenario 4. However, there is more variation in overland flow, with a maximum difference of +66% between the current situation and scenario 6. This reflects the impact of the land cover type (100% agricultural use) and the adopted management practices (without soil protection). In this scenario, the base flow decreased by 15.5% because of the decrease in infiltration rates and the consequent increase in overland flow.

Table 3 also shows the sediment transport simulated for the different scenarios. With the removal of the soil conservation practices in scenario 1, there was a sharp increase +35.6% in sediment transport, which confirms the importance of soil conservation practices in reducing soil erosion. In scenario 2, where the forest area was increased by riparian forest restoration, the sediment transport reduced slightly from 85.22 to 80.60 t day^{-1} (–5.4%). It should be noted that in scenarios 1 and 2 the configuration of land cover was not changed radically from the current condition and that all the changes were basically due to changes in land management.

In scenario 3, where the agricultural area is increased by +49.9%, the sediment transport increased by +61.6%. This confirms that agricultural areas are susceptible to a greater degree of erosion because the soil has a reduced degree of protection against raindrop impact and entrainment by overland flow. That is why if the forest cover is increased in the watershed the sediment transport can be reduced in a short period of time. This is demonstrated in scenario 4 where the whole watershed is covered with forest and there is a drastic reduction in sediment transport of 88.9%. This scenario is likely to represent the initial situation of the studied watershed before human occupation.

By comparing scenarios 3 and 5, it can be seen that the sediment transport is very sensitive to the soil conservation practices. In the case of the Apucaraninha River watershed, agricultural land use without conservation practices can increase the sediment transport by +33.9% compared with the same land use with conservation practices. Scenario 6 shows the worst situation in terms of the sediment transport with the increase of +141.7%. As stated above, this can be explained by the increase of overland flow (Table 3). The comparison between scenarios 6 and 7 also demonstrates the positive effect of conservation practices for reducing the sediment transport.

Using the values listed in Table 3, sediment transport is strongly positively correlated with the overland flow (R = 0.898) and is inversely correlated with the base flow (R = –0.935). This confirms why land use management practices that reduce overland flow must be promoted in order to reduce the sediment transport flux of receiving streams and rivers.

CONCLUSIONS

The present study shows that the SWAT model is able to simulate water discharge and sediment transport in the Apucaraninha River watershed, Paraná State, Brazil. For the period of calibration and validation, the *COE* values were both >0.7 for the daily discharge. The total values of observed and simulated discharges were very close (difference = 0.75%).

In the case of sediment transport, the *COE* values for the calibration and validation periods were satisfactory for the monthly data (*COE* = 0.61), although values were lower for the daily data. The difference between the observed and simulated values of total sediment transport was 2.6%. This demonstrates that the SWAT model was able to determine accurately the average sediment transport in the study river over the long term.

After confirmation of the adequacy of the SWAT for the Apucaraninha River watershed, seven scenarios with different land uses and management options were simulated with respect to the discharge and sediment transport in the watershed. Over the long term, there was little variation in the total discharge between scenarios. On the other hand, there was a large variation (±60%) in the values of overland flow. This implies that the modelled changes in land use and management affect the discharge generation mechanisms more than its total quantity. For the estimates of sediment transport, the land use and management changes were more significant in causing variations between the scenarios and present-day conditions. The simulations using the SWAT model show the importance of forest and soil conservation practices for reducing soil erosion processes and sediment transport in rivers.

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