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Application of models to estimate erosion, sediment production and future scenarios in two Brazilian tropical watersheds

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Abstract The main objective of this study was to evaluate the application of two different tools; the USLE (Universal Soil Loss Equation) to estimate soil erosion and the SWAT (Soil Water Assessment Tool) to estimate sediment production in two tropical ungauged basins, subjected to different land uses, located within the state of São Paulo, Brazil. The Guabirobas watershed (51 km^2) is used for agricultural production and the Jataí watershed (80 km^2) includes the Ecological Station of Jataí (36%), which is a preservation area. The models were effective in identifying areas most susceptible to erosion and sediment production and in simulating different environmental scenarios. The results of USLE epitomized the values expected for the regions whereas the SWAT model was found to overestimate stream flow when compared with monitoring data observed in one of the basins.

Key words erosion; hydrologic processes; hydrographical basin; USLE; SWAT; scenarios

INTRODUCTION

The expansion of agricultural activities in Brazil, mainly the cultivation of sugar cane for the production of biofuels, in addition to the prospect of climate change and intensification of the hydrological processes in the tropics, underlines the need for improvement in rural planning practices, and also requires that future scenarios can be forecasted and assessed. However, data for these ungauged basins are rare, but are essential to support sustainable rural planning in these areas.

Assessing different land uses and their impacts on soil and water resources of a watershed is an extremely important task, which contributes to the understanding of the implications of each management option. In this sense, it becomes increasingly important to conduct intensive studies in watersheds to identify critical areas and their specific management needs.

Mathematical simulation models can assist the investigation of future scenarios, in quantitative terms, as they allow the incorporation of various factors influence the decision-making process. Their use represents a valid method for the optimization of integration of varied information.

The Universal Soil Loss Equation, USLE (Wischmeier & Smith, 1965, 1978) is one of the most widely used models in the world (Kinnell, 2010), even serving as an indicator of soil quality (Podmanicky *et al.*, 2011). In Brazil, for example, it is widely applied in agricultural planning. The USLE model was widely tested using over 25 years of experimental data in different soils and regions, specifically in the State of Sao Paulo.

The Soil and Water Assessment Tool, SWAT (Arnold *et al.*, 1998) is a simulator developed by the Agricultural Research Service (ARS) of the United States. It consists of various mathematical models which incorporate knowledge of the physical characteristics of agricultural catchments. It was developed to predict the impact of soil management practices on surface and groundwater environments in complex watersheds with varying types of soils, land use and management practices over long periods of time.

Similar to USLE, the SWAT model has been applied worldwide in recent years to estimate and simulate hydrological parameters, loads and non-point sources of pollutants, including sediment, nutrients and pesticides (Hiepe, 2008; Lam *et al.*, 2010; Wang *et al.*, 2010).

In this study, USLE and SWAT models were applied in two rural ungauged basins in the central region of São Paulo to evaluate the performance of these tools and to develop specific protocols for rural watersheds, which are otherwise poorly studied.

METHODOLOGY

Study area

The study area is located in the central region of São Paulo, southeastern Brazil. The two study units (basins Jataí and Guabirobas) drain into opposite sides of the Mogi Guaçu, a tributary of the Parana River (La Plata basin). The location of the watersheds and land use are shown in Fig. 1.

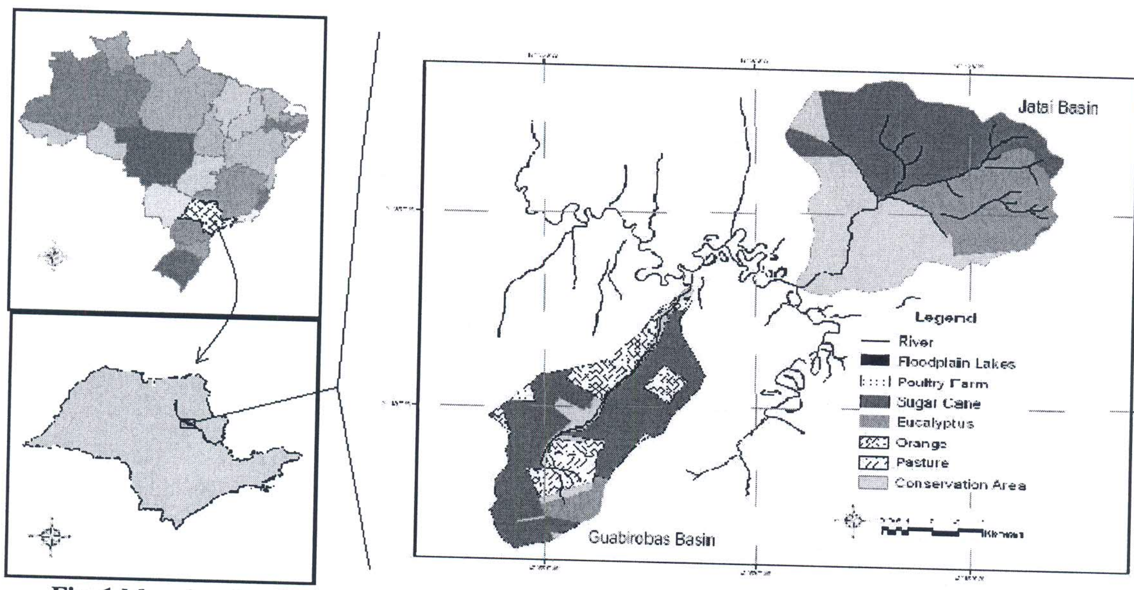

Fig. 1 Map showing the location of Jataí and Guabirobas river basins and land use.

Elevations in the Jataí basin range from 529 to 851 m a.s.l. and in the Guabirobas basin range from 530 to 718 m a.s.l. The Jataí basin (80 km^2) is occupied by sugarcane (39%), eucalyptus (25%) and the Ecological Station of Jataí (36%), which is a preservation area. The Guabirobas basin (51 km^2) is used for agricultural production with its area occupied mainly by sugarcane (60%), eucalyptus (6%), orange (18%), pasture (6%) and natural vegetation (9%).

The USLE model

The USLE empirical model (Wischmeier & Smith, 1965, 1978) is given as:

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

where A is average (mean) annual soil loss (mass area^{-1}/year) over the long term, R is the rainfall-runoff erosive factor, K is the soil erodibility factor, L and S are the topographic factors that depend on slope length and gradient, C is the crop and crop management factor, and P is the soil conservation practice factor.

The SWAT model

The SWAT model was developed by the US Department of Agriculture, USDA/ARS (Arnold *et al.*, 1998) to predict the impact of land management practices on water, sediment and chemical transport in complex river basins. SWAT is a physically-based, watershed-scale, continuous-time, distributed-parameter hydrologic model that uses spatially-distributed data on topography, land use, soil and weather for hydrologic modelling and operates on a daily time step. Detailed descriptions of the methods used in the SWAT model can be found in Arnold *et al.*, (1998), Di Luzio *et al.* (2002) and Neitsch *et al.*, (2002a,b).

In this study the AVSWAT 2000 version was used together with the Soil Conservation Service (SCS) runoff curve number method to estimate surface runoff.

Models inputs

The construction of the base map by Geographic Information Systems (GIS) used survey data prepared by the Brazilian Institute of Geography and Statistics (IBGE), soil data from the Agronomy Institute of Campinas (IAC) and data from a study by Lorandi *et al.* (1990). Land-use was delineated based on Landsat-7 satellite images.

The values of the parameters of the USLE for the study region in the State of São Paulo (Brazil) were obtained from the work of Bertoni & Lombardi-Neto (1999), Lombardi-Neto *et al.* (1999), and Lagrotti (2000). The slope length–gradient factor (LS factor) was determined based on the LS-USLE2D Program (Desmet & Govers, 1996).

The soil data required for data entry in the SWAT model were obtained from the work of Lorandi *et al.* (1991). Climatic data were derived from a weather station at the Brazilian Agricultural Research Corporation (Embrapa). Values of the runoff curve number (CN), which suited the study area, were obtained from the work of Sartori (2004).

Considering the continuous expansion of sugar cane culture in São Paulo State during recent years, three simulation scenarios were built for the two basins using the SWAT model: fully preserved scenario, current scenario (Fig. 1) and sugar cane scenario.

RESULTS AND DISCUSSION

Simulation of erosion

The highest values of soil loss by water erosion were observed in the Jataí basin. Although 36% of the basin area are occupied by natural vegetation (the Jataí Ecological Station, EEJ), the region upstream, with a steep relief, is occupied by eucalyptus and sugar cane. In the Guabirobas basin the average loss and maximum loss was much lower (Fig. 2). This basin has shallower slopes and land use is predominated by crops.

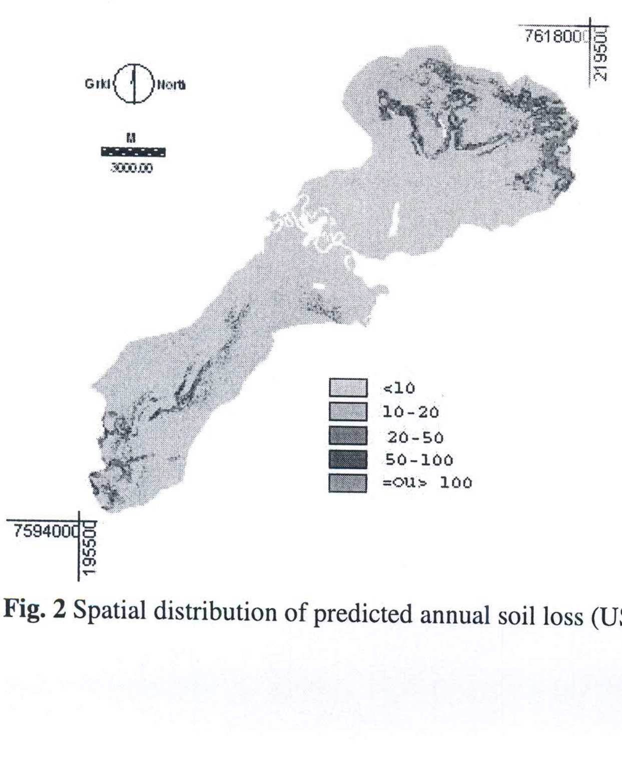

Fig. 2 Spatial distribution of predicted annual soil loss (USLE – ton ha^{-1} year^{-1}) in 2006.

Lin *et al.* (2002) stated that by using the USLE in combination with Geographical Information System (GIS) it would be possible to generate overestimates of erosion in watersheds, caused by faults in determining the parameters of the equation.

The R factor, which gives the distribution of rainfall throughout the year observed in the input data, was applied in the SWAT model. It indicated that there is a high potential for erosion in the rainy season between October and March, during which the erosive value should be higher. This temporal or seasonal variation was not considered by USLE, as this model uses the total annual value of erosion potential.

According to Haregeweyn & Yohannes (2003) extreme weather events contribute significantly to soil erosion compared to the average annual soil loss. Hence, simulating erosion in extensively worked area, e.g. sugar cane fields during events would be interesting for comparing the erosion processes during different periods, including the bare period of soil (off season).

One of the most critical parameters in the application of the USLE is the slope length–gradient factor (LS factor). According to Lin *et al.* (2002), the estimation of factor L for a watershed presents the problem of determination in real and complex landscapes in a GIS environment. The peaks of soil loss by erosion, both in Jataí basin (2538 ton ha^{-1} $year^{-1}$) and in Guabirobas basin (450 ton ha^{-1} $year^{-1}$) were related to the high values obtained for the LS factor in some regions of these units of study. Considering that the automated method was used (Model USLE-2D) for determination of the LS factor, it was not possible to test these factors.

In the absence of data from field experiments, quantification and validation of the USLE model was based on data specific to the State of São Paulo and the studied region. The model results compared well with data from other studies conducted in watersheds of the State of São Paulo. According to Bertoni & Lombardi Neto (1999), the tolerance for soil loss by water erosion for the soils found in the studied basins varies from 7.1 ton ha^{-1} to 14.2 ton ha^{-1}. Despite the high values of erosion in some points of the basins, the average soil loss was of 7.77 ton ha^{-1} for Guabirobas basin and 16 ton ha^{-1} for Jataí basin. The results found were different from what was expected.

Guabirobas basin, almost entirely occupied by agricultural areas, presented lower than average erosion values. For Jataí basin, despite the presence of natural vegetation in a large part of its area (36% of the basin area), the results showed a higher average soil loss by superficial erosion. The differences in slope which influence the slope length–gradient factor of USLE was one of the determinant factors for the obtained results. The average slope of the Guabirobas basin is 3.3% (1% of the area of the basin presents fix slopes in the range of 13–45%) while the average slope of Jataí basin is of 4.2% (8% of the basin area presenting fix slopes ranging from 13 to 45%). In addition, agriculture production in Jataí basin is located in the areas of higher slope, in the upstream region of the basin.

The comparison of the results obtained with the direct application of the USLE with the coefficients calibrated by Bertoni & Lombardi Neto (1999) using the maps generated by geographical information system (GIS) with the results obtained directly by the SWAT model, showed remarkable differences. The values obtained through the application of the USLE with the calibrated coefficients vary from 39 977 ton ha^{-1} at Guabirobas basin and 127 723 ton ha^{-1} at Jataí basin and the results obtained using SWAT model directly varied from 106 634 ton ha^{-1} at Guabirobas basin and 564 448 ton ha^{-1} at Jataí basin. These results showed that remarkable differences in USLE coefficients are expected for USA and Brazilian agricultural areas due to different tillage practices and soil characteristics. Further studies are needed for confirmation.

Simulation of flow and sediments

With the application of the SWAT model for the studied basins it was possible to simulate the basin outlet flow and sediment loads generated annually in both sub-basins, and calculate the loads exported to the Mogi Guaçu River.

The model outputs for the ungauged basins, as simulated by the SWAT model were compared with observed data from a monitored basin, which is also part of the River Mogi Guaçu catchment, but about 70 km downstream from the area studied here, and an area about 10 times the areas of the simulated basins. The results are seen in Fig. 3.

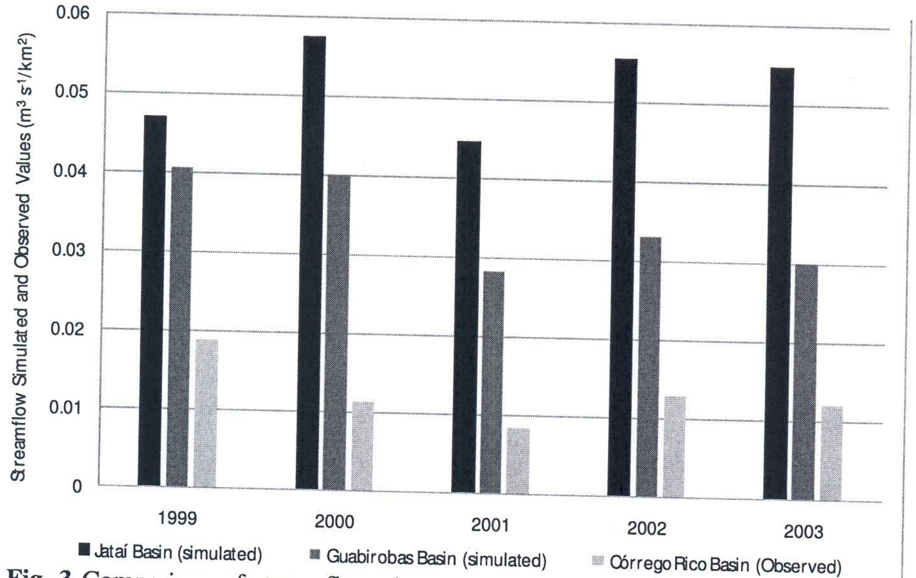

Fig. 3 Comparison of streamflow simulations with SWAT model (Jatai basin, case 1 and Guabirobas basin, case 2) and observed streamflow (Córrego Rico basin).

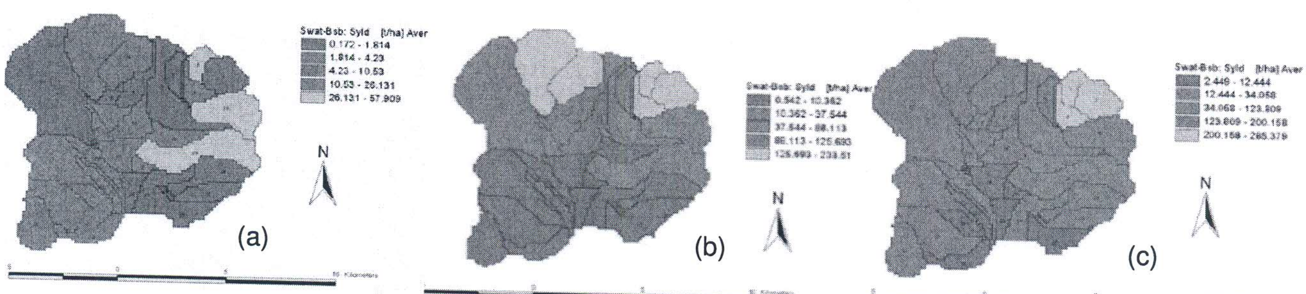

Fig. 4 Simulation of the annual sediment yield of the Jataí basin using the SWAT Model: (a) fully preserved scenario (t ha^{-1}), (b) current scenario (t ha^{-1}), (c) sugar cane scenario (t ha^{-1}).

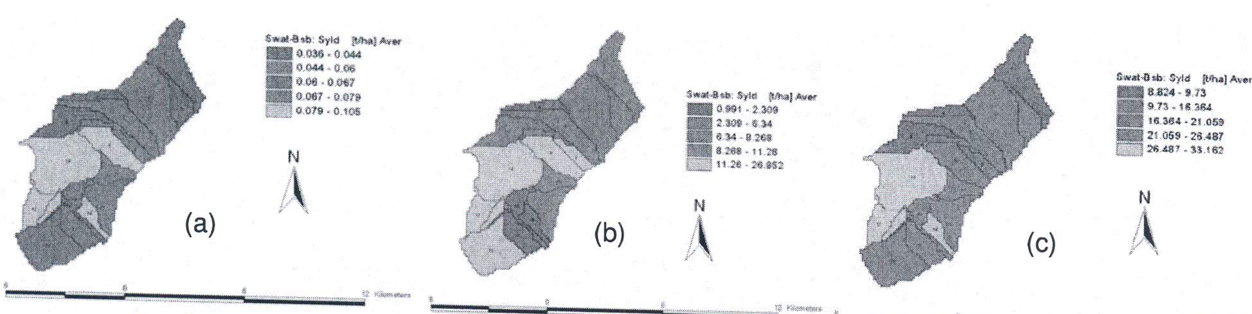

Fig. 5 Simulation of the annual sediment yield of the Guabirobas basin using the SWAT Model: (a) fully preserved scenario (t ha^{-1}), (b) current scenario (t ha^{-1}), (c) sugarcane scenario (t ha^{-1}).

The simulated flows are 2–3 times the observed values. The discrepancies are difficult to explain without a better evaluation based on field data. In spite of that, it is reasonable to suppose that the evapotranspiration of the existing crops and vegetation are greater than those calculated, considering the coefficients and types of cultures existing in the SWAT tables. In the present paper, for example, *Pinus* culture was used from the data basis of the SWAT model, while bearing in mind that the data basis of the eucalyptus culture was not parameterised. Eucalyptus are known to consume higher amounts of water, but this is one of the effects that was not corrected in the simulation.

Figures 4 and 5 present simulation results for annual sediment loads produced by the studied basins using SWAT. The paler areas in Figs 4 and 5 show the steeper regions with higher sediment production values.

SWAT simulations were sensitive to the scenario changes. Sediment generation for the preserved scenario was low and for the sugarcane scenario, mainly to Jataí basin, was very high.

CONCLUSION

The focus of the study was to identify areas of greatest vulnerability to erosion and sediment production in the studied ungauged basins. In order to achieve this, the USLE and SWAT models were jointly applied.

The purpose of using the USLE model was to compare results of this traditional model, widely used in Brazil, with studies of different scales, including river basins, with the results generated by the more complex SWAT model, developed for use in areas with scarce data. The USLE model, traditionally used in studies of rural planning in the State of São Paulo (Brazil), led to results expected for the region.

The qualitative interpretation of the results generated by the SWAT model has been consistent with the results obtained by applying the USLE; both indicating the most critical areas of the basins. The SWAT model was sensitive to changes in land use scenarios and to the set of available data related to the study area.

However, due to difficulties in conducting studies in the selected basins, flow and sediment loads are not monitored, and thus model calibration and verification is very difficult in these cases.

Although the SWAT model has been developed for use in ungauged watersheds, the results obtained here for soil loss erosion (when compared with the application of the USLE based on the use of GIS) and for streamflow (when compared with observed data) were much higher.

One possible reason for the discrepancy about the streamflow data is that the monitored basin is much larger than the modelled basins, and therefore it would be expected that the specific flow rates observed would be greater than the specific flow rates estimated. A reason for the discrepancy about the soil loss erosion data could be related to the transpiration, soil characteristics and tillage, considering that we are dealing with tropical cultures and soils that can have strong impacts on flow generation and thus on erosion.

The distributed approach, both by the USLE as well as by the SWAT model, helped to identify the most critical areas related to erosion and sediment yield. The prospect of developing scenarios confirmed the identification of critical areas and created information related to the risks of extensive cultivation of sugarcane in this region. The results obtained using these models could be used in the identification of more appropriate land uses and management practices best suited to the most vulnerable sectors of the basins. Further studies must be carried out to improve the application of SWAT model in these areas.

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