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Application of the Soil and Water Assessment Tool (SWAT) for sediment transport simulation at a headwater watershed in Minas Gerais State, Brazil

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Introduction

Natural resources are essential to life and irreplaceable in various human activities and, in addition, they are responsible for keeping the environmental equilibrium. Due to a rapid population growth observed during the last decades, the need for natural resources has increased significantly because of food production and water supply for population and industry.

Hydrological modeling has been widely used as a tool for evaluation of hydrological processes, thus allowing prediction of: (i) sediment accumulation in rivers and reservoirs; (ii) soil degradation and water erosion; and (iii) water quality for water supply and electric energy generation. Therefore, hydrological modeling makes possible to estimate the impact of land-use scenarios on water and sediment yield. It should be highlighted that the use of modeling for analysis of different land-use and management scenarios can support a rational use of water resources and implementation of adequate conservation practices for the desirable sustainable development.

Objectives

To calibrate and to validate the SWAT model for hydrology and sediment transportation simulation in an experimental headwater watershed located in the Mantiqueira Range region (Minas Gerais State, Brazil).

Material and Methods

Study area

This research was carried out at Lavrinha Creek Watershed (LCW) which is located in the Mantiqueira Range region, Minas Gerais – Brazil (Figure 1). The drainage area is about 6.88 km² with altitudes ranging from 1,159 m to 1,704 m (mean value of 1,364 m) and mean slope equal to 39.5%. The climate is classified as Cwb (Koppen's classification), characterized as meso-thermal with mean annual precipitation of 1,860 mm and mean annual temperature around 15ºC.

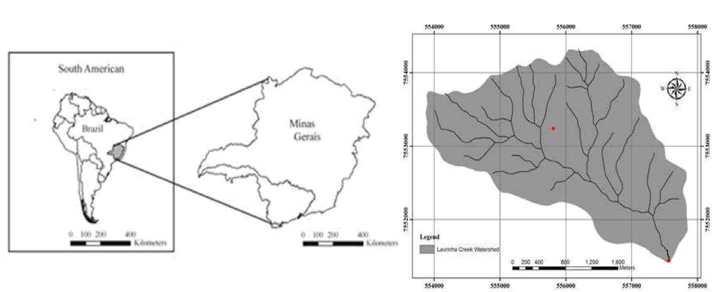

Figure 1. Location of the Lavrinha Creek Watershed (LCW).

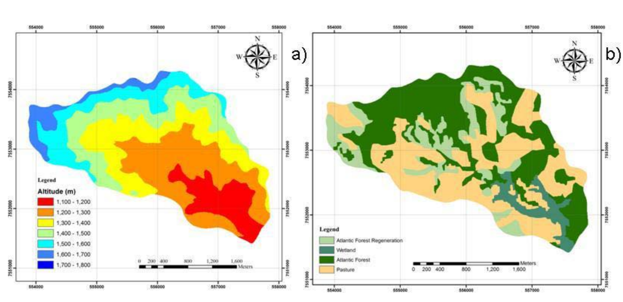

Figure 2. (a) Digital elevation model (DEM); and (b) land-use map of the Lavrinha Creek Watershed.

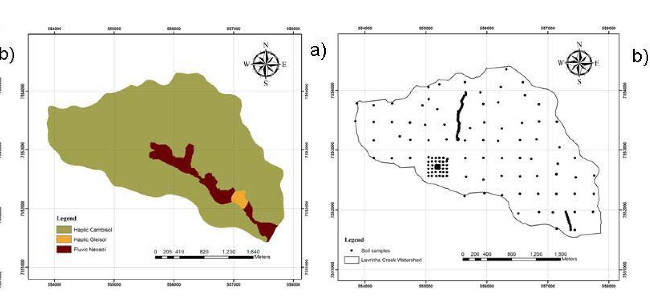

Figure 3. (a) Soil map; and (b) location of the soil samples in the Lavrinha Creek Watershed.

SWAT model

SWAT model is composed of a command structure to route runoff, sediments and agrochemicals within a given watershed. Its main components are associated with hydrology, climate, sediments, soil temperature, crop growth, nutrients, pesticides and agricultural management. The hydrological component includes subroutines of surface runoff, percolation, lateral subsurface flow, return flow from shallow aquifer and evapotranspiration. It requires daily data related to precipitation, maximum and minimum air temperature, solar radiation and relative humidity (Neitsch et al., 2005).

Relative to the calculation of surface runoff, SWAT employs a modified approach of the Curve Number Method (CN) (USDA, 1972). Sediment yield is estimated by using the well-known Modified Universal Soil Loss Equation (MUSLE).

Database

Topographic maps were obtained from the Brazilian Institute of Geography and Statistics (IBGE) at 1:25,000 scale. These maps were essential to create a digital elevation model (DEM) where relief is represented by gridded elevation data. The final DEM presented spatial resolution of 5 m (Figure 2a).

The land-use map (Figure 2b) was created by means of a 5-m-resolution Quickbird satellite imagery. Using a supervised classification was employed for such analysis in which a statistical classifier, known as Maximum Likelihood, was selected. Figure 2b illustrates the land-use map with four land-use classes: Atlantic Forest, Atlantic Forest Regeneration, Grassland and Wetland. An existing soil survey, which was carried out by Menezes et al. (2009), indicated that there are three soil classes in the LCW (Figure 3a): Haplic Cambisol, Haplic Gleisol and Fluvic Neosol.

SWAT model requires many physical-hydrological soil parameters. Such parameters were obtained by Junqueira Junior (2006) in an experiment conducted in the LCW to survey 198 soil samples (Figure 3b).

An automatic weather station installed within the LCW was responsible for the acquisition and storage of meteorological temporal series. To obtain information the stream flow an automatic water level gauge (equipped with a pressure sensor) was installed at the LCW's outlet, where water levels have been measured at 30-minute intervals. The resulting stage-discharge rating curve for LCW was:

$$Q = 0.3788 * h^{2.1099}$$

where Q corresponds to stream flow, in $m^3.s^{-1}$; and h is water level, in m, indicated by the gauge station.

For an analysis of suspended sediment concentration a temporal series was made up after several field measurements. For this study suspended sediment concentration (C_{SS}) was considered as a function of stream flow (Q), providing a discharge-sediment rating curve:

$$C_{SS} = 1975.2 * Q^{3.8254}$$

where C_{SS} represents suspended solid concentration, in $mg.L^{-1}$; and Q corresponds to stream flow, in $m^3.s^{-1}$.

Calibration and Validation

SWAT makes use of the Shuffled Complex Evolution (SCE) method (Duan et al., 1992) for automatic calibration. Objective functions are optimized in this approach using a global optimization criterion in which the most important data for calibration are the observed records.

Nash-Sutcliffe (COE), equation 3, was adopted as statistical coefficient for calibration and validation (Arnold et al., 2005; Neitsch et al., 2005).

$$COE = 1 - \frac{\sum_{i=1}^{n} \left(E_{obs_i} - E_{sim_i}\right)^2}{\sum_{i=1}^{n} \left(E_{obs_i} - \overline{E}_{obs}\right)^2}$$

where *COE*= Nash-Sutcliffe coefficient; E_{obs} = observed values; E_{sim} = simulated values; = mean value of the observed hydrological series; *n* = size of the hydrological series.

Results and Discussion

Sensitivity analysis

ArcSWAT interface executes the sensitivity analysis automatically. It was found in this analysis (Figure 4a) that the most sensitive parameters linked to stream flow were base flow alpha factor (Alpha_bf), effective hydraulic conductivity in main channel (Ch_K2), initial SCS curve number for moisture condition II (CN2), surface runoff lag coefficient (Surlag), saturated hydraulic conductivity (Sol_K), Manning's "n" value for the main channel (Ch_N2), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), soil evaporation compensation factor (ESCO), average slope steepness (SLOPE), groundwater delay time (GW_Delay). For the sediment related factors, sediment transport coefficient (Spcon), and its exponent (Spexp), and the P-Factor (USLE-P) were the most sensitive SWAT parameters.

Calibration e Validation

January 1st, 2006 to August 31st, 2006 was the period chosen to warm up the model. The warm-up period is very important for hydrological simulation since initial conditions, especially soil moisture, are unknown in most of situations at watershed scale (Mello et al., 2008). SWAT was calibrated considering a hydrological series from September 1st, 2006 to August 31st, 2008.

Firstly, an automatic calibration was tested for stream flow simulation, generating results incompatible with LCW reality. In this phase it was detected that stream flows were underestimated during recession periods and overestimated during rainy periods. Under this circumstance, a manual calibration was carried out for this watershed taking into account recommendations described by Griensven (2005). The runoff-related parameters selected for calibration as well as value ranges and calibrated values are listed in Table 1.

Table 1. Parameters, ranges and calibrated values used or obtained in simulations.

Parameter	Lower Bound Upper Bound	Initial value	Variation Method	Calibrated value
Alpha_bf	0 – 1	0.048	Replace by value	0.012116
Ch_K2	0 – 150 $mm.hr^{-1}$	0	Replace by value	24.133
CN2	-25% – 25%	-	Multiply by value (%)	-24.065
SURLAG	0 – 10 days	4	Replace by value	1.325
Sol_K	-25% – 25%	-	Multiply by value (%)	-25%
Ch_N2	0 – 1	-	Replace by value	0.0427
GWQmn	-1000 – 1000	0	Add to value	-950.07
ESCO	0 – 1	0.95	Replace by value	0.6847
Slope	-25% – 25%	-	Multiply by value (%)	-24.91%
GW_Delay	-10 days – 10 days	31	Add to value	9.056

Table 2. Parameters, ranges and calibrated values used or obtained in simulations related to suspended sediment .

Parameter	Lower Bound – Upper Bound	Calibrated value
Spcon	0.0001 – 0.01	0.0034
Spexp	1 – 2	1.8194
USLE_P	0 – 1	0.814

Figure 4 depicts observed and simulated hydrographs. Analyzing this Figure one can visually infer that SWAT was capable of simulating stream flow adequately since there was a good fit between observed and simulated stream flows. Some discrepancies can be observed in different periods, such as February 2008 to April 2008, which are associated mainly with recession stream flows. The Lavrinha Creek Watershed (LCW) has a rapid response time for both peak discharges and recession discharges, thus making simulation more difficult somehow. Figure 4b represents observed and simulated hydrographs for validation period in the Lavrinha Creek Watershed. The same behavior can be noticed during validation period, in other words, the model tends to underestimate stream flow for recession periods and overestimate stream flow for some rainy events. However, SWAT model also resulted in a good value of Nash-Sutcliffe (COE) coefficient (0.793) during the validation period. Analyzing SWAT results in the calibration and validation periods, we can conclude that this model tends to generate good results when applied in time periods other than the ones adopted in this study and in other land-use scenarios in the LCW. Therefore, SWAT model can be considered a robust computational tool for the planning of water resources management in the Mantiqueira Range Region. The sediment-related parameters used for SWAT calibration as well as ranges and calibrated value are presented in Table 2.

Figure 5a illustrates the calibration of SWAT model for suspended sediment concentration, while Figure 5b represents the validation of this model for the same hydrological variable. Readers can notice in Figure 5 that SWAT model was also capable of simulating suspended sediment concentration values adequately at the LCW's outlet. The model resulted in a Nash-Sutcliffe coefficient (COE) of 0.683 in the calibration phase, being classified as acceptable for simulation (Zaapa, 2002).

It was considered the period from September 1st, 2008 to August 31st, 2010 for the SWAT validation. In spite of having underestimated peak discharges in the rainy period (2009/2010 hydrological year), SWAT presented a good performance (COE = 0.645) when sediment transport simulation was tested. Machado et al. (2003) obtained COE values between -0.06 and 0.78, depending on the area discretization and selection method (dominant by sub-watershed or percentage of the area).

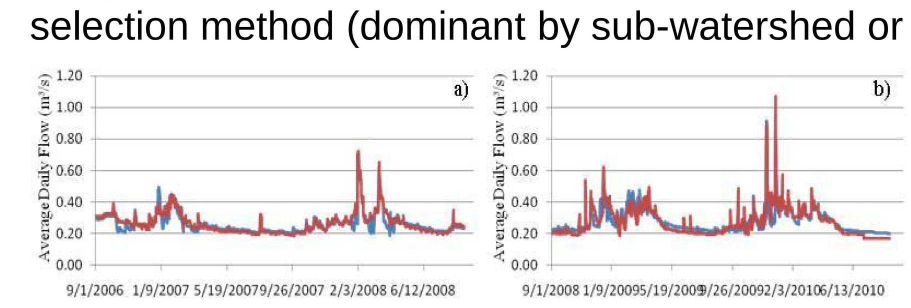

Figure 4. Observed hydrograph and simulated hydrograph for (a) calibration period; (b) validation period in the Lavrinha Creek Watershed.

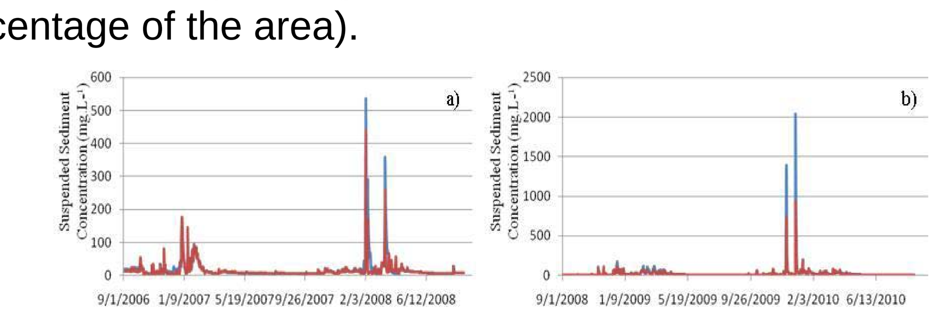

Figure 5. Observed and simulated values of suspended sediment concentration at the LCW's outlet for the (a) calibration period; and (b) validation period.

Conclusions

Due to the COE results found during calibration and validation of the SWAT model it was concluded that such model was capable of simulating adequately both stream flow and suspended sediment concentration at the Lavrinha Creek Watershed's outlet.

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