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Impact of changes in land use in the flow of the Pará River Basin, MG

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Key words:
'Cerrado'
seasonal semideciduous forest
flow

ABSTRACT
Plant cover plays an essential role in the maintenance and balance of the hydrological cycle, performing functions in the control of water availability, which guarantee flow permanence. The use of mathematical models is an alternative to represent the hydrological system and help in the understanding of phenomena involving the variables of the water cycle, in order to anticipate and predict impacts from potential changes in land use. In the present study, the hydrological model SWAT (Soil and Water Assessment Tool) was used to analyse the dynamics of flow and water flow in the Pará River Basin, Minas Gerais, Brazil, aiming to evaluate the impact caused by changes in land use in water availability. The adjusted model was assessed by the coefficient of efficiency of Nash-Sutcliffe (between -0.057 to -0.059), indicating high correlation and coefficient of residual mass (0.757 to 0.793) and therefore a satisfactory fit. An increase of about 10% in the basin flow was estimated, as a function of changes in land use, when simulating the removal of the original 'Cerrado' vegetation and of the seasonal semideciduous forest for pasture implementation in 38% of the basin.

Palavras-chave:
Cerrado
floresta estacional semidecidual
vazão

Impacto de alterações no uso do solo na vazão da Bacia do Rio Pará, MG

RESUMO
A cobertura vegetal exerce papel fundamental na manutenção e no equilíbrio do ciclo hidrológico, desempenhando funções no controle da produção de água que garantem a permanência de vazões. O uso de modelos matemáticos é uma alternativa para representar o sistema hidrológico e auxiliar na compreensão dos fenômenos que envolvem as variáveis do ciclo da água para antecipar impactos decorrentes de eventuais mudanças no uso da terra. Neste trabalho é utilizado o modelo hidrológico SWAT (Soil and Water Assessment Tool) para analisar a dinâmica da vazão na bacia do Rio Pará, em Minas Gerais, Brasil, com o objetivo de avaliar o impacto provocado pelas alterações de uso do solo na disponibilidade de água da bacia do Rio Pará. O ajuste do modelo foi avaliado pelo coeficiente de eficiência de Nash-Sutcliffe (entre -0,057 a -0,059) indicando alta correlação e coeficiente de massa residual (0,757 a 0,793) e, portanto, um ajuste satisfatório. Estima-se que houve incremento de cerca de 10% na vazão da bacia em função das alterações no uso do solo, contemplando basicamente a supressão da vegetação original de Cerrado e de Floresta Estacional Semidecidual para implantação de pastagem em 38% do território da bacia.

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Introduction

Plant cover plays an essential role in the maintenance and balance of the hydrological cycle (Gregory et al., 1991), acting on the control of water production and minimum flow permanence, which ensures the stability and balance of aquatic and terrestrial ecosystems (Tucci & Clarke, 1997). The use of land and plant cover has a preponderant role, since water is stored in the basin and subsequently distributed, feeding springs and tributaries of the main channel (Llerena et al., 2007).

In this context, mathematical modeling is an alternative for obtaining information about the dynamic behavior in anticipation of events and possible impacts in a watershed, resulting from any changes in land use, among other factors. Hydrological models are important tools to represent systems, their processes, and to help in the understanding of phenomena involving the variables of the hydrological cycle (Tucci, 1998).

In this context, hydrological models have received considerable attention, representing technical tools for water resources management. Among them, the hydrological model SWAT (Soil and Water Assessment Tool) is highlighted, since it is capable of projecting trends and effects of climate changes, as well as changes in land use for water production in the basin (Neitsch et al., 2011).

SWAT allows to assess impacts from changes in land use in different variables of the hydrological cycle, such as surface runoff, groundwater flow, evapotranspiration, sediment yield, nutrient and water quality of a watershed. Because of these capabilities SWAT has widely employed to investigate several landscape aspects, such as slope erosion (Machado et al., 2003), groundwater recharge in mountain areas (Eckhardt & Ulbrich, 2003), nutrient balance in watersheds (Neves et al., 2006), effects of climate change on water availability (Chaplo, 2007; Abbaspour et al., 2009; Githui et al., 2009a). Notably, SWAT is used to evaluate the impacts of land cover change on water availability (Githui et al., 2009b; Blainski et al., 2011; Baker & Miler, 2013).

In this study, the impact caused by changes in land use for water availability in the Pará River Basin (Minas Gerais) was evaluated using the hydrological model SWAT.

Material and Methods

The Pará River Basin is located in the Upper São Francisco River, in the state of Minas Gerais, Brazil, occupying an area of 12,300 km^2 and comprising 35 municipalities. Geographically, the basin is located in the rectangle enclosed by the coordinates E = 451,525.57 m and N = 7,873,768.77 m and E = 581,888.17 m and N = 7,697,371.28 m, UTM System, Zone 23, Southern Hemisphere, SAD 69 Geodetic System (South American Datum 1969) (Figure 1). The river is a tributary of the right bank of the São Francisco River, with a total thalweg of about 212 km and altitudes between 600 and 1,340 m.

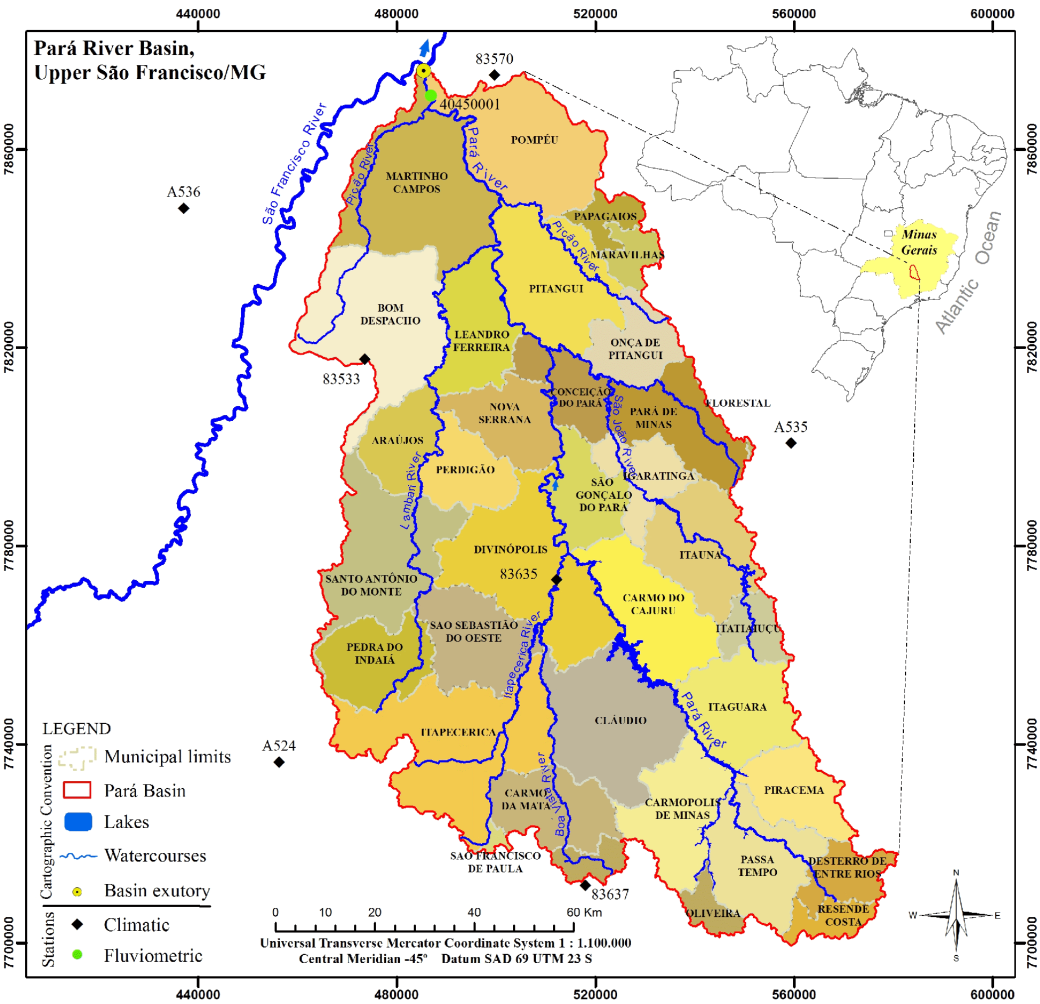


Figure 1. Limits, municipalities and stations of the Pará River basin, MG, Brazil

The region presents Aw, Cwa and Cwb climates, in accordance with Köppen, characterized by dry winters and rainy summers, with mean temperatures of 16 °C in winter and 29 °C in summer, and annual mean of 23 °C. Annual rainfall ranges between 1,200 and 1,700 mm.

The predominant original plant cover in the basin belongs to the 'Cerrado' biome, along with seasonal semideciduous forest formations, which belong to the Atlantic Forest biome (CETEC, 1983).

In order to adjust the hydrological model SWAT to the Pará River Basin, a database containing information on topography, land use and plant cover, pedology and hydrology, was assembled. Hydroclimatic information related to fluviometry, precipitation, temperature, wind, air humidity, and solar radiation also integrated the data used in the model, for purposes of calibration and representation of the hydrological behavior of the basin.

The meteorological database was provided by Instituto Nacional de Meteorologia – INMET. These stations, identified as A536, A535, A524, 83570, 83533, 83635, 83637, are located within the geographic area of influence of the watershed. The runoff data were obtained from station 40450001 (Porto Pará) administered by the Agência Nacional de Águas (Figure 1). The topographic base of the area was obtained from an ASTER GDEM altitude image (digital elevation model), with a 30 m spatial resolution. For preparation of the map of current use and land cover, methods for classification and pattern recognition in orbital images from Landsat 5 TM sensors, acquired on 07/19/2012, were applied, provided by Instituto Nacional de Pesquisas Espaciais (INPE). To cover the entire length of the basin, three Landsat images were used from orbits 465/72 and 466/74, composed in the form of mosaic. The map of original vegetation cover was generated from information on the original native vegetation associated with each type of soil unit, as described in the soil survey of the Centro Tecnológico de Minas Gerais (CETEC, 1983). The detailed characteristics of pedogenic portions were obtained from the study conducted by CETEC (1983), according to which pedology in the basin is quite diverse. Most parts of the basin (38.60%) show associations of Latosol and Cambisol, distrofic humic and allic of undulating relief. Associations of clay soils and lithic soils, distrophic and allic with undulating relief occur in 32.17% of the area. In about 18.60% of the basin area prevail associations of Cambisols, clay soils and lithic soils of undulating relief. Alluvial soils occur in 8.07% of the territory, predominantly on the banks of watercourses, forming slightly narrow and discontinuous bands. Finally, 2.56% of the basin area are characterized by occurance of association of Lithic soils, Cambisols, and rock outcroppings with relief varying from undulating to mountainous.

The algorithm used in hydrologic modeling was ArcSwat 2012, coupled to the ArcInfo 10.1 geoprocessing platform.

The hydrological model SWAT was adjusted to the Pará River Basin to simulate changes in land use under different plant cover scenarios, considering physical and climatic variables. The stages of supply and adjustment of the SWAT model are illustrated in Figure 2.

In the initial phase, parameter sensitivity was evaluated combining the methods One-factor-At-a-Time – OAT and Latin Hypercube – LH (Griensven et al., 2006), identifying

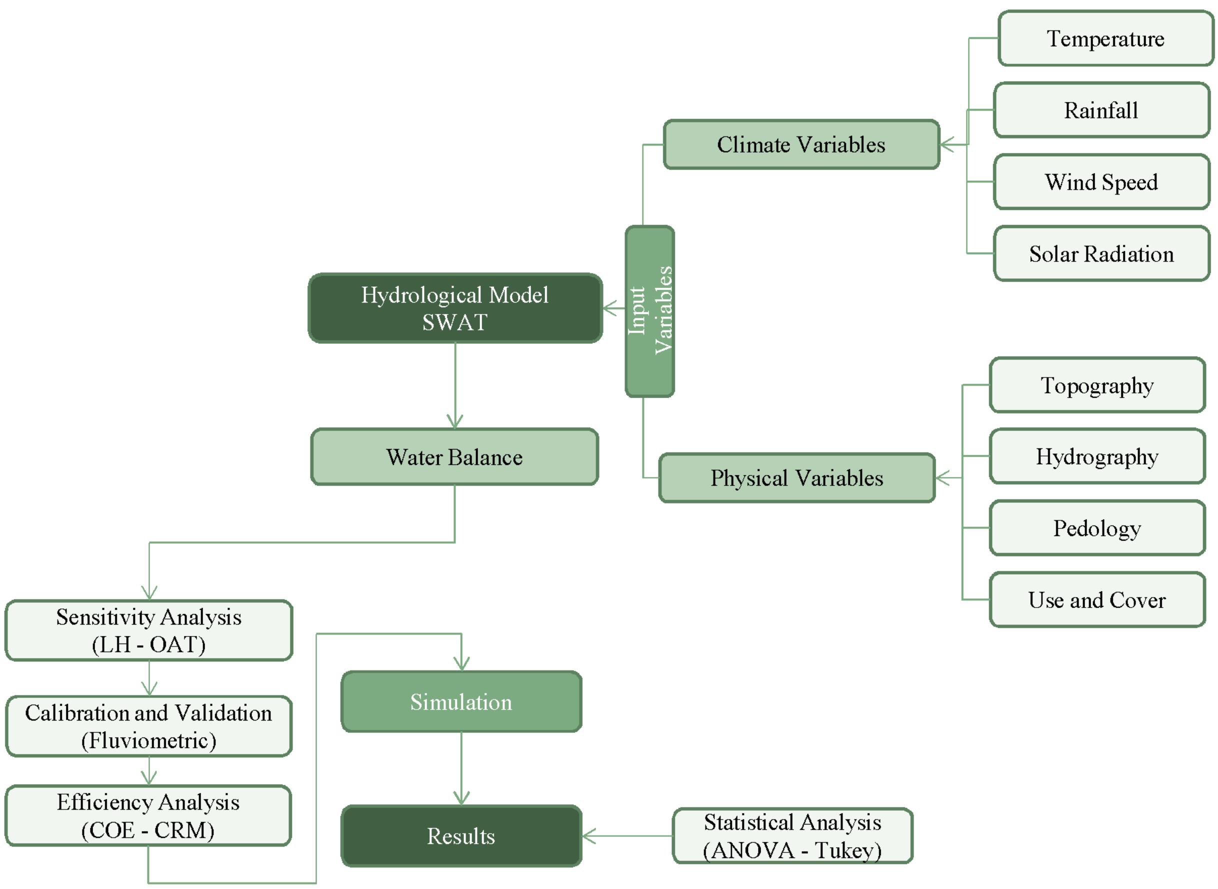


Figure 2. Flowchart of the steps for the adjustment of the hydrological model SWAT

and classifying the parameters that have the most significant impact in model outputs (Saltelli et al., 2000; Green & Griensven, 2008).

Subsequent to the sensitivity analysis, the calibration and validation of the model were performed. In the calibration, the parameter values are changed within the allowed range, so that the model can replicate the conditions known in advance in the natural modeled process (Viessman Júnior & Lewis, 2002). In this phase, a time series of the measured data was used in two periods: one for calibration (January 1980 to December 1996) and the other for model verification (January 1997 to December 2012). The data measured in fluviometric station 40450001 (Porto Pará) were used in these steps.

During calibration, the model input parameters were changed, in order to obtain an acceptable fit. During validation, the parameters obtained in the calibration were employed in the execution of the model and the adjustment was analysed by statistical methods (Arnold et al., 2000; Neitsch et al., 2011).

The performance evaluation of the model adjustment was checked by the coefficient of Nash-Sutcliffe efficiency (COE), which is the most widely used method for evaluating the efficiency of hydrological models, and is expressed by Eq. 1.

$$COE = 1 - \frac{\sum_{t=1}^{n}\left(E_{ob} - E_{cal}\right)^2}{\sum_{t=1}^{n}\left(E_{ob} - E_{m}\right)^2} \quad (1)$$

where:

E_{ob} - observed value
E_{cal} - calculated value
E_m - average of the series of values observed in the period

The COE ranges from negative infinity to the maximum value of 1, which represents the maximum efficiency.

The coefficient of residual mass (CRM) indicates when the model overestimates (negative values) or underestimates (positive values) the simulated variables. The CRM is expressed by Eq. 2.

$$CRM = \frac{\sum_{i=1}^{n} E_{ob} - \sum_{i=1}^{n} E_{cal}}{\sum_{i=1}^{n} E_{ob}} \quad (2)$$

where:

E_{ob} - observed value
E_{cal} - the calculated value

The equation in the SWAT model that determines the production of surface water in the basin is based on the water balance equation, expressed by Eq. 3.

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_i - Q_i - ET_i - P_i - QR_i\right) \quad (3)$$

where:

SWt - final amount of water in the soil
T - time, days
R_i - precipitation, mm
Q_i - runoff, mm
ET_i - evapotranspiration, mm
P_i - percolation, mm
QR_i - return flow, mm

In order to evaluate the impact of land use changes on water production in the basin, two scenarios were analysed:

Scenario I: Original plant cover - Obtained from the pedological mapping performed by CETEC (1983), which presents the information of the corresponding original plant cover in each pedological unit.

Scenario II: Current land use - Obtained through the classification of Landsat 5 orbital images.

The model was calibrated to the current use scenario. Data on the mean annual flow were subjected to analysis of variance (F test) and test of Tukey, for comparison of means at 0.05 level of significance.

Results and Discussion

The adjustment of the hydrological model SWAT to the Pará River Basin, evaluated by Coefficients of Residual Mass (CRM) and Nash-Sutcliffe (COE), showed a significant correspondence between simulated and observed values. The difference presented by the CRM was almost negligible (between -0.057 and -0.059), indicating a high correlation between the observed and simulated flows by the SWAT model. The COE value between 0.757 and 0.793 also indicates a satisfactory adjustment of the model, according to the criteria proposed by Krysanova et al. (1998).

Therefore, the SWAT model adequately predicted the hydrological functioning of the Pará River Basin, both for peak values, and for minimum runoff values, proportionally responding to the actual precipitation rates of the basin (Figure 3).

The comparison between the scenarios of current use and plant cover reveals the advance of pastoralism, currently holding 38% of the territory, plus 7.5% of eucalyptus forests and 4.5% agriculture (Figure 4). The reduction to approximately half the area originally occupied by the Seasonal Forest (Mata Atlântica) is noteworthy, while the 'Cerrado' biome has been reduced to about 25% of the original area.

Data simulated by the SWAT model indicate an increase in flow, due to the changes in land use and in the original plant cover of the Pará River Basin (Figure 5). The current scenario provided the highest mean flow and amplitude, compared to the scenario of the original plant cover.

The annual water balance reveals the magnitude of the impact of land use changes on water flow in the Pará River Basin (Table 1). Changes in land use and occupation (current use scenario) resulted in an increase of about 10% in water flow of the Pará River Basin, corresponding to 19.8 $m^3 s^{-1}$ or 51 mm $year^{-1}$, in relation to the original condition. This increase in flow can be explained by reduction of the mean evapotranspiration of the basin from 634.01 mm in the original land cover scenario to 581.01 mm in the current cover scenario.

The replacement of the original plant cover, predominantly 'Cerrado' and Seasonal Forest, by pasture, in approximately 38% of the total basin area, i.e. 4,680 km².

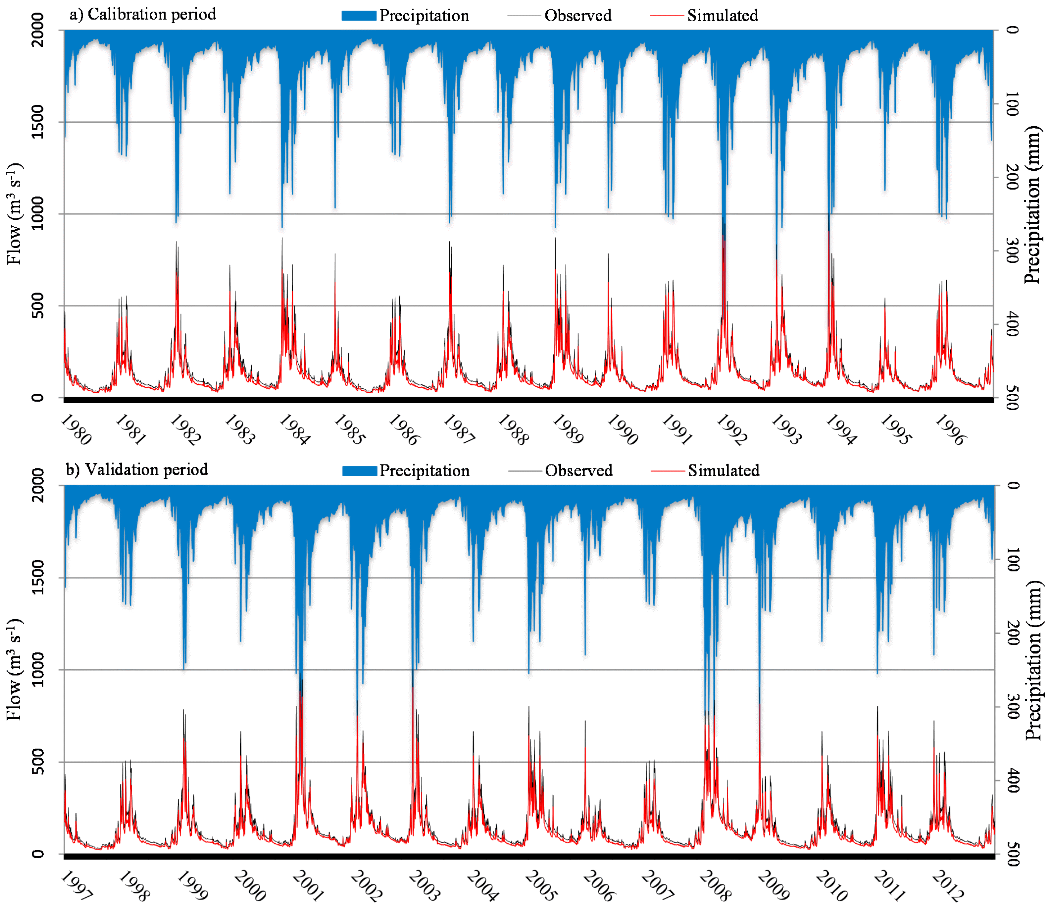
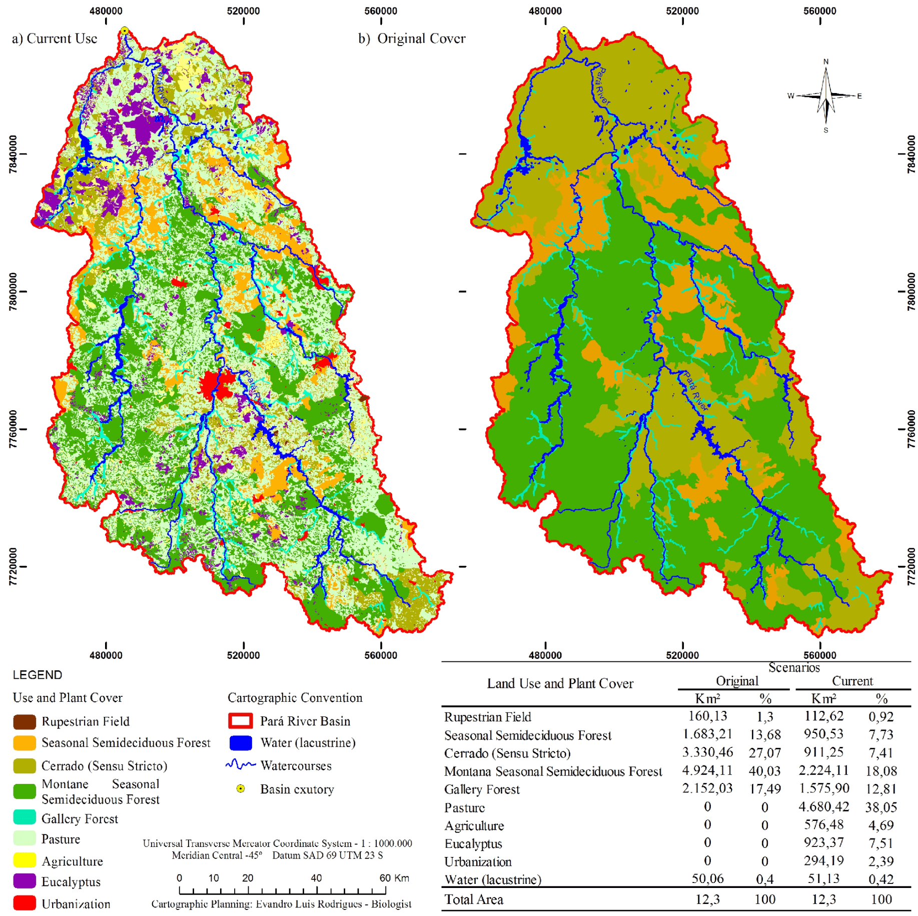


Figure 3. Hydrograph of simulated and observed daily flow in the Pará River Basin - MG, (a) calibration (1980-1996) and (b) validation periods (1997-2012) of the SWAT model



Land Use and Plant Cover	Scenarios: Original Km²	%	Current Km²	%
Rupestrian Field	160,13	1,3	112,62	0,92
Seasonal Semideciduous Forest	1.683,21	13,68	950,53	7,73
Cerrado (Sensu Stricto)	3.330,46	27,07	911,25	7,41
Montana Seasonal Semideciduous Forest	4.924,11	40,03	2.224,11	18,08
Gallery Forest	2.152,03	17,49	1.575,90	12,81
Pasture	0	0	4.680,42	38,05
Agriculture	0	0	576,48	4,69
Eucalyptus	0	0	923,37	7,51
Urbanization	0	0	294,19	2,39
Water (lacustrine)	50,06	0,4	51,13	0,42
Total Area	12,3	100	12,3	100

Figure 4. Original vegetation and current land use in the Pará River Basin, MG, Brazil

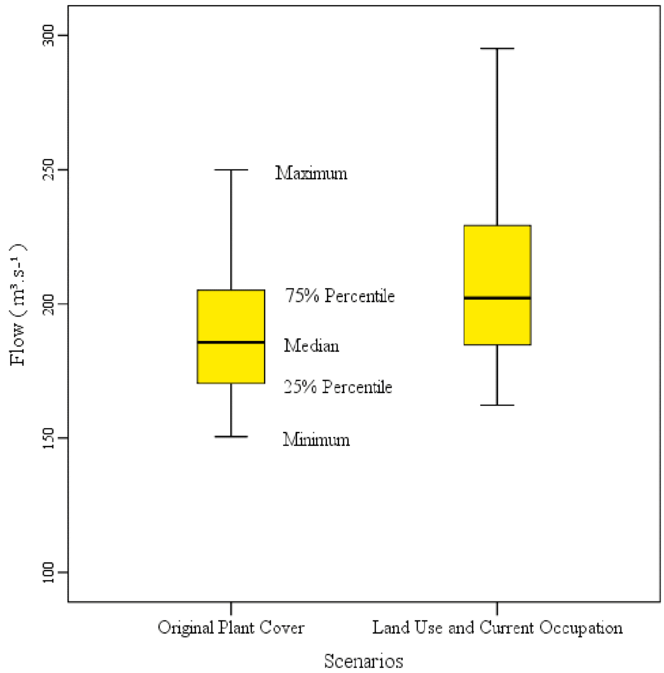


Figure 5. Amplitude and dispersion of data on simulated flow in scenarios of original plant cover and current use in the Pará River Basin, MG

Table1. Mean precipitation and flow for the scenarios of current use and original plant cover in the Pará River Basin, MG

Variable	Scenario	
	Original	Current
Flow ($m^3 s^{-1}$)	189.0 A	208.8 B
Precipitation (mm $year^{-1}$)	1.403	1.403
Evapotranspiration (mm $year^{-1}$)	634	581
Flow (mm $year^{-1}$)	486	537
Flow (%)	100	110

Means followed by the same letter do not differ statistically by the Tukey test at the probability level of 0.05

Pasture is characterized by a small biomass and a shallow root system, promoting a reduction in evapotranspiration and an increase in direct runoff (surface and subsurface) to the drainage network, increasing the values of annual mean flow in the basin (Lima et al., 2012). Comparatively, the native 'Cerrado' vegetation and the seasonal semideciduous forest intercept more water in the canopy, and also transpire more than low grasslands. Furthermore, the original vegetation has a deep root system, which allows the exploration of a larger soil volume and, consequently, a higher consumption of water reserves in the soil profile (Oliveira et al., 2005).

Studies performed in 'Cerrado' areas report evapotranspiration values between 554 and 569 mm $year^{-1}$ (Santana et al., 2010; Lima, 2011; Ferraz et al., 2013). For pasture areas, evapotranspiration is between 182 and 437 mm $year^{-1}$ (Sumner & Jacobs, 2005; Santana et al., 2010; Brauman et al., 2012; Du et al., 2013). According to Best et al. (2003), evapotranspiration is the most important component of the hydrological cycle, because its magnitude usually exceeds that of other components, such as recharge, runoff and soil moisture variation.

The results obtained in this study confirm the importance of plant cover in the set of determining factors for water flow in a watershed (Tucci & Clarke, 1997).

Conclusions

1. The hydrological model SWAT – Soil and Water Assessment Tool – was properly adjusted and allowed to satisfactorily simulate the dynamics of water availability in the Pará River Basin, MG, Brazil.

2. The main change in land use involved replacing the original vegetation by pasture in an area corresponding to 38% of the basin.

3. The conversion of 38% of natural vegetation to pasture resulted in a 8.36% evapotranspiration mean decrease in the whole basin.

4. Changes in land use caused an increase of about 10% in the Pará River Basin flow.

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