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Impacts of Using Different Soil Databases on Streamflow Simulation in an Experimental Rural Catchment of the Brazilian Savanna

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A B S T R A C T

The purpose of this study is to analyze the soil database influence on streamflow simulation with the SWAT model in the experimental catchment of the Pipiripau river, located in Brazilian savanna (Cerrado biome). To achieve this goal, two databases were used, one developed with data collected nearby the Pipiripau region, and another one with data from literature. The evaluation was performed using a streamflow historical time series of 10 years (1989-1998), on monthly basis. The analysis was made without calibration, using only the results from SWATs first simulation, as it was applied in an ungagged basin. The comparison between the observed and simulated water budget and the evaluation results shows that soil database can influence the hydrological simulation and affect modeling. The results demonstrated that the simulated relation between baseflow and precipitation using the soil database developed for the Pipiriau region was similar to the one extracted from observed data in the studied basin. The results indicate the importance of developing specific soil databases for different regions, as well as research on other parameters in order to improve SWATs physical basis.

Keywords: Hydrological modeling, SWAT model, soil parameters, Cerrado biome.

Impactos do Uso de Diferentes Bases de Dados na Simulação da Vazão em uma Represa Experimental Rural da Savanna Brasileira

R E S U M O

O objetivo desse estudo foi analisar a influência da base de dados de solos na simulação da vazão da bacia experimental do ribeirão Pipiripau, localizada no Bioma Cerrado, utilizando o modelo SWAT. Para atingir essa meta, foram utilizadas duas bases de dados: a primeira elaborada com dados coletados nas proximidades da bacia; e a segunda obtida com dados disponíveis na literatura. A avaliação foi conduzida utilizando a série histórica de vazões no período entre 1989 e 1998, com base mensal. A análise foi feita sem calibrar o modelo, utilizando os parâmetros do mesmo modo como seria feito em bacias não monitoradas. As comparações do balanço hídrico anual e das relações entre seus componentes, e dos índices de avaliação, entre os dados observados e os resultados obtidos com o modelo, demonstram que a base de dados de solos utilizadas nas simulações afeta a simulação hidrológica. Os resultados demonstram a importância de desenvolver base de dados de solos específica para diferentes regiões do território brasileiro e de pesquisar outros parâmetros para melhorar a base física do modelo SWAT para simulações no Brasil.

Palavras-chave: Modelagem hidrológica, modelo SWAT, parâmetros do solo bioma Cerrado.

Introduction

Knowledge about physical and hydraulic characteristics of soils is fundamental for the proper application of conceptual and physically-based hydrological models with distributed parameters (Romanowicz et al., 2005; Peschel et al., 2006; Geza e McCray, 2008), such as the SWAT model - Soil and Water Assessment Tool (Arnold et al., 1998; Arnold e Fohrer, 2005).

Considering that hydrological behavior of tropical soils of the Cerrado biome (Brazilian savanna) is totally different from the one observed in temperate regions soils, for which the SWAT model was designed, recently, a reference soil database for applying SWAT in catchments of the Brazilian savanna, by using measured data, was developed (Lima et al., 2013). Before that, many studies with SWAT

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were conducted in the region, but all of them using adapted data from literature or pedotransfer functions developed for other regions (Sarmento, 2010; Strauch et al., 2011; Ferrigo et al., 2011; Minoti et al., 2011; Ferrigo et al., 2012; Salles, 2012; Strauch et al., 2012; Strauch et al., 2013). Obviously, all that introduce uncertainties in the modeling process and problems related to the physical basis of the model will represent a limitation for using this tool, for example, to predict future scenarios or to simulate hydrological processes in ungagged basins.

The impacts of soil input database on SWAT's simulations were evaluated by many authors (Boluwaed e Madramootoo, 2013; Bossa et al., 2012; Julich et al., 2012; Sheshukov et al., 2011), showing that the model is really sensible to this information.

Therefore, the purpose of this study was to analyze the influence of a specific soil input database, developed for the region, on streamflow simulation with SWAT model in an experimental rural catchment of the cerrado biome.

Materials and Methods

Study area

The Pipiripau River Basin-PRB is an experimental rural catchment of the Brazilian savanna (Cerrado biome). It has a drainage area of 235 km², and is located in the northeast part of the Brazilian Federal District, although with, approximately, 10% of its area, its upper part is located at Goiás State (Figure 1). The central coordinate of the basin is 15°35'92.0" S, and 47°32' 6.51" W.

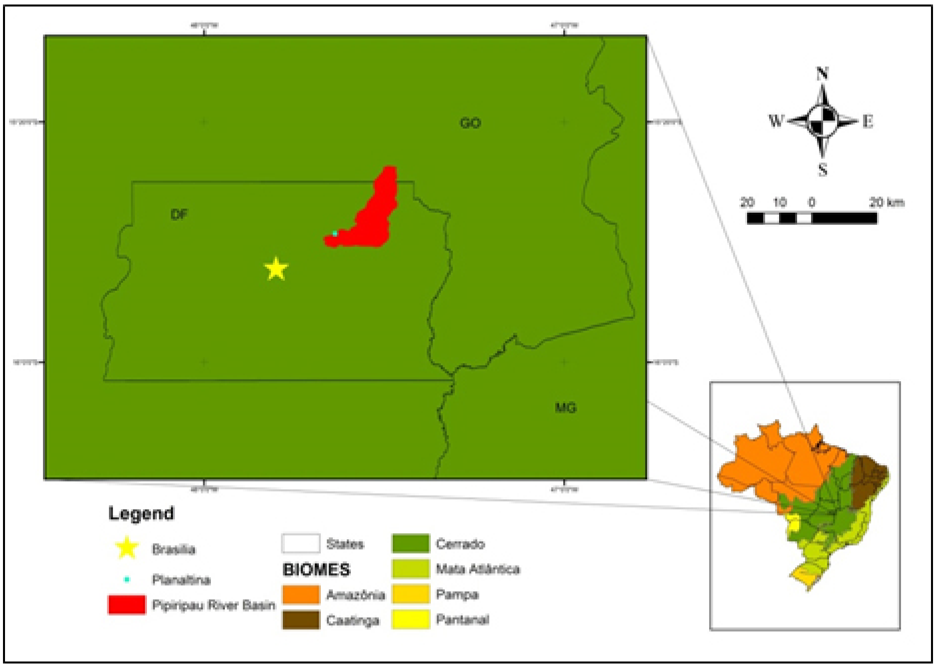

Figure 1. The location of the Pipiripau River Basin (PRB) in relation to Brazilian Biomes and the Federal District (DF).

The climate in the PRB is typical for the Brazilian Central Plateau region, having a rainy season from October to April, and a dry weather from May to September, with only some precipitation during the drought period. The average annual rainfall was 1,306 mm between 1972 and 2004, on the Taquara's precipitation station, which is situated inside the PRB (Chaves e Piau, 2008). Following the classification of Köppen, the climate in the basin is Tropical with a dry winter (Aw).

Due to the relevance of PRB for the water supply of the Federal District population, and to the important water conflict between the sanitation company (CAESB) and irrigated farms, this catchment was included as an experimental basin of the UNESCO's HELP initiative (Hydrology for the Environment, Life and Policy), It is coordinated by the International Hydrological Programme (IHP) and has 91 basins spread over 67 countries (UNESCO, 2010). PRB is also part of a Brazilian initiative involving payment for environmental services in order to stimulate farmers to implement best management practices in their properties. This action is called Water Producer Programme and it is coordinated by the National Water Agency (ANA), involving many institutions, companies, water users, and other partners from the society.

Input data - maps

The input data used to run the model was achieved from different sources developed by the Brazilian Government. Figure 2 shows the land use, soils, and a digital terrain model maps.

The PRB land use map was developed on a 1:10,000 scale (Brasil, 2010) using the Federal District Cartography System, SICAD database (CODEPLAN, 1992), and the interpretation of a SPOT image from 2008. The land use was classified in the following classes: large-scale cropping (43.2%), pasture (21.5%), natural savanna - cerrado (10.7%), semi-natural vegetation (6.6%), irrigated agriculture (4.5%), riparian vegetation (4.2%), native pasture (3.5%), low density residential area (1.6%), unpaved roads (1.5%), urban area (1.2%), silviculture (0.6%), bare soil (0.5%), paved roads (0.3%) and water (0.1%).

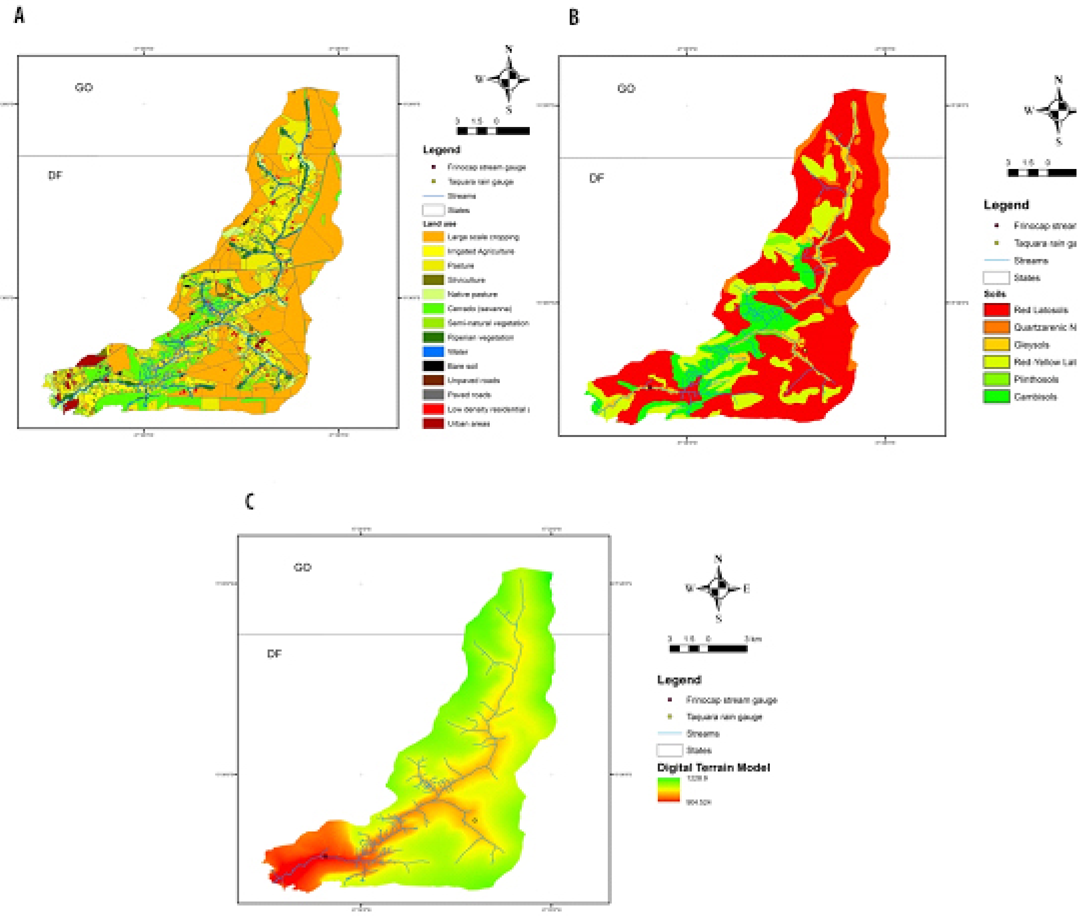

Figure 2. Land use of soils, and a digital terrain model maps in the Pipiripau River Basin (PRB): A. land use; B. soil types; C. digital terrain model.

The soil map was produced by EMBRAPA (1978), on a 1:100,000 scale with updates (Brasil, 2000; Brasil, 2010). The PRB is mainly covered by Red (59.36%) and Red and Yellow Latosols/Oxisols (15.18%), followed by Cambisols (11.73%), Quartzarenic Neosols (7.54%), Gleisoils (5.75%), and Plinthosols (0.45%).

The Digital Terrain Model used to represent the PRB topography was generated from 1:10,000 contour lines, with 5 m vertical distance, obtained from SICAD (CODEPLAN, 1992). According to the digital terrain model, the average altitude on the PRB is 1095 m and the amplitude varies from 904 to 1228 m. Up to 68% of the slopes on the PRB have less than 10°.

Concerning the meteorological input data, Brasilia's weather station (Figure 1), INMET 83377, coordinates 16º13'12" S and 48º04'12" W, provided temperature, wind, and humidity data (http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep). The precipitation data came from Taquara's rainfall gauge available at the website HIDROWEB/ANA (Brasil, 2010), coordinates 15º37'56" S and 47º31'13" W, ANA 01547013, which is inside the PRB (Figure 2). The solar radiation was calculated according to Vianello and Alves (1991), using deterministic relations based on the latitude and longitude position.

The streamflow data was obtained from FRINOCAP's gauge station also available at the website HIDROWEB/ANA (Brasil, 2010), coordinates 15º39'26" S and 47º37'30" W, ANA 60473000, with a drainage area of about 215 km² (Figure 2). The average streamflow between 1989 and 1998 was 2.81 $m^3.s^{-1}$, while the minimum and maximum values for this period were, respectively, 0.51 $m^3.s^{-1}$ and 10.89 $m^3.s^{-1}$, which shows that the Pipiripau River is perennial.

Model setup and evaluation

SWAT is a conceptual model that operates on a daily time step (Arnold et al., 1998). The model was integrated with Geographic Information Systems (GIS) to easily extract input data for modeling a basin, and spatially distribute model parameters in order to provide large-scale basin simulations in continuous-time (Srinivasan e Arnold, 1994). Thus, SWAT is a complex conceptual model with spatially explicit parameterization (Arnold et al., 2000).

The objective of SWAT's development was to predict the impact of management on water, sediment and agricultural chemical yields in large ungagged basins (Arnold et al., 1998). Regardless the type of study that is done with SWAT, the model's simulation will be function of the water balance in the watershed, where the hydrological cycle is divided into two phases: 1- the land phase, that controls the amount of water, and the sediment loadings toward the main channel, and 2- the routing phase, which can be defined as the movement of water, and of the sediments through the channel network of the watershed to the outlet (Neitsch et al., 2005).

By controlling different hydrological processes, such as the amount of water available on soil layers, the soil parameters play an important role in SWATs land phase simulation and influence the routing phase. In addition, their variability can cause uncertainties in the models simulation.

In order to analyze the influence of the soil database on streamflow simulation with SWAT model in Pipiripau river basin, two soil databases were used. The first one (SDB1) was developed with measured data from another experimental catchment located nearby (~20 km) the PRB (Lima, 2010, Lima et al., 2013a, Lima et al., 2013b), whose soils represent the typical physical characteristic of the soils of the region. Triplicate samples were collected in around 66 different points in the Rio Jardim River Basin. In each point, samples were also collected in two depths (15 and 60cm). The other soil database (SDB2) was developed by Baldissera (2005), for the same soil types, with information available in the literature. The parameters tested for each soil type were: the maximum rooting depth of the soil profile (SOL_ZMX); the available water capacity of the soil layer (SOL_AWC); the moist bulk density (SOL_BD); the saturated hydraulic conductivity (SOL_K); the moist soil albedo (SOL_ALB); the organic carbon content (SOL_CBN); the USLE equation soil erodibility factor (USLE_K); the clay content (CLAY); the silt content (SILT); and the sand content (SAND). Both SDB1 and SDB2 used the hydrological groups classification proposed by Sartori et al. (2005).

As examples, Figures 3A and 3B illustrates some differences between the values of the Saturated Hydraulic Conductivity (SOL_K) and the Moist Bulk Density (SOL_BD), respectively, for each soil type, for SDB1 and SDB2.

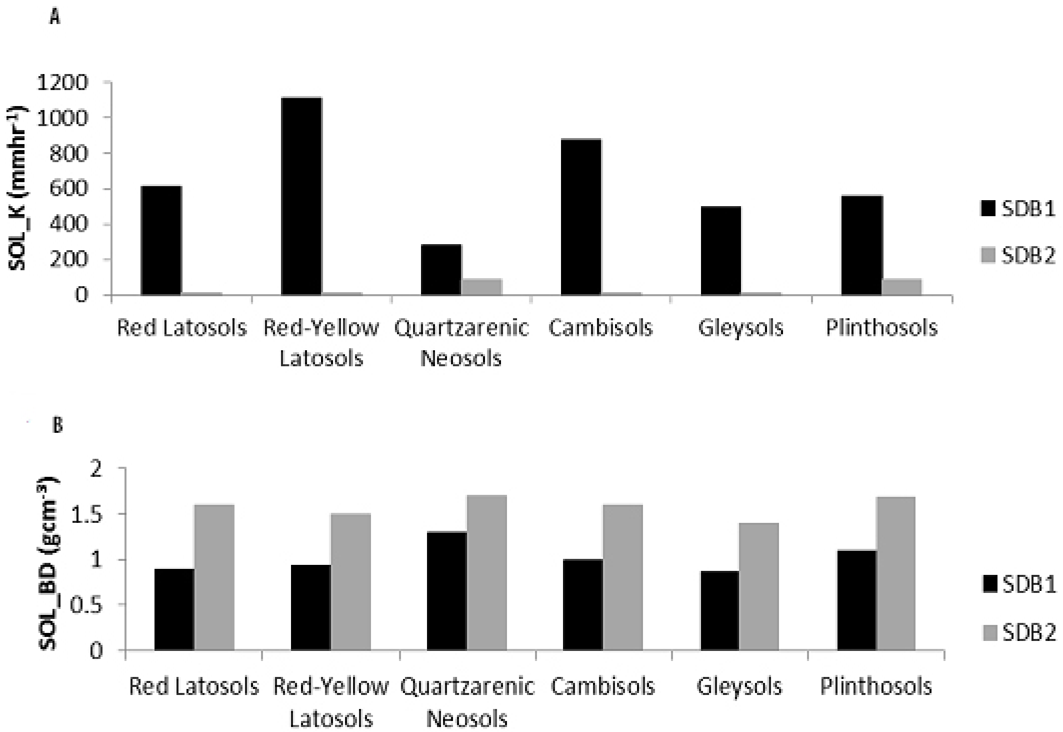

Figure 3. Difference of values between: A. the Saturated Hydraulic Conductivity parameter; B. the Moist Bulk Density parameter for SDB1 and SDB2.

Figure 3A shows that the Saturated Hydraulic Conductivity values, for all soil types, have much higher values on SDB1 than the values proposed on SDB2. In Figure 3B it may be observed that the Moist Bulk Density values are smaller, for all soil types, on SDB1. The main difference among the Saturated Hydraulic Conductivity values is that laboratory measurements were conducted (Klute, 1965) in SDB1, while SDB2 used relations between texture and hydrological conductivity (Dent e Young, 1981). This kind of difference, laboratory measurements and secondary information, is the major distinction between the soil databases. It is remarkable that these parameters are directly related to the soils hydrologic behavior and may influence the hydrological cycle in the basin and in the model results. For instance, the saturated hydraulic conductivity has influence on the lateral flow travel time and on the travel time for percolation (Neitsch et al., 2005).

Evapotranspiration was calculated by the Penmann-monteith method, while the surface runoff was estimated using the Soil Conservation Service, SCS, Curve Number. The evaluation was performed using 10 years of streamflow time-series (1989-1998), on monthly and daily basis. The analysis was made without calibration using only SWATs first simulation.

The annual water budget extracted from the observed data, Frinocap and the Taquara gauge stations, from 1989 to 1998, was calculated using an automatic method for estimating base flow as described in Arnold et al. (1995) and Arnold e Allen (1999), available in the internet (http://swat.tamu.edu/software/baseflow-filter-program/), on the assumption that the annual evapotranspiration is equal to the difference between annual precipitation and annual average streamflow and that hydrologic cycle inside the PRB is closed, without losses of water.

The quantification of SWAT's streamflow simulation accuracy and the criteria used to evaluate the results were done according to ASCE (1993) and Moriasi et al. (2007). The Percent Bias, PBIAS, was used for measuring the average tendency of the simulated flows, if it is larger or smaller than their observed counterparts (Gupta et al., 1999), computed as shown in Equation 1.

$$PBIAS = \left(\frac{\sum_{i=1}^{n}(Q_{obs}-Q_{sim})}{\sum_{i=1}^{n} Q_{obs}}\right) * 100 \qquad (1)$$

where Qi_{obs} is the observed streamflow at time *i*, and Qi_{sim} is the simulated streamflow at time *i*.

The Nash and Sutcliffe Efficiency (1970), NSE, which measures the relative magnitude between the residual variance ("noise") and the streamflow measured data variance (Gupta et al., 1999), was used and is computed as shown in Equation 2:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs}-Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs}-Q_{mean})^2} \qquad (2)$$

where Q_{mean} is the mean of the observed streamflow data.

For observed time series showing a strong but relatively constant seasonality, for example, related to climate, as happens in the Brazilian's Central Plateau region, it is recommended to use the adapted Nash and Sutcliffe model efficiency (ANSE), as proposed by Schaefli e Gupta (2007). For this reason, the ANSE was used in this study for measuring the efficiency of the SWAT model applications to predict streamflow. The ANSE is computed as shown in Equation 3:

$$ANSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs}-Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs}-Q_{b}(t))^2} \qquad (3)$$

where $Q_b(t)$ is the interannual mean value for every month between 1989 and 1999.To evaluate the model performance the criteria recommended by Moriasi et al. (2007), was used.

Results and discussion

Model simulation and water budget

The following results belong to the simulation using the SDB1 and SDB2, with the uncalibrated model and default parameters setup. Table 1 gives the comparison of the annual water budget extracted from the observed data, considering the Frinocap and the Taquara gauge stations and the period from 1989 to 1998, with the simulated results obtained with SWAT using SDB1 and SDB2.

Table 1. Comparison of observed (Frinocap and Taquara gauge stations) annual water budget and ones simulated with the SWAT model using SDB1 and SDB2 (1989-1998).

Reference	**Frinocap/ Taquara**		**SWAT SDB1**		**SWAT SDB2**	
Variable	**$mm.yr^{-1}$**	**%**	**$mm.yr^{-1}$**	**%**	**$mm.yr^{-1}$**	**%**
Precipitation	1,373.10	100.00	1,373.10	100.00	1,373.10	100.00
Evapotranspiration	996.76	72.59	817.60	59.54	563.30	41.02
Surface Runoff	57.25	4.17	157.59	11.48	157.40	11.46
Baseflow	319.08	23.24	348.64	25.39	581.93	42.38
Total Steamflow	376.34	27.41	506.23	36.87	739.33	53.84

As shown in Table 1, the data observed in PRB indicate that, in annual terms, from the total rainfall, 72.59% returns to the atmosphere through evapotranspiration, and 27.41% is converted into streamflow, being 4.17% through surface runoff, and 23.24% through baseflow. Noteworthy is the fact that these values are very similar to those measured in other basins of the Federal District (Silva e Oliveira, 1999; Lima, 2000; Lima et al., 2001; Lima, 2010).

Comparing the uncalibrated results obtained with the SWAT model (SDB1 and SDB2), it is possible to identify the impacts of the different soil database on the hydrological processes simulations in the basin. In relation to runoff, for example, the results obtained with SDB1 and SDB2 presented practically no changes, even with the significant modifications in some soil hydrological characteristics (Figure 3). The most significant changes were observed in the baseflow and the actual evapotranspiration simulations. As no factor related to evapotranspiration was changed, it can be concluded that changes in soil data (SDB1) generated a reduction in the base flow, leaving more water available for evapotranspiration.

It is notable that only changes in soil database were not able to properly resolving the simulation of the water balance in the basin. However, when comparing the results of SWAT SDB1 and SWAT SDB2 with the observed data, it is possible to conclude that the use of the specific soil database, developed with data measured in the region (SDB1), provided better results than those obtained with literature data (SDB2), especially in relation to the baseflow simulation.

Improving the better understanding the water budget results and the impact of the soil databases on the SWAT outputs, Figure 4 shows the average monthly values of surface runoff, lateral flow, evapotranspiration, and water yield when simulating with SDB1 and SDB2.

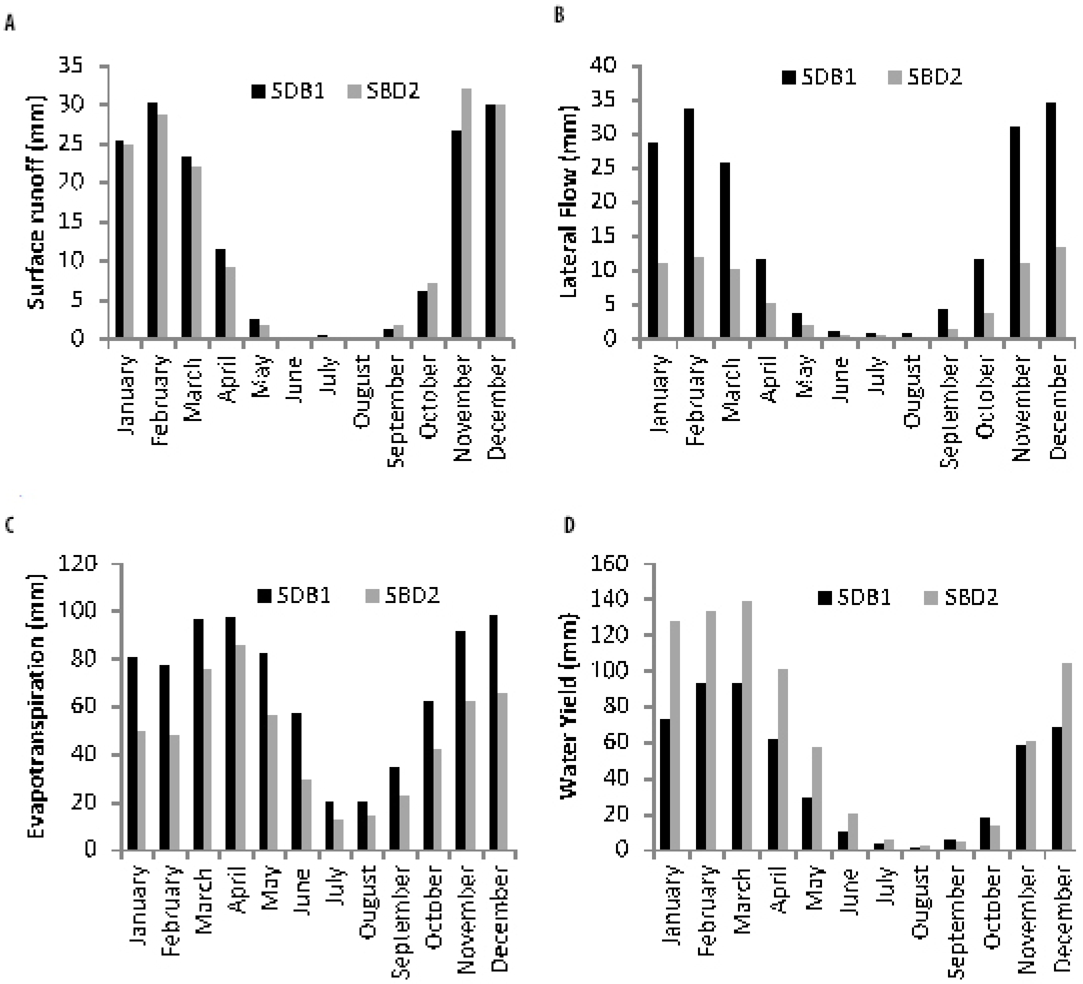

Figure 4. Average monthly values of surface runoff. A. lateral flow; B. evapotranspiration: C. water yield; D. simulated with SDB1 and SDB2.

Although the surface runoff displayed very similar results with both soil database, the simulation with SDB1 had higher lateral flow and evapotranspiration, and lower water yield than the simulation with SDB2. Lateral flow will be significant in areas with soils having high hydraulic conductivities in surface layers (Neitsch et al., 2005). Therefore, a larger amount of lateral flow in the simulation that used SDB1 was expected, since the SOL_K values for all soil types using this database are larger than those proposed in SDB2, as shown on Figure 3(a).

The difference between the evapotranspiration simulations using SDB1 and SDB2 showed on Figure 4(c), explains why the simulation with SDB2 had larger water yield results.

Figure 5 gives a visual comparison between observed streamflow data and monthly streamflow simulation with SWAT model, using SDB1 and SDB2.

The simulated results follow the pattern of observed streamflow data, but the model's simulation consistently over predicts the peak flows using SDB1 and SDB2. As shown before, the annual surface runoff results using SDB1 and SDB2 were equally larger than the results extracted from the observed data. Thus, the annual water budget results of the simulation, which used SDB2, were considered worst when compared to the information extracted from observed data (Table 1).

Although the annual water budget results of observed baseflow were similar to the SDB1 simulated baseflow results (Table 1), the monthly simulation underestimates baseflow using SDB1 and SDB2 in the drought period (Figure 5). The model's peak flows over prediction and baseflow underestimation on the monthly basis seem to balance the amount of water in the annual water budget analysis. It is important to remember that no calibration procedure was made and, therefore, the simulation results demonstrate the influence of each soil database, since all other parameters were the same.

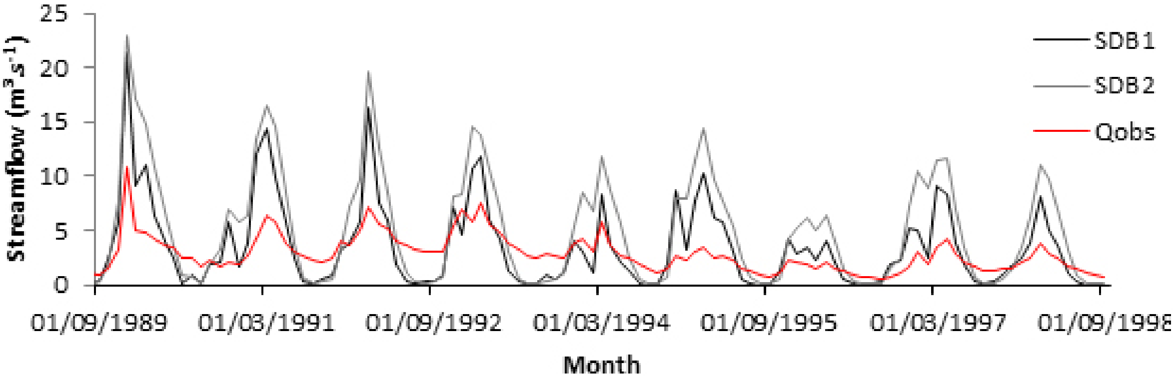

Figure 5. Visual comparison between observed streamflow data and monthly streamflow simulation, using SDB1 and SDB2.

The uncalibrated model had problems simulating streamflow in the drought period and peak flow with both soil databases. Nevertheless, the water yield was larger using SDB2. This result has to be emphasized by the fact that the soil database has been the only improvement made in the modeling process. Another important point is the fact that the SDB1 was developed from measured data collected in the study region, expanding the physical basis of the model.

Model performance

Table 2 gives the statistical results for monthly simulation obtained with SWAT SDB1 and SWAT SDB2.

The NSE, ANSE, and PBIAS results were, respectively, -1.78, -2.98, and -24.53% for SDB1, and -6.51, -9.88, and -84.72% for SDB2. The negative results of NSE and ANSE indicates that the simulations failed to represent observed data. It is important to remark that objective functions based on the mean square root, such as the NSE and the ANSE, are very sensitive to peak flows (Beven, 2001), and Figure 5 demonstrated that the peak flows were overestimated in both simulations, with SDB1 and SDB2. The PBIAS analysis had also better results for SDB1, and can be considered satisfactory according to the performance rate recommended by Moriasi et al. (2007).

Table 2. Statistical results for monthly simulation with SDB1 and SDB2.

Evaluation criteria	Monthly results	
	SDB1	**SDB2**
NSE	-1.78	-6.51
ANSE	-2.98	-9.74
PBIAS	-24.53	-86.49

The negative values of PBIAS indicate model overestimation bias (Gupta et al., 1999). Figure 6 shows the relationship between observed data and simulated daily and monthly streamflow using SDB1 and SDB2, and demonstrates that the model overestimation bias happens especially when the model is simulating higher magnitudes.

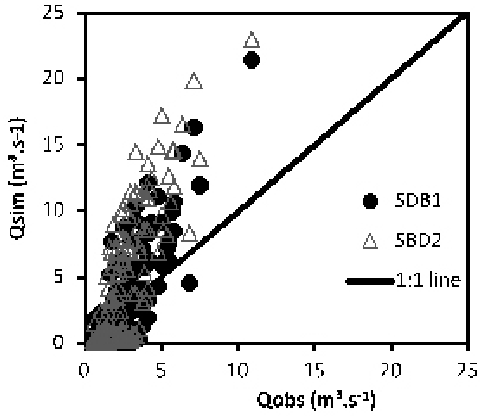

Figure 6. Relationship between observed data and simulated monthly streamflow using SDB1 e SDB2.

Although manual and automatic calibration can improve the models performance compensating soil and weather input database resolution (Bossa et al., 2012; Sheshukov et al., 2011; Strauch et al., 2012), while producing acceptable results concerning the model evaluation in the PRB (Salles, 2012; Strauch et al., 2012; Strauch et al., 2013), the results do not necessarily mean that the components of the water budget are being well simulated (Bossa et al., 2012).

The development of soil databases for specific regions throughout the Brazilian territory, such as SDB1 produced by Lima et al. (2013), certainly improved SWAT's model physical basis, reducing the uncertainties produced by the input data. Nevertheless, the results in this paper as well as in other papers available in the literature (Strauch et al., 2011; Strauch et al., 2012) demonstrate that further research on SWAT's conceptual model, input datasets are necessary in order to improve the physical basis and reduce uncertainties in SWAT's simulations for tropical regions.

Conclusions

The study indicates the importance of developing soil databases for specific regions throughout the Brazilian territory. However, further research on other parameters and inputs in order to improve the physical basis beyond the models inputs are necessary, since calibration is still indispensable in order to achieve satisfactory performance rates. There was an improvement of the annual water budget using the soil database developed for the PRB region (SDB1). The simulated relation between baseflow and precipitation using the soil database developed for the region (SDB1) was similar to the one extracted from observed data in the studied basin.

Acknowledgments

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