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Impacts of land-use change on southeast Amazonia basin streamflow

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ABSTRACT

The Amazon region is the subject of growing interest in the international scientific community due to the environmental services provided by its dense forests in climate regulation and freshwater. Despite many efforts from environmental management agencies and research centers, this region can still be considered poorly monitored, especially given its large regional and global importance. Rainfall-runoff models are presented as a good alternative to the estimated flow rates in inaccessible or difficult to watch places. This study simulated stream flows for a representative part of the Amazon basin using the Soil and Water Assessment Tool (SWAT) redistributed hydrological model, adopting as reference the streamflow observed in Altamira gauge station. The authors emphasize that a database was specially prepared with physical parameters such as land use, topography and soil types, and weather data encompassing the years from 1985 to 2012, at a daily time step. The chosen approach allowed carrying out hydrologic simulations that were consistent with the flow values observed at the Altamira gauge station, providing better understanding of hydraulic-hydrological processes in the Xingu subbasin and information for planning and decision-making on the management of water resources in this important river basin.

Keywords: Amazon basin, hydrologic modeling, land use change.

Impacto na mudança de uso do solo na vazão de uma bacia do sudeste da Amazônia

RESUMO

A Região Amazônica vem despertando interesse crescente da comunidade científica internacional devido às amplas possibilidades ambientais que suas densas florestas têm a oferecer no que diz respeito à regulação climática e recursos hídricos. Apesar dos muitos esforços de agências reguladoras de meio ambiente e centros de pesquisa, esta região ainda pode ser considerada pouco monitorada, especialmente dada sua grande importância regional e global. Modelos de vazão são apresentados como uma boa alternativa para taxas de fluxos estimadas em lugares inacessíveis ou de difícil monitoração. O objetivo deste trabalho é simular vazões para uma porção significativa da Bacia Amazônica usando o modelo hidrológico semidistribuído SWAT (Soil and Water Assessment Tool), adotando como referência as vazões observadas na estação de monitoramento de Altamira. Ressaltamos que um banco de dados foi especialmente preparado com parâmetros físicos, como uso do solo, topografia e tipos de solo, e informações do clima compreendidas entre os anos de 1985 e 2012, numa escala de tempo diária. A abordagem metodológica permitiu que fossem realizadas simulações hidrológicas muito condizentes com os valores de fluxos observados na estação de monitoramento de Altamira, permitindo um melhor entendimento dos processos hidráulico-hidrológicos na sub-bacia do Xingu e fornecendo informação para planejamento e tomada de decisões no que concerne ao gerenciamento de recursos hídricos nesta importante bacia.

Palavras-chave: bacia Amazônica, modelagem hidrológica, mudança de uso do solo.

1. INTRODUCTION

The Amazon is one of the most complex ecosystems in the world; it is a place where it is possible to find researchers from all over the Earth trying to find new species or new medicine from plants (Gutbelert, 2002). Non-governmental and governmental organizations from all over the world also pursue the preservation of animals, plants and water resources (Goodwin, 2014).

Although it is known that natural resources must be preserved, the Amazon is facing issues with deforestation, especially for wood, commerce and plantations (Ferreira *et al*., 2005). According to Brazil's Ministry of the Environment, deforestation has decreased since 2004. However, the region still loses about 6000 km^2 of natural forest every year. Another significant issue is the construction of the Belo Monte hydroelectric power plant, which is going to generate 11.233 MW of electricity and cause the inundation of 668 km^2 (Berman, 2012).

Analyzing all that has been said, it was possible to conclude that studies should be done on that area to guarantee a sustainable exploitation of all natural resources. One type of study that is increasing worldwide is the use of mathematical models.

To plan the use of a basin and predict how this basin will respond to changes in soil use, deforestation and occupation, a mathematical model is used that simulates reality and provides an important tool to make the decisions. With a long data series, it is possible to estimate the impact of an action on a basin (Lenhart *et al.*, 2002). Models are mathematical equations that intend to describe and simulate what will occur in the basin, and there are different models that can be used for a variety of purposes, according to the author's goal (Souza, 2015).

The model being used in this article is the Soil and Water Assessment Tool (SWAT) model. The SWAT model was developed by USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research (Arnold *et al.*, 1998). This model has recently been used in different hydrological studies in Brazil (Bressiani *et al.*, 2015; Pereira *et al.*, 2016). This research simulates different scenarios and how the streamflow responds to changes in land use.

2. MATERIALS AND METHODS

2.1. Study Area

The hydrological modeling was made in the Xingu River's subbasin (Figure 1), in the Amazon, between the coordinates UTM 8330743.862 m and 9851708.200 m; 1319966.175 m and 1915083.081 m. The basin has an approximate area of 509 000 km^2 that is distributed along the states of Mato Grosso (MT) and Pará (PA).

According to Koppen's classification model, the basin has two climates; the north part is classified as Am – Tropical Monsoon, with most of the rain occurring during the 7 to 9 hottest months. The rest of the basin the classification is Aw – Tropical Wet and Dry, where the precipitation occurs during the summer season and has a dry winter (Sampaio et al., 2011).

Figure 1. Xingú sub-basin, located in Amazon basin.

2.2. Meteorological Data

The meteorological data (relative humidity, solar radiation, wind speed and temperature) were obtained from 40 weather stations from INMET - National Meteorology Institute. Using this data, it was possible to calculate the necessary statistics for the model to run the simulation. It is noteworthy that rainfall data from 204 ANA – National Water Agency rainfall stations were used too.

2.3. Types of Soil, Land Use Map, and Types of Soil and Land Use Map

The main types of soils found in the Amazon basin are: Acrisol (38.47%), Ferrasol (37.64%) and Leptosol (11.78%). The soil map (Figure 2a), with 5 km resolution was obtained in the ISRIC global database. The soil characteristics were obtained from the Pedo-Transfer Function (Saxton and Rawls, 2006). The land-use map (Figure 2b) was obtained from the MODIS sensor with a 1 km resolution (Friedl *et al.*, 2010). The digital elevation models (Figure 3a) and slope maps (Figure 3b) were obtained from the TOPODATA global database (Hydrosheds), with a 1 km resolution.

The model was previously prepared in ArcGis with the following data: soil use, soils type, climatological data and the digital elevation model (DEM). The database comprehends the years between 1985 and 2012.

The model was used to simulate streamflow in the basin cited above, during a period of 28 years, between 1985 and 2012, of which the first two years were used to warm-up the model.

The simulation results were imported to the Soil & Water Assessment Tool – Calibration and Uncertainty Procedures (SWAT-CUP), where it is possible to do a static analysis and compare the data simulated by the program with the observed data. It is also possible to verify which parameters are more sensible, which allowed the calibration and validation of the model, making it possible to predict the stream flow in a more accurate way.

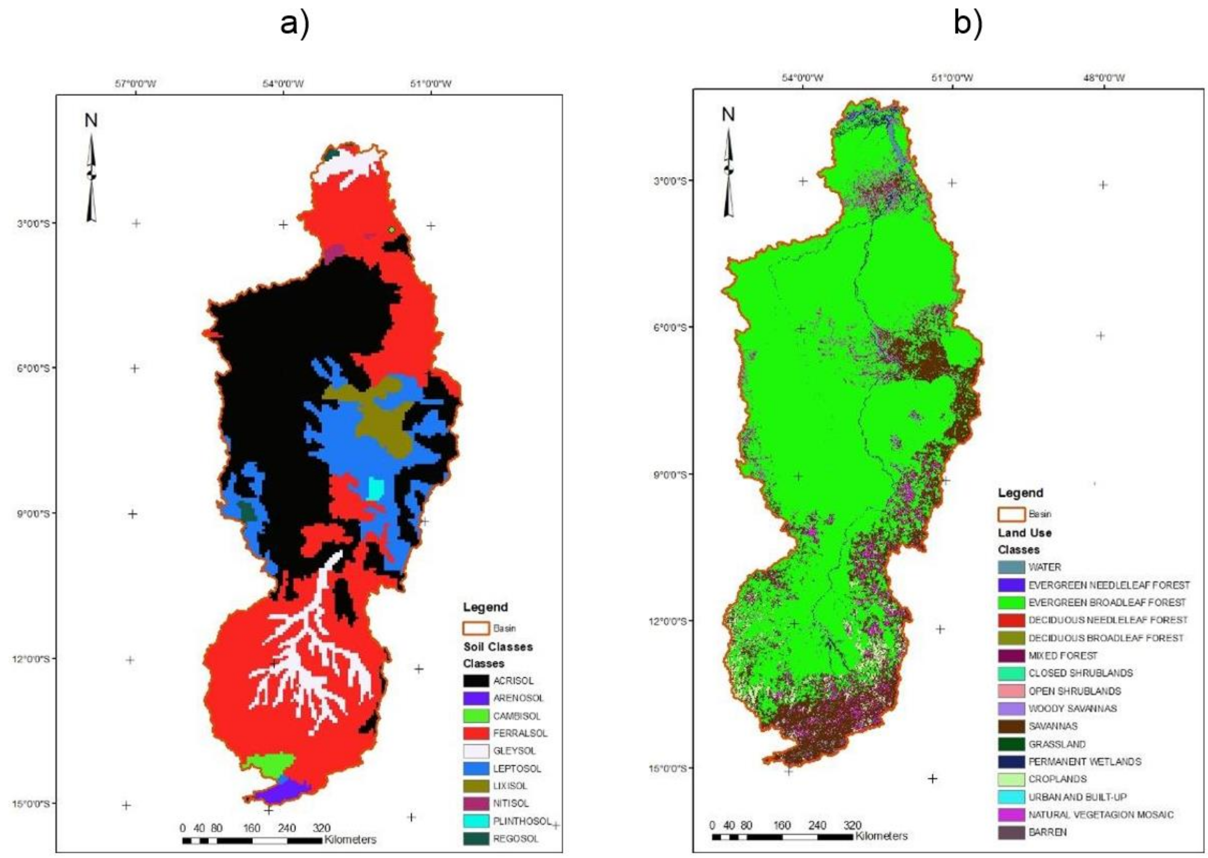

Figure 2. a) Types of soil; b) Land-use map.

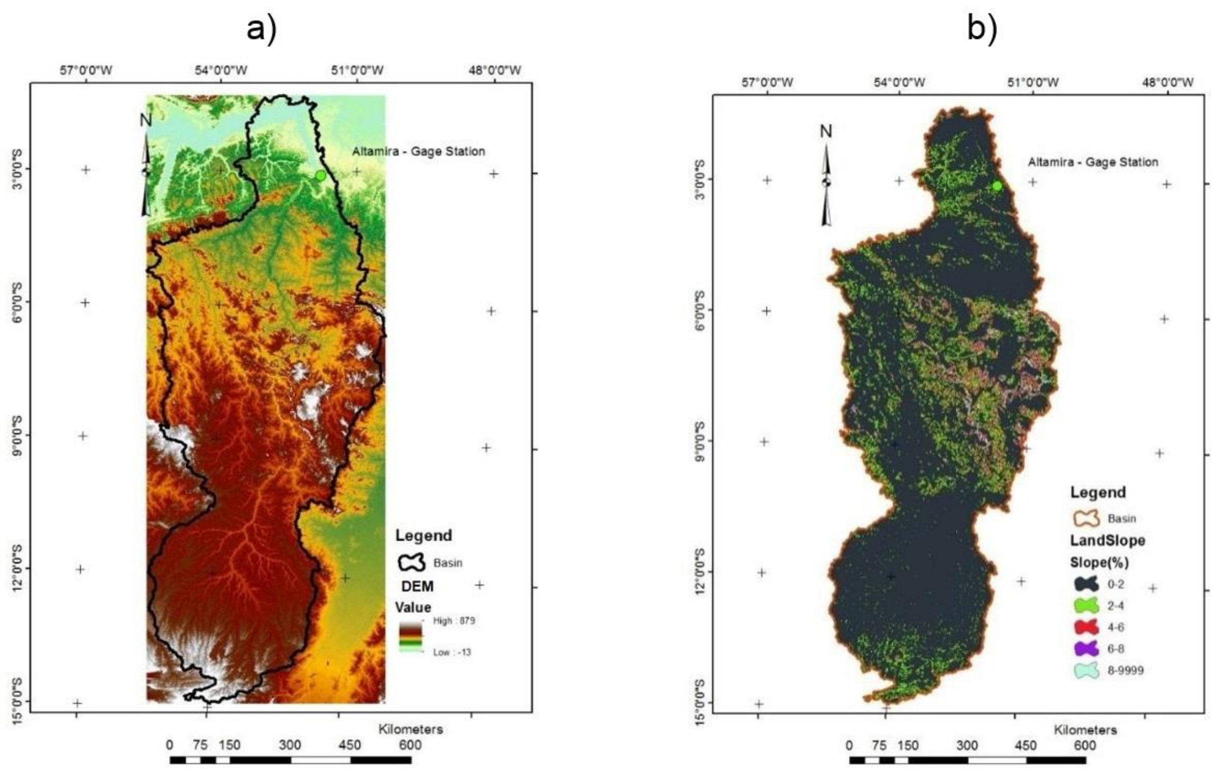

Figure 3. a) Digital Elevation Model; b) Slope map.

For the calibration process, data from two monitoring points were used, belonging to the ANA – National Agency of Water. The first one at the beginning of the basin and the second at another point located in the course of the same river. The first monitoring point is named Boa Sorte (code 18460000). On this point, there is data available from January 1976 to February 2009. However, the model's database only starts on 1985; therefore, data from before that year was not taken into consideration.

After calibrating and validating the model, the values in all subbasins that contribute to the point where the first monitoring point is located were replaced. After changing the values, the model was run one more time. Next, the calibration and validation process for the second point, called Altamira (code 18850000), was initiated. Once again, the database available was larger than the model, so the authors only considered data from after 1985.

In the calibration and validation process for the second point, the values were only replaced on the subbasins between the first and the second points; the authors did not change any values on the subbasins that contribute for the first calibration point or the subbasins after the second point.

The second point was of interest because it is situated where the government of Brazil is building a hydroelectricity plant. Once the model is calibrated and validated, it will be possible to simulate and verify the impact of land use change in streamflow and power generation.

SWAT-CUP makes some statistical analyses and gives a few parameters to evaluate the model's efficiency. In this paper, the authors are going to use three parameters to check if the model is corresponding in a good way to reality.

2.4. Statistical Evaluation Criteria

Streamflow simulations were evaluated using different statistical criteria. According to Moriasi *et al*. (2007), the parameters that can be used are:

Coefficient of determination (R^2): describe the proportion of the variance in measured data. R^2 ranges from 0 to 1 and values greater than 0.5 are acceptable.

Nash-Sutcliffe efficiency (NSE): determine the relative magnitude of data variance compared to the measured data variance.

Percent bias (PBIAS): indicates the tendency of the simulated data to be larger or smaller than the observed values (Equations 1 and 2).

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Yobs-Ysim)^2}{\sum_{i=1}^{n}(Yobs-Ymean)^2} \tag{1}$$

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(Yobs-Ysim)*100}{\sum_{i=1}^{n}(Yobs)} \tag{2}$$

Model evaluations used in this study were based on performance ratings suggested by Moriasi *et al.* (2007) for a monthly time step, as shown in Tables 1 and 2.

Table 1. Reported performance ratings for PBIAS.

Model	Value	Performance rating	Modeling Phase	Reference
SWAT	<10%	Very Good	Calibration and Validation	Van Liew *et al.* (2007)
SWAT	<10% to <15%	Good	Calibration and Validation	Van Liew *et al.* (2007)
SWAT	<15% to <25%	Satisfactory	Calibration and Validation	Van Liew *et al.* (2007)
SWAT	>25%	Unsatisfactory	Calibration and Validation	Van Liew *et al.* (2007)

Adapted from Moriasi et al. (2007).

Table 2. Reported performance ratings for NSE.

Model	Value	Performance rating	Modeling Phase	Reference
SWAT	>0.65	Very Good	Calibration and Validation	Saleh *et al.* (2000)
SWAT	0.54 to 0.65	Adequate	Calibration and Validation	Saleh *et al.* (2000)
SWAT	>0.50	Satisfactory	Calibration and Validation	Santhi *et al.* (2001); adapted by Bracmort *et al.* (2006)

Adapted from Moriasi et al. (2007).

2.5. Land Use Change

Images with the different types of land use were obtained from the MODIS Land Cover Product Type, (MCD12Q1). These products have annual basis and its historical series is available from 2001. These images were produced by supervised classification algorithms, with a spatial resolution of 500 m, covering the soil surface of the planet (Friedl *et al.*, 2010).

3. RESULTS AND DISCUSSION

3.1. Calibration Process

Lelis *et al*. (2012), Paim and Menezes (2009) and Andrade *et al*. (2013) present the most common parameter used to calibrate the SWAT model, especially for hydrology variables. Based on the parameter they presented, a few tests were made to check which one would be more sensitive for the specific model. After the simulations, the best parameters were determined and are shown in Table 3.

Table 3. Most sensitive parameters.

Parameter	Description	Range of parameter	Best Value	Units
CN2	Surface runoff	35 to 98	75.163	-
ESCO	Compensation of soil evaporation	0 to 1	0.2958	-
ALPHA_BF	Base flow	0 to 1	0.40416	l/day
RCHRG_DP	Deep aquifer percolation	0 to 1	0.5458	-
SLSUBBSN	Average length of lateral ramp	10 to 150	32.75	m
EPCO	Compensation for plant grown	0 to 1	0.85416	-
SURLAG	Surface runoff retardation coefficient	0.05 to 24	20.3078	-
CH_W2	Average width of main channel at top of bank	0 to 1000	287.5	m
CH_L2	Length of main channel	-0.05 to 500	160.383	km
CH_N2	Manning’s roughness coefficient value for the main channel	-0.01 to 0.3	0.200	-

After determining which parameters should be changed, a simulation including all ten variables was made as to define the best value for each one. The statistical analysis is shown in Table 4. The data shown in the table is for the second point used.

Table 4. Calibration results.

R^2	NSE	PBIAS
0.63	0.59	17.3

As stated by Rocha *et al*. (2012), the SWAT model is highly sensitive to the input data and R^2 represents the correlation between observed and simulated data. As cited by the author and by Moriasi *et al.* (2007), values of R^2 greater than 0.5 are usually acceptable. This shows a good correspondence between the values estimated by the model and the ones simulated by the program.

For the NSE parameter, Moriasi *et al.* (2007) defines the range between 0.54 and 0.64 as adequate. This corroborates what Rocha *et al*. (2012) present values higher than 0.5 are not discarded, and other authors have used this efficiency. The value of 0.59 is classified as adequate for the specific model.

The last parameter used to evaluate the model was PBIAS; according to Moriasi *et al.* (2007), PBIAS can indicate poor model performance. The range of 15% to 25% is considered adequate by Van Liew *et al*. (2007). The value of 17.3% found after calibration was considered satisfactory.

All three parameters used to evaluate calibration process are sensitive to input data quality and indicate how well the model is representing the observed values in the basin. Analyzing the results shown in Tables 1 and 2, based on the literature, it was found that the model satisfactorily corresponds to the observed data.

3.2. Land Use Change

The land-use spatial-temporal analysis for the *Xingu* watershed was performed using MODIS images with 500 m spatial resolution along the 2001-2012 period, with sixteen different classes of land cover, as follows: evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, savannas, grasslands, woody savannas, permanent wetlands, cropland/natural vegetation mosaic – CNVM, cropland, mixed forest, closed shrublands, open shrublands, urban and built-up and barren or sparsely vegetated.

The greatest identified coverage loss in *Xingu* watershed between 2001 and 2012 refers to the evergreen broadleaf forest class (Figure 4a), while the largest expansions occurred in the areas of savannas (Figure 4b) and croplands (Figure 4c), respectively.

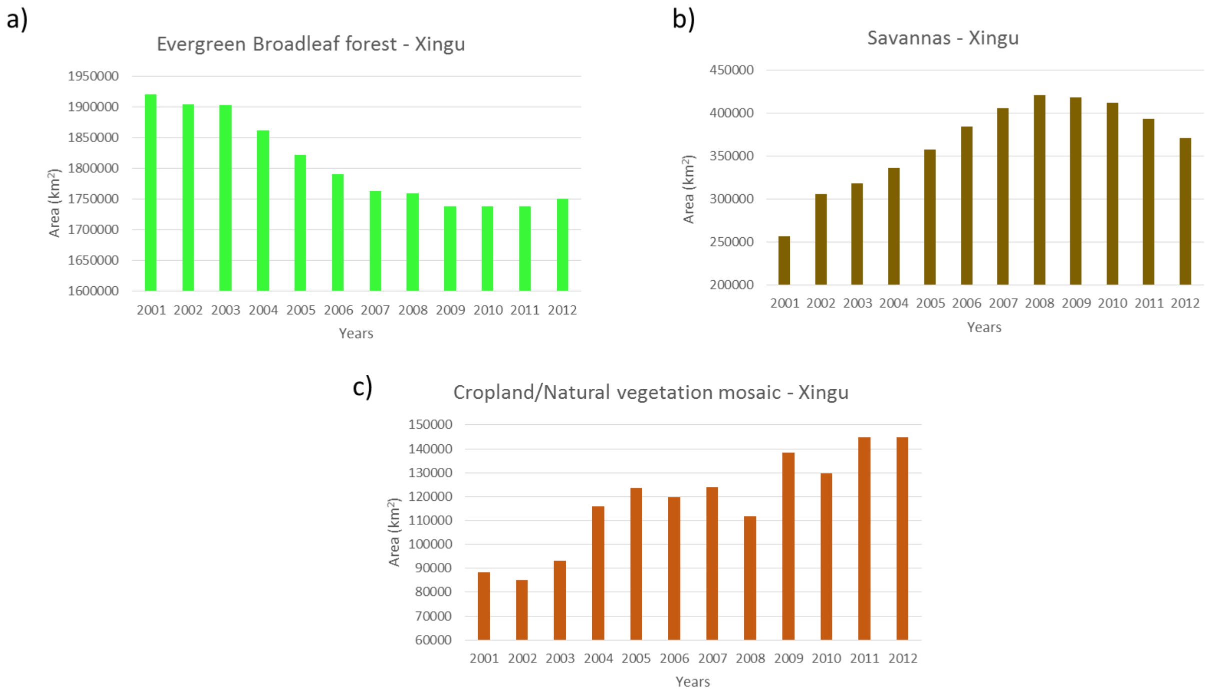

Figure 4. Land use change in *Xingu* watershed: a) Evergreen Broadleaf Forest; b) Savannas, c) Cropland/Natural Vegetation Mosaic.

3.3. SWAT Simulation

After the calibration, two simulations were made using different land use maps: one for 2002, and another to 2012. The simulation dataset project present 307 watersheds with average area of around 1769.84 km^2 (Figure 5).

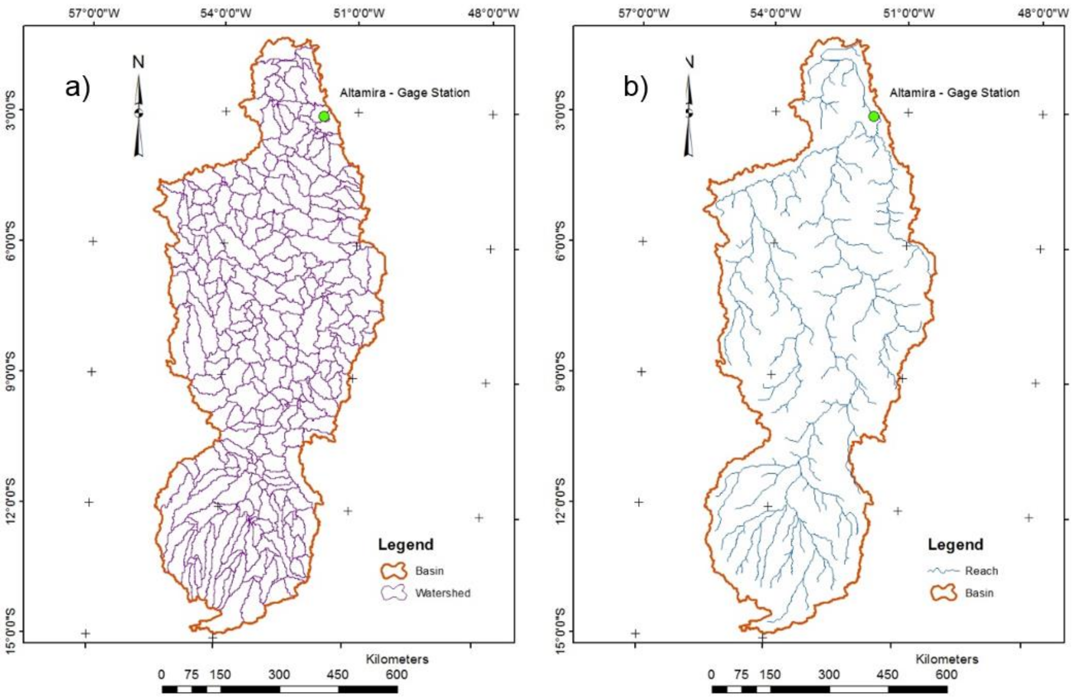

Figure 5. Discretization of representation watershed in SWAT model project for the *Xingu*: a) Watersheds; b) Stream.

Simulated and observed monthly flows at Altamira gauge station are presented for 01/1985 to 12/2012 in Figure 6, to visually evaluate the performance.

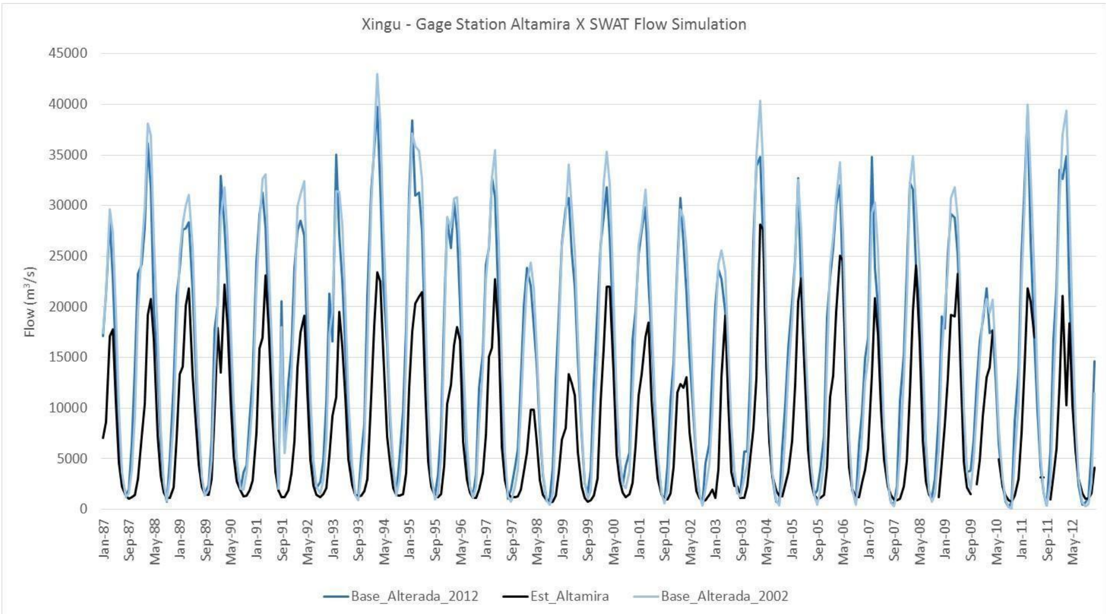

Figure 6. Observed and simulated monthly flows from 01/1985 to 12/2012.

Figure 6 shows that the simulated stream flows for 2002 and 2012 are higher than the observed data from Altamira station. It is also possible to observe on the graphic that simulated flow for 2002 is almost the same as for 2012, with a few higher peaks for the year of 2002. This fact goes against prediction, due to changes in land use, once the Evergreen Broadleaf forest had decreased as the Savanna had increased, less evapotranspiration and rainfall is expected, and an increase of water percolation, resulting in the decrease of streamflow in the *Xingu* River.

4. CONCLUSION

The model has been calibrated for the subbasin of *Xingu* River, presenting satisfactory results for the years between 1997 and 1999. However, it is still possible to improve the calibration of the model, achieving a model that represents the reality in a more accurate way.

The streamflow results demonstrate that the land use change from 2002 to 2012 did not cause a significant difference at the Altamira gauge station. There little difference in power plant energy generation in Belo Monte during this period.

When properly calibrated and validated, the SWAT model is a very efficient tool to plan interventions and changes in basins. It saves time and can predict results for any modifications that may occur at the site.

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