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THE IMPACTS OF CHANGES IN LAND COVER ON WATER RESOURCES IN THE WESTERN AMAZON

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The semi-distributed hydrological model SLURP was applied in the Jamari River basin, Brazil, to investigate the impacts on hydrological processes caused by changes in surface land cover and land use, as well as climate change. Realistic and extreme scenarios of deforestation were analyzed. An increase was found of runoff when deforestation occurred. Since less water is intercepted by canopy, evapotranspiration and groundwater tend to decrease with deforestation. In climate change scenarios, increases in temperature and precipitation tend to increase evapotranspiration and runoff, while decreases in temperature and precipitation tend to increase evapotranspiration and decrease runoff and groundwater flow. During drought, runoff tends to increase remarkably. This suggests that if the annual rate of deforestation stays the same or increases, the socio-environmental problems may worsen during both dry and wet seasons.

INTRODUCTION

The consequences of changes in land cover and land use on water resources have been studied for years (Charney et al., 1975; Eagleson, 1982; Williams and Balling, 1996). The direct effect of deforestation on variables such as temperature, evapotranspiration, heat and moisture transport, and also runoff, has been well established in many parts of the globe, for instance Yangtze in China (Yin and Li, 2001; Yang et al., 2002), Mekong in Asia (Goleti and Lettenmaier, 2001; Kite, 2000), Buji in Asia (Shi et al., 2007) and Mississippi in the USA (Cherkauer and Lettenmaier, 2000), as well as in several catchments in Africa (Calder et al., 1995; Hetzel and Gerold, 1998; Li et al., 2007).

Deforestation is the major environmental problem in the Amazon River basin nowadays, and its impacts affect both the local and global scale. In fact, this region is responsible for approximately 13% of all global runoff into the oceans (Foley et al., 2002) and its abundant vegetation releases large amounts of water vapor through evapotranspiration leading to a recycling in precipitation of about 25-35% (Brubaker et al., 1993; Eltahir and Bras, 1994; Trenberth, 1999).

There are some difficulties in hydrological modeling in the Amazon. These include lack of meteorological data and difficulty getting parametric information, essential for distributed modeling. Also, the small slopes of some sub-basins tend to lead to systematic errors in runoff calculations, since the physiographic parameterization is not the most suitable (Costa and Foley, 1994; Nijssen et al., 2001; Ecuyer, 2003).

The Jamari watershed was chosen for this study. It is a basin with small slopes that has been heavily deforested. In this study, changes in land cover and climate, including trends and extreme scenarios, are examined to determine the effect on regional hydrology. More detailed input data than are usually applied are used to obtain a more detailed parameterization of the flat physiography.

MATERIALS AND METHODS

Study Area

The state of Rondônia, which is shown in Figure 1, is in the Brazilian Amazon and has the highest rate of deforestation per area. The drainage network of this state is represented by the Madeira River (an important tributary of the Amazon river) and its streams that form eight important sub-basins, including the Jamari river basin. About 28% of Rondônia has already been deforested[1] , which is why it is the subject of this study.

The climate is equatorial and temperature variation is mainly due to rainfalls, altitude, and intrusion of cold-air masses from southern South America. The annual temperature average ranges from 24º to 26ºC, with maximum temperature oscillating from 28º to 34ºC, and minimum from 15º to 21ºC. Annual precipitation varies between 1800 and 2400 mm. The dry period occurs between June and August, and the rainy period between October and April. May and September are considered transitional months (Nóbrega, 2008). Slope in the Jamari watershed varies from 265m to 5m from south to north.

From 2002 to 2007 the deforested area on the Jamari river watershed (Table 1) was 5993 km^2,

[1] This deforestation rate increases to 47% if one considers that 38% of the state is formed by units of preservation where deforestation is not allowed. Data up to 2008.

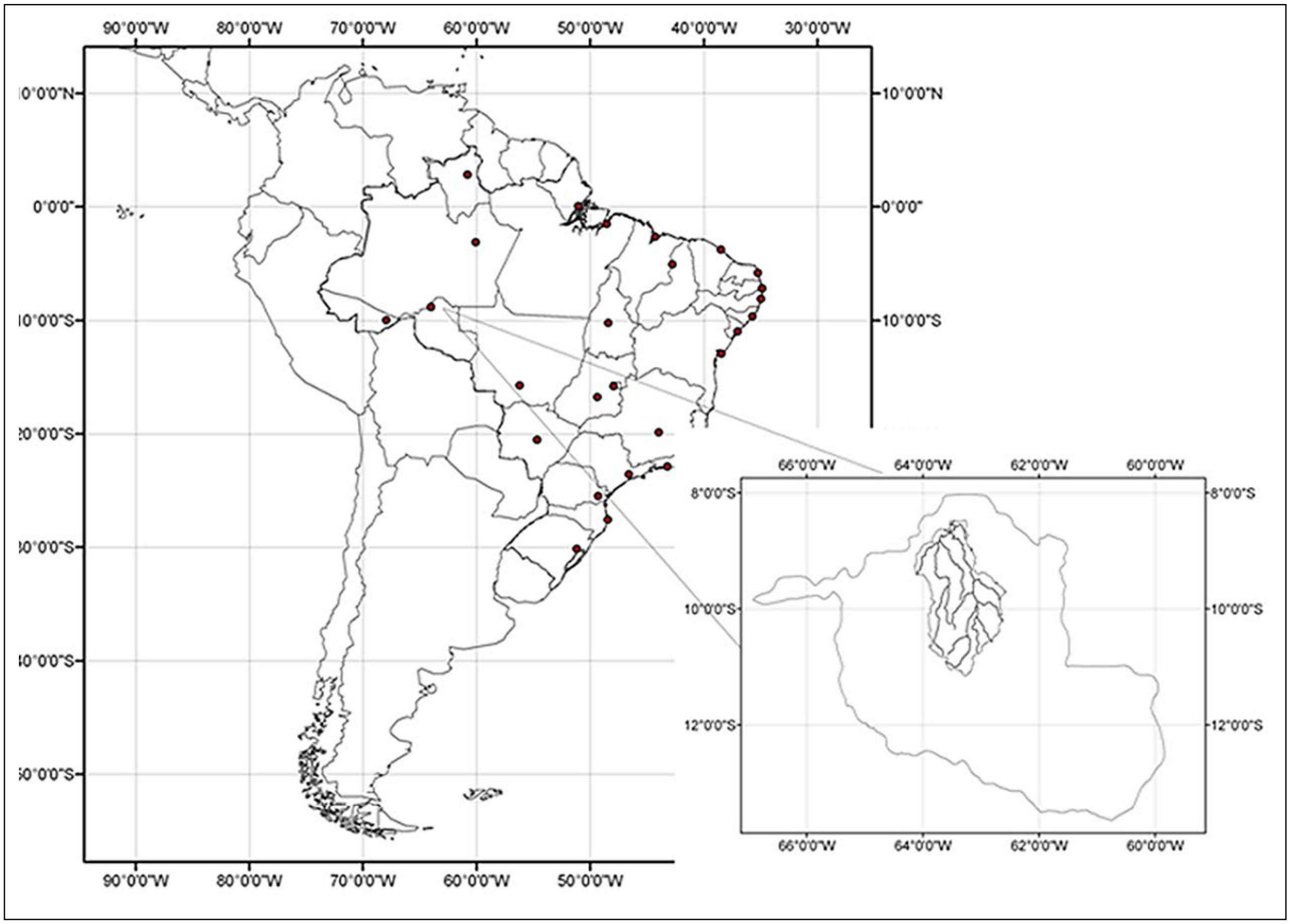

Figure 1. Location of the Jamari sub river basin.

Table 1. Deforested area (km^2) in the Jamari river basin.

Year	Deforested Area
2002	988.6
2003	943.0
2004	1318.2
2005	1231.4
2006	658.2
2007	854.2
Amount	5993.6

and the total area of the basin is 28,846 km^2, totaling 20.7%, or a rate of 3.45% per year, on average.

The hydrological model SLURP

This model uses basically three types of data: i) digital elevation data (DEM); ii) land cover data; and iii) climatic data. The matrix data of both DEM and land cover data must have the same dimension. Climatic data should contain: precipitation, air temperature, dew-point temperature (or relative humidity), solar radiation, and wind intensity.

The model has been applied in many countries at scales ranging from small prairie wetlands (Su et al., 2000) to large basins such as the Mackenzie in Canada (Kite et al., 1994). It was developed to make maximum use of remote sensing data. Applications of the model include studies of climate change (Kite, 1993), hydropower (Kite et al., 1998), water productivity (Kite, 2005), irrigation (Kite and Droogers, 1999) and wildlife refuges (de Voogt et al., 1999), contribution of snowmelt to runoff (Laurente and Valeo, 2003; Thorne and Woo, 2006), and large mountainous catchment (Thorne and Woo, 2006). The SLURP model has not been used in the Amazon. Its conceptual approach allows use in regions with little data, as well as the possibility of direct use of remote sensing data. Physical parameters can be retrieved with good accuracy, even in basins with small slopes, as found in the study basin and other sub-basins in the Amazon.

DEM and land-cover data

The DEM from the Shuttle Radar Topography Mission (SRTM) was used with 90-m horizontal resolution. In order to correct errors, the techniques of space filtering and interactive filling were used .

For actual land cover data, seven images of Landsat 7 scenes 2007 over the Jamari sub-river basin were used, with resolution of 30m, provided by Amazonian Protection System (SIPAM). First, the scenes were georeferenced and a mosaic was composed. Second, NDVI performed a supervised classification to obtain the land-cover image. The data were then sampled again at 90m resolution, since the SLURP requires that the matrix of land cover have the same size of the DEM. Finally, the data was classified into four classes: water, forest, non-forest and man-modified (urbanized). The non-forest class includes agricultural areas and the savannah.

Model calibration

The model was calibrated by using the automatic method Shuffled Complex Evolution of the University of Arizona (SCE-UA), which is a mix of techniques of random search, genetic algorithm and the Simplex method of Nelder and Mead (for details see Duan et al., 1994). During the calibration procedure the method works with a population of points that "evolve" to a global optimum point through repeated interactions and evaluations of the object function. This method was incorporated in SLURP. The model was calibrated between 1 Jan 1999 and 31 Dec 2003; and it was verified from 1 Jan 2004 to 31 Dec 2007.

Climatic, rainfall and runoff data

Climatic, rainfall and runoff data are some of the main difficulties in hydrometeorological modeling in the Amazon. The time series available is short and has many flaws. In this paper, we use the data set from four stations with information about precipitation, temperature, air temperature and dew point of the Agency for Environmental Development in Rondônia (SEDAM). We also use data from five rainfall gauges of the National Water Agency (ANA). The data sets are from the period between 1 January 1999 and December 31, 2007.

Model performance evaluation criteria

Model performance was evaluated by using four different error measures: Nash and Sutcliffe (NS), Percent BIAS (PBIAS), Daily Root Mean Square (DRMS) error criteria (Zhi et al., 2009; Moriasi et al., 2007), and Deviation Volume (D%) (Kite, 2005).

The equations were given as shown below:

$$NS = 1 - \frac{\sum_{i=1}^{n} (Q_{obs} - Q_{\mathrm{mod}})^2}{\sum_{i=1}^{n} (Q_{obs} - \overline{Q_{obsd}})^2} \tag{1}$$

where Q_{obs} and Q_{mod} are the measured and modeled data, respectively; $\overline{Q_{obsd}}$ is average modeled data; and n is the total number of data records. The coefficient can range from -8 to 1 and represents the amount of data oscillation that is explained by the model. The model is considered optimal if NS = 1, appropriate and good if NS > 0.75, acceptable if 0.36 <NS <0.75, and unacceptable if NS <0.35. If NS < 0, the predictor is worse than the average (Nóbrega, 2008).

$$PBIAS = \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{\mathrm{mod}})}{\sum_{i=1}^{n} Q_{obs}} \tag{2}$$

where Q_{obs} and Q_{mod} are the measured and modeled data, respectively. The optimal value of PBIAS is 0. Low magnitude values indicate accurate model simulation; PBIAS > 0 indicate model underestimation bias; and PBIAS < 0 indicate model overestimation bias (Zhi, 2009).

$$RSR = RMSE / STDE_{obs} = \frac{\sqrt{\sum_{i=1}^{n}(Q_{obs} - Q_{\mathrm{mod}})^2}}{\sqrt{\sum_{i=1}^{n}(Q_{obs} - \overline{Q_{obs}})^2}} \tag{3}$$

RSR varies from optimal value of 0, which indicates zero RSME or residual variability and therefore perfect model simulation, to large positive values; the smaller RSR the better the model simulation performs (Zhi, 2009; Kannan et al., 2007).

The Deviation Volume criterion is simply a change in the pattern of calculated and observed average in the simulated period, which is a statistical test comparing the simulated discharge volumes to measures during the event, generating information about performance of the water balance total modeled. A value of zero indicates optimal modeling, or no difference between the volumes measured and simulated. A positive value indicates underestimation of the simulated volumes (losses in origin). A negative value indicates that the calculated average flow is high (losses in sinks) (Kite, 2005).

The Simulations

Based on the percentage of deforestation in the basin obtained from the PRODES (Program of Monitoring of the Brazilian Amazon Forest for satellite - http://www.obt.inpe.br/prodes) data (Table 1), two trend scenarios were defined: i) DEFOR+20 or 20% more deforestation area, and ii) DEFOR+30 or 30% more deforestation area.

Three extreme scenarios of land cover were defined to investigate the relationship between soil-cover change and runoff within the SLURP model. The experiments are: i) One hundred per cent with forest and water (100%FOR); ii) One hundred per cent with savannah plus pasture and water (100%NOFOR); and iii) One hundred per cent man-modified area and water (100%MANMODIF).

Problems identified – implementation of necessary remedial measures

The SLURP model needs data from weather stations which contain precipitation, temperature, humidity and wind. The average is calculated using the Thiessen polygon method for each ASA. If there are no data, the model does not perform the simulation (for example, when there is rainfall data, but temperature is lacking).

In some countries, such as Brazil, it is common to have only a rainfall station, instead of a weather station, making the rainfall network much denser than the weather network. But the compilation of the model does not allow the use of these data. Aiming to overcome this limitation, we tried to develop a methodology that would use the climatic stations without changing the source code of the model.

The method adopted is based on the concept that the spatial variability of precipitation is less than the other data, such as temperature. Then, without the model, the mean rainfall was calculated for each ASA also using the Thiessen method, but including the data from rainfall stations. After that, the files of average precipitation for each ASA were replaced.

RESULTS

The Jamari sub-river basin was automatically divided by SLURP into five aggregate similar areas (ASAs) according to the DEM and land cover data (Figure 2). For each ASA, the percentile area was obtained of land cover occupied for each of the four classes: i) water; ii) forest; iii) non-forest; and iv) man-modified (Table 2). The total basin area modeled is 28.847 km^2 (~99% of the total area).

Figure 2. ASAs for Jamari sub river basin; X – weather stations; • – rainfall station.

Table 2. Land coverage and total area for each ASA (%).

ASA Name	Water	Forest	Non forest	Man modified	Total (km^2)
ASA 01	9.0	63.0	7.8	20.2	3.025.81
ASA 02	3.6	67.3	11.7	17.4	5.007.65
ASA 03	9.3	61.3	7.0	22.4	9.239.68
ASA 04	3.9	62.2	11.4	22.5	10.999.55
ASA 05	4.1	93.8	2.0	0.1	573.94

Calibration and verification of SLURP

The model was calibrated and checked by the two different types of data: i) weather station data (OBS1); and ii) weather station data added rainfall gauge station (OBS2). Obviously it is expected that the use of a denser network of precipitation within a basin simulation would result in improvement, since the data quality is consistent, but it was not clear if the model would accept the manual modification.

The NS, RSR, PBIAS and D(%) for OBS2(OBS1) calibration period were 0.88(0.74), 0.31(0.45), -7%(-12%) and -0.94%(-10.1%), respectively. The NS, RSR, PBIAS and D(%) for OBS2(OBS1) validation period was 0.84(0.71), 0.34(0.48), -8%(-15%) and -13.4%(-10.3%). The verification of the model efficiency criteria indicates that the values are acceptable during both the calibration and validation period. (Table 3), but it is clear that the model did better with the inclusion of climatic stations. From this point, we used OBS2 data with SLURP climate input.

Table 3.Performance of SLURP model.

OBS2 (OBS1)	NS	RSR	PBIAS	D(%)
Calibration Period	0.88 (0.74)	0.31(0.45)	-7%(-12%)	-0.94 (-10.1)
Verification Period	0.84 (0.71)	0.34(0.48)	-8% (-15%)	-13.4 (-10.3)

Hydrographs for the calibration which were observed and simulated as well as their validation periods are shown in Figure 3. It is clear that timing of runoff events is well predicted by SLURP.

As can be seen in Figure 5, the agreement between the modeled and the observed curve is very good. This suggests that the method SCE-UA was suitable for calibrating the model. The use of the 90m resolution DEM together with SLURP showed the accuracy in modeling of surface runoff in a basin with small slopes, such as the Jamari.

The impact of deforestation

Taking into account the current deforestation rate in the area under study, trend scenarios can be conducted for 2013 and 2016, respectively. The results for DEFOREST+20% and DEFOREST+30% indicated increased runoff compared to the average from 1999-2007, 825.3 $m^3.s^{-1}$, to 1048.1 $m^3.s^{-1}$ and 1163.7 $m^3.s^{-1}$, resulting in increases of 27% and 41%, respectively. During the dry season (characterized by weak runoff), the flow tends to increase remarkably, which can be a concern for the local population who use these rivers for supply, navigation (in some places, the only kind of transportation), and also for power generation. If these scenarios become real, the rivers of the basin will have different runoff patterns, which are likely to result in socioeconomic impacts.

Although the extreme scenarios are not realistic, the results are instructive because they clarify the non-linear response of the hydrological cycle to progressive changes in land cover.

When modifying the land cover to 100%FOR, the annual calculated runoff average decreased from 825.3 $m^3.s^{-1}$ to 329.1 $m^3.s^{-1}$, i.e., a decrease of about 60%. On the other hand, for the

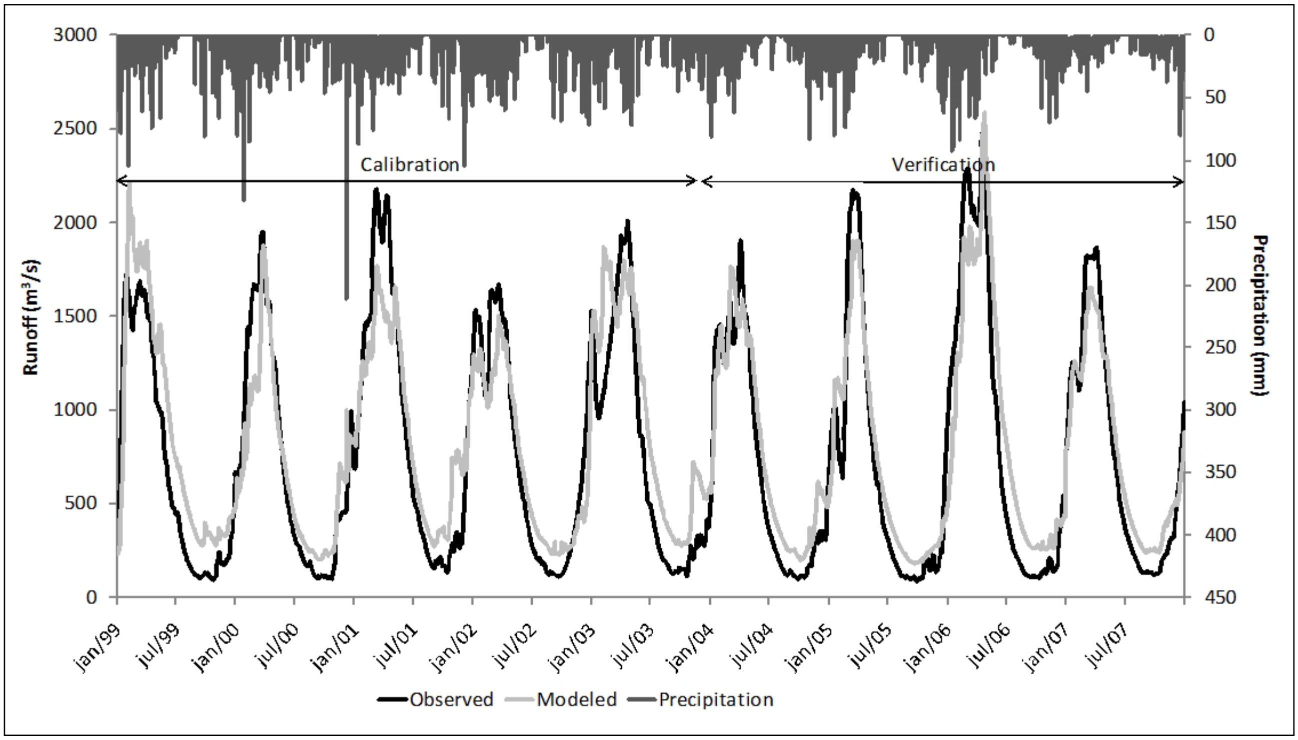

Figure 3. Comparison between modeled and observed runoff in Jamari sub-river basin.

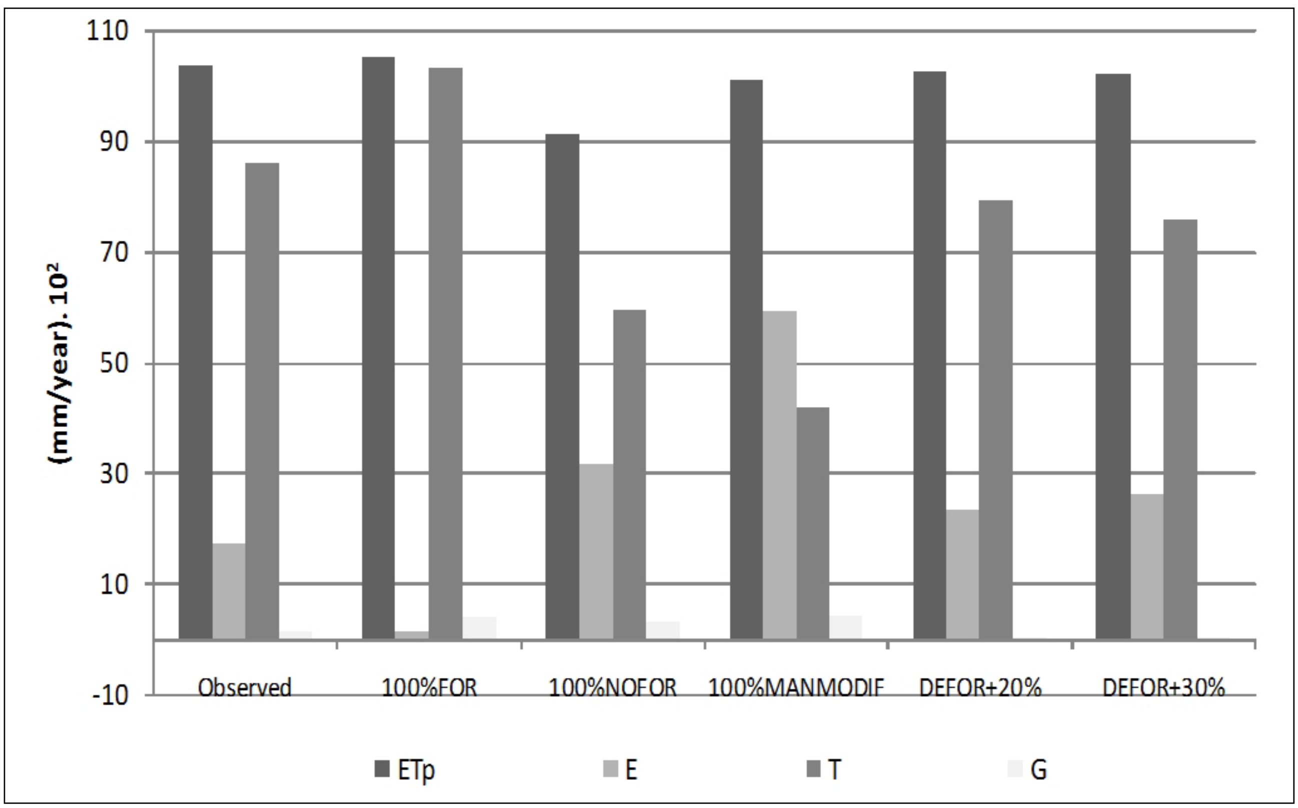

Figure 4. Comparison between trends sceneries and observed runoff in Jamari sub river basin.

scenarios with 100%NOFOR and 100%MANMODIF, runoff increased to 2313.1 $m^3.s^{-1}$, and 1729.4 $m^3.s^{-1}$, an increase of 181%, and 109% of the observed annual runoff average, respectively.

The parameters that most influenced the results in these scenarios were related to the amount of available soil water for evapotranspiration and canopy interception, which were modified according to the soil cover. The high interception in scenario 100%FOR leads to a reduction of precipitation that reaches the soil and thus reduces runoff. It also reduces the amount of water available for evaporation. Furthermore, the increase of flow in scenarios 100%NOFOREST and 100%MANMODIF is due to the substantial decrease in evapotranspiration and rainfall interception by the canopy. It is worth mentioning that this study used the same series of precipitation for all scenarios, but the precipitation in the region is a variable that has its intensity largely influenced by local evaporation. Hence, a decrease in evapotranspiration tends to reduce rainfall. The use of SLURP coupled to an atmospheric model can reveal more about this feedback mechanism in further studies.

The elements of water balance are shown in Figure 5. It may be seen that evapotranspiration varies slightly between the scenarios, except the 100%NOFOR, where evapotranspiration is approximately 90% the value of the other scenarios. However, when the exchange of water between the surface and the atmosphere is divided into evaporation and transpiration, the peculiarities of each scenario are quite evident. In 100%FOREST, transpiration contributed to the increase of evapotranspiration. This is quite obvious, since in this scenario, the interaction between the surface and free atmosphere is dominated by the exchange of processes in the vegetation canopy. In 100% NOFOREST, the land cover formed by the typical savanna and pasture vegetation makes the transpiration about twice as much as evaporation. In 100% MANMODIF, the deforested soil with urban characteristic implies a greater contribution in evaporation than in transpiration.

It can be seen that the evapotranspiration and groundwater flow reduce slightly with the decrease of forest areas when we compare with the trend scenarios. In terms of numbers the evapotranspiration decreased from 20% to 30%, respectively; groundwater flow decreased 20% and 8%, respectively. As long as deforestation leads to less water interception by vegetation, the contribution of evaporation increases with the expansion of the deforested area.

Several studies suggest the local contribution of evapotranspiration as responsible for about 50% of the precipitation that occurs in western Amazonia (Nóbrega, 2005; Marengo, 2006; Nóbrega, 2008). Therefore, a decrease in vegetation cover over a region can alter the precipitation regime in this region (and neighborhood), decreasing the amount of water vapor originating there, because the evapotranspiration decreased in these simulated scenarios. This trend, combined with the increase in flow during dry periods, may worsen social and environmental problems during more critical periods.

SUMMARY AND CONCLUSIONS

First, it was necessary to ensure that the model could be used in this region, due to the lack of some meteorological data and the small slopes of the region. Based on the NASH, RSR, PBIAS and D% criteria, the results indicate acceptable values. Furthermore, since it is a semi-distributed model, it requires less startup parameters than the distributed models, and also is able to calculate results faster.

The use of climatic stations improved the simulations, indicating that the methodology adopted to add the precipitation data was efficient.

Deforestation in Amazonia has been occurring for some decades and the rate of annual growth is noticeable. In addition, this might be influenced by climatic and socio-economic factors. Land

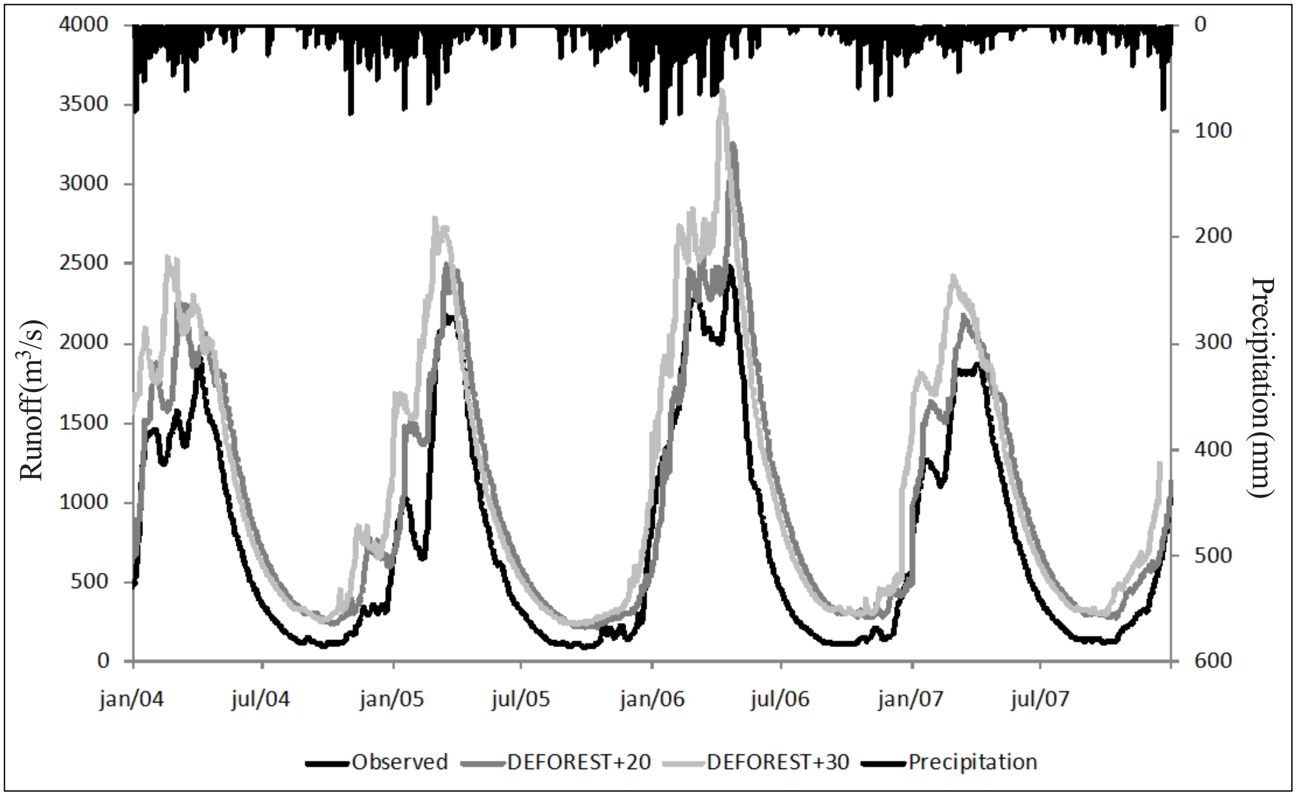

Figure 5. Observed and Simulated water balance components for scenarios 100%FOR, 100%NONFOREST, 100%MANMODIF, DEFOR+20% and DEFOR+30.

cover/use change simulations indicated that the runoff can be changed. The results suggest that there is an increase in runoff when deforestation occurs in the extreme and trend scenarios, associated with less interception of water by the canopy. If the average rate of deforestation continues to be about 3.45% per year in the basin, our simulations predict that the annual runoff will increase about 27% by 2013 and 41% by 2016. Samuel Hydropower, located on the Jamari river, began to be built in 1982. Between 2004 and 2006, the hydropower floodgates had to be opened because the river level reached its maximum level.

The results suggest that the ongoing deforestation could be responsible for having to open these floodgates, since the observed data do not indicate more rain than the average. In SLURP the sediment load that affects the level increase of the river is not taken into account, but it is likely to result in a sediment increase due to the silt produced by deforestation.

Evapotranspiration and groundwater flow tend to decrease with deforestation. Results show that the main impact might occur on transpiration, which tends to decrease with deforestation, while the evaporation tends to increase. Alterations in water balance in the Amazon can result in modifications in the local hydrological cycle and, in agreement with other studies, it will affect rain patterns there and in adjacent areas.

Finally, the methodology proposed in this paper worked well, and can be used to analyze other basins in the Amazon region.

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