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A hydrological-modeling study of the impact of land use/land cover and climate change on runoff in a watershed in the western Brazilian Amazonia

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ABSTRACT

In this work we investigate the effect of land use and land cover in the Jamari sub river basin, located in the Brazilian Amazonian. The objective is twofold: 1) to study the impact of deforestation and climate change on the basin's runoff, and 2) to test the feasibility of using a semi-distributed hydrological model for studying runoff of a low-slope river basin such as Jamari. We use a wide variety of data such as Landsat imagery, digital elevation data as well as conventional precipitation and near-surface data. We defined scenarios ranging from a completely forested basin to a completely man-modified one. In addition, we tested realistic scenarios for the ongoing deforestation process with 20% and 30% deforestation and tested scenarios hypothetic for climate change. Our scenarios suggest that for extreme and realistic scenarios there is an increase of runoff when deforestation occurs, since less water is intercepted in canopy, evapotranspiration and groundwater tends to decrease with deforestation. In climate change scenarios, increase temperature and precipitation tends to increase evapotranspiration and runoff and, increase temperature and decrease precipitation tend to increase evapotranspiration and decrease runoff and groundwater. The results suggest that Semi-distributed Land Use-based Runoff Processes (SLURP) is suitable for use in the Jamari sub river basin with the advantage of being a light model, in terms of internal parameters. The proposed methodology is suitable for use in other basins of the region.
Keywords: deforestation, climate change, Amazonia; runoff, water resources

INTRODUCTION

The consequences of changes in land cover and land use on the hydrological cycle have been studied for years (Charney et al., 1975; Eagleson, 1982; and Williams and Balling, 1996). The direct effect of deforestation on climate variables such as temperature, evapotranspiration, heat and moisture transport, and eventually on the basin's runoff, has already been detected in many parts of the globe: in river basins such as Yangtze in China (Yin and Li, 2001; Yang et al., 2002), Mekong in Asia (Goteti and Lettenmaier, 2001; Kite, 2000;), Buji in Asia (Shi et al., 2007) and Mississippi in the USA (Cherkauer et al., 2000), as well as in several catchments in Africa (Calder et al., 1995; Hetzel and Gerold, 1998; van Langenhove et al., 1998; and Li et al., 2007). Recently, many studies have focused the tropical region.

We can highlight two interesting aspects here: 1) Amazonian, that holds more than 40% of all remaining tropical rainforest of the world (Laurence et al., 2001), is a region of paramount interest in this field; and 2) about 70% of the Brazil fresh water is in Amazonian. Deforestation is the major environmental problem that the Amazonian river basin faces today. Amazonian is the whole region comprehended by the great river basin of the Amazon river. This is the planet's largest river basin, formed by a complex of 25.000 km of navigable rivers distributed in about 6.900.000 km², roughly 3.800.000 km² of them in Brazilian territory. Besides Brazil, the area of the Amazon river basin embraces five other countries, namely Peru, Bolivia, Ecuador, Colombia and Venezuela (Becker, 1991).

Amazonian's abundant vegetation releases large amounts of water vapor through transpiration which in addition to evaporation induce a precipitation recycling of about 25-35% (Brubaker et al., 1993; Eltahir and Bras, 1994; and Trenberth, 1999). Moreover, the region is responsible for approximately 13% of all global runoff into the oceans (Foley et al., 2002).

Measuring the impacts of deforestation and climate changes on a river basin's runoff can be accomplished either through studies in experimental river basins or by using mathematical models. For experimental studies they use two river basins for evaluating the changes. Such river basins should be similar in area, morphology, geology, soil, climatology and land use.

Hydrological modeling is a powerful tool for evaluating the deforestation effect on a river basin since it is more flexible than experimental studies. Moreover, it has the ability of producing rapid results, with a lower operation cost. Several authors have used hydrological modeling for studying the change in the hydrological processes due to land cover and land use within a scale of a river basin (e.g. Li et al., 2007; Hundecha and Bárdossy, 2004).

There are some difficulties in using hydrological models in the Amazonian river basin, mostly in the Brazilian Amazonian. Besides the lack of meteorological data, obtaining parametric information is a difficult task, and this information is necessary to feed distributed models. Furthermore, the small slope of some sub-basins tends to induce systematic errors in the runoff calculation, since the physiographic parameterization may not be the ideal (Costa e Foley, 1997; Nijssen et al., 2001; Ecuyer, 2003).

Moreover, hypothetical sceneries of deforestation in the Amazon basin have been modeled along the last years and almost all the models present a significant reduction in the precipitation, evapotranspiration, superficial flow and increase in the temperature (Marengo, 2006). Rocha (2004) simulated impacts in the climate of the region Amazon due to the deforestation with CPTEC/COLA's global model, and it found the next consequences in Amazon climate: air temperatures increase between 1 to 2,5° C, evapotranspiration decreases between 5% and 20% and the station drought becomes longer.

Most current modeling are performed in general circulations models (GCM), demanding much computational calculation and input data. To overcome this drawback, an option is the use of semi-distributed models. The main objective of this work is study the impacts of the changes in land use/land cover and climate on runoff using a methodology based on data smaller demand and, consequent, computational performance, enabling to generate knowledge's about of how these impacts modify water resources and, consequently, the environment in a river basin in western Amazon. We also verify the feasibility of using the semi-distributed model SLURP in a river basin with low slope, as it is characteristic of some sub river basins of Amazonian. In section 2 we present the methodology that includes the study area, the SLURP model, data and calibration; in section 3 we present and discuss the results, and conclude in section 4.

MATERIALS AND METHODS

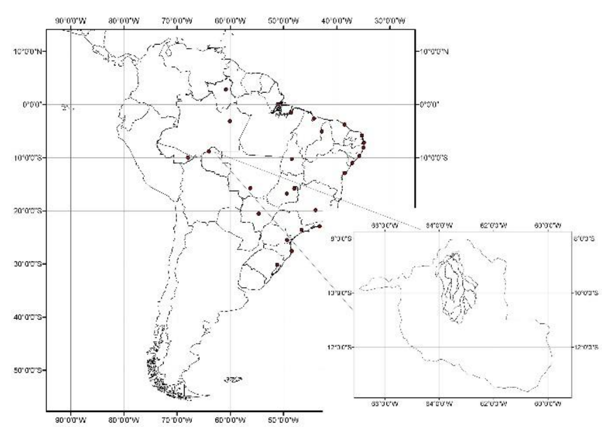
1. The study area

The Rondônia state, whose area of about 234.000 km2 is shown in Figure 1, is a state in the Brazilian Amazonian. The state's network runoff is represented by Madeira river (an important tributary of the Amazonian river basin) and its streams that form eight important sub river basins, among them, it is the Jamari sub river basin. About 28% of the Rondônia state have already been deforested .

The Jamari river basin has suffered a substantial deforestation due to the advance of the agricultural frontier in the Rondônia state. Kruschen et al. (2005) indicate the following causes for that advance: 1) between 1970 and 1990 colonists coming from other regions increased the state occupation; 2) extensive bovine cattle breeding became the main economic activity of the state; 3) most of the state's soil is old, except for some sub river basins, including Jamari; and 4) the occupation pattern is of the fishbone type, associated with the main state's highway (Fearnside, 2005). This basin is economically strategic since it is crossed by the main highway of Rondônia, namely BR-364. In Amazonian it is usual the formation of articulated urban networks around the axis of the highways thus contributing for modifications in land cover.

The basin is crossed by two important rivers namely Jamari and Candeias. Jamari river has its nascent in the southwest part of "Serra do Pacaás Novos", in Rondônia, and streams northward flowing into the right bank of Madeira river, whose river basin is defined by the geographical coordinates 08º 28'S to 11º 07'S of latitude and 62º 36'W to 64º 20'W of longitude with about 29.066.68 km² of area (Figure 1).

Figure 1 – Localization Jamari sub river basin.



The Jamari river basin is also economically important because it has been dammed for formation of the first hydroelectric power plant of Rondônia state, the Samuel Hydropower, in one of its main tributaries (Jamari river). Besides electric power generation, it also used for transportation of people and loads in the region comprehended between Porto Velho and Ariquemes, the main cities of Rondônia.

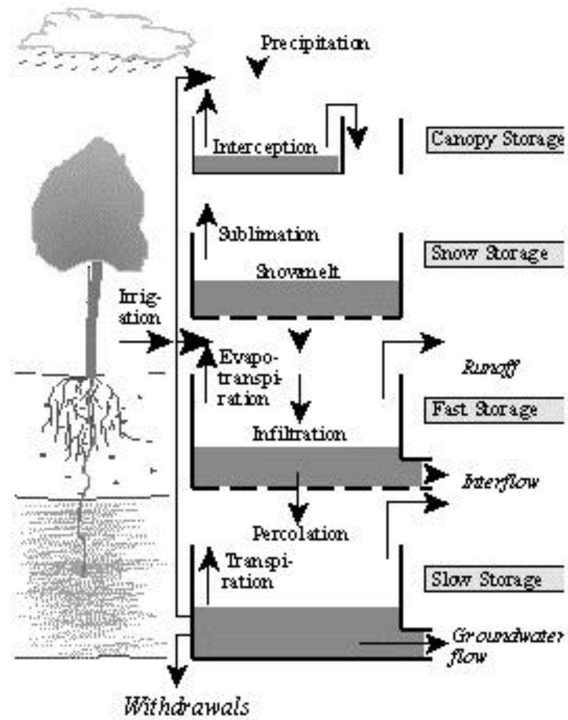
The basin's climate is of the equatorial type and the temperature variation is due to the rainfall regime, the altitude, and the intrusion of cold-air masses from southern South America. The annual average temperature ranges from 24 to 26ºC, the maximum temperature from 28 to 34ºC, and the minimum from 15 to 21ºC. Annual precipitation varies between 1.800 and 2.400 mm. The dry period occurs between June through August, and the rainy period between October through April. Are considered as transition the months of May and September.

2. The hydrological model SLURP

Semi-distributed Land Use-based Runoff Processes (SLURP) is a basin model that simulates the hydrological cycle from precipitation to runoff including the effects of reservoirs, regulators and water extractions (Kite, 2005). It first divides a basin into sub-basins using topography from a digital elevation map. These sub-basins are further divided into areas of different land covers using data from a digital land cover classification. Each land cover class has a distinct set of parameters in the model.

The SLURP simulates the vertical water balance for each land cover within each sub-basin each day. That is, the model approximates the physical processes controlling the transformation of precipitation into evapotranspiration, groundwater and runoff separately for each land cover within each sub-basin. Each element of the sub-basin/land cover matrix is represented by four nonlinear reservoirs or tanks representing canopy interception, snowpack, fast storage and slow storage (Figure 2).

Figure 2 – Schematic representation of the vertical water balance of the SLUP watershed model.



SLURP uses basically three types of data for initialization: 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, mean air temperature, dew-point temperature (or relative humidity), solar radiation and wind intensity. It initially divides a hydrological basin into sub river basins and then divides each sub river basin into its component land cover using the public-domain topographic analysis software TOPAZ (Garbreht and Martz, 1999). These homogeneous areas are based on the hydrological response unit (HRU) concept described in Kite (2005). SLURP defines these areas in Aggregated Simulation Areas (ASA).

The model has previously been applied in many countries for basins ranging in size from prairie sloughs measuring only a few hectares (Su et al., 2000) to large basins such as the Mackenzie with an area of 1.8 million square kilometers (Kite et al., 1994) and has been designed to make maximum use of remotely sensed data. Applications of the model have included studies of climate change (Kite, 1993), hydropower (Kite et al., 1998), water productivity (Kite, 2002), irrigation (Kite and Droogers, 1999) and wildlife refuges (de Voogt et al., 2000), contribution of snowmelt for runoff (Laurent and Valeo, 2003; Thorne and Woo, 2006).

The evapotranspirative demand for each land cover in each sub-basin is calculated using the Food and Agriculture Organization's (FAO) version of the Penman-Monteith method :

$$\lambda \cdot ET = \frac{\Delta(R_n - G_h) + \rho_a c_p \frac{e_s - e_a}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (1)$$

where λ is the latent heat of vaporization, *ET* is the potential transpiration rate (mm), R_n is the net radiation, G_h is the soil heat flux γ is the psychrometric constant, r_a is the aerodynamic resistance, r_s is the surface (crop) resistance, e_s is the saturated vapour pressure, e_a is the actual vapour pressure, ρ_a is the air density, and c_p is the heat capacity of moist air. The evapotranspiration method used here was Linacre due to the lack of some required data to use another method.

The resulting evapotranspirative demand is calculate by evaporation from intercepted precipitation stored on the canopy, from soil evaporation and from crop transpiration. The canopy capacity is computed by multiplying a specified maximum leaf capacity by the leaf area index (LAI) for a particular crop and date.

If a snowpack exists and the temperature exceeds a critical value, snowmelt will be computed using either a simple degree-day method or a modified energy balance approach.

Excess precipitation and any snowmelt will infiltrate into a fast groundwater store at a rate computed by Equation 2. The fast store represents that soil water storage which provides the rapid-response part of the streamflow hydrograph.

$$Inf = \left(1 - \frac{S_1}{S_{1,\max}}\right) \cdot Inf_{\max} \quad (2)$$

where, S_1 is the current contents of the fast store (mm), $S_{1,max}$ is the maximum possible contents of the fast store (mm), *Inf* is the current infiltration rate ($mm.day^{-1}$) and Inf_{max} is the maximum possible infiltration rate ($mm.day^{-1}$) specified for the particular land cover. If the current infiltration rate is not sufficient to transmit all the excess precipitation, then the surplus will be spilt as surface runoff.

The fast store generates outflow, $Q_{1,out}$, using equation (3):

$$Q_{1,out} = \frac{1}{k_1} \cdot S_1 \quad (3)$$

where k_1 is the retention constant for the fast store. The outflow $Q_{1,out}$ is then separated into deep percolation, RP, flowing to a lower (slow) store and to interflow, RI, using equations (4) and (5):

$$RP = \frac{Q_{1,out}}{1 + \frac{S_2}{S_{max}}} \quad (4)$$

$$RI = Q_{1,out} - RP \quad (5)$$

where S_2 is the current contents of the slow store (mm) and S_{max} is the maximum possible contents of the slow store (mm). The slow store contains groundwater that contributes to the baseflow of the stream hydrograph.

Finally, the slow store generates groundwater flow, G, using equation (6). If the slow store overflows, the surplus water will be added to the interflow (RI):

$$G = \frac{1}{k_2} * S_2 \quad (6)$$

where k_2 is the retention constant for the slow store.

From each land cover in a sub-basin the surface runoff, interflow and groundwater runoff are accumulated using a time/contributing area relationship for each land cover and the combined runoff is converted to streamflow and routed between each sub-basin. For first order sub-basins (those which directly discharge to the river) the streamflow is routed by simply accumulating the flows down the basin with no delay or attenuation. For second order or higher sub-basins, either the Muskingum or Muskingum/Cunge routing method is used to describe the relationship between inflow, outflow and storage of the channel reach. The Muskingum weight function, x, is set to a default value of 0.25 and the time of travel, K, is computed from the change in elevation along the stream channel.

3. DEM and land-cover data

Here we use DEM from the Shuttle Radar Topography Mission (SRTM) with 90-m resolution horizontal. DEM use is becoming of the highest importance in hydrological modeling and in water resources management because they can produce a wealth of important hydrological parameters such as the basin drainage and the basin limits. However, since DEM data are remotely collected they are subject to a series of factors that may change the representation of the actual existing landscape. Their use, therefore, requires the development of pre-treatment processes for they can attend, or approach, to the relief modeling technical demand for Systems of Geographical Information (SIG) and its integration with any other type of information.

In some regions there are gaps in the data due to lack of contrast in the radar image, presence of water, or excessive atmospheric interference. This occurs especially along the rivers, in lakes, and in steep regions thus directly affecting the utilization of such data in hydrological modeling. Several algorithms for filling of failures have been developed and tried (Martz and Garbrecht, 1999). Here we use the technique of space filtering, interactive filling and interpolation technique to produce the 90-m resolution DEM from the mission SRTM.

In order to obtaining the land cover data we used seven image scenes of Landsat 7 of the year 2006 over the Jamari sub river basin. The image's resolution is of 30 m available from the Amazonian Protection System (SIPAM). The scenes were firstly georeferenced and then a mosaic was composed. Following, NDVI was calculated and a supervised classification was employed to obtaining the land-cover image according to with Kite (2005). The data were then resized for 90-m resolution since SLURP requires the land-cover matrix data to have the same dimensions of the DEM data matrix. After resample the data they were divided into four classes: water, forest, non-forest and man-modified. Due to large deforested area and small urban area in this region, we considered as man-modified areas the urban and the deforested ones. Furthermore, the non-forest class includes agricultural areas and the savannah.

4. Soil data, NDVI and LAI

The soil types were obtained from the Agricultural and Forest Plan of Rondônia state – PLANAFORO. Results indicate the presence of three main types: sand, clay and latosoil. The values of porosity, wilting point and field capacity were obtained from Kite (2005).

NDVI (Normalized Difference Vegetation Index) and LAI were obtained from consultations bibliographies, as table 1 and 2, respectively.

Table 1 – NDVI values by soil coverage.

Soil coverage	NDVI
Forest	0,75
Non forest	0,6
Man modified	0,3

Reference: Nóbrega, 2008.

Table 2 - LAI values by soil coverage.

Soil coverage	Jan	Feb	Mar	Apr	May	Jun
Forest[3]	9,6	9,6	9,6	9,6	9,6	7
Non forest[4]	3,9	3,9	3,9	3,9	3,9	0,5
Man modified[5]	1,0	1,0	1,0	1,0	1,0	0,3

Cont. Table 2 – LAI values by soil coverage.

Soil coverage	Jul	Aug	Sep	Oct	Nov	Dez
Forest[3]	7	7	7	9,6	9,6	9,6
Non forest[4]	0,5	0,5	0,5	3,9	3,9	3,9
Man modified[5]	0,3	0,3	0,3	1,0	1,0	1,0

5. Model calibration

The model was calibrated by using the automatic method Shuffled Complex Evolution of the University of Arizona (SCE-UA) (Duan et al., 1994), which combines techniques of random search, genetic algorithm and the Simplex method of Nelder and Mead. During the calibration procedure, the method works with a population of points that "evolves" for a point optimum global through successive interactions and evaluations of the object function. The time period for calibrating the model was from 1 Jan 1999 to 31 Dec 2003 and for verification, we used the period from 1 Jan 2004 to 31 Dec 2006.

6. Climatic and runoff data

Climatic and runoff information are among the main difficulties of hydrometeorological modeling of Amazonian. The available time series is either too short or have several gaps. In this work we use the data set of four stations containing information of precipitation, air temperature, and dew-point temperature of the Rondônia's Agency for Environmental Development (SEDAM). We also use data of five rain-gauge stations of National Water Agency (ANA). The data sets cover the period between 1 Jan 1999 and 31 Dec 2006.

7. Manning roughness coefficient

The use of the Muskingun-Cunge method requires determining the Manning roughness coefficient for a more effective modeling of the flow propagation within a basin. The value of this parameter can be determined based on the characteristics of the banks and stream of the river for everyone ASA. However, considering the model's low sensitivity to this parameter (Kite, 2005), it can have a fixed value for the basin as a whole. Here, we use a value of 0.030 for the Manning roughness coefficient.

8. The Simulations

We defined three extreme scenarios of soil cover for investigating the relationship between soil-cover change and runoff. The experiments are: i) One hundred per cent with forest and water (100%_F); ii) One hundred per cent with savannah plus pasture and water (100%_Non); and iii) One hundred per cent man-modified area and water (100%_Man). We were also simulated more realistic scenarios using data from the PRODES[1] that produces annual estimate of the deforestation rate in Legal Amazonian. The experiments are: i) FOR_20, meaning a 20% reduction of the forested area, and ii) FOR_30, meaning a 30% reduction of the forested area.

For analysis by climatic impacts have been identified two scenarios. The scenarios were hypothetic, however, are based on futures projections o climate in the region. In both scenarios is assumed that the temperature rise 2°C, and rainfall varies 20%, decreasing and increasing. The climate scenarios are: i) P+20, meaning 20% increase in rainfall, with an increase in temperature of 2 degrees, and ii) P-20, meaning 20% reduction in rainfall, with an increase in temperature of 2 degrees.

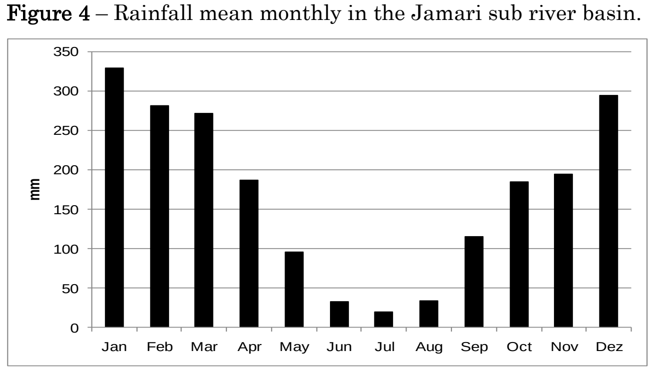
RESULTS AND DISCUSSION

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 3). For each ASA it was obtained the percentile area of land cover occupied for each of the four classes: i) water; ii) forest; iii) non-forest; and iv) Man-modified. The values are shown in Table 1. The total basin area obtained by the model is 28.847 km^2 (~99% of the total area).

Figure 3 – ASAs for Jamari sub river basin.

The average precipitation in the basin was calculated by Thiessen polygons method with weight coefficients based on stations location and elevation. Figure 4 showed seasonal variation of precipitation mean where can observe two distinct rainy periods, dry (October-April) and drought (June-August); May and September are transitions monthly.

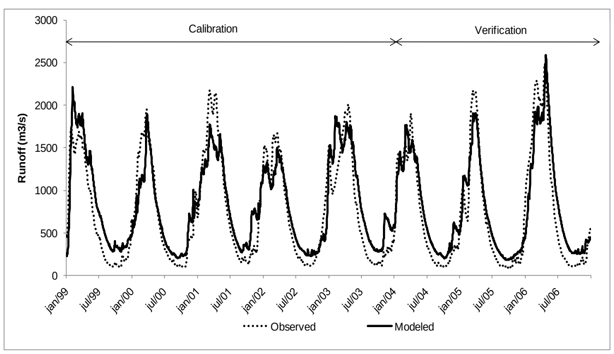
Figure 4 – Rainfall mean monthly in the Jamari sub river basin.



Before performing the calibration process, the Nash-Sutcliffe coefficient was -1.03 and the annual average runoff calculated by the model was 487.2 $m^3.s^{-1}$, whereas observed runoff was 759.2 $m^3.s^{-1}$.

After calibration, the annual average runoff increased to 766.41 $m^3.s^{-1}$, for a calibration period, with Nash-Sutcliffe coefficient of 0.88, and average runoff of 756.90 $m^3.s^{-1}$, with Nash-Sutcliffe of 0.84, for a verification period. As it might be expected the model's performance was not good before calibration since it had not been subjected to any parameterization. As it can be seen in Figure 5, the agreement between the modeled and the observed curve is pretty good. This suggests that the method SCE-UA is suitable for calibrating the model. The utilization of the 90-m DEM together with SLURP showed skill in the modeling runoff in a basin with little slope, such as Jamari.

Figure 5 – Comparison between modeled and observed runoff in Jamari sub river basin..



1. The impact of deforestation

In order to address the impact of deforestation, SLURP was run again using the same meteorological input data for the calibration and verification periods. However, a surface characteristic was changed to test the effect of three different types of soil cover on runoff. The first scenario was generated assuming a cover of 100% forest in the whole basin's area, the second and the third scenarios were used to analyze the impact of deforestation on runoff. Soil cover was changed into non-forest and man-modified areas, respectively. For simulating impacts over realistic scenarios we used the deforestation average rate data for the Jamari river basin that is of about 3.5% per year, according to PRODES data. In the Forest_20%, and Forest_30% scenarios, it is considered that the basin would lose, respectively, 20%, and 30% of the forested area. Considering the present rate of annual deforestation, with these scenarios one can consider the results as realistic for 2012, and 2015, respectively.

Even the scenarios 100% forest, 100% non-forest, and 100% man-modified areas are not realistic the results are instructive because they allow one to gain insight about the non-linear response of the hydrological cycle to progressive changes in land cover.

When modifying the land cover to 100% forest, the mean annual calculated runoff decreased from 829.4 $m^3.s^{-1}$ to 331.3 $m^3.s^{-1}$, i.e., the runoff decreased by about 60%. On the other hand, for the scenarios with 100% non-forest area, and 100% man-modified area, the calculated runoff increased to 2403.8 $m^3.s^{-1}$, and 1835.4 $m^3.s^{-1}$ that means an increase of 189%, and 121% of the observed mean annual runoff, respectively.

The parameters that influenced the results for these scenarios are related to the quantity of available water in the soil for evapotranspiration and the canopy interception capacity that are modified according to the land cover. The high interception in the scenario of 100% forest leads to a reduction of the precipitation that reaches ground and, therefore, reduces the runoff. In addition, it also reduces the quantity of water available for evaporation. On the other hand, the runoff increase in the scenarios with 100% non-forest and 100% man-modified areas is due to the substantial decrease in both evapotranspiration and rainy interception by the canopy. It is worth to stress that in this study it was used the same series of precipitation for all the scenarios, but precipitation is a variable that owns its intensity, in a large extent, to the local contribution of evapotranspiration. Hence decreasing evapotranspiration leads to less precipitation. The use of SLURP coupled to an atmospheric model can shed light on this feedback mechanism in future studies.

For the two realistic scenarios namely Forest_20%, and Forest_30% runoff increased from the present mean value of 829.4 $m^3.s^{-1}$ to 1059.1 $m^3.s^{-1}$, and 1173.9 $m^3.s^{-1}$, meaning an increase of 27.5%, and 41.5%, respectively. Another interesting feature of these scenarios is that during the dry season (characterized by a weak runoff), the scenarios' runoff remains quite larger than the actual one. It is a characteristic of this river basin (as well as other basins of Amazonian) that the river's level decreases considerably during the dry period. That raises concerns to the local population who use these rivers for human supply, power generation, and also for navigation. If these scenarios become real, the rivers of the basin will be subjected to a different pattern of runoff that might cause some socioeconomic impact.

The elements of the water balance are displayed in Figure 6. It can be seen that evapotranspiration varies slightly among the cases, except in the non-forest case, whose evapotranspiration is roughly 90% of the value of the other scenarios. However, when the water exchange between surface and atmosphere is separated into evaporation and transpiration, the particular characteristics of each scenario become quite evident. In the 100% Forest scenario, transpiration responds for almost the total evapotranspiration. This is intuitive, since in such a scenario, the interaction between surface and the free atmosphere is dominated by the exchange processes at the vegetation canopy. In the non-forest scenario, the soil cover formed by Savannah, pasture and water causes the transpiration to be twice the direct evaporation. In the man-modified scenario, the soil with urban-deforested characteristic implies in an evaporation contribution greater than the transpiration one. In the realistic scenarios, one can observe that, compared with the actual case, evapotranspiration decreases slightly and groundwater decreases less with the decrease of the forested area. Accordingly, transpiration also decreases as the forested area is reduced by 20% and 30%, respectively and ground water all decreases by 20% and 8%, respectively. Since deforestation leads to less interception of water by vegetation, the contribution of evaporation increases as the cover of bare soil becomes larger.

Several studies suggest that the local contribution of evapotranspiration is responsible for about 50% of the precipitation that occurs in western Amazonia (e.g. Marengo, 2006). Thus a modification in the forested land cover may, consequently, modify the precipitation regime of the region, decreasing the moisture quantity locally originated, since evapotranspiration decreased in the scenarios with less forest.

Figure 6 – Observed and Simulated water balance components for scenarios 100%_F, 100%_Non, 100%_Man.

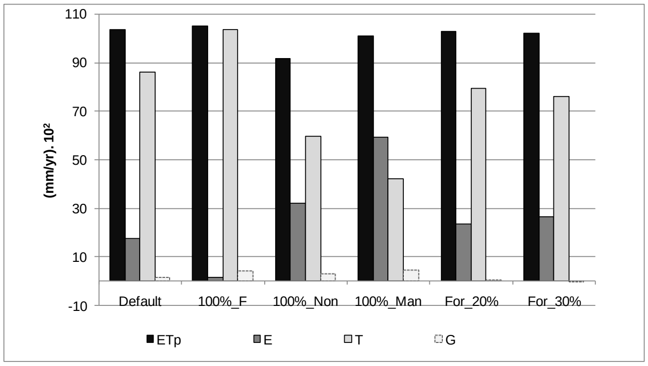
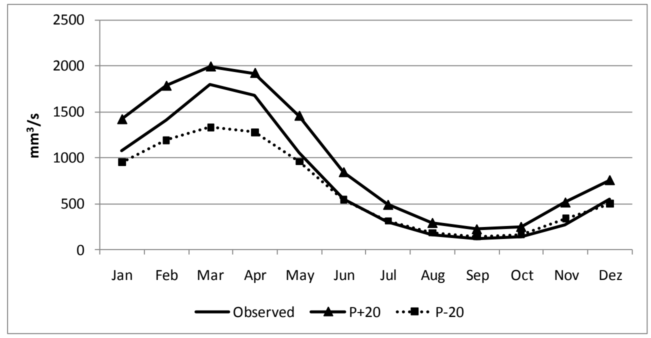


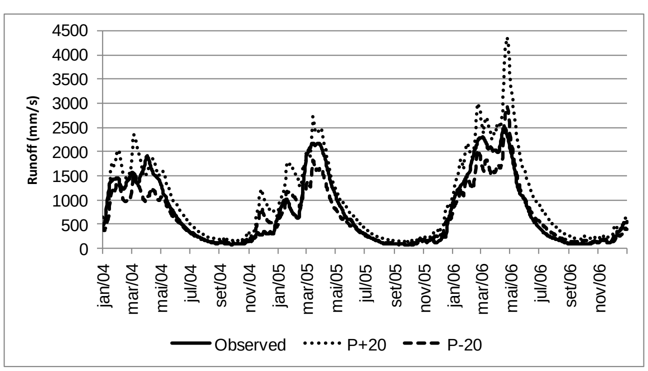
Figure 8 – Mean monthly observed and simulated runoff for the validation period under two scenarios.



2. The impact of climate change

The changes in the daily runoff as a function of temperature and precipitation changes are show in the Figure 7. The effect when adding or subtract 20% of precipitation for the period from validation period was as expected. Precipitation increase tends to increase the runoff and the decrease tends to reduce the runoff, more notably during the rainy period, when rainfall is more significant. For scenario P+20, runoff increased 31% in mean and scenario P-20, runoff decreased 13% in mean. With decreasing precipitation the effect could be critical, particularly during rainy period, affecting, for example, the navigation, agricultural production, energy generation and consume human. The Figure 8 show the seasonal average flow for the verification period, confirming that the impacts are more significant during the rainy period.

Figure 7 – Simulated runoff under two incremental scenarios.



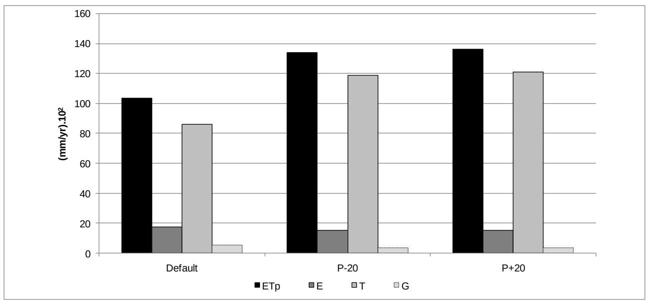
When analyzing the changes in the water balance due alterations in the temperature and precipitation, observed that the increase in temperature tends to increase the transpiration in both scenarios, but decrease the rainfall tends to decrease the evaporation (Figure 9). The model simulated accurately the change in the temperature and precipitation in the water balancing. For evapotranspiration increases in 30% and 54%, the evaporation decreases 21% and increases 3%, the transpiration increases 37% and 41% and groundwater decreases 35% and 33% to the scenarios P-20 and P+20, respectively.

It's important to affirm that in the simulation were not analyzed the deforestation impacts in the changes climatic variables. Although of this, with the here obtained results, is possible to analyze that, inside the physical processes of hydrological cycle, the evapotranspiration will suffer significant alterations.

The impacts can be more sensitive mostly during the rainy period. Moreover, with less available water for evapotranspiration, the vegetation will proceed suffering larger water stress. Although some authors have found precipitation increase in deforested areas (Marengo, 2006), if the deforestation process continue increasing, the alterations in water cycle processes can become unsustainable. The modifications in land cover/land use of the soil can lead the current system to a new state of drier equilibrium, could the vegetation suffer modifications to if adapt the present climatic terms.

To conclude, it is evident that the model presented satisfactory results and that can be better explored with joining to CGM´s for scenarios of climatic changes.

Figure 9 – Observed and simulated water balance components for scenarios P+20 and P-20.



3. The impact of deforestation

In order to address the impact of deforestation, SLURP was run again using the same meteorological input data for the calibration and verification periods. However, a surface characteristic was changed to test the effect of three different types of soil cover on runoff. The first scenario was generated assuming a cover of 100% forest in the whole basin's area, the second and the third scenarios were used to analyze the impact of deforestation on runoff. Soil cover was changed into non-forest and man-modified areas, respectively. For simulating impacts over realistic scenarios we used the deforestation average rate data for the Jamari river basin that is of about 3.5% per year, according to PRODES data. In the Forest_20%, and Forest_30% scenarios, it is considered that the basin would lose, respectively, 20%, and 30% of the forested area. Considering the present rate of annual deforestation, with these scenarios one can consider the results as realistic for 2012, and 2015, respectively.

Even the scenarios 100% forest, 100% non-forest, and 100% man-modified areas are not realistic the results are instructive because they allow one to gain insight about the non-linear response of the hydrological cycle to progressive changes in land cover.

When modifying the land cover to 100% forest, the mean annual calculated runoff decreased from 829.4 $m^3.s^{-1}$ to 331.3 $m^3.s^{-1}$, i.e., the runoff decreased by about 60%. On the other hand, for the scenarios with 100% non-forest area, and 100% man-modified area, the calculated runoff increased to 2403.8 $m^3.s^{-1}$, and 1835.4 $m^3.s^{-1}$ that means an increase of 189%, and 121% of the observed mean annual runoff, respectively.

The parameters that influenced the results for these scenarios are related to the quantity of available water in the soil for evapotranspiration and the canopy interception capacity that are modified according to the land cover. The high interception in the scenario of 100% forest leads to a reduction of the precipitation that reaches ground

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