Impacts of Agricultural Expansion on Surface Runoff: A Case Study of a River Basin in the Brazilian Legal Amazon

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Abstract

This work presents an analysis of the Land Use and Land Cover (LULC) changes of a region in the Brazilian Legal Amazon, and an evaluation of their impacts on the surface runoff regime. This case study took place at the Suiá-Miçu River basin, located in the northeast region of Mato Grosso State. LULC maps were produced for the years 1973, 1984 and 2005 using remote sensing data. After analyzing the agricultural expansion in the study area, the Automated Geospatial Watershed Assessment Tool (AGWA) was applied in performing the surface runoff modeling for each of the analyzed years using the SCS curve number method. The results showed that by 1984, 13% of the natural vegetation had been replaced by pasture in this drainage basin. These changes were responsible for a 5.7% increase in the annual average surface runoff volume when compared with the baseline values of 1973. In 2005, the agricultural areas increased to around 40% of the drainage basin, being 28% occupied by pasture and 12% by crop fields. In this last scenario, the annual average surface runoff was 37% higher than in 1973.

1. Introduction

The replacement of forests, wetlands, savannahs and other native landscapes by agriculture is a severe threat to the capacity of the environment to maintain freshwater, sustain food production and other ecosystem services (Foley et al., 2005). Currently, almost one-third of the world's land surface is under agricultural use and millions of hectares of natural ecosystems are converted to croplands or pastures every year. In Brazil, the deforestation of the Amazon forest due to the agricultural expansion and logging activities is one of the biggest problems currently faced in this important biome. Tardin et al., (1980) showed that while the deforested area in the 1970's was around 10 million hectares, by 2005 this area had increased to 67 million hectares (INPE, 2006). Land use and land cover change modelling studies predict that if current trends persist, by the year 2050 around 40% of the Brazilian Legal Amazon will be deforested in favor of agricultural activities (Soares-Filho et al., 2006). One of the natural phenomena significantly affected by land cover changes is the hydrological cycle. The forest protects the soil against the impacts of the precipitation water and provides organic matter to the soil. These factors improve infiltration and allow the recharging of groundwater reservoirs. When this vegetation cover is displaced the soil can be compacted and the water that would otherwise have infiltrated the soil would now be turned into runoff, which will carry out sediments and nutrients to the rivers, and decrease recharge of the groundwater reservoirs. This will have as consequence problems such as erosion, silting of the rivers, eutrophication, water contamination, among others (Van Dessel et al., 2008, Bordman, 2006 and Szilassi et al., 2006).The identification and monitoring of areas most susceptible to such environmental problems are essential to allow improved planning and implementation of conservation practices. In addition, studies with the objective of measure and map the spatial distribution of the changes can not only help the development of public policies, but are necessary to warn the society about the problem and its possible consequences. Several models developed in the last few decades are contributing to make this work possible and more efficient (Miller et al., 2007). However, little research has been done with the objective of implementing hydrological and erosion models within the Brazilian Legal Amazon and the impacts of the deforestation that has occurred in the last few decades are still not well known. The objective of this work was to perform an analysis of the land use and land cover changes on a region in the Brazilian Legal Amazon, and to evaluate the impacts of these changes on the surface runoff regime using remote sensing techniques and a hydrological model.

2. Study Area

The study was carried out at the Suiá-Miçu River Basin, located in the northeast region of Mato Grosso state, and part of the Amazon River Basin (Figure 1). The drainage area of the basin comprises approximately two million hectares, and is part of six municipalities: São Felix do Araguaia, Querência, Alto da Boa Vista, Ribeirão Cascalheira, Canarana and Bom Jesus do Araguaia. The predominant soil types, according to the soil taxonomy classification, are Rhodic Hapludox and Typic Hapludox. However, different types of soils can be found in some smaller regions, mainly in the southern part of the basin and in the rivers' floodplains. One factor that enhances the importance of this region is the presence of the Xingu Indigenous Reserve in the Suiá-Miçu River downstream (Figure 2). The Xingu Reserve is one of the most important regions from the point of view of its biodiversity and cultural significance to Brazil. It is located at the banks of the Xingu River, an important tributary of the Amazon River. As illustrated in Figure 2, most of the drainage area of the watershed is located outside the indigenous reserve. This contributed to the deforestation of large areas next to the preservation area, mainly due to the expansion of agricultural activities. Consequently, besides the degradation in the Xingu River spring, the agricultural activities can impact the preservation area as a result of carrying sediments, nutrients and pesticides within it.

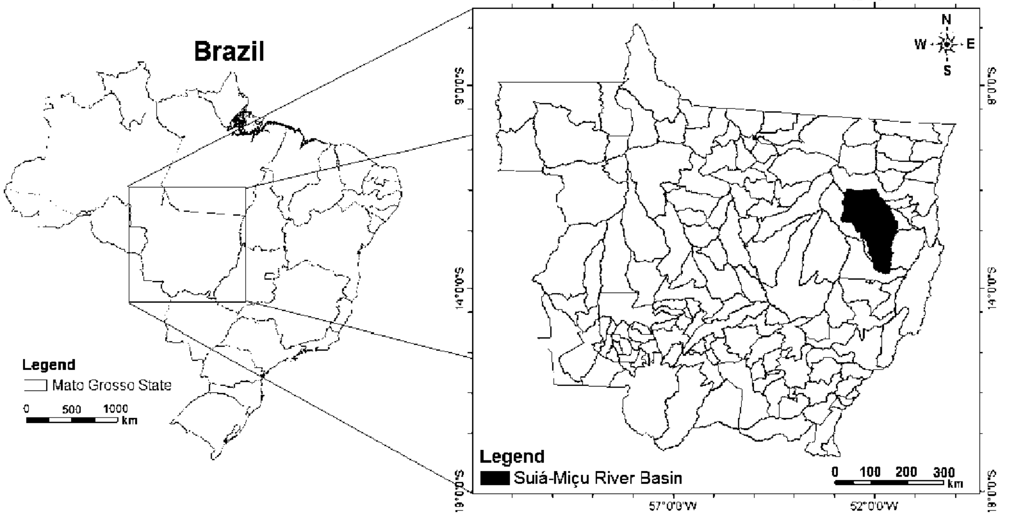

Figure 1: Geographic location of the Suiá-Miçu River Basin

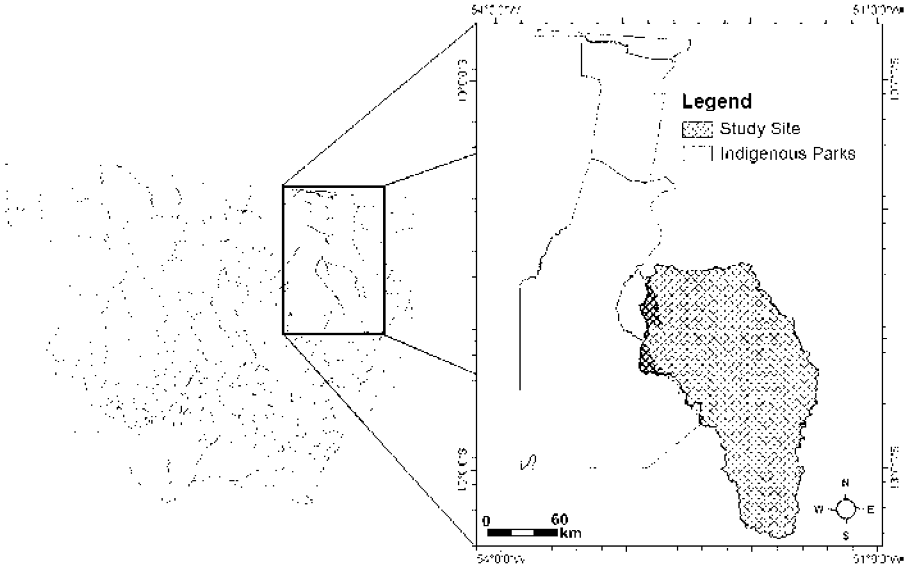

Figure 2: Geographic location of the Indigenous areas close to the study site

3. Methods

A comparative analysis was performed taking into account the Land Use and Land Cover (LULC) scenarios observed in the study area during the following years:

I. 1973, before the beginning of the agricultural expansion in the Brazilian Amazon;
II. 1984, a time at which many deforested areas were already evident due to the implementation of agricultural activities;
III. 2005, a period of intense agricultural expansion.

LULC maps for each of the described years were created using remote sensing images from the MSS/Landsat-1 (1973) and TM/Landsat-5 (1984 and 2005) sensors. The deforested areas were identified and mapped using the same methodology proposed in the Amazon Deforestation Monitoring Project – PRODES (INPE, 2006). Namely, the linear spectral mixing model (Shimabukuro et al., 1998) was applied to the images in order to generate the vegetation, shade and soil fractions. Next, the soil fraction image was segmented and classified using a non-supervised region classification algorithm (ISOSEG) (Bins et al., 1993). The deforested areas were then overlapped with the original vegetation map of the region obtained from the Mato Grosso State Planning Department (SEPLAN). For the years 1973 and 1984, all the deforested areas were classified as pasture, given that during these periods the areas planted with crops were insignificant (IBGE, 2006). However, in 2005 the deforested areas were separated into pasture or seasonal crops. The identification of the crop areas was made using the methodology presented by Epiphanio (2007). This method is based on the Crop Enhancement Index (CEI), which is calculated using the minimum and maximum Enhanced Vegetation Index (EVI) values observed along the crops' growing season (Equation 1).

$$CEI = \frac{MaxEVI - MinEVI}{MaxEVI + MinEVI}$$

Equation 1

High changes in biomass throughout the crop season result in high positive difference between MaxEVI and MinEVI values for a certain pixel, retrieving high CEI values. In pastures or forests, few or no changes in biomass are observed during a crop season, resulting in low differences between MaxEVI and Min EVI images and CEI values close to zero. The process described was carried out using EVI images from the MOD13Q1 product (Justice et al., 2002), which provides NDVI and EVI 16 days composite images from the MODIS/Terra sensor. The image processing procedures and the creation of the LULC maps were made with the software SPRING, a free GIS and remote sensing image processing system developed by Brazil's National Institute for Space Research (Camara et al., 1996). After that, an assessment of the impacts of the LULC changes on the surface runoff regime was performed using the Automated Geospatial Watershed Assessment Tool (AGWA). The AGWA is a hydrologic analysis system designed to perform watershed- and basin-scale studies (Miller et al., 2007), by providing input for the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). Besides the LULC maps, the input data required by the model include a digital elevation model (DEM), a soil map, and precipitation data. According to Kepner et al., (2004) the tasks involved in the watershed analysis using AGWA are divided in five major steps: 1) watershed location and delineation; 2) watershed subdivision; 3) land cover and soils parameterization; 4) rainfall input files; and 5) model execution, visualization and comparison of results. The DEM was obtained from the Shuttle Radar Topography Mission (SRTM) (Grohman, 2006). In order to improve the representation of land forms and drainage features, the SRTM spatial resolution data was resampled from 90 to 30 meters, according to the method proposed by Valeriano et al. (2006). Although AGWA provides the option to use global FAO soil maps for works outside the USA, the scale of such maps (1:5000 000) was not adequate to represent the soil distribution of the study area. Hence, soil maps in a scale of 1:250,000 provided by the RADAMBRASIL project (1981) survey were implemented into AGWA. Daily average precipitation values were defined for an entire year based on observations from 1983 to 2005. This information was obtained from a ground meteorological station of the Hydrological Information System hosted by the Brazilian Water Agency (ANA, 2006). The SWAT model provides two methods for estimating surface runoff: the SCS curve number procedure (SCS, 1972) and the Green & Ampt infiltration method (Green and Ampt, 1911). In the particular case of this study, the Soil Conservation Service (SCS) method was chosen in performing the runoff modeling. The SCS runoff equation is an empirical model developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller, 1981). The basic assumption of this method is that the ratio between the actual soil retention on the watershed and the potential maximum retention is equal to the ratio of direct storm runoff to potential maximum runoff. It is important to notice that, due to the lack of accurate hydrological data, a quantitative validation of the model was not performed. Therefore, the evaluation of the results was based only on comparative analysis and on the spatial distribution of the changes, following the procedure proposed by Kepner et al. (2004) and Miller et al. (2002). Such procedure assumes that the parameters incorporated in an eventual calibration would be partially canceled in a comparative study.

4. Results and Discussion

The results of the LULC classification for each one of the analyzed periods are shown in Figure 3. The deforested areas in the watershed increased from 480 km^2 in 1973 to 2850 km^2 in 1984. In 2005, around 40% of the study area (8555 km^2) was deforested. This is approximately a 200% increase over that in 1984, and a 1680% increase from 1973 (Figures 4a and 4b). The creation of pasture areas and logging activities were the main causes of deforestation in 1973 and 1984. During these years, the north and east parts of the basin were the most affected. In 2005, there was an evident increase in the deforestation along the central part of the basin, in the region that surrounds the city of Querência. The results show that the main cause of deforestation in this central part of the study area was the expansion of areas planted with seasonal crops. In general, the alluvial forests and pioneer vegetation areas were not significantly deforested. These results can be explained by the fact that these phytoecological regions are located in flooding areas, and therefore, not suitable for agricultural activities. A more detailed description of the agricultural expansion in this region had been described by Maeda et al., (2008).

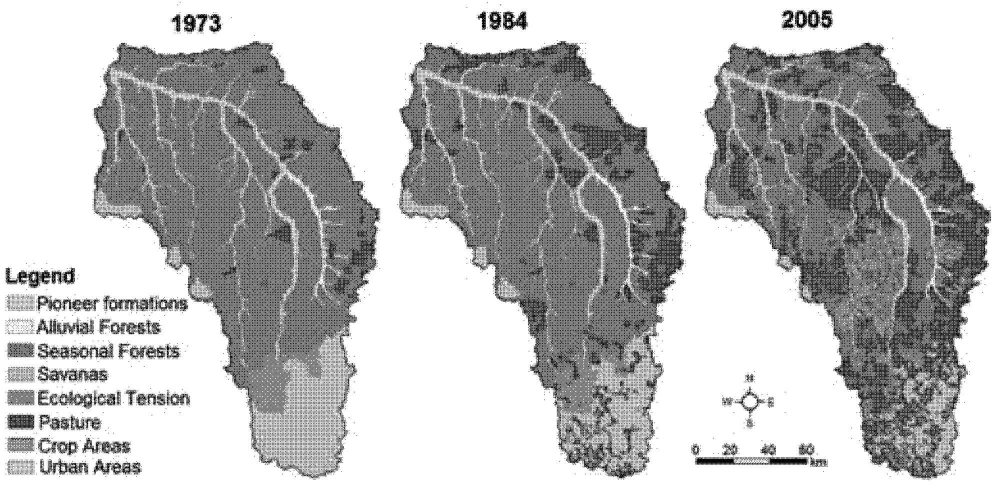

Figure 3: Land Use and Land Cover Maps of the study area for the years of 1973(left), 1984(center) and 2005(right)

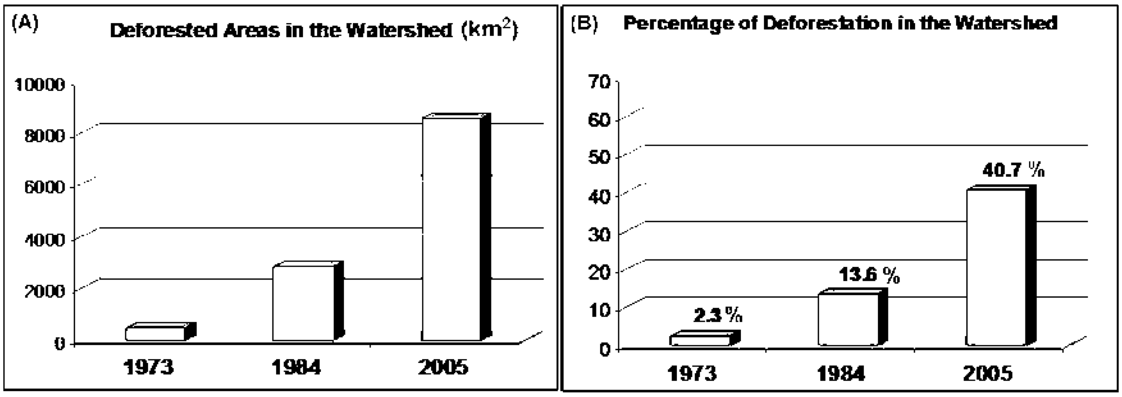

Figure 4: (a) Deforested areas in the study site for each of the analyzed years; (b) Percentage of Deforestation in the study site

4.1 Input Data and Model Results

The DEM with a spatial resolution of 30m, used in this work, is presented in Figure 5a. The improvement of the spatial resolution of the SRTM data from 90 to 30m resulted in a better representation of the drainage features, especially in the areas with a higher drainage density, as seen in the south part of the basin. Along the flat areas the results of this process are less noticeable, however in such areas this procedure was helpful in order to eliminate the roughness and interferences caused by the canopy in the SRTM data. The watershed delineation was satisfactory, with accurate identification of the drainage basin boundaries confirming the suitability of SRTM data for this task. However, a limitation of this data was observed in the automated extraction of the drainage networks. This limitation was observed mainly in the length of the rivers' floodplains, in boundaries of deforested areas or roads, where the effects of the canopy on the SRTM resulted in an erroneous delineation of the drainage network, as it is exemplified in Figure 6. In Figure 5b, the watershed subdivision is shown. The subdivision was performed automatically by AGWA based on a threshold drainage area required to define a channel, referred to as the Contribution Source Area (CSA) (Miller et al., 2007). The CSA value used was 2%, which was, after a few tests, the value that best represented the drainage distribution of the watershed, based on visual analysis. As a result, the watershed was divided in 55 sub-regions. The soil map used in this work as an input to AGWA is showed in Figure 5c.

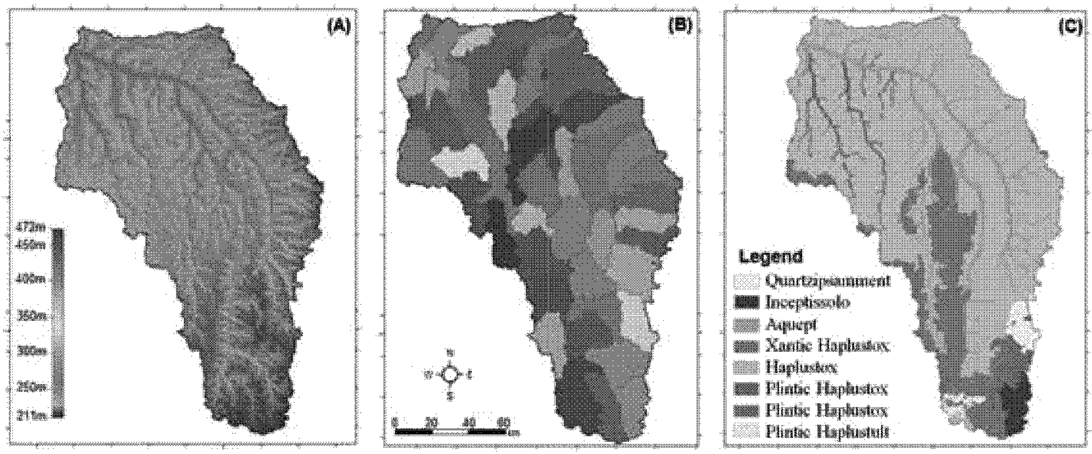

Figure 5: (a) Digital Elevation Model of the study site; (b) Result of the Sub-Division on the watershed using a CSA of 2%; (c) Soil Map used as an input to AGWA

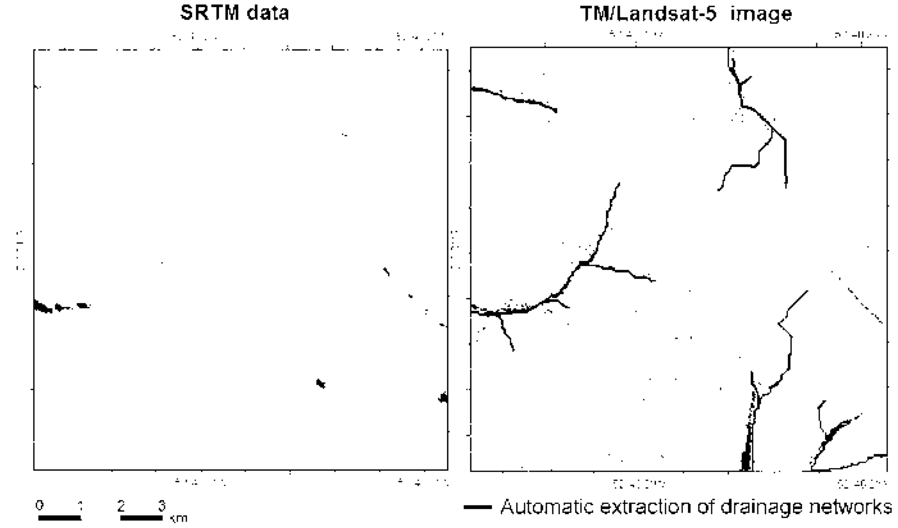

Figure 6: SRTM data (left) and the results of the automatic extraction of the drainage network over a TM/Landsat-5 image (right)

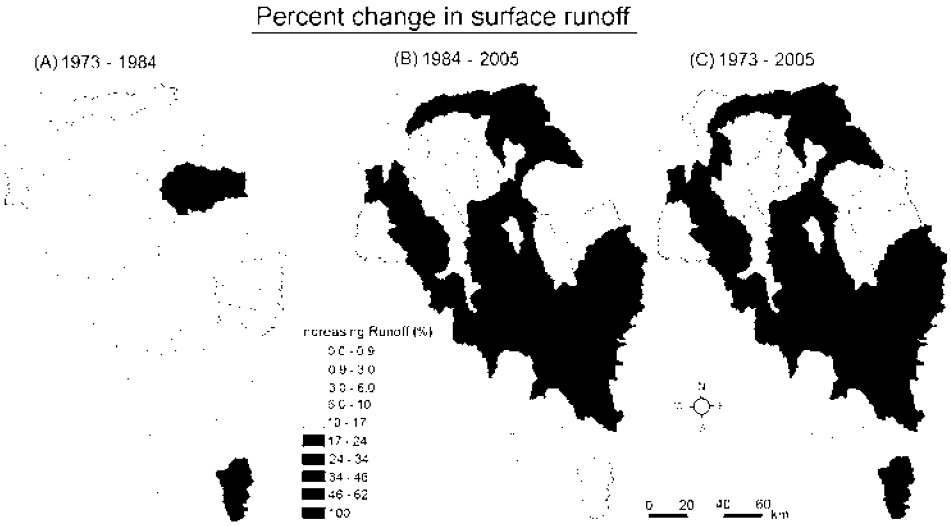

Figure 7: Percent change in surface runoff (a) from 1973 to 1984; (b) from 1984 to 2005 and (c) from 1973 to 2005

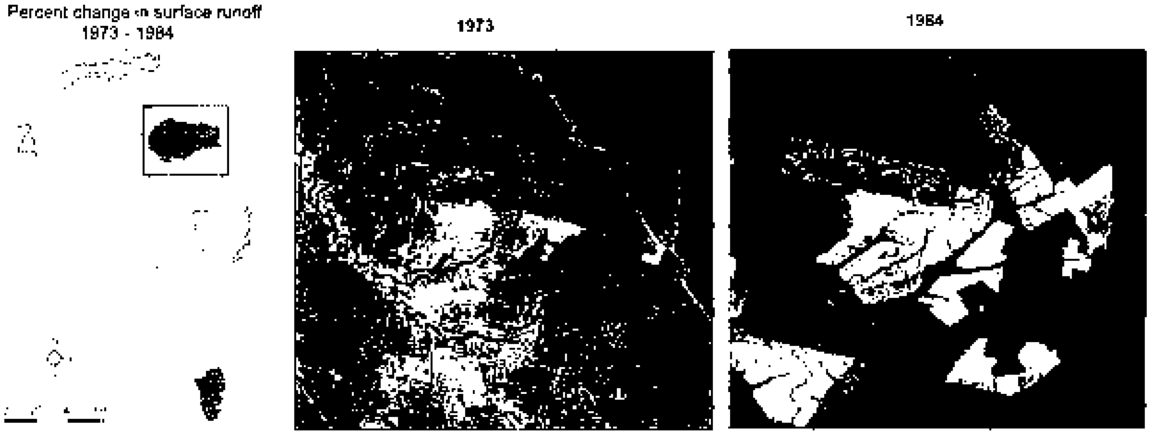

Figure 8: Changes in the vegetation cover along the region with highest increase in the surface runoff from 1973 to 1984

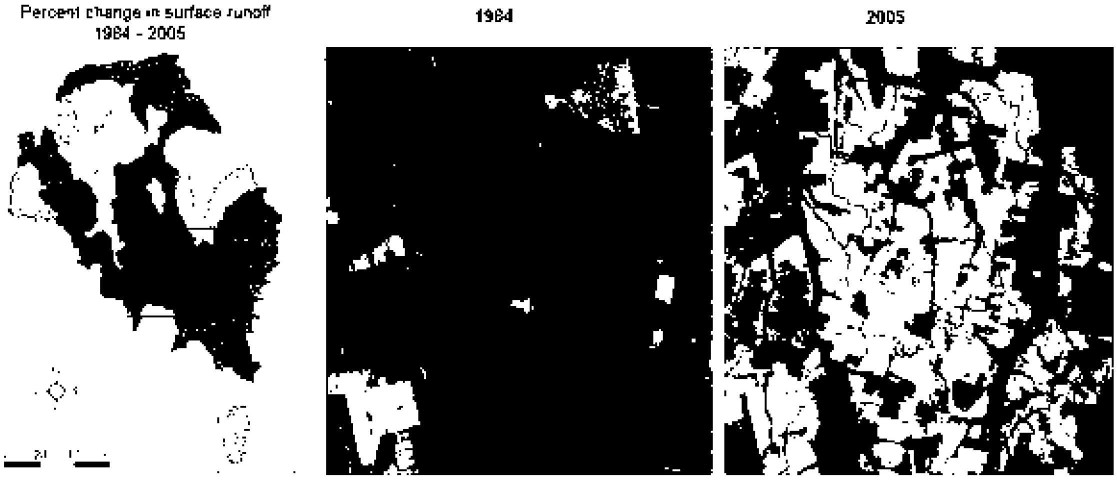

Figure 9: Changes in the vegetation cover along the region with highest increase in the surface runoff from 1984 to 2005

The soil types are classified based on the Brazilian Soil Classification System, and the necessary data for this characterization were obtained from the RADAMBRASIL project (1981) and from other available works that describe the soil parameters for the Brazilian conditions (Tucci, 1993). Next, the results of the surface runoff modelling are presented (Figure 7). Comparisons are based currently analyzed period, that is, a 50% increase means that the surface runoff doubled from one analyzed period to another. In the same way, a value of 100% means that a certain volume of surface runoff started to occur in a region where no surface runoff was observed in the previous period. From 1984 to 1973, the north and east regions of the basin were the most affected, showing the highest annual average increases in surface runoff (Figure 7a). In the southwest and central parts of the basin, the sub-regions showed little to no increase in the surface runoff average, since those regions had the natural vegetation still preserved or had just small areas deforested in this period. The region shown in Figure 8 was the one with the highest percent change around 19%, between 1973 and 1984. The increase associated to this region is mainly due to the replacement of the natural vegetation with pasture areas. The results of the 2005 comparisons with 1984 and 1973 are shown in Figures 7b and 7c. In these analyses the attention is drawn to the center region of the study area, where a high increase in the surface runoff is observed. This increase took place after 1984, and can be explained by the expansion of areas planted with seasonal crops in the outskirts of Querência city. The regions most affected between 1984 and 2005 are shown in detail in Figure 9. The increase in surface runoff in these areas ranged from 50 to 60% in 2005 when compared with 1984. Two sub-regions of the watershed presented a 100% increase in 2005, indicating small volumes of surface runoff in areas where previously all the precipitation water was infiltrated in the soil or lost by evapotranspiration. Over the watershed as a whole, the annual average of the surface runoff had a 5.4% increase from 1973 to 1984, and 23.3% from 1984 to 2005. Figure 10 presents an analysis of the surface runoff monthly averages for the entire watershed. The highest volumes of surface runoff occur in January and December. Despite the precipitation monthly average in March being very close to that in November, the averages in the surface runoff values are significantly different in these two months. This difference can be explained by the fact that March is preceded by a rainy season, consequently the soil moisture is kept high, and the water infiltration in the soil is reduced. November, however, is preceded by a dry season, thus the soil is initially drier and has a higher infiltration capacity. In November, the model indicates an increase of 100% between 1973 and 1984, which means that initially (1973) the monthly average of the surface runoff volume was zero, while in 1984 the model started to indicate a certain volume. Despite the low volumes, the occurrence of runoff in November can cause great impacts for the soil, since in this period of the year the soils are being prepared for the summer crops plantation. This fact results in a higher susceptibility to the carrying of sediments, and therefore, higher risk of soil erosion and silting of the rivers. The increases observed in February and March also demands careful attention, giving that this is the summer crops harvesting period. After the harvest, the soil stays without any vegetation protection, being this fact, associated with the frequent use of agricultural machines, a serious aggravating in the sediment yield and carrying of nutrients and pesticides to the rivers.

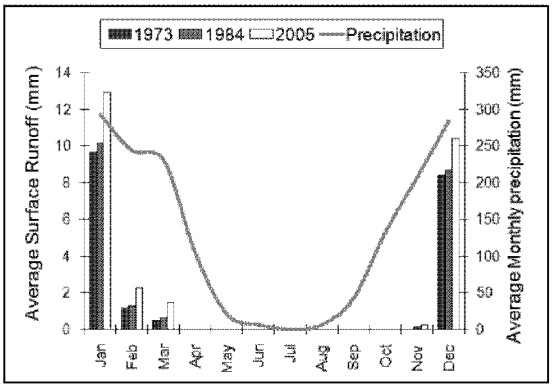

Figure 10: Surface runoff monthly average for the entire watershed

5. Conclusions

The expansion of agricultural activities in the Suiá-Miçu river basin resulted in the deforestation of approximately 40% of the original vegetation of the region by 2005. The introduction of pasture areas was the main cause for the beginning of the deforestation in the study area, however, seasonal crops started to play an important role in the LULC changes from 1984 onward. In the last analyzed period in this study, the areas planted with seasonal crops represented 12% of the watershed. The AGWA was effective in the analysis of the LULC changes impacts on the surface runoff regime through a comparative study, and in the description of the spatial distribution of the changes. In the period between 1973 and 1984 the model detected a 5.4% increase in the surface runoff values for the entire basin. From 1984 to 2005 this increase was

23.3%; introduction of crop areas was the main driver of this difference. Therefore, the results confirmed the great importance of the vegetation cover in the maintenance of the natural hydrological cycle patterns, and in the soil and natural resources conservation. The model also allowed the identification of areas where the impacts of the agricultural activities are happening with higher intensity and, consequently, where policies aiming sustainable practices must be taken.

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