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Discussions

Towards the response of water balance to sugarcane expansion in the Rio Grande Basin, Brazil

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Abstract

This study explores the short-, medium- and long-term impacts of expansion of the sugarcane plantation on the water balance of the Rio Grande Basin, Brazil, as estimated by changes in evapotranspiration, soil moisture content and surface runoff calculated by a hydrological model. Twenty years of simulation are made using three different land use scenarios that include the basin area planted with sugarcane in 1993, 2000 and 2007 as estimated from satellite images. Complementary, it is used a scenario for sugarcane plantation defined by the Brazilian Institute for Agricultural Research (EMPRAPA) as all areas suitable for sugarcane cultivation within the Rio Grande Basin. In addition, parameters for sugarcane fields were specifically defined via calibration and validation of the hydrological model for all growth phases based on the annual cycle of sugarcane phenology in the Rio Grande Basin.

According to results from the land use classification of satellite images, the expansion of sugarcane fields mostly replaced pasture lands. Modelling results for short-, medium- and long-term clarify that impacts of this expansion depended not only on the amount of areas planted with sugarcane, but also the type of land use replaced, location of the expansion within the basin and regional soil properties. Largest impacts on the water balance are observed if areas located close to headwaters with low soil water capacity are planted with sugarcane. In case all areas suitable for sugarcane plantation, as defined by EMBRAPA will actually be planted, simulations showed that the annual accumulated values of evapotranspiration increase up to 180 % while surface runoff is reduced to 20 % of the values calculated using a land use scenario from 1993.

1 Introduction

The search for sustainable sources of energy has found a realistic replacement to fossil fuels in ethanol and methanol. Nowadays, the production of ethanol from sugarcane is among the most effective and sustainable techniques for making ethanol from food crops, particularly when compared to the production of ethanol from other commercial crops (e.g. wheat, corn and barley). The reason for this is that sugarcane grows at a faster rate than other crops (Herrera, 1999), and can be cultivated with many different farming practices, which opens up possibilities for enhancing productivity but protecting the environment (AgSri, 2012; Maraddi, 2006; Mui et al., 1996).

In response to these properties and its high potential to become a renewable energy source, many countries have significantly increased their sugarcane production during the last two decades (e.g. China, India, Brazil). In this context, Brazil is the country that retains the largest area of sugarcane cultivation in the world. It is responsible for approximately one third of the global harvested area and production (Zuurbier and van de Vooren, 2008). Since 1975, when the Pro-Álcool (ethanol program) began as a response to the 1973 oil crisis (Borges and Almeida, 1985), the Brazilian area of sugarcane plantation increased by 170 %, reaching 5.4 million hectares in late 2005 (Nitsch, 1991; Bolling and Suarez, 2001; IEA, 2006).

One of the negative environmental consequences by increasing the amount of a particular land use type in a catchment may be its possible impact on regional hydrological processes (Gedney et al., 2006; Sampaio et al., 2007). Addressing this question, many studies have recently been developed to estimate the effects of land use changes on local water balance. Hlavcova et al. (2009), for example, showed the impacts of land use changes on maximum daily discharges in a catchment considering both rainfall and snowmelt as incoming water. In addition, Warburton et al. (2011) have applied a hydrological model over three catchments with different land covers. They showed that the runoff generation in the three catchments were closely related to their geographic distribution of land use. Finally, a hydrologic model was also used by Wijesekara et al.

(2012) as a tool to analyze the expansion of built-up areas according to land use predictions, and, by means of these analyses, they could estimate variations in surface runoff, evapotranspiration, baseflow and infiltration for an urban catchment.

Despite many insightful studies on land use changes affecting the surface hydrology, large speculations are still being made about such changes. In Brazil, for instance, impacts of the rapid expansion of sugarcane on surface runoff after the Pro-Álcool were not carefully investigated since sugarcane fields were not completely mapped (Cheesman, 2004; James, 2008). In order to fill up this gap, this work aims to map sugarcane fields and their expansion during the past 20 yr in a Brazilian river basin. Moreover, by using this mapping, it is also intended to estimate the response of water balance to such expansion.

Since most of the recent sugarcane expansion occurred in São Paulo state, River Grande Basin was chosen as a case study.

2 Study area

Rio Grande Basin is a sub-basin of the Paraná basin formed by the rivers Grande, Pardo, Sapucaí, Verde, das Mortes and Mogi-Guaçu. It has an area of 145 000 km^2 located in the eastern upper Paraná basin (Fig. 1) where altitudes vary from 300 to 2700 m a.s.l. The classification of land use in the Rio Grande Basin includes three distinct categories: Atlantic Rainforest, pasture and agriculture (IBGE, 1991). Agricultural activity represents a large portion of the Rio Grande Basin and, for this study, it was classified into sugarcane and agriculture of grain.

Regarding types of soils, Rio Grande Basin presents five major types: latosols, lithosols, cambisols, podzolics and alluvial soils which may be broken down into three groups: high, medium and low infiltration capacity (FAURGS, 2007). Soils with high and medium infiltration capacity are equally distributed across the Rio Grande Basin, whereas soils with low infiltration capacity are concentrated along the drainage network.

Although most of surface runoff in the River Grande Basin is regulated by dams, its hydrological regime is strongly induced by land use changes due to harvesting practices, shifting cultivation and deforestation (WWFBrasil, 2008). Discharges at the outlet of the Rio Grande Basin varies from minimum values of 500 $m^3 s^{-1}$ during the dry season (June–August) to maximum values over 12 000 $m^3 s^{-1}$ during the rainy season (December–February).

3 Methods

In this study, impacts of sugarcane expansion on river basin water balance were locally and globally estimated for the Rio Grande Basin using a distributed hydrological model. To reproduce the sugarcane expansion in the Rio Grande Basin during the latest 20 yr, three land use scenarios were defined based on satellite images and are compared to a scenario based on the mapping of areas suitable for cultivation of sugarcane made by the Brazilian Institute for Agricultural Research – EMBRAPA (BRASIL, 2009).

The extension of sugarcane fields over the basin were identified from satellite images captured in 1993, 2000 and 2007. Once calibrated, the model was used in four runs of 20 yr of simulation. Except for the land use map, the same input data was used for each of these runs. Finally, model estimates of evapotranspiration, soil moisture and surface runoff were evaluated at different time scales.

3.1 Distributed hydrological model

MGB-IPH is a large scale distributed hydrological model (Collischonn, 2001) conceptually based on the LARSIM (Bremicker, 1998) and VIC-2L (Liang et al., 1994) models. It consists of modules for calculating soil water budget, evapotranspiration estimation, surface and subsurface flow generation, which are interconnected by river routing. Full details of all hydrological processes and how these processes are incorporated into MGB-IPH can be found in Collischonn et al. (2007).

MGB-IPH provides the choice of smaller sub-basins (Paiva et al., 2011) or uniform grid cells (Paz et al., 2011) as computational units. For both methods, MGB-IPH divides each computational cell in hydrologic response units (HRUs) based on its land use/cover and soil distribution. HRUs are then defined by intersecting land use and soil groups within a computational cell.

Once all computational cells are classified into different groups with similar hydrological response, MGB-IPH calculates the soil water budget, evapotranspiration and flow propagation using adapted versions of the ones presented in LARSIN and VIC-2L models. These adaptations were made in order to facilitate its applications in large tropical basins.

MGB-IPH generates surface flow by direct precipitation on saturated areas and subsurface flow comes from the non-linear relationship between texture, hydraulic conductivity and moisture of soil proposed by Rawls et al. (1993). A linear reservoir concept is used to propagate surface and subsurface flow using different retention times along every computational cell. After passing through the linear reservoirs, surface and subsurface flows are summed and routed from cell to cell along the river network using the Muskingum–Cunge method.

MGB-IPH has been tested and used in several South American basins, from rapid-response ones of southern Brazil and Uruguay to very low response ones as the Pantanal. It has also been applied for several purposes, such as to predict runoff (Tucci et al., 2008), to estimate daily water balance in large basins (Collischonn et al., 2008) and to analyse the impacts of climate changes upon river flow (Paiva and Collischonn, 2010).

By default, MGB-IPH is employed using a daily time step. However, its time step may fluctuate depending on the purpose of study. In this work, MGB-IPH was used to simulate rainfall-runoff processes on a daily basis.

3.2 Data collection and processing

In general, hydrological models require plenty of data which quite often need to be preprocessed before they are used as input. MGB-IPH may be performed in simulation and calibration modes, each of these modes present different input data. For the simulation mode, MGB-IPH is dependent upon spatially distributed data that include land use, soil and elevation maps together with meteorological time series such as rainfall and evaporation. For the calibration mode, in contrast, discharge time series must be aggregated to the input dataset.

The necessary digital elevation model (DEM) was freely obtained at Department of Ecology of the Federal University of Rio Grande do Sul. Their DEM preprocessing includes data gap filling and mosaicking of elevation data from the Shuttle Radar Topography Mission (SRTM) for the whole Brazil (Hasenack et al., 2010).

The soil map of the Rio Grande Basin was derived from a soil survey data created by RADAM Brasil project (RADAMBRASIL, 1982) at scale of 1 : 1 000 000. Although at a larger scale than RADAM Brasil soil survey data (1 : 3 000 000), digitalized soil maps from the Food and Agriculture Organization of the United Nations (Food and of the United Nations, 1974) were resampled and used to overcome missing data. The RADAM Brasil database includes over 12 different types of soils in the Rio Grande Basin, (FAURGS, 2007) has then been reclassified into two groups as deep and shallow soils according to their hydrological behavior and provided to us (A. R. Paz, Federal University of Paraíba, Brazil, personal communication, 2012).

Rainfall depths were selected using the Agência Nacional de Águas (ANA) database (http://hidroweb.ana.gov.br/). Observed daily precipitation values were obtained from 483 precipitation stations over the River Grande Basin and its surroundings. Daily rainfall depths were then spatially interpolated by the inverse distance-squared weighted method at the centroid of each MGB computational cell. Further meteorological data sets were taken from three meteorological stations and they include monthly time series of air temperature, sunshine, relative humidity, wind speed and atmospheric pressure (Fig. 2). These data sets were provided by Centro de Previsão de Tempo e Estudos Climáticos (CPTEC).

MGB-IPH was calibrated for the Rio Grande Basin using calibration mode. For doing so, discharge stations were also used as input. Daily discharge data were collected from six gauging stations at six hydropower plants along the drainage network: Camargos, Funil, Furnas, P. Colômbia, Marimbondo and A. Vermelha (Fig. 2). All discharge data were found at Operador Nacional do Sistema Elétrico (ONS) webpage (http://www.ons.org.br/home/). Both discharge and meteorological time series cover a period ranging from 1970 to 2010.

3.3 Mapping of sugarcane plantations

Multi-temporal Landsat images were used for the characterization of sugarcane evolution in the Rio Grande Basin. Land use maps were derived through analysis of satellite images made by Landsat TM 7 and extracted from US Geological Survey. The selection of satellite images was driven by the availability of cloud-free Landsat data over the Rio Grande Basin from 1970 to 2010. Fourteen Landsat satellite images (170 × 183 km) were captured in 1993, 2000 and 2007, and used to generate three land use maps.

An automatic classification of Landsat satellite images showed in Rudorff et al. (2010) was used for mapping sugarcane fields. This automatic classification is based on a linear spectral mixing which consists of a linear combination of spectral signatures from two or more types of land use, such as agriculture, pasture, forest etc. The particular sugarcane spectral signature as presented by Aguiar et al. (2011) has been used to identify sugarcane fields in the Rio Grande Basin. Moreover, a visual inspection was made to support this automatic land use classification. Figure 3 shows the results the automatic identification of areas of sugarcane plantation in 1993, 2000 and 2007. In addition, it is shown the suitable areas for sugarcane plantation in the basin as defined by the Brazilian Institute for Agricultural Research (EMBRAPA).

Each land use map was classified into five dominant types as areas covered by water bodies, Atlantic Rainforest, agriculture of grain crops, pasture lands and sugarcane

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fields according to their spectral signatures. Except for sugarcane fields, all spectral signatures were adopted as defined by Mendes and Cirilo (2001).

3.4 MGB-IPH specific parameters for sugarcane: calibration and validation

MGB-IPH presents a set of parameters related either to types of soil or land use that are adapted for different river basins during the calibration process. To represent hydrologic processes over different types of soil, MGB-IPH uses soil parameters such as maximum water storage in the soil, mean percolation and mean groundwater flow. Based on this, MGB-IPH estimates the exchange of water between ground and surface so that infiltration, sub-superficial flow and groundwater contributions to the baseflow are estimated. On the other hand, land use parameters such as leaf area index, canopy resistance, albedo and average height of trees are used by MGB-IPH to calculate the water fluxes between atmosphere and land surface as evapotranspiration. The calibration of the MGB-IPH model is usually done by trial-and-errors adjustments of these parameters.

In order to reduce the number of parameters to be calibrated and to identify the key parameters controlling the model behavior when simulating surface runoff, sensitivity analyses were carried out by Collischonn (2001). Based on these analyses, seven parameters were identified as being important during calibration. They are called adjustable parameters and are the maximum water storage, mean percolation, hydraulic conductivity, mean groundwater flow, upward flux of water and a shape parameter that regulates surface runoff based on the soil storage capacity. Although leaf area index, albedo and average height of trees were not found as sensitive as the other seven adjustable parameters previously listed, they are carefully defined for each type of land use and their seasonal variability is also taken into consideration. As these parameters are not consider in the calibration, they are referred to as fixed parameters.

MGB-IPH has been successfully calibrated and validated for the Rio Grande Basin by Nóbrega et al. (2011). Their calibration includes sets of fixed and adjustable parameters for Atlantic Rainforest, areas covered by water bodies, pasture lands and agriculture of grain crops according to ranges recommended by Collischonn et al. (2007). Differently from previous application of the MGB-IPH, this work pays special attention to the effects of the plantation of sugarcane, as such, special parameters representing this culture were estimated taking into consideration the characteristics and timing of the sugarcane planting and harvesting in Brazil.

In Australia, Robertson et al. (1999) carried out field experiments to evaluate consequences of water deficit on sugarcane productivity. Their analysis included the estimation of leaf area index for sugarcane in four different growth phases: germination (0–30 days), tillering (30–120 days), grand growth (120–270 days) and maturation (270–360 days). In addition, André et al. (2010) studied the radiation balance over sugarcane plantations and defined values for albedo and height of trees for each sugarcane growth phase. They also concluded that albedo varies proportionally to leaf area index in sugarcane fields.

Table 1 shows fixed and adjustable parameters adopted in this study. Sugarcane planting and harvesting timing were defined using analysis made in BRASIL (2009) for sugarcane plantations located in the Southeast Region of Brazil. These analysis indicated that higher values of leaf area index, height of trees and albedo are predominant during the maturation stage from March to May whereas lower values are concentrated over the germination stage in June.

The adjustable parameters for sugarcane were estimated via calibration. The calibration was performed for a eleven-year period (1990–2000), and consisted in fine-tuning the adjustable parameters by comparing calculated and observed discharges using relative volume error (RVE), Nash–Sutcliffe coefficient (NS) and root-mean-square error (RMSE) as efficiency criteria. Moreover, the set of the adjustable parameters for sugarcane defined during the calibration were validated over the seven-year period 2001–2007.

For the calibration of sugarcane parameters, Rio Grande Basin was firstly divided into six smaller sub-basins where each sub-basin has a correspondent gauging station at its outlet. Also, as the land use map of 1993 was chosen as the control scenario, it is been used in the calibration.

The calibration was performed only for those sub-basins where sugarcane fields represented a significant portion of their drainage area. In this study, particularly, this portion was set to 15 % of the sub-basin since adjustments of parameters in sub-basins with areas covered by sugarcane fields lower than 15 % did not present significant changes in their hydrographs. For these sub-basins, parameters for sugarcane were set equal to parameters used to represent agriculture of grains and considering the annual cycle of sugarcane phenology instead. Thus, MGB-IPH parameters for sugarcane were calibrated for P Colômbia, Marimbondo and A Vermelha sub-basins. Their gauging stations were used to evaluate values of discharge estimated by MGB-IPH using different sets of adjustable parameters.

During the calibration, MGB-IPH ran simultaneously in both calibration and simulation mode. Since the adjustable parameters were individually calibrated for each sub-basin, MGB-IPH ran in calibration mode when calibrating downstream sub-basins and, at the same time, it ran in simulation mode at upstream sub-basins.

By fine-tuning, the adjustable parameters for sugarcane fields were calibrated and are shown in Table 1. In addition, values of discharge simulated by MGB-IPH using these parameters during the whole calibration period were compared to observed hydrographs at P Colômbia, Marimbondo and A Vermelha gauging stations (Fig. 4). As performance criteria for this calibration, Table 2 presents NS coefficients, RMSEs and RVEs computed for each sub-basin.

Results from the calibration revealed that MGB-IPH could correctly reproduce the hydrological regime of all sub-basins which presented areas covered by sugarcane fields over the 10 yr calibration period. Despite baseflow recessions were slightly overestimated by MGB-IPH, peak flows and rising and falling limbs of the simulated hydrographs closely matched the observed hydrographs which may be noticed by minor RMSEs and RVEs. Morevover, NS coefficient values up to 0.9 were obtained for all sub-basins which indicated a good agreement between observed and simulated discharges.

In order to test and validate the parameters previously calibrated, MGB-IPH was applied to the Rio Grande Basin using a different meteorological data set which spans from 1 January 2001 through 31 December 2007. Again, RVE, NS coefficient and RMSE were used to measure the quality of the fitting (Table 2). Figure 5 shows the simulated and observed hydrographs at P Colômbia, Marimbondo and A Vermelha gauging stations.

Overall, results of the validation showed that MGB-IPH could provide a good agreement with observed data using the adjustable parameters for sugarcane defined in the calibration. Although NS coefficient values, RMSEs and RVEs pointed to a small decrease in the quality of the fit compared to the calibration, they still remained in the ranges of 0.85 to 0.88 for NS coefficient, 300 to 510 $m^3 s^{-1}$ for RMSEs and 20 to 23 % for RVEs. MGB-IPH showed to be satisfactorily capable of reproducing peak flow patterns and seasonal recession for all sub-basins covered by sugarcane fields.

3.5 Land use scenarios and model runs

To represent the expansion of sugarcane plantation at the Rio Grande Basin, the three land use scenarios generated from Landsat satellite images in 1993, 2000 and 2007 were used. Also, an additional land use scenario was generated based on the mapping of all areas suitable for sugarcane crops as defined by EMPRAPA (BRASIL, 2009).

The four land use scenarios were used as input for four different model runs which were performed with daily time step covering the period of 1 January 1990 to 31 December 2010. All runs were preceded by a warming-up period of one year (January 1989–December 1989). The run which incorporated the land use map of 1993 was considered as the control run and together with the runs that included land use scenarios of 2000, 2007 and from the EMBRAPA mapping will be respectively called CR1993, R2000, R2007 and REMBRAPA hereafter. The difference between each scenario and the CR1993 represents the expansion of the area planted with sugarcane over the basin.

Surface runoff were calculated in CR1993, R2000, R2007 and REMBRAPA, and statistically compared to each other. Statistical comparisons of surface runoff were made by means of bootstrap analyses based on 1000 resamplings using a 99 % confidence interval as described in Lall and Sharma (1996). In addition, a better assessment of the impacts of sugarcane expansion was achieved by comparing surface runoff generated in sub-basins with different concentrations of sugarcane fields.

4 Results and discussion

In this section, an overview of the sugarcane expansion as estimated by Landsat satellite images captured in 1993, 2000 and 2007 is presented. Results from the land use classification of these satellite images are discussed for each sub-basin of the Rio Grande Basin. Moreover, short-, medium- and long-term impacts of sugarcane expansion on the water balance of the Rio Grande Basin were separately evaluated.

4.1 An overview of the sugarcane expansion in the Rio Grande Basin

In general, terrain slope and altitude were equally important factors for sugarcane expansion in the Rio Grande Basin as sub-basins with areas which presented terrain slopes lower than 12 % and altitudes varying between 300 and 700 m a.s.l. significantly increased the concentration of sugarcane fields in their drainage areas. Table 3 shows the percentage of areas covered by sugarcane fields for each sub-basin.

According to Table 3, Funil, Camargos and Furnas did not present sugarcane expansion in their drainage areas from 1993 to 2007. This is because, despite having areas with terrain slope less than 12 %, the altitude at Funil, Camargos and Furnas sub-basins are higher than 800 m a.s.l. These results agree with what has been suggested by EMBRAPA as areas potentially suitable for cultivation of sugarcane in Brazil

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as seen in Fig. 3. On the other hand, a large increase of sugarcane fields is pointed at P Colômbia, Marimbondo and A Vermelha sub-basins.

A chronological analysis pointed to different expansion rates among P Colômbia, Marimbondo and A Vermelha sub-basins. Between 1993 and 2000, areas covered by sugarcane increased by almost 90 % in P Colômbia whereas, for the same period, Marimbondo and A Vermelha had a sugarcane expansion of only 11.4 % and 30.8 %. In contrast, from 2000 to 2007, sugarcane expansion rates were higher in Marimbondo (35 %) and A Vermelha (140 %) than P Colômbia (22 %). In 2007, sugarcane fields represented approximately 26 % of the P Colômbia sub-basin area, 30 % of the A Vermelha sub-basin and more than 40 % of the Marimbondo sub-basin.

Overall, sugarcane fields replaced mostly pasture lands and areas of agriculture of grain. Comparisons made between land use distribution in 2007 and 1993 showed that the replacement of pasture lands by sugarcane fields achieved 6.8 %, 7.5 % and 8.9 % of the Marimbondo, P Colômbia and A Vermelha sub-basins, respectively. It is followed by the replacement of areas of agriculture of grain crops with 5.2 %, 4.7 % and 7.6 %, and then Atlantic Rainforest with 2.1 %, 1.6 % and 3.8 %, respectively.

4.2 Impacts of sugarcane expansion on daily surface runoff

Three runoff data sets were generated based on the percentage differences in daily surface runoff simulated using R2000, R2007 and REMBRAPA land use scenarios and the runoff simulated using CR1993 one. As each run was performed over a simulation period of 20 yr, each of these sets corresponded to 7300 daily runoff differences. The statistical significance of these percentage differences were tested by means of bootstrap, using 1000 random samples, for a significance level of 0.01 and are presented in Fig. 6b per sub-basin.

From 1993 to 2007, the expansion of sugarcane resulted on reduction of daily runoff from 0.25 % to 1.5 %. This reduction is directly proportional to the expansion area over each sub-basin. In this case, daily surface runoff at the outlet of the Marimbondo sub-basin were the most affected by sugarcane expansion with values reduced by up to

1.5 %. The sub-basins of Funil, Camargos and Furnas did not present any expansion of sugarcane plantation within their area consequently, no reduction was observed in their daily runoff.

When surface runoff generated using the REMBRAPA scenario is compared to the ones generated by CR1993, it becomes clear that the location where the expansion occur is a key factor. On the REMBRAPA scenario, expansion might occur also on the headwater sub-basins such as Camargos and Funil. At these sub-basins, the reduction in surface runoff is greater that 10 % if the total area suggested by EMPRAPA as suitable for sugarcane plantation is occupied by sugarcane (Fig. 6b). In the case of A Vermelha, the reduction is of about 9 % and at the outlet of the of Rio Grande Basin the reduction of daily surface runoff would be of about 8 % (Fig. 6b). All values presented are statistically significant at 0.01 level as tested by bootstrap considering 1000 random re-sampling with replacement.

4.3 Evaluation of seasonal patterns per sub-basin

For a better understanding of the influence of sugarcane expansion on the water balance of the Rio Grande Basin, daily values of evapotranspiration, soil moisture as well as surface runoff obtained from CR1993, R2000, R2007 and REMBRAPA were aggregated to monthly totals. In this section, percentage differences in monthly evapotranspiration, soil moisture and surface runoff between CR1993, R2000, R2007 and REMBRAPA were estimated and, together with observed monthly rainfall, they were used to identify shifts and modifications in the hydrological regime under sugarcane expansion. The results from these analyses are presented and discussed per sub-basin.

4.3.1 Funil sub-basin

Funil is a headwater sub-basin of the Rio Grande Basin where values of altitude are up to 900 m a.s.l. For this reason, only the land use scenario proposed by EMBRAPA presented areas for cultivation of sugarcane in this sub-basin. EMBRAPA suggested that 4.7 % of the Funil sub-basin are suitable for sugarcane fields from which 4.4 % were previously classified as pasture lands and 0.3 % as Atlantic Rainforest.

A period of four years was randomly selected from the entire simulation period to present seasonal patterns of surface runoff response to land use changes. Thus, Fig. 7 shows the percentage differences calculated between values of surface runoff simulated in REMBRAPA and CR1993 together with the monthly rainfall hyetograph from 1 January 1997 to 31 December 2000.

According to Fig. 7a, except during the rainy seasons, values of surface runoff simulated with REMBRAPA were predominantly lower than those calculated with CR1993. During the dry seasons, runoff differences pointed to a reduction of more than 70 %. As most of the sugarcane fields replace pasture lands which implies to an increase in the average leaf area index and height of trees of the sub-basin, it indicates that this reduction is explained by the increase of evapotranspiration rates.

On the other hand, during the rainy seasons, average values of interception and infiltration showed that sugarcane fields presented higher interception and infiltration rates than pasture lands. Due to this particular characteristic, values of surface runoff in REMBRAPA were 35 % larger than CR1993 after wet periods.

4.3.2 Camargos sub-basin

Similarly to Funil, Camargos is a small headwater sub-basin. Here, only 2 % of the sub-basin was categorized as suitable to be used for cultivation of sugarcane by EMBRAPA. All other three land use scenarios did not indicate any sugarcane expansion. For its land use scenario, EMBRAPA proposed that sugarcane fields replaced only pasture lands.

The percentage differences in monthly surface runoff between CR1993 and REMBRAPA fluctuated from −100 % to 65 % as shown in Fig. 7b. Comparing to Funil, impacts of sugarcane expansion on surface runoff were larger in the Carmagos sub-basin. Despite the area suitable for plantation in Camargos being smaller. The large impact in Camargos is due to the lower soil moisture content at this basin, that leads to higher evapotranspiration rates.

Figure 7b reveals two distinct patterns; one for the wet and another for the dry season. In the dry seasons, the replacement of pasture lands implied low surface runoff due to an increase of the mean evapotranspiration. During the wet seasons, when evapotranspiration rates decrease, values of surface runoff simulated in REMBRAPA were up to 50 % higher than in CR1993. This increase might be explained by the higher soil moisture content in the simulations with REMBRAPA if compared to the ones from CR1993, that increases the sub-superficial and baseflow contributions to the surface runoff.

4.3.3 Furnas sub-basin

Furnas is the first sub-basin downstream Funil and Camargos, and already at CR1993 presents 1.5 % of its drainage area covered by sugarcane fields. This portion remained constant in R2000 and R2007, but is expanded to 17 % in REMBRAPA. At REMBRAPA scenario, the expansion of sugarcane fields basically replaced pasture lands (14 %), followed by Atlantic Rainforest (2 %) and agriculture of grain crops (1 %).

Furnas sub-basin is characterized by high water soil capacity which implies high soil moisture all over its drainage area. Despite Furnas presenting the same portion of areas covered by sugarcane fields as Camargos and Funil, this regional soil property prevented evapotranspiration rates to increase in the same proportion as the one noticed in Camargos and Funil. On the local water balance, it represents a lower reduction of surface runoff than the one computed for Camargos and Funil. Converting to numbers, percentage differences indicated that the sugarcane expansion suggested by EMBRAPA reduces by 50 % the surface runoff calculated in CR1993 during the dry period whereas, in the rainy season, it increases by 30 % as presented in Fig. 8a.

Comparing to Camargos and Funil, Furnas sub-basin has a larger portion of sugarcane fields over its drainage area at CR1993. However, as seen in Fig. 8a it does not imply higher fluctuations in the percentage differences between monthly surface runoff from CR1993 and REMBRAPA than those calculated for Camargos and Funil. This may be explained the fact that in Furnas, values of surface runoff were not only driven by evapotranspiration but also by soil moisture content, sub-superficial flow and baseflow. Consequently, during dry seasons, surface runoff is regulated by sub-superficial flow and baseflow while high soil moisture prevented high values of evapotranspiration.

4.3.4 P. Colômbia sub-basin

P Colômbia sub-basin has a drainage area of 113 hectares and is located downstream Furnas sub-basin. For P Colômbia sub-basin, sugarcane expansion was observed in all land use scenarios and it is briefly described for each of them as follows.

In 1993, sugarcane fields represented 11 % of the area of the sub-basin and after seven years, this portion expanded to 20.8 %. From 1993 to 2000, sugarcane fields replaced areas with pasture lands (5 %), agriculture of grain crops (3.2 %) and Atlantic Rainforest (1.6 %). In 2007, the sugarcane expansion plantation area covered about 26 %. This expansion meant a reduction of 3.6 % of pasture lands and 1.5 % of agriculture of grain crops. In the land use scenario proposed by EMBRAPA, sugarcane fields covers one third of the sub-basin and expands over 16.4 % of pasture lands, 3.2 % of Atlantic Rainforest and 3.1 % of agriculture of grain crops.

Since differences between values of surface runoff from R2000 and R2007 were not significant (less than 0.2 % of the mean surface runoff), the influences of sugarcane expansion on surface runoff were only evaluated between CR1993, R2007 and REMBRAPA.

Comparisons of water balance variables calculated in CR1993 and R2007 revealed that the replacement of pasture lands with sugarcane fields increased monthly rates of interception and infiltration and, hence, soil moisture content. In terms of monthly rates of soil moisture, percentage differences varied from 0.2 % to 1.7 %. As soil moisture content and evapotranspiration are closely related, this increase in monthly rates of soil moisture represented a reduction of up to 3 % of monthly values of evapotranspiration in the sub-basin. On monthly values of surface runoff, however, percentage differences between CR1993 and R2007 did not exceed 0.8 %.

The comparison of percentage differences in monthly surface runoff for CR1993 and REMBRAPA showed that the sugarcane expansion induced a reduction of up to 40 % during the dry season. In addition, despite evapotranspiration rates calculated from REMBRAPA remained up to 100 % higher than those from CR1993, their impacts on surface runoff at the outlet of the sub-basin were lower than for Camargos and Funil have smaller areas of cultivation of sugarcane. Similarly to Furnas, P Colômbia presented higher values of soil moisture content which controls evapotranspiration rates in the sub-basin (Fig. 8b).

4.3.5 Marimbondo sub-basin

Unlike P Colômbia, Furnas, Camargos and Funil sub-basins, contributions to surface runoff in the Marimbondo sub-basin come exclusively from rivers in the southern part of the Rio Grande Basin. Here, sugarcane plantation was also found in all land use scenarios. In 1993, land use distribution in the Marimbondo sub-basin consisted of 40.8 % of pasture lands, 27.9 % of sugarcane fields, 17.2 % of agriculture of grain crops, 13.1 % of Atlantic Rainforest and 1 % of areas covered by water bodies. Sugarcane fields expanded over 1.1 % of pasture lands and, 1 % of each agriculture of grain crops and Atlantic Rainforest in 2000. And, in 2007, sugarcane fields covered 42 % of the Marimbondo sub-basin replacing mainly pasture lands.

Particularly for this sub-basin, the land use scenario suggested by EMBRAPA presented less areas for cultivation of sugarcane than 2000 and 2007. And, since differences between values of surface runoff from CR1993, R2000 and REMBRAPA were fairly small, comparisons between these runs are not presented. Instead, this section focused on the results obtained from CR1993 and R2007.

Already in 1993, sugarcane fields represented a considerable part of the Marimbondo sub-basin. Therefore, sugarcane expansion was not as important to the local water balance in this sub-basin as it was for the previously presented ones. After the sugarcane expansion occurred between 1993 and 2007, for instance, values of percentage difference in monthly evapotranspiration between CR1993 and REMBRAPA oscillated in a range of −10 % to 15 % which basically drove surface runoff response to sugarcane expansion in this sub-basin as shown in Fig. 8c.

Figure 8c shows that seasonal patterns of evapotranspiration in the Marimbondo sub-basins were closely associated with variations of percentage differences of surface runoff calculated from CR1993 and R2007. For Marimbondo sub-basin, however, the reduction of surface runoff due to sugarcane expansion were lower than 3 % of the surface runoff estimated under CR1993.

4.3.6 A Vermelha sub-basin

A Vermelha is the first sub-basin upstream the outlet of the Rio Grande Basin and downstream Marimbondo and P Colômbia sub-basins. For this reason, effects of sugarcane expansion on this sub-basin mostly due to land use changes on the upstream sub-basins rather than over its own drainage area. In the A Vermelha sub-basin, the portion of sugarcane fields started from 9.4 % in 1993, expanded to 12.3 % in 2000 and then to 30 % in 2007 whereas EMBRAPA suggested 58 % of areas may be covered by sugarcane fields. Unlike all other sub-basins, between 1993 and 2007, sugarcane fields equally replaced pasture lands and agriculture of grain crops (approx. 8 % each), and 5 % of Atlantic Rainforest.

As most of the sugarcane expansion happened from 2000 to 2007, comparisons were only made for CR1993, R2007 and REMBRAPA. Between CR1993 and R2007, percentage differences in monthly surface runoff indicates that effects of sugarcane expansion over A Vermelha were attenuated by the propagation of surface runoff from upstream sub-basins (Figs. 8c and 9). Another peculiarity was observed in the simulated values of evapotranspiration, since sugarcane fields expanded with similar proportion over different types of land use, percentage differences in monthly evapotranspiration between CR1993 and R2007 varied from −4 % to 3 % with no seasonal patterns (Fig. 9).

On the other hand, the sugarcane expansion suggested by EMBRAPA was approximately twice as much as the one from 1993 to 2007. In this case, percentage differences in monthly surface runoff fluctuated according to rates of monthly evapotranspiration (Fig. 10a) which results on reduction of surface runoff during dry seasons. In addition, Fig. 10b also shows that this expansion represented an increase of soil moisture content once sugarcane fields mostly replaced pasture lands in the land use scenario proposed by EMBRAPA.

4.4 Annual water balance

Long-term impacts of sugarcane expansion on the hydrological cycle were evaluated by estimating and comparing the annual water balance for each sub-basin of the Rio Grande Basin. Accumulated annual volumes of water evaporated, infiltrated and flowing through the sub-basins were calculated for each of the twenty years of simulation using R2000, R2007 and REMBRAPA and they were compared to the ones obtained in CR1993 (the control run) by percentage differences. For a better assessment of land use changes due to sugarcane expansion, these annual values were accumulated over the annual cycle of sugarcane which means from June to May. As percentage differences of the water balance variables between R2000 and CR1993 had the same range of values as those calculated between R2007 and CR1993, only values of percentage differences between R2007 and CR1993, and REMBRAPA and CR1993 are presented in Fig. 11.

A general pattern which emerges from Fig. 11 is that soil moisture content was inversely proportional to evapotranspiration for all sub-basins. Therefore, those sub-basins with high soil water storage capacity had lower evapotranspiration losses due to sugarcane expansion. In addition, Fig. 11 shows that implications of sugarcane expansion in the annual water balance presented different trends according to the hydrological behaviour of each sub-basin. These trends were separately analysed for R2007-CR1993 and REMBRAPA-CR1993.

Percentage differences computed between R2007 and CR1993 indicated that land use changes due to sugarcane expansion from 1993 to 2007 represented less than 2 % of the annual soil water content, evapotranspiration and surface runoff calculated from CR1993. Although Marimbondo and P Colômbia had presented similar sugarcane expansion over their drainage area, surface runoff decreased in Marimbondo while increased in P Colômbia. This difference may be explained by P Colômbia sub-basin being predominantly composed of soils with high water storage capacity so that surface runoff at its outlet counts on contributions from sub-superficial and base flows differently from Marimbondo sub-basin where soils with low water storage capacity results on higher evapotranspiration rates.

For the comparison EMBRAPA-CR1993, percentage differences showed that even a small sugarcane expansion over the headwater sub-basins results in great changes in their annual hydrological cycle. Driven by high evapotranspiration rates, soil water content and surface runoff achieved respectively reductions of more than 50 % and 20 % of the annual values calculated in CR1993 for Funil and Camargos, respectively. Even though sugarcane expansion represented a small portion of these headwater sub-basins (less than 4 %), low soil water storage capacity, sub-superficial and base flows in these sub-basins contributed to amplify the effects of sugarcane expansion in their annual water balance. For instance, in terms of annual values of evapotranspiration, percentage differences between CR1993 and REMBRAPA revealed an increase of up to 180 % in the Camargos sub-basin. These effects were attenuated along the drainage network by the downstream sub-basins and, at the outlet of the Rio Grande Basin, annual surface runoff was reduced by 10 to 12 % whereas the annual average evapotranspiration has been increased to 60 %.

5 Conclusions

In this study, daily, seasonal and annual impacts of the sugarcane expansion on the water balance of the Rio Grande Basin were estimated using values of evapotranspiration, soil moisture content and surface runoff calculated over twenty years of simulation using four different land use scenarios based on satellite images, and based on the mapping of areas suitable for cultivation of sugarcane made by EMBRAPA.

For the analysis of short-term impacts, sets of daily values were generated and trends were highlighted by means of bootstrap analyses. The medium-term impacts were evaluated using monthly accumulated values in order to capture seasonal patterns of the annual cycle of sugarcane phenology in the water balance. Finally, the long-term impacts were estimated from comparisons of annual accumulated values between the germination and maturation stages of sugarcane (from June to May) for each of the twenty years of simulation. The short-, medium- and long-term impacts were locally and globally evaluated in the Rio Grande Basin.

Overall, the influence of sugarcane expansion on the water balance in the Rio Grande Basin depended upon a combination of factors, such as amount of areas replaced with sugarcane, type of land use replaced, location of the expansion within the basin and regional soil properties. This study showed that the sugarcane expansion mostly impacts the water balance if it happens over the headwater areas with low soil water retention. For these areas, sugarcane expansion significantly increased evapotranspiration rates and reduced soil moisture content and surface runoff.

For the land use scenario proposed by EMBRAPA where all areas suitable for growing sugarcane were covered by sugarcane fields, short-term impacts on the water balance represented daily reductions of surface runoff of up to 8 % for all sub-basins of the Rio Grande Basin. Seasonally, the combination of dry seasons and maturation stage of sugarcane fields implied in a water deficit period between April and May when incoming water from precipitation over the basin is lower than outflow of water by evapotranspiration and surface runoff in the basin. During this period, outflow of water by surface runoff is mainly generated by contributions from sub-superficial flow and baseflow.

Finally, annual analysis made between results from CR1993 and REMBRAPA revealed that annual surface runoff were reduced by up to 20 % whereas annual values of evapotranspiration reached to an increase of 180 % of the values calculated in the control run after each year of simulation in the headwater sub-basins. Despite annual values of surface runoff were only reduced by 12 % at the outlet of the basin, locally, sugarcane expansion represented high impacts on the annual water balance of the Rio Grande Basin.

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Table 1. Fixed and adjustable parameters adopted in this study. The set of fixed and adjustable parameters for agriculture of grain crops, pasture lands and Atlantic Rainforest were assumed as defined via calibration and validation by Nóbrega et al. (2011) in the Rio Grande Basin. On the other hand, for sugarcane fields, fixed parameters were adopted according to ranges obtained in the literature whereas adjustable parameters were calibrated and validated in this study.

		Fixed Parameters											
Type of Land Use	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Agriculture of grain crops	Albedo	0.13	0.13	0.13	0.13	0.16	0.16	0.17	0.17	0.16	0.15	0.14	0.13
	Leaf Area Index ($m^2\,m^{-2}$)	4.00	4.00	4.00	5.00	1.00	1.00	2.00	2.00	2.00	2.00	3.00	3.00
	Height of trees (m)	1.00	1.00	1.00	1.00	0.50	0.80	0.80	0.80	0.80	0.90	0.90	0.90
Pasture lands	Albedo	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20
	Leaf Area Index ($m^2\,m^{-2}$)	2.00	2.00	2.00	3.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Height of trees (m)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Atlantic Rainforest	Albedo	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
	Leaf Area Index ($m^2\,m^{-2}$)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
	Height of trees (m)	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
Sugarcane fields	Albedo	0.28	0.28	0.29	0.31	0.31	0.24	0.25	0.25	0.25	0.27	0.27	0.27
	Leaf area index ($m^2\,m^{-2}$)	7.00	7.00	8.00	9.00	9.00	3.00	5.00	5.00	5.00	6.00	6.00	6.00
	Height of trees (m)	3.60	3.60	3.80	3.80	3.80	0.50	1.20	1.20	1.20	2.80	2.80	2.80

	Adjustable Parameters		
Type of Land Use	Parameter	Unit	Value
Agriculture of grain crops	Maximum water storage	mm	625.0
	Mean percolation	mm d^{-1}	3.5
	Residual water storage	mm	62.5
Pasture lands	Maximum water storage	mm	446.0
	Mean percolation	mm d^{-1}	2.1
	Residual water storage	mm	44.6
Atlantic Rainforest	Maximum water storage	mm	711.0
	Mean percolation	mm d^{-1}	6.2
	Residual water storage	mm	71.1
Sugarcane fields	Maximum water storage	mm	654.0
	Mean percolation	mm d^{-1}	3.9
	Residual water storage	mm	65.4
Same for all types of land use	Mean groundwater flow	mm d^{-1}	146.0
	Upward flux of water	mm d^{-1}	0.0
	Shape parameter	–	0.10
	Hydraulic conductivity	mm d^{-1}	2268.0

Table 2. Summary of results of the calibration and validation of parameters for sugarcane in the Rio Grande Basin.

Calibration			
Gauging station	NS	RMSE ($m^3 s^{-1}$)	RVE(%)
P Colômbia	0.92	270.97	6.79
Marimbondo	0.92	370.40	–8.62
A Vermelha	0.96	130.50	3.12
Validation			
Gauging station	NS	RMSE ($m^3 s^{-1}$)	RVE(%)
P Colômbia	0.88	301.14	12.30
Marimbondo	0.87	436.10	12.31
A Vermelha	0.85	508.92	13.27

Table 3. The portion of areas covered by sugarcane fields per sub-basin in 1993, 2000 and 2007.

		(%)	
Sub-basin	1993	2000	2007
Funil	0.0	0.0	0.0
Camargos	0.0	0.0	0.0
Furnas	1.5	1.5	1.5
P Colômbia	11.0	20.8	25.9
Marimbondo	27.9	31.1	42.0
A Vermelha	9.4	12.3	30.1

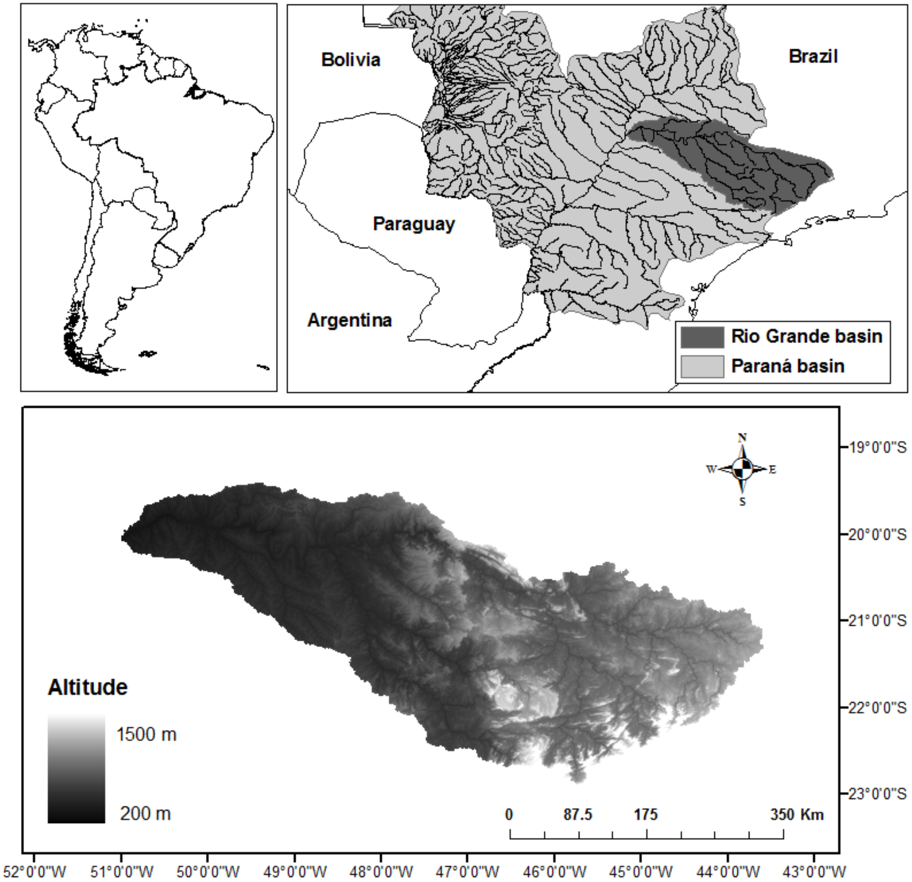

Fig. 1. Location and elevation map of the Rio Grande Basin.

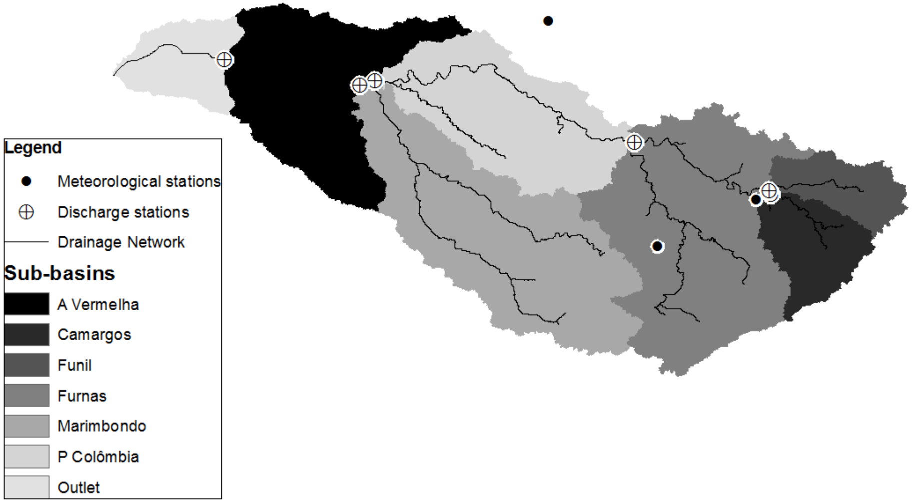

Fig. 2. Meteorological data network, discharge gauging stations and all the sub-basins of the Rio Grande Basin.

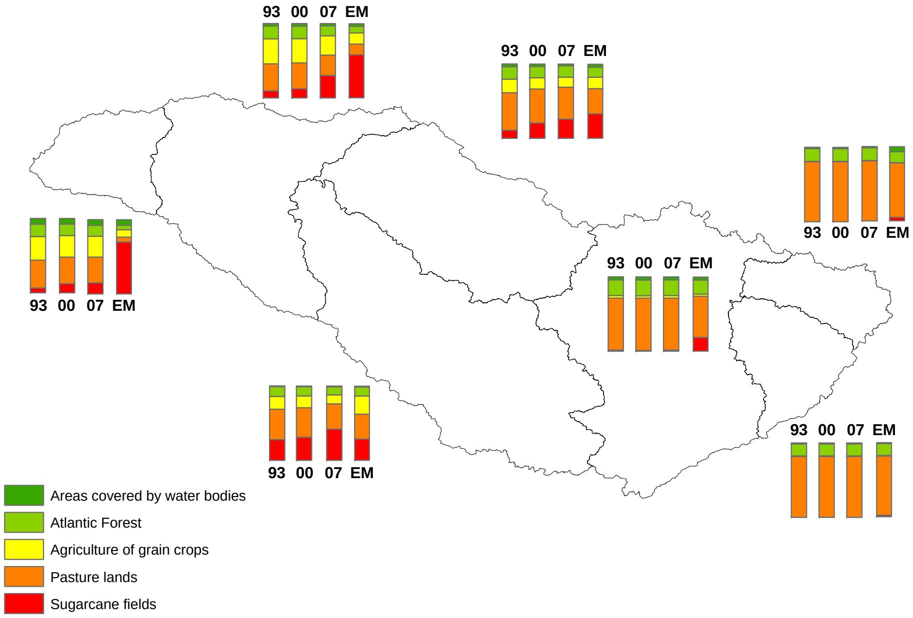

Fig. 3. Land use distribution of each sub-basin of the Rio Grande Basin for all four land use scenarios used in this study: 1993, 2000, 2007 and EMBRAPA.

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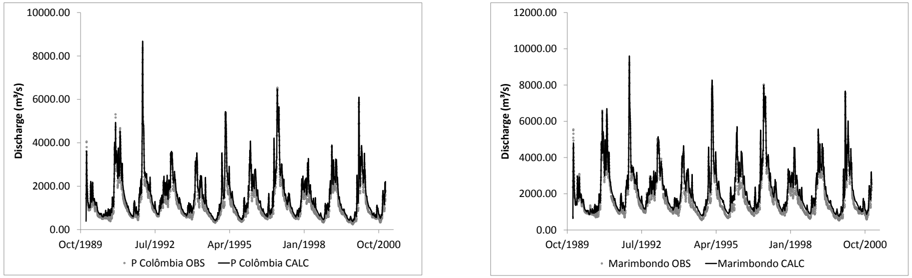
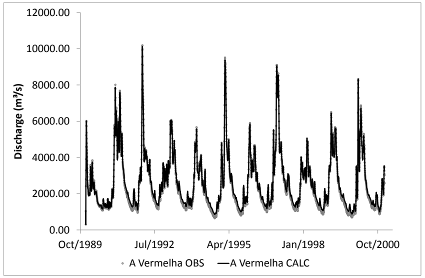


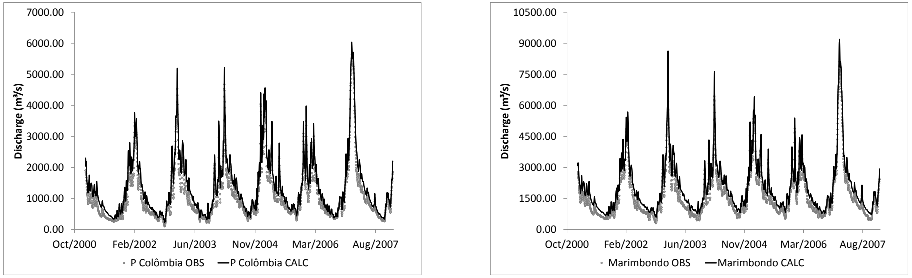
(a) P Colômbia

(b) Marimbondo



(c) A Vermelha

Fig. 4. Calibration of the MGB-IPH parameters for sugarcane. Calculated and observed hydrographs at the outlets of the P Colômbia, Marimbondo and A Vermelha sub-basins.



(a) P Colômbia

(b) Marimbondo

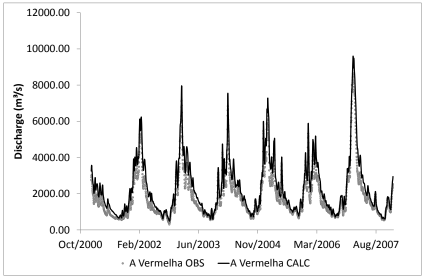
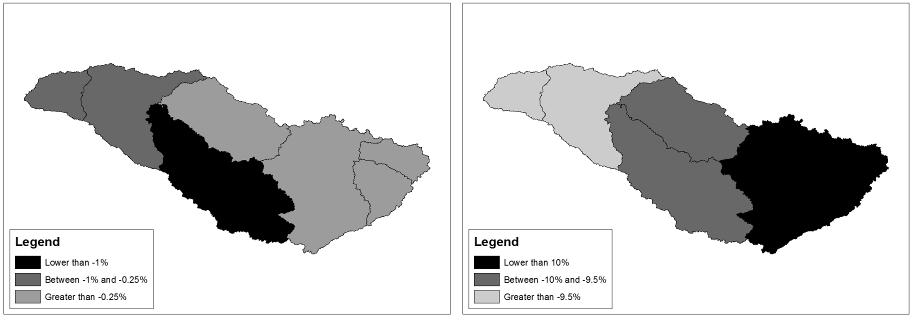


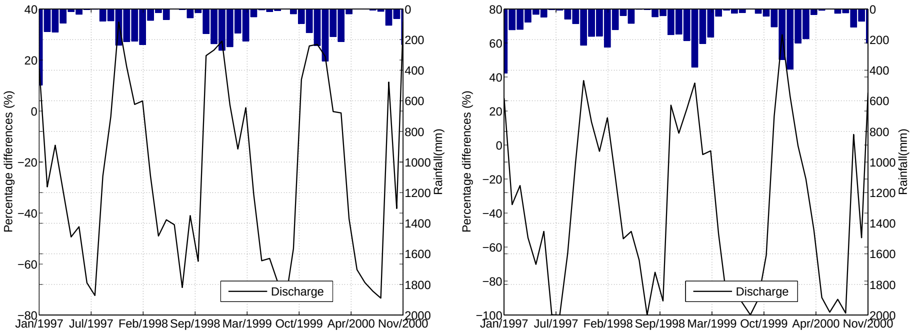
Fig. 5. Validation of the MGB-IPH parameters for sugarcane. Calculated and observed hydrographs at the outlets of the P Colômbia, Marimbondo and A Vermelha sub-basins.



(a) 1993 - 2007

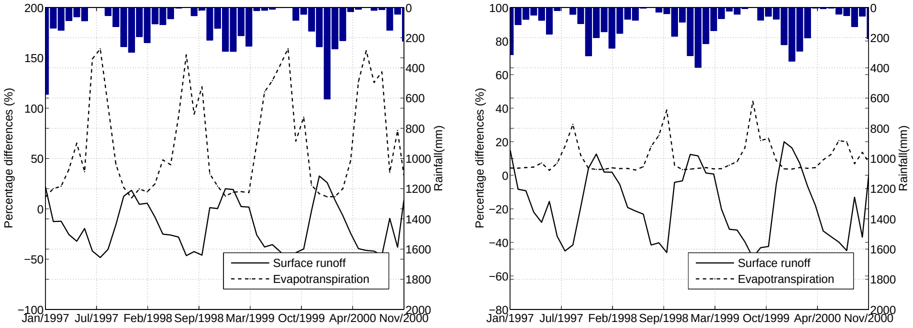
(b) 1993 - EMBRAPA

Fig. 6. Results from bootstrap analysis of the percentage differences of daily surface runoff between CR1993 and R2007 **(a)** and CR1993 and EMBRAPA **(b)**.

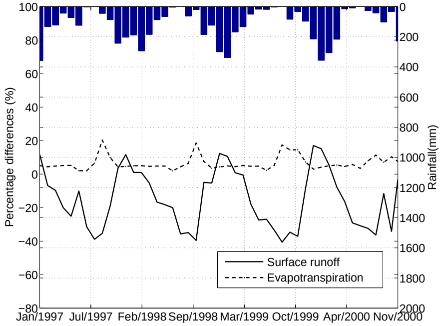


(a) Funil **(b)** Camargos

Fig. 7. Percentage differences of daily surface runoff between CR1993 and REMBRAPA together with accumulated monthly rainfall in the Funil **(a)** and Camargos **(b)** sub-basins.



(a) Furnas **(b)** P Colômbia



(c) Marimbondo

Fig. 8. Seasonal variations of percentage differences of accumulated monthly values of surface runoff and evapotranspiration computed between CR1993 and REMBRAPA in the Furnas **(a)**, P Colômbia **(b)** and Marimbondo **(c)** sub-basins.

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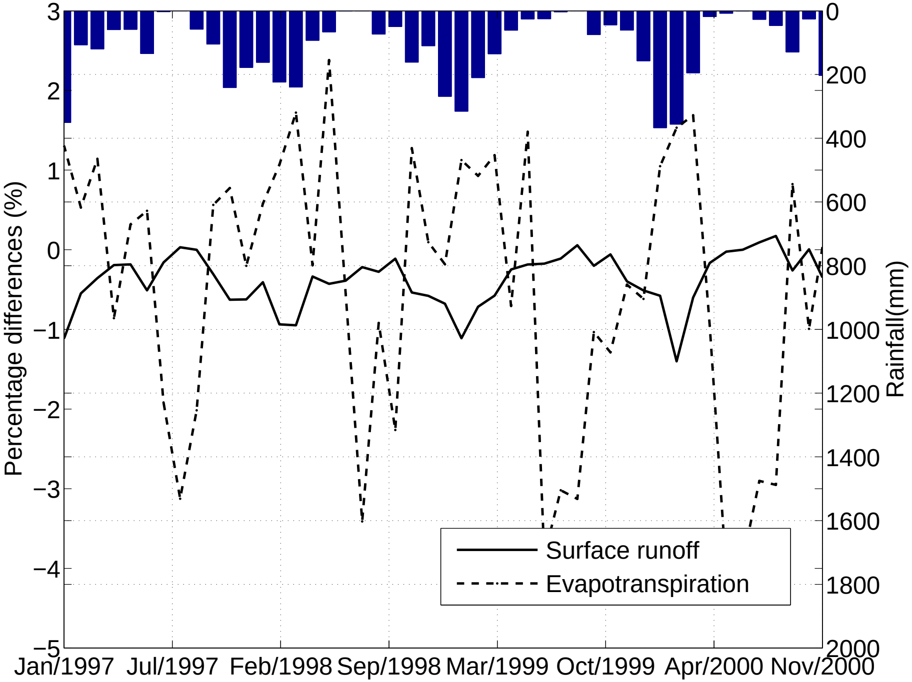
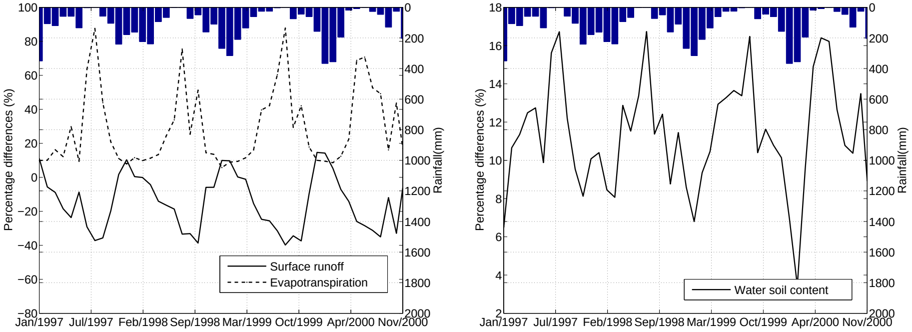


Fig. 9. Seasonal variations of percentage differences of accumulated mothly values of surface runoff and evapotranspiration computed between CR1993 and R2007 in the A Vermelha sub-basin.



(a)

(b)

Fig. 10. Comparisons of the percentage differences calculated between accumulated monthly values of evapotranspiration and surface runoff **(a)**, and water soil content **(b)** in the A Vermelha sub-basin.

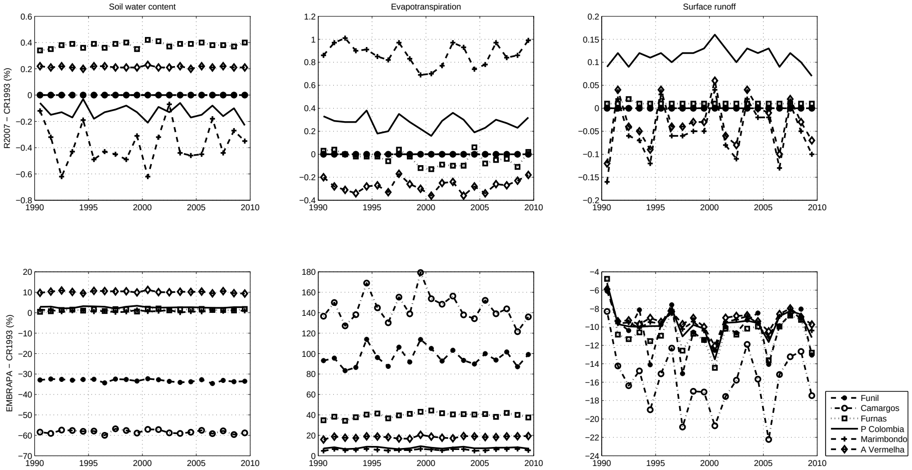


Fig. 11. Percentage differences of accumulated annual values of soil water content, evapotranspiration and surface runoff for all sub-basins during the entire simulation period between CR1993 and R2007, and CR1993 and REMBRAPA. Accumulated annual values were accumulated along the annual cycle of sugarcane phenology.