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EFFECTS OF SUGARCANE EXPANSION ON RUNOFF AND EVAPOTRANSPIRATION IN THE RIO GRANDE BASIN, BRAZIL

Effekter av sockerrörsplantagers utbredning på avrinning och avdunstning i Rio Grandes avrinningsområde i Brasilien

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Abstract

The demand for biofuel has increased in recent years as more countries desire to reduce their dependence on fossil fuels. Therefore, the amount of sugarcane plantations has rapidly increased in Brazil, one of the largest producers of ethanol from sugarcane in the world. This increase raises concerns of what effects this replacement of native vegetation and traditional crops to sugarcane plantations may have on local hydrology and climate. In order to fill up this gap, this study aims to evaluate the effects of sugarcane expansion on surface runoff and evapotranspiration in the Rio Grande basin, Brazil. For the numerical experiments carried out in this study, scenarios of sugarcane were generated based on topographic features and mapping of suitable areas for sugarcane plantation made by the Brazilian Institute for Agricultural Research (EMBRAPA). These land use scenarios were provided as input to a distributed hydrological model, which estimated surface runoff and evapotranspiration rates for the river basin. Results from simulations showed that sugarcane expansion implied to a reduction of up to 10.8 % of surface runoff and an increase of evapotranspiration rate by 9.0 %.

Key words – Sugarcane expansion, Rio Grande basin, MGB-IPH, Land use changes, Surface runoff, Evapotranspiration

Sammanfattning

Efterfrågan på biobränsle har de senaste åren ökat i takt med att allt fler länder strävar efter att minska sitt beroende av fossila bränslen. Som en följd har antalet sockerrörsodlingar kraftigt ökat i Brasilien vilket har medfört en oro inför vilka effekter denna omvandling av ursprunglig mark till sockerrörsplantager kan ha på hydrologin och klimatet i en regional skala. För att fylla denna kunskapslucka syftar den här studien till att utreda utbredningen av sockerrörs påverkan på ytavrinning och avdunstning i Rio Grandes avrinningsområde, Brasilien. För de numeriska experimenten i studien genererades ett flertal sockerrörsscenarion baserade på topografiska egenskaper och, enligt det agrara forskningsinstitutet EMBRAPA, lämpliga områden för framtida sockerrörsodlingar. Dessa scenarior användes sedan som indata till en distribuerad hydrologisk modell som uppskattade ytavrinning och avdunstning för avrinningsområdet. Resultaten från simuleringarna indikerade att expansionen av sockerrörsodlingar kan ge upphov till en minskad avrinning med upp till 10.8 % och en ökning av avdunstningen med upp till 9 %.

Introduction

The global warming and climate change debate in recent years can hardly have escaped anyone's notice. Therefore, motivated by our common obligation to protect the environment and fear for what consequences a higher oil price could have on economic growth, more and more countries have adopted policies to reduce their dependence on fossil fuels (Persson, 2006).

In Sweden and several other countries, the introduction of bioethanol has become a popular method to reduce the transport sector contribution to global warming. However, even though Sweden has a fairly good possibility to produce ethanol from paper pulp and cereals, this production is still not efficient enough to cover the total demand. Accordingly, about 70 % of the ethanol used as fuel in Swedish cars is imported, a majority of the amount originating from Brazil (Energimyndigheten, 2011). The number of sugarcane plantations in Brazil has rapidly increased since the government launched a national bioethanol program, Pro-Álcool, as a solution for the oil crisis in 1973 (Goldemberg, 2006). From 1973 to 2005, the sugarcane plantations in the country reached 5.4 million hectares and they are predicted to further increase up to 12.2 million hectares by the end of 2015 (Bolling and Suarez, 2001, IEA, 2006).

The quick replacement of native vegetation by sugarcane plantations raises concerns of what effects of this rapid sugarcane expansion can have on the local and regional hydrological processes (Gedney et al., 2006). Changes in vegetation and land cover can, for example, affect infiltration, runoff, evapotranspiration, interception and other hydrological variables (Sampaio et al., 2007). The hydrological changes could have major consequences for the stakeholders in the river basin, such as hydropower suppliers and farmers. Since 76.9 % of the electricity generated in Brazil comes from hydropower (EPE, 2010) the country is vulnerable to changes in the hydrology. The Brazilian energy crisis in 2001, caused by a dry summer period in combination with low water storage in the hydropower dams, demonstrated how sensitive the system really is (Krishnaswamy and Stuggins, 2007). The precipitation deficit causing the drought was just barely larger than for earlier droughts but still it led to a considerable larger runoff deficit (Simões and Barros, 2007).

Thus, the present study investigates the effects of sugarcane expansion on hydrology and local climate in the Rio Grande basin using a distributed hydrological model. The sugarcane expansion was expressed in terms of land use scenarios where the native vegetation and traditional crops were replaced by sugarcane. Two more realistic land use scenarios were also analyzed, of which one was provided by the Brazilian Institute for Agricultural Research (EMBRAPA) and the other was based on sugarcanes limitations to grow at certain areas in the river basin.

Study area

The Rio Grande basin (Fig. 1) is located in the southeastern part of Brazil and covers approximately 145 000 km^2 (Nóbrega et al., 2011). The landscape in Rio Grande basin can be described as hilly with elevations ranging from 200 m above sea level (m.a.s.l) at the basins outlet in the west to more than 1800 m.a.s.l at the Mantiqueira Mountains in the east. The climate has two distinct seasons with hot rainy summers and cold dry winters. Of the 1400 mm average annual precipitation,

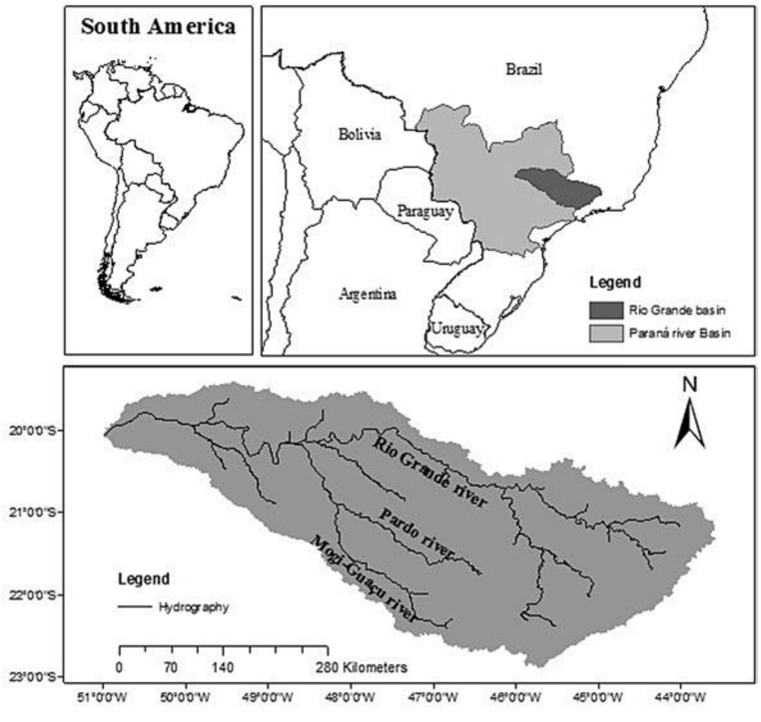

Figure 1. *Maps showing the location of the Rio Grande basin.*

85 % falls under the austral summer and the average annual evapotranspiration is around 950 mm.

The river basin has become very important for Brazil as a source of electricity from hydropower. Approximately 12 % of the total hydropower produced in Brazil is generated along Rio Grande River together with its subsidiaries Mogi-Guaçu and Pardo (ANEEL, 2005). In the basin there are 15 hydropower plants (HPPs), four of them have a capacity to generate more than 1000 MW (Nóbrega et al, 2011). The Rio Grande River and its subsidiaries are, apart from generating hydropower, extensively used for irrigation of agricultural land and as a source of drinking water for the urbanized areas in the river basin.

Methodology

The MGB-IPH model

In the present study, the MGB-IPH hydrological model was used to study the effects of different land use scenarios on the hydrology in the Rio Grande River basin. The model was used in seven runs of 20 years of simulation (1990–2009) with a daily time step.

The MGB-IPH model is a distributed hydrological model developed for large scale basins which is based on VIC-2L (Liang et al., 1994) and LARSIM (Bremicker, 1998). It is equipped with modules for calculating soil water budget, evapotranspiration, flow propagation within a cell, and flow routing through the drainage network (Collischonn et al., 2007).

To represent the spatial distribution of sugarcane plantations the model divides the river basin into 10 sub basins. The sub basins are in turn divided into catchment cells interconnected by channels. Each catchment cell is divided into Grouped Response Units (GRUs), areas with similar combinations of vegetation and soil. The runoff generated from the different GRUs in each cell is summed and the flow is routed to the stream network using three linear reservoirs; surface flow, subsurface flow and groundwater flow (Nóbrega et al., 2011). The Muskingum-Cunge method is used for stream flow propagation through the river network (Allasia et al., 2006). For evapotranspiration calculations the Penman-Monteith equation based on air temperature, relative humidity, solar radiation, atmospheric pressure and wind velocity was used (Nóbrega et al., 2011). For a full description of the model, see Collischonn et al. (2007).

The model has earlier been successfully applied to the Rio Grande basin. Nóbrega et al. (2011) analyzed how future runoff in Rio Grande basin could be affected by possible climate changes. Their simulations indicated that runoff could increase with between 8 % and 51 % for a 1 to 6 degrees higher global mean temperature.

Parameters

To describe hydrological processes over different types of soil, each sub basin has a number of adjustable parameters related to the soil water capacity and drainage rate for the different soil-vegetation combinations in the area, such as maximum water storage in soil, mean percolation and mean groundwater flow. Based on this, the model estimates the exchange between ground and surface so that infiltration, subsuperficial flow and groundwater contributions to the base flow are calculated. The adjustable parameters were calibrated in earlier work (Pereira et al., 2013a) by trial and error method using recorded hydrographs and relative stream flow volume error. The adjustable parameters for forest, agriculture of grain, water and pasture were set according to ranges recommended by Collischonn et al. (2007) and the parameters for sugarcane were estimated via calibration by Pereira et al. (2013a).

The model also uses "fixed" parameters that were not considered in the calibration process. They describe changes in vegetation over the year, such as leaf area index and plant height, to calculate the water fluxes between the atmosphere and land surface as evapotranspiration. These parameters are the same for all sub basins, and they are leaf area index, albedo, canopy resistance and height of trees. Values for these parameters were adopted according to ranges suggested by Collischonn (2007) and Nóbrega et al. (2011).

Input data

Precipitation and discharge data has been used as input for calibrating and validating MGB-IPH parameters for sugarcane (Pereira et al., 2013a). In order to consider spatial heterogeneity for precipitation, 483 gauging stations with daily measurements spread across the river basin and its surroundings were collected from the Agência Nacional de Águas (ANA). Daily discharge data for the HPPs was provided by the Operador Nacional do Sistema Elétrico. The HPPs chosen for this study were Camargos, Funil, Furnas, Porto Colombia, Marimbondo and Agua Vermelha (Fig 2).

To calculate the evapotranspiration, additional data regarding air temperature, sunshine hours, wind speed, relative humidity and atmospheric pressure is needed. Three meteorological stations were considered in the study and the data was provided by the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC). Two stations were located within the river basin and one, Araxá, north of the basin. Monthly averages were calculated for all meteorological variables of the three stations in earlier works by Pereira et al. (2013) and were given as input in the hydrological model.

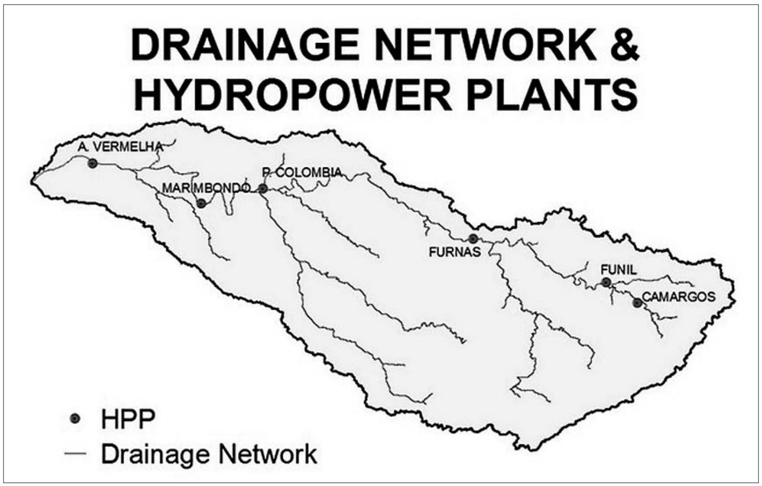

Figure 2. *Map of hydropower plants in the Rio Grande basin.*

Elevation data for the Rio Grande basin was collected by the Shuttle Radar Topography Mission (SRTM) and was available from the Department of Ecology, University of Rio Grande do Sul. The US Geographical survey provides free access to satellite maps around the world. These maps have been used to classify land use as pasture, sugarcane, forest, agriculture of grain and water in previous works by Pereira et al. (2013a; b). In order to classify the soil in the basin, Pereira et al. (2013a; b) used a soil type mosaic based on soil survey data created by the RADAM Brasil project (RADAMBRASIL, 1984) and FAO database (1972).

Scenarios of sugarcane expansion

For the simulations, six sugarcane scenarios were generated based on satellite images and topographic features of the Rio Grande basin, four of the scenarios considered "gradual expansion" and two "realistic future expansion". Each scenario contained information of vegetation type, soil type and elevation. A land use scenario (Fig 3) representing true vegetation and soil condition in 1993, was used as a reference (control scenario) when calculating the changes in discharge and evapotranspiration for the different scenarios. The year 1993 was chosen as reference because it is the earliest land use scenario we could establish for the area.

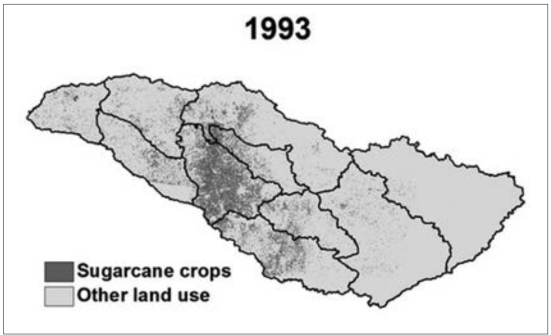

Figure 3. *Map of sugarcane distribution for the control scenario.*

The gradual expansion scenarios were generated to investigate how sensitive the hydrology of Rio Grande basin is for conversion of traditional land use to sugarcane. These scenarios were later used to analyze in which pace the discharge and evapotranspiration changes. For the four expansion scenarios, sugarcane gradually expanded to higher elevations in the river basin. The four different expansion scenarios were; 340–500 m.a.s.l, 340–700 m.a.s.l, 340–900 m.a.s.l and 340–1100 m.a.s.l.

To estimate possible future changes in runoff and evapotranspiration in the Rio Grande basin related to the ongoing sugarcane expansion, two realistic scenarios were generated. The first realistic scenario was based on data describing suitable areas for future sugarcane plantations in the river basin according to EMBRAPA. EMBRAPA is the Brazilian Institute for Agricultural Research with focus on developing and solve problems within agriculture (EMBRAPA, 2008).

An alternative future scenario was generated based on sugarcane limitations to grow at certain areas in the river basin. For this scenario, sugarcane plantations expanded up to 700 m.a.s.l where the slope is lower than 12 %. This limitation was chosen due to the cooler temperature and rocky landscape implied by higher altitudes, and because steeper slopes prevent mechanized sugarcane harvesting (Sparovek et al., 1997). The gradual expansion scenarios and the realistic scenarios are shown in Figure 4.

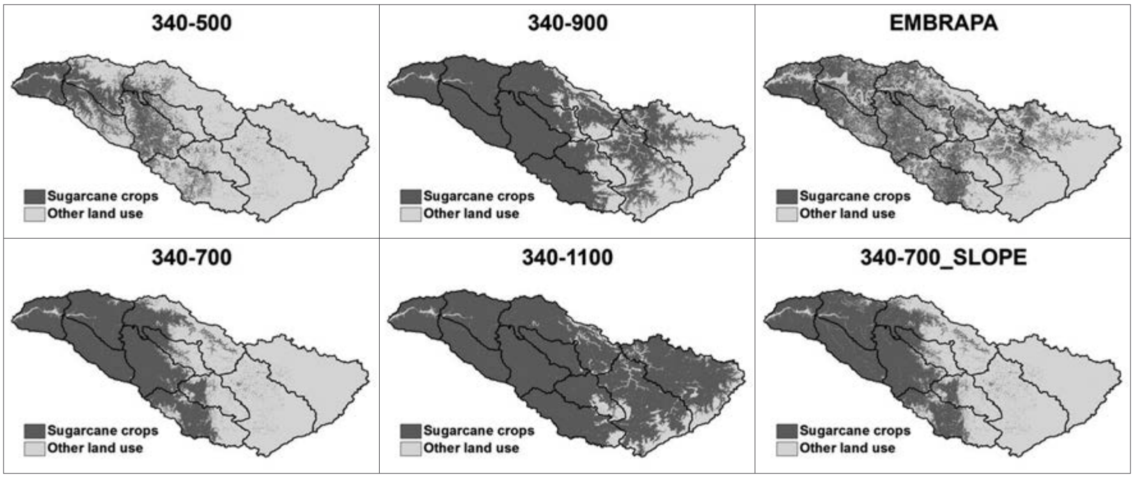

Figure 4. *Maps of sugarcane distribution for gradual expansion scenarios 340–500, 340–700, 340–900 and 340–1100 and realistic expansion scenarios Embrapa and 340–700_slope.*

Output files and data adaptation

Except for the land use maps that changed for the different scenarios, the same input data and parameters were used for all runs. For every scenario, the model run generated two output files which contained information on daily discharge and evapotranspiration rate for the catchment cells contributing to the hydropower plants; Camargos, Funil, Furnas, P. Colombia, Marimbondo and A. Vermelha. The relative changes between estimated discharge and evapotranspiration for each scenario and the control scenario (1993) were then analyzed and presented. These changes were calculated and the result was plotted in graphs over a 5-year period (2000–2004). Finally, relative changes in total discharge volume for the entire simulation period were calculated and presented in tables.

The other output file contained data on daily evapotranspiration rate for all catchment cells in the river basin. This data was processed and the average evapotranspiration rate for the entire area upstream each HPP was calculated. The relative changes in evapotranspiration rate for the scenarios were presented in graphs and the relative changes in total evapotranspiration for the entire simulation period were summarized in tables.

Results and discussion

Table 1 summarizes the changes in relative discharge and evapotranspiration that resulted from the model runs for all scenarios.

The effects of sugarcane expansion were most noticeable for the severest scenario at HPP Funil where the discharge decreased with 10.8 % and the evapotranspiration for the area upstream increased with 9.0 %.

The impact on discharge for the hydropower plants situated in eastern parts of Rio Grande basin is more

Table 1. *Relative changes in discharge and evapotranspiration for a 20 year period (1990–2009).*

	Camargos		Funil		Furnas		P. Colombia		Marimbondo		A. Vermelha	
	dV_{20} (%)	dE_{20} (%)	dV_{20} (%)	dE_{20} (%)	dV_{20} (%)	dE_{20} (%)	dV_{20} (%)	dE_{20} (%)	dV_{20} (%)	dE_{20} (%)	dV_{20} (%)	dE_{20} (%)
340–500	0.0	0.0	0.0	0.0	0.0	0.0	–0.2	0.5	–0.2	0.5	–0.8	0.8
340–700	0.0	0.0	0.0	0.0	0.0	0.0	–1.1	0.8	–1.2	0.8	–2.0	1.4
340–900	0.0	0.0	–0.8	3.3	–3.9	4.1	–4.9	4.2	–3.7	4.2	–4.3	3.4
340–1100	–6.2	5.4	–10.8	9.0	–9.3	7.1	–9.4	6.7	–6.4	6.7	–6.7	4.9
340–700_slope	0.0	0.0	0.0	0.0	0.0	0.0	–1.1	0.7	–1.2	0.7	–2.0	1.4
Embrapa	0.0	0.0	–0.7	2.4	–1.8	2.6	–2.5	2.5	–2.0	2.5	–2.3	2.2

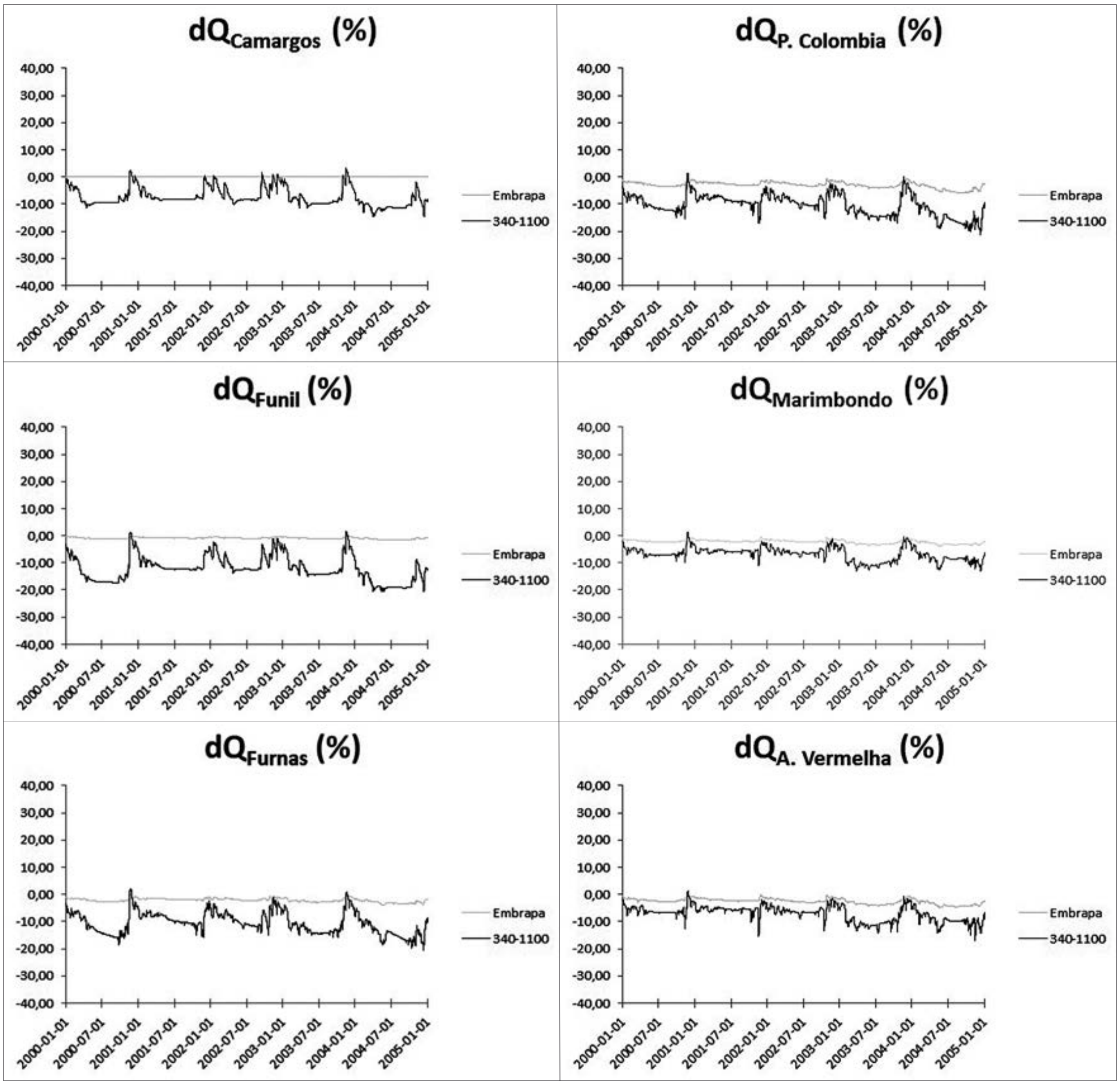

Figure 5. *Relative changes in discharge at the HPPs for the 340–1100 and Embrapa scenarios (2000–2004).*

severe than for the HPPs located in the west. This is related to the land use in the different parts of the river basin. In the eastern mountainous part, the vegetation mainly consists of pasture while in the western parts agricultural land is more common. Converting areas with pasture to sugarcane fields gives a higher evapotranspiration rate, and thus less runoff, compared to conversion from agricultural land to sugarcane. The relative changes in discharge and evapotranspiration for the simulations are shown in Figures 5 and 6, respectively.

The changes in surface runoff and evapotranspiration rate for the sugarcane converted land are not constant throughout the simulation period. Effects of the sugarcane annual cycle can be clearly seen in the evapotranspiration graphs (Fig 6). From being larger than the control scenario in the beginning of the year, the evapotranspiration rapidly decreases and becomes significantly lower after the sugarcane harvest. When new crops start to grow, the evapotranspiration rate recovers to the same level it was before harvest.

Regarding the surface runoff, the decrease in discharge is greater during the austral winter but recover most of the loss during the storms in the summer. The soil water capacity in sugarcane fields on shallow soils is the same,

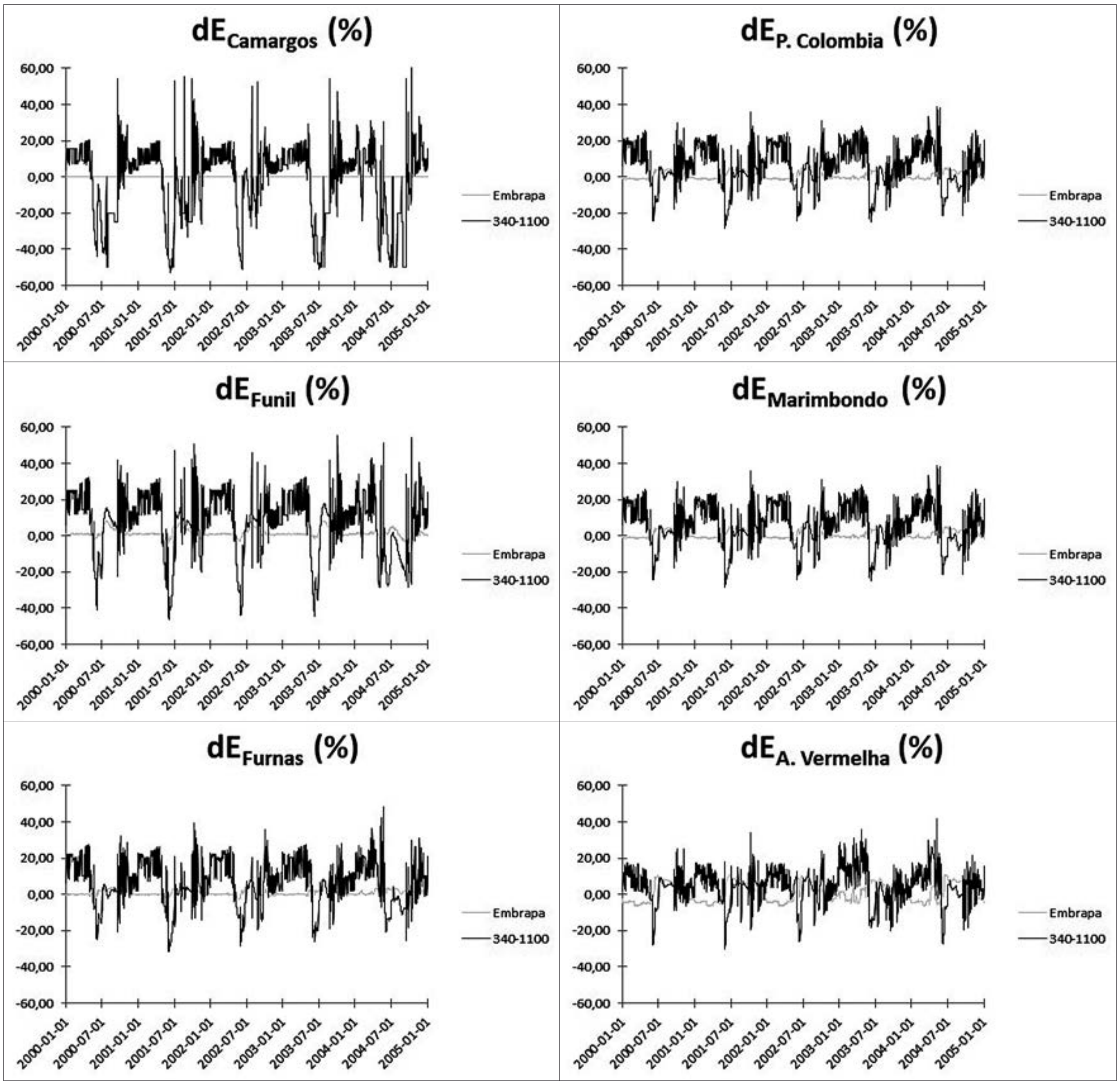

Figure 6. *Relative changes in evapotranspiration at the HPPs for the 340–1100 and Embrapa scenarios (2000–2004).*

or lower, than for the other vegetation types on shallow soils. This actually increases the runoff during the rainy summer months, as the soil store less water, which can be seen in the results for the HPPs in the eastern part of the basin. Consequently, the discharge increases in the austral summer months due to the heavy rainfalls, and decreases during the austral winter when the evapotranspiration increases. This seasonal variation is unfortunate as the decrease in runoff coincides with the dry winter season when the water level at the HHP reservoirs is low. Therefore, even if the decrease in runoff for the total simulation period is small, it could increase the risk for low reservoir levels during possible summer droughts significantly.

For the realistic scenarios, the largest changes in runoff occurred at HPP P. Colombia where the discharge decreased with 2.5 %. The evapotranspiration for the realistic scenarios increased most for the area upstream HPP Furnas with 2.6 %.

Considering sensitivity of the hydrology in Rio Grande basin, it can be assumed that the ongoing sugarcane expansion will request adjustment in the management of HHP to avoid damage on the hydropower generation.

Conclusions

Overall, simulations showed that the replacement of native vegetation by sugarcane fields has a significant impact on the hydrology and climate of the Rio Grande basin. Gradually expanding sugarcane in the river basin resulted in a very clear trend of decreased surface runoff and increased evapotranspiration. This is because the sugarcane expansion changed the hydrological behaviour of the basin over the year according to its phenological cycle, which implied variations of surface runoff and evapotranspiration rates.

In terms of the surface runoff, the influence of sugarcane expansion depended upon a combination of factors, such as amount of areas replaced with sugarcane, type of land use replaced and location of the expansion within each basin. This study showed that the sugarcane expansion mostly impacts the surface runoff if it happens over headwater areas consisting of pasture land with low soil water retention as in the sub basins located in the eastern part of the Rio Grande basin. For this area, sugarcane expansion significantly reduced the surface runoff.

Regarding the evapotranspiration, the results of the simulations showed that sugarcane expansion mostly affect same areas as runoff e.g. eastern part of the Rio Grande basin. The evapotranspiration rate also increased significantly from this area when sugarcane expanded over the original pasture land. However, the changes in evapotranspiration rate were not constant throughout the year, the harvest reduced evapotranspiration considerably and it was not restored until new sugarcane crops started to grow.

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