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Effects of sugarcane expansion on surface runoff and evapotranspiration in the Rio Grande basin

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Abstract

The demand for sugarcane has increased in recent years as more countries desire to reduce its dependence of fossil fuels. Therefore, the number of sugarcane plantations has rapidly increased in Brazil which raises concerns for what effect these conversion of original land to sugarcane plantations have on local hydrology and climate.

In this thesis, the effects of sugarcane expansion on surface runoff and evapotranspiration in the Rio Grande basin, Brazil were evaluated. Rio Grande basin is an area of great importance for the country in terms of hydropower generation and sugarcane cultivation.

For the numerical experiments carried out in this thesis, several sugarcane scenarios were generated based on topographic features and mapping of areas suitable for growing sugarcane made by the Brazilian Institute for Agricultural Research (EMBRAPA). A distributed hydrological model was used to estimate surface runoff and evapotranspiration rates in the river basin. Surface runoff and evapotranspiration rates were compared to a control scenario that corresponded to land use observed before sugarcane expansion.

Results from simulations implied a reduction of 10.8% in surface runoff and an increase in evapotranspiration rate by 9.0% for the most severe scenario, which occurred at the Funil hydropower plant.

Keywords: Sugarcane, Hydropower, Rio Grande basin, MGB-IPH, Land use change, Surface runoff, Evapotranspiration

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Sammanfattning

Efterfrågan på sockerrör har de senaste åren ökat i takt med att fler länder strävar efter att minska sitt beroende av fossila bränslen. Som en följd har antalet sockerrörsodlingar kraftigt ökat i Brasilien vilket medfört en oro inför vilka effekter denna omvandling av ursprunglig mark till sockerrörsodling har på lokala hydrologin och klimatet.

I det här arbetet har påverkan av sockerrörs expansion på ytavrinning och avdunstning i Rio Grandes avrinningsområde, Brasilien, utretts. Rio Grandes avrinningsområde är av stor betydelse för landets vattenkraftproduktion och sockerrörsodlingar.

För de numeriska experimenten i studien genererades ett flertal sockerrörs scenarion baserade på topografiska egenskaper och, enligt forskningsinstitutet EMBRAPA, lämpliga områden för framtida sockerrörsodlingar. En distribuerad hydrologisk modell användes för att uppskatta ytavrinningen och avdunstningen för avrinningsområdet. Ytavrinningen och avdunstningen jämfördes med ett kontrollscenario som motsvarade markanvändningen före sockerrörsexpansionen.

Resultaten från simuleringarna visade på en minskning med 10.8 % i ytavrinning och ökning i avdunstning med 9 % för det mest allvarliga scenariot, vilket inträffade vid vattenkraftverket Funil.

Nyckelord: Sockerrör, Vattenkraft, Rio Grande avrinningsområde, MGB-IPH, Markomvandling, Ytavrinning, Avdunstning

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Claes Borglin & Sara Borglin

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1 Introduction

1.1 Background

The global warming and climate change debate in recent years can hardly have escaped anyone's notice. In Sweden the debate has from time to time been fierce and as a consequence the former government in the early 2000's adopted a national strategy to become independent from oil before year 2020 (Persson, 2006). The decision to become an oil free nation was largely based on our common obligation to stop climate change but also fear for what consequences a higher oil price would have on economic growth and employment rate in Sweden played an important role (Persson, 2006). The national strategy proposed several methods to reduce oil consumption in transport, industry and the heating sector. As the transport sector is the sector which contributes most to greenhouse gas emission and transports are predicted to continually increase both nationally and globally it is of utmost importance to find more sustainable fuels and methods to travel (Persson, 2006; UNFCCC, 2008).

In several countries introduction of bioethanol has become a popular method to reduce the transport sector dependence of fossil fuels. In Sweden, for example, subsidiaries for environmental friendly cars and new laws which demanded all bigger filling stations to offer at least one biofuel as an alternative rapidly increased the number of ethanol driven private cars in the country (Petersson, 2007; Energimyndigheten, 2011). The ordinary petrol nowadays also contains up to a 5% blend of ethanol which the current government proposes to increase up to 10% (Finansdepartementet, 2012). Even though Sweden has a fairly good possibility to produce ethanol from paper pulp and cereals the production is still not efficient enough to cover the total demand and as a consequence the majority of ethanol is imported.

Most of the ethanol imported to Sweden originates from other countries in Europe but around 20% is imported from Brazil (Energimyndigheten, 2012). Brazil has a long history of cultivating sugarcane and is also a country that early adopted bioethanol as a fuel for transports. The number of sugarcane plantations in Brazil has rapidly expanded since the mid-seventies when the government launched a national alcohol program, Pro-Álcool, to counter the high petroleum prices caused by the oil crisis in 1973 (Goldemberg, 2006). From 1973 to 2005 the sugarcane plantations in the country grew with 170% to 5.4 million hectare and they are predicted to further increase up to 12.2 million hectare by the end of 2015 (Bolling and Suarez, 2001; IEA, 2006).

The fast conversion of original land use to sugarcane plantations raises concerns for what effects it could have on local and regional hydrological process (Gedney et al., 2006). Changes in vegetation and surface 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 operating in the river basin. Hydropower and sugarcane plantations, for example are industries that not infrequently co-exist in the same river basin. Small changes caused by substituting the original land to sugarcane could have significant impacts on the power generation.

As Brazil is extremely dependent on hydropower, 76.9% of the electricity is generated from water power (EPE, 2010), it is more vulnerable than many other countries for changes in hydrology. The Brazilian energy crisis in 2001 caused by a draught period in combination with low reserves demonstrated how sensitive the system really is (Krishnaswamy & Stuggins, 2007). The precipitation deficit that caused the drought was barely larger than for earlier droughts but still it led to a considerable larger runoff deficit (Simoes & Barros, 2007). To avoid blackouts during the crises a national rationing plan was adopted and therefore consumptions fell with 20%. For the customers the crisis was expensive, the price of electricity rose with 140% during just a couple of years (Krishnaswamy & Stuggins, 2007).

Rio Grande basin is an important area due to its reliance on hydropower generation and sugarcane cultivation. There are ongoing plans to expand sugarcane plantations in the river basin and it would be of great interest to investigate how this expansion would affect the discharge to the hydropower plants (HPPs) in the river basin. It would also be of interest to find out which areas may be most suitable for this expansion considering its effects on surface runoff in the River Grande basin. For Sweden, this study might also support future decisions regarding its policy to import ethanol derived from sugarcane in order to become an oil free nation.

1.2 Objective and research questions

This master thesis is part of a larger Brazilian-Swedish research project which purpose is to develop a hydrological model able to simulate changes to hydrology and local climate caused by expansion of biofuel crops into natural land and already existing agricultural fields. The conversion from original land use to biofuel plantations is ongoing in many tropical regions, and it is essential its impact on the local environment.

In this master thesis we will analyze the effects of sugarcane expansion on hydrology in Rio Grande basin using the hydrological model MGB-IPH. The model was calibrated and adapted to the research area in earlier works by Pereira et al. (Submitted). The sugarcane expansion will be expressed in terms of land use scenarios where the original vegetation is replaced by sugarcane up to different altitudes. We will also consider a realistic scenario given by the Brazilian Institute for Agricultural Research (EMBRAPA) where they define areas suitable for sugarcane expansion in the future.

The general objective of this thesis is to estimate surface runoff and evapotranspiration for several sugarcane expansion scenarios based on topographic features. We aim to answer the following questions;

- How sensitive are the local hydrology and climate in Rio Grande basin for land use changes? How will the discharge at the hydropower stations along Rio Grande be affected by the possible change in hydrology?
- How will the runoff and evapotranspiration change for a likely future scenario?
- Does the period after harvest significantly affect runoff?

1.3 Rio Grande Basin

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

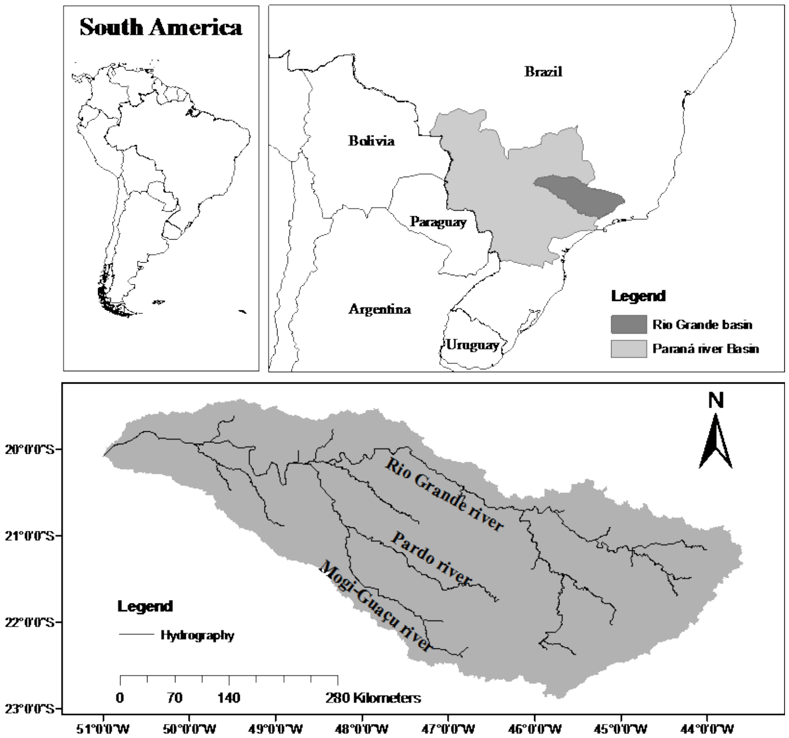

Figure 1: Maps describing the location of the Rio Grande basin.

The landscape in Rio Grande basin can be described as fairly hilly with elevations ranging from 200 meter above sea level (MASL) at the basins outlet in the west to more than 1800 MASL at the Mantiquira 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, 85% falls under the austral summer and the average annual evapotranspiration is around 950 mm.

Originally, a large part of the river basin was covered by cerrado, a tropical savanna vegetation. Nowadays only a fraction of the original vegetation remains, mostly in the lower part of the basin. In its place, agricultural land has expanded and covers, today, more than 70% of the area. The agriculture land is dominated by pasture in the higher eastern part of the basin. In the central basin, sugarcane plantations have expanded intensively over the last two decades. Natural and planted forests make up about 20% of Rio Grande basin.

Due to Rio Grande's importance for hydropower generation the river basin is well monitored by 216 rain gauges, 15 river stations and 14 meteorological stations. All available hydrological and atmospherically data has made Rio Grande a popular place to conduct research projects.

1.4 Sugarcane

Sugarcane is composed of several species of perennial grass originally grown on the south pacific islands but can now be found in many tropical and subtropical regions around the World (Britannica, 2012). The crop contains more calories per unit area than any other species in the World (Heiser, 1981). Most of its energy is accumulated in the lower part of the stalk as sucrose. Sucrose is primarily used as a sweetener in the food industry and as a raw material for producing ethanol through fermentation. The interest for using ethanol as a biofuel has increased in recent years as more countries tries to reduce its fossil fuel dependency.

The high demand for ethanol has made sugarcane the world largest crop and plantations covering roughly 20 million hectares divided over more than 70 countries (FAO, 2012; Galdos, 2009). Brazil is the major producer of sugarcane and the plantations in southeastern parts of the country generate one year after plantation more than 104 ton per hectare (Cuadra, 2012). The yield has increased year after year due to new pesticides, artificial fertilizers and successful breeding programs (Sharpe, 1998). All sugarcane cultivated for commercial purpose today are complex hybrids which have been extensively developed to resist diseases and produce maximum economical yield (Sharpe, 1998).

Sugarcane is cultivated by taking stem cuttings from the upper part of an immature plant. These seed canes are then planted with a space between of 1.4 to 1.8 meters between each cutting. With favourable environment the cutting will germinate and within a month a new sugarcane plant grow up. When the sugarcane is fully grown it can reach heights up to between three to seven meters (Britannica, 2012). Depending on location, it takes between 9 to 24 months for the sugarcane to grow ripe and be ready for harvesting (Purseglow, 1979).

Sugarcane can be grown in many different soils but it needs to be well drained in order to help the root system to absorb all oxygen. As sugarcane is a fast growing crop it give rise to a high evapotranspiration rate, and consequently needs access to a great amount of water in order to a produce a high yield, 2000-2300 mm (Britannica, 2012). It also demands a warm climate, over 20 °C, for a high crop growth.

1.5 The MGB-IPH model

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).

For this project an updated version of the MGB-IPH has been used. In the earlier version the drainage basin was divided into a uniform grid composed of square cells while in the current version the model divides the drainage basin into smaller catchment cells (Collischonn et al., 2007).

The river basin is divided into catchment cells interconnected by channels. Each catchment cell is in turn divided into Grouped Response Units (GRUs), i.e. areas with similar combinations of vegetation and soil (Fig. 2).

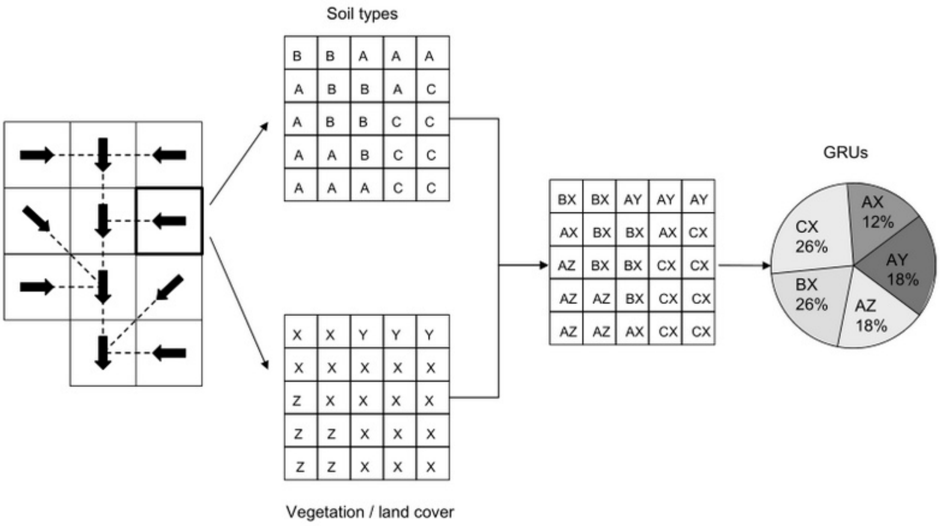

Figure 2: Illustration of GRU concept (Kouwen & Mousawi, 2002).

Soil water budget is calculated for each GRU using rainfall data and evapotranspiration according to equation (1) (See Fig 3):

$$W_{i,j}^{k} = W_{i,j}^{k-1} + \left(P_i - ET_{i,j} - Dsup_{i,j} - Dint_{i,j} - Dbas_{i,j}\right)\Delta t \qquad (1)$$

where k,i and j are indexes related to time step, cell and GRU respectively and Δt is the time step. P is the percolation, i.e. rainfall that reaches the soil and ET is the evapotranspiration. Dsup is the surface runoff, Dint is the subsurface flow and Dbas is the base flow (Collischonn et al., 2007).

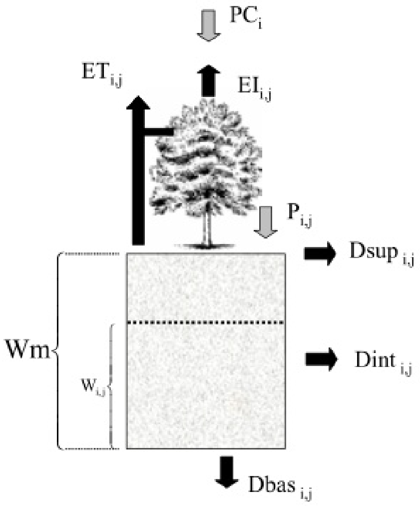

Figure 3: Schematic of soil water budget in each GRU of a cell (Collischonn et al., 2007).

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 MGB-IPH model has been used for many different purposes. Allasia et al. (2006) have tested the MGB-IPH model over several large river basins in South America to evaluate how it performs for different geological landscapes, climates and data availability situations. Their tests proved that the MGB-IPH model was able to estimate runoff fairly well and the obstacles were often related to shortage of data (Allasia et al., 2006).

The model has also been adapted to the Rio Grande basin where it has been successfully applied. Nóbrega et al. (2011) analyzed how future runoff in Rio Grande basin could be affected by possible climate changes. In their work they used the MGB-IPH model with meteorological data from a Global Circulation Model (HadCM3) to simulate changes in discharge at HPPs in the river basin. Their simulations indicated that runoff could increase between 8% and 51% for increases in global mean temperature by 1 to 6 degrees, and from 8% to 10% for increased greenhouse gas emission scenarios.

2. Methods and Data

In this study, the impacts of sugarcane expansion on the water balance for the Rio Grande were investigated using a distributed hydrological model, MGB-IPH. The sugarcane expansion was expressed in terms of land use scenarios. The model was used in seven runs of 20 years of simulation. Except for the land use maps that changed for the different scenarios, the same input data was used for all runs. For every scenario the model generated two output files which contained information on daily discharge and evapotranspiration rate for the catchment cells contributing to the HPPs.

2.1 Generation of scenarios

For the experiments six sugarcane scenarios, four with “gradual expansion” and two with “realistic future expansion”, were generated based on satellite images and topographic features of Rio Grande basin. Each scenario contained information of vegetation type, soil type and elevation. A control scenario was also generated to be used as a reference when calculating the changes in discharge and evapotranspiration for the expansion and realistic scenarios.

In this investigation the soil was divided into three types; deep, shallow and water bodies. The vegetation was divided into five different types; pasture, agriculture of grain, forest, sugarcane and water bodies. Together the vegetation and soil types generated nine different combinations. The sugarcane scenarios were generated with a GIS software. First, the topographic layer (Fig. 4) was reclassified into mask layers representing altitudes for sugarcane expansion. Then the mask layers were merged with the layer describing Rio Grande’s five types of vegetation (Fig. 5). Finally, the new vegetation layers were combined with the soil layer (Fig. 6) to add shallow or deep soil characteristics to the scenarios. The land use distribution for the generated scenarios can be found in Appendix C.

The generated sugarcane scenarios were together with layers describing topography, flow propagation, sub basins and catchment cells merged and converted from graphical images into text files. This conversion was done to make the MGB-IPH model able to read the data as input.

2.1.1 Elevation, vegetation and soil data

The elevation, soil and vegetation data has been used to create maps with current and possible future scenarios of the river basin. These maps were used to make input files to the MGB-IPH model describing the vegetation, soil and topography of the region.

Elevation data for the Grande River 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 topographic map over Rio Grande basin is presented in Fig. 4.

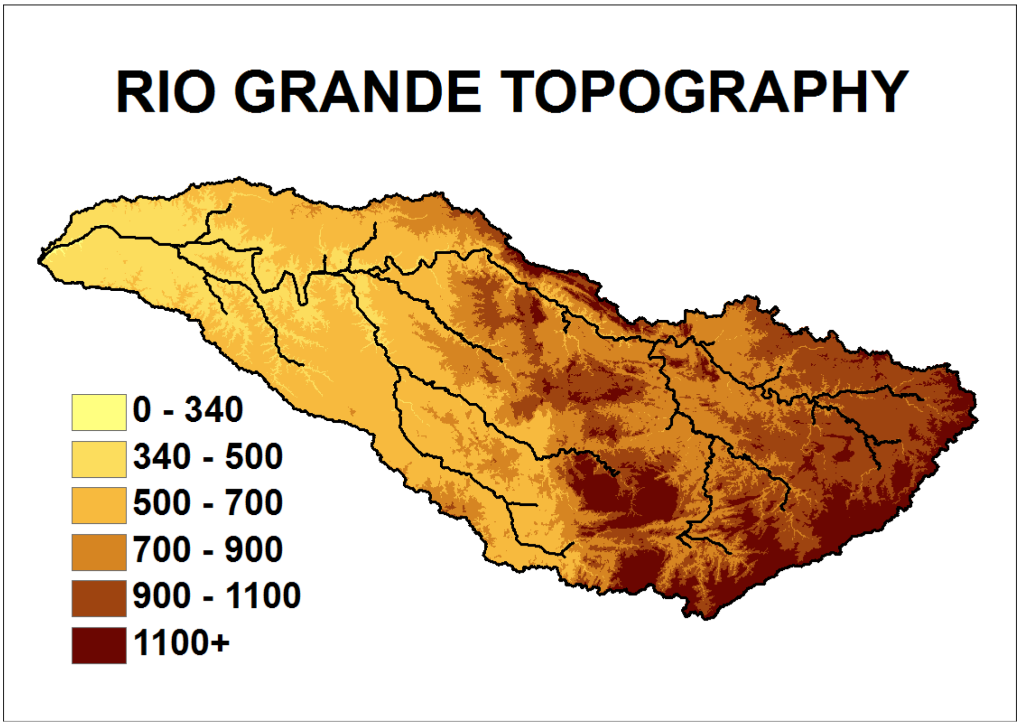

Figure 4: Map describing the Rio Grande basin's topography.

The US Geographical survey provides free access to satellite maps around the world. These maps have maps been used to classify land use as pasture, sugarcane, forest, agriculture of grain and water in previous works by Pereira et al. (Submitted). The land use in the Rio Grande basin can be seen in figure 5.

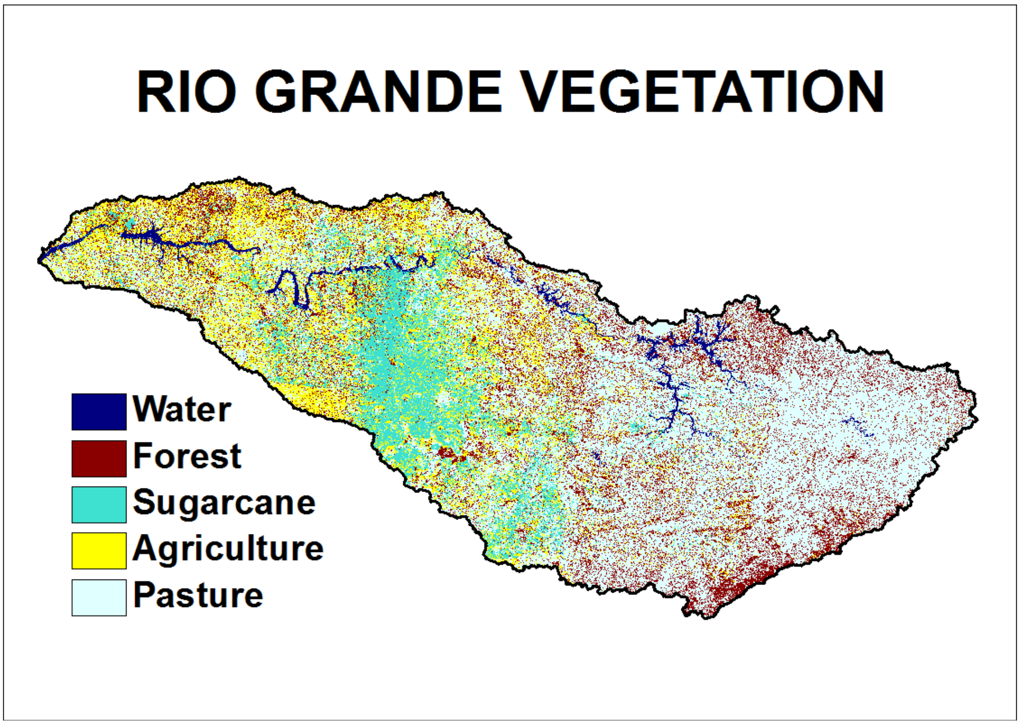

Figure 5: Map describing the Rio Grande basin's five types of vegetation; water, forest, sugarcane, agriculture and pasture.

In order to classify the soil in the basin Pereira et al. (Submitted) used a soil type mosaic, generated by FINEP (2007) using RADAMBRASIL (1984) and FAO database (1972). In Fig. 6 the distribution of shallow soil, deep soil and water is shown.

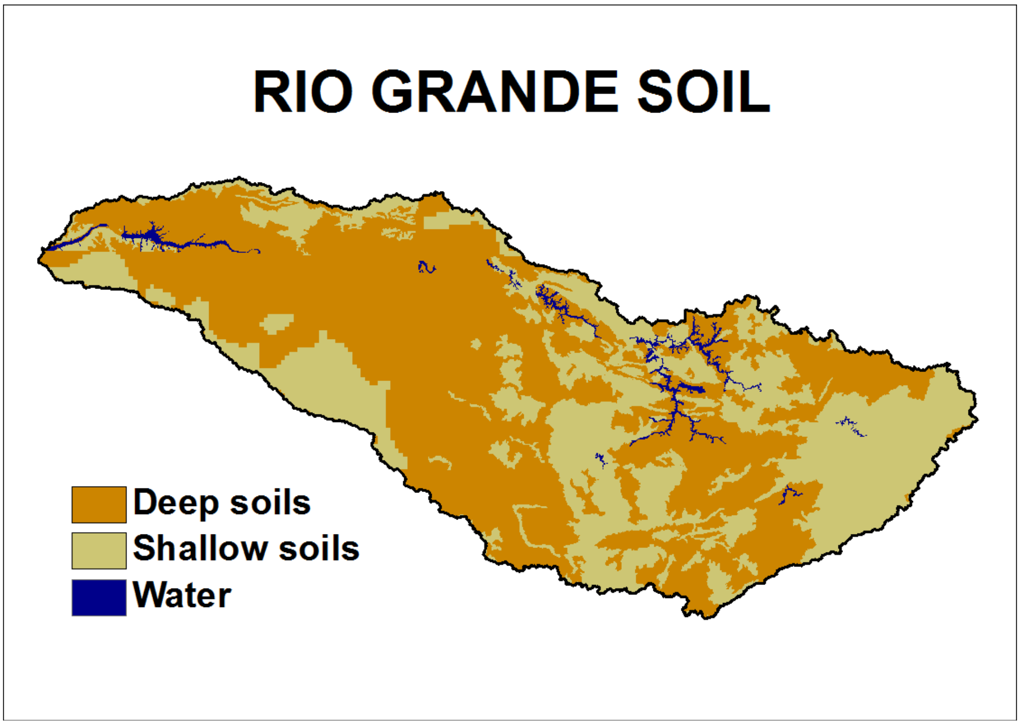

Figure 6: Map describing the Rio Grande basin's three types of soil depth; deep, shallow and water.

2.1.2 Control scenario

A control scenario was generated to represent the true vegetation and soil condition for a specific year. The year chosen was 1993 due to availability of data. The discharge and evapotranspiration for the control scenario was later used as a reference when computing changes caused by sugarcane expansion. The control scenario can be seen in Fig. 7, for this historical scenario most of the sugarcane plantations are concentrated in and around sub basin 3, 4, 6 and 7.

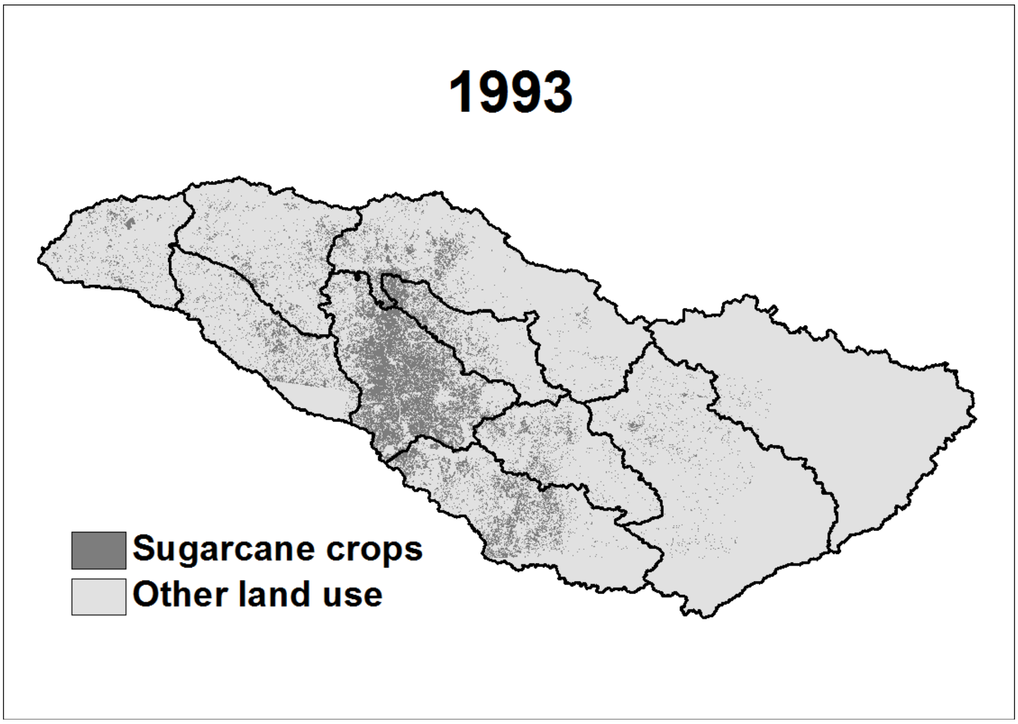

Figure 7: Map of sugarcane distribution for the control scenario.

2.1.3 Sugarcane expansion scenarios

The sugarcane expansion scenarios were generated to investigate how sensitive Rio Grande basin is for conversion of original land to sugarcane. These scenarios were later used to analyze in which interval the discharge and evapotranspiration changes.

For the four expansion scenarios (Fig. 8), sugarcane gradually expands to higher elevations in the river basin. In the first scenario, 340-500, sugarcane expands up to 500 MASL which affects sub basin 8, 9 and 10. For the second expansion scenario, 340-700, sugarcane continue to expand up to 700 MASL and is now almost completely covering sub basin 7, 8, 9 and 10. In addition, sub basin 3, 4, 5 and 6 are partly covered by sugarcane. In scenario 340-900, sugarcane is present in all of Rio Grande's sub basins. The sub basins in the western half of Rio Grande basin are almost completely filled with sugarcane while the sub basins in the eastern part are partly filled. The last scenario generated for the sensitivity analysis is 340-1100. For this scenario, almost all the area of the river basin is covered by sugarcane and only some mountainous areas and river channels are left unaffected from the expansion.

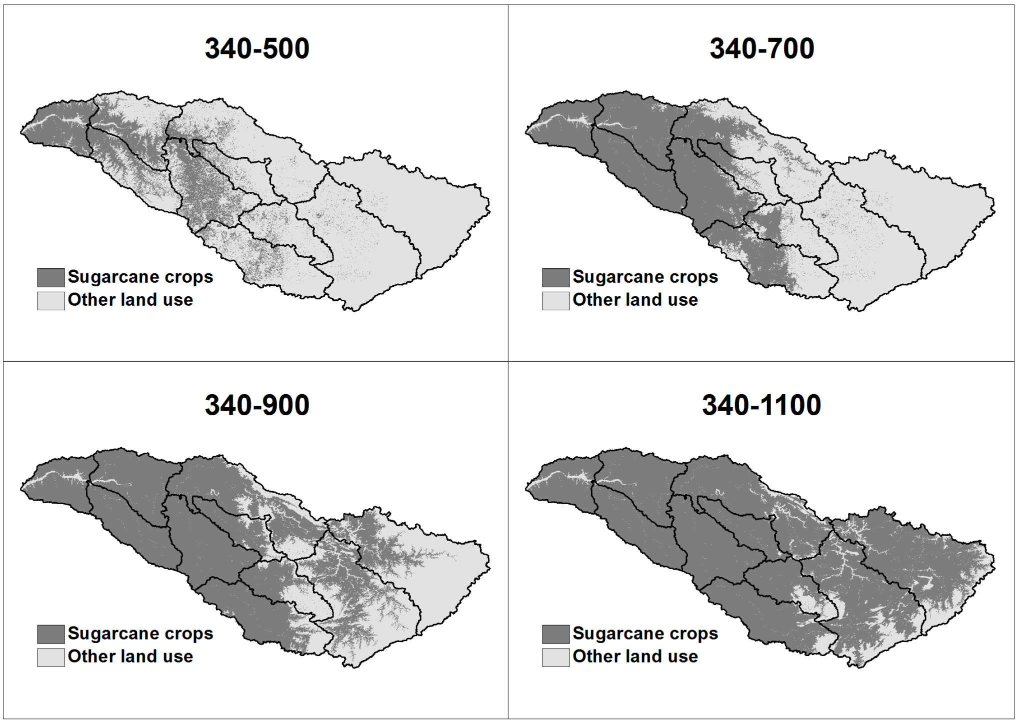

Figure 8: Maps of sugarcane distribution for expansion scenarios 340-500, 340-700, 340-900 and 340-1100.

2.1.4 Realistic future scenario

To estimate possible future changes in runoff and evapotranspiration in the Rio Grande basin related to the ongoing sugarcane expansion two realistic scenarios (Fig. 9) were generated. These scenarios were created based on data from EMBRAPA and sugarcanes limitation to grow at certain environments.

EMBRAPA is the Brazilian Institute for Agricultural Research with focus on developing and solve problems within agriculture (EMBRAPA, 2008). They have examined where it is suitable to grow sugarcane in the Rio Grande basin (BRASIL, 2009). A realistic future scenario was generated based on their recommendations for future sugarcane plantations.

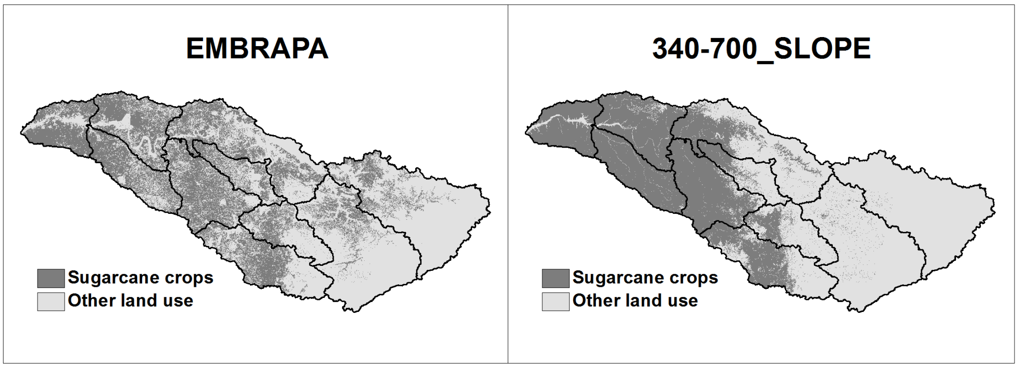

Figure 9: Maps of sugarcane distribution for realistic scenarios Emprapa and 340-700_slope.

An alternative future scenario was also generated based on sugarcane limitations to grow at certain areas in the river basin. A more restrictive environmental legislation in Brazil that prohibits burning of sugarcane before harvest, has mechanized the harvest (Pinto et al., 2011). The mechanized harvest limits the slope sugarcane can be grown at to less than 12% (Sparovek et al., 1997). Sugarcane is also prevented to expand up to certain altitudes due as it implies cooler temperature and a more rocky landscape. Consequently, in the alternative future scenario sugarcane is expanded up to 700 MASL in areas where the slope is below 12%.

2.2 Hydrologic model

The hydrologic model was calibrated in earlier works by Pereira et al. (Submitted). During the calibration process the model for Rio Grande basin was divided into 6 sub basins. In this study, however, the river basin is divided into 10 sub basins to better represent the spatial distribution of sugarcane (Fig 10). The river basin was also divided into 43 catchment cells (Fig 11). Each catchment cell contains nine GRUs, representing the different combinations of soil and vegetation.

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 maximums 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 baseflow are calculated.

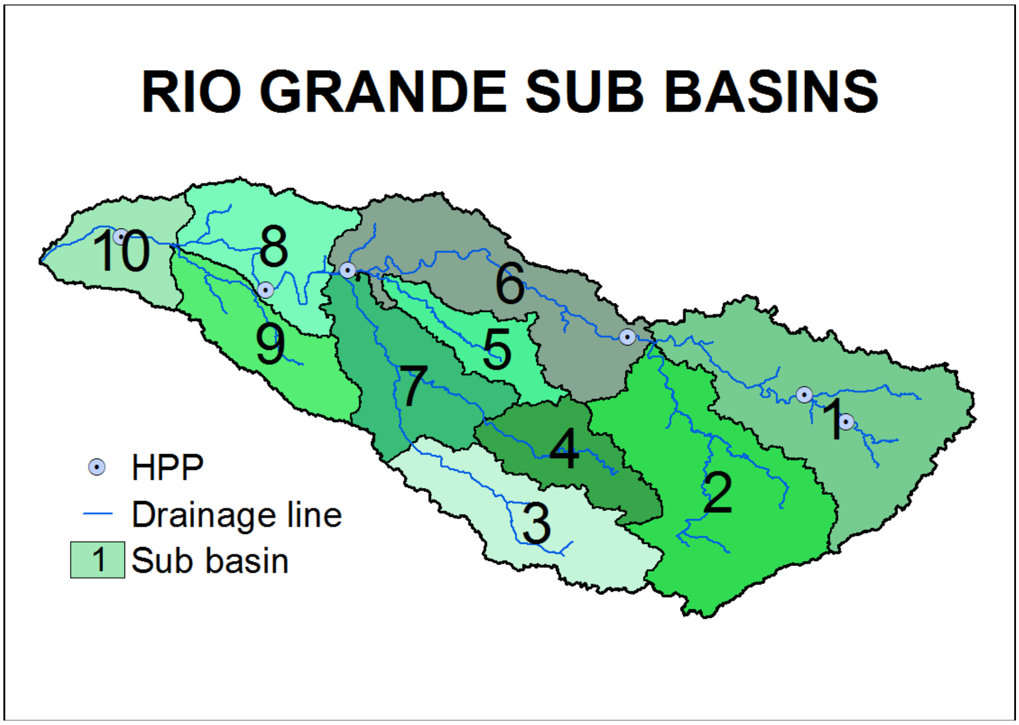

Figure 10: Map of sub basins in Rio Grande basin.

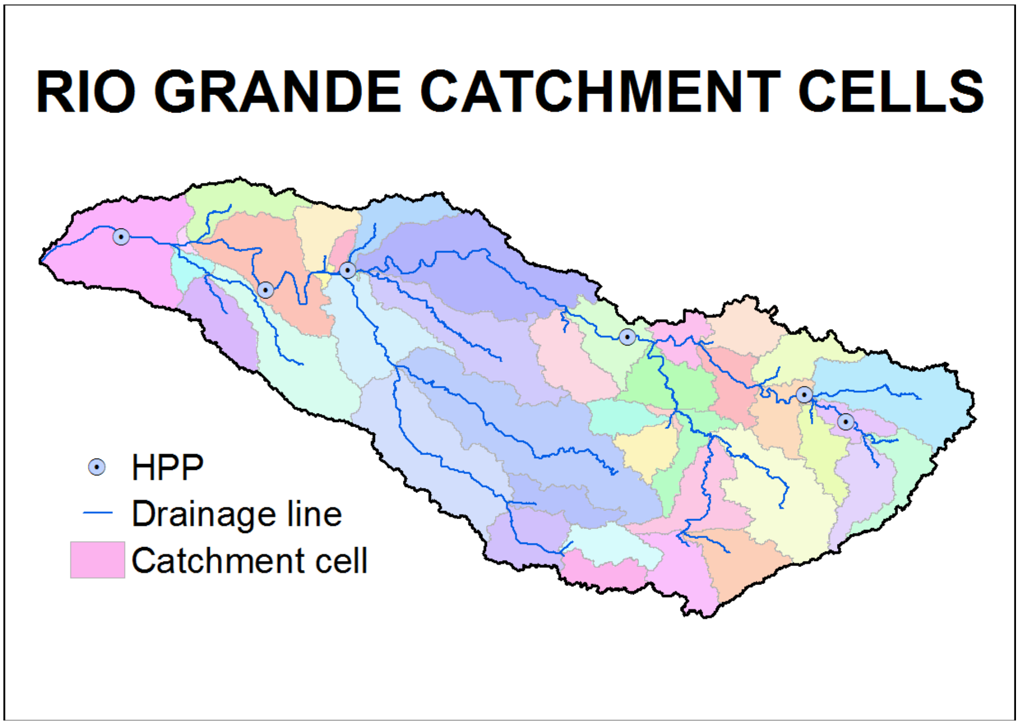

Figure 11: Map of catchment cells in Rio Grande basin.

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.

The different land use scenarios, including the control scenario, were applied over 20 simulation years (1990-2010) with a daily time step. The same rainfall was given as input to MGB-IPH for all scenarios.

2.2.1 MGB-IPH parameters

The MGB-IPH model contains both fixed, i.e. not used for calibration, and adjustable parameters related to type of vegetation and soil. The fixed parameters 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).

The fixed parameters are defined for each type of land use and their seasonal variation is taken into consideration. For pasture, agricultural grain and forest, the fixed parameters remained constant during the year due to their perennial characteristic. Sugarcane however has a marked annual cycle and, hence, the fixed parameters present a seasonal variability. The height of sugarcane trees varied from 0.5 m in June (germination stage) to 3.8 m in May (maturation stage). Values of leaf area index increased from 3.0 m^2/m^2 in June to 9.0 m^2/m^2 in April and May. Values of albedo for sugarcane fluctuated from 0.24 in June to 0.31 in April and May. The albedo varies proportionally to leaf area index in sugarcane fields (André et al., 2010). The values of canopy resistance were kept constant throughout the year. The complete list of fixed parameters adopted in this study can be found in Appendix A.

The adjustable parameters were calibrated by Pereira et al. (Submitted) by trial and error method using recorded hydrographs and relative streamflow 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. (Submitted). The calibration was performed for a period of eleven years (1990-2000), and the parameters of the model was then validated a seven-year period (2001-2007). The Nash-Sutcliffe (NS) coefficients, Root-mean-square-error (RMSE) and relative volume error (RME) for the calibration and validation are shown in Table 1 (Pereira et al., Submitted).

Table 1: NS coefficients, RMSEs and RVEs for calibration and validation of the MGB-IPH for Rio Grande basin.

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

The calibration procedure included 7 parameters: Wm, b, Kbas, Kint, CS, CI and CB. These parameters were identified as key parameters in earlier works by Collischonn, (2001). Wm is the maximum water storage in the soil layer. It is related to soil types and land cover. The magnitude of this parameter is affected by the plants roots, soil depth, porosity and texture. A decrease of Wm will saturate the soil faster during a storm and consequently give a shorter lag time and a sharper hydrograph. The parameter b describes how soil water capacity varies over the area. A value of zero will corresponds to a totally homogenous area with constant water storage capacity of Wm while a positive value implies that some parts of the area have storage capacity lower than Wm. A high value of b will lower infiltration and evaporation and consequently generate more runoff. Changing this parameter tends to have more impacts on smaller rains and increasing this will give small fluctuations on the hydrograph. Kint and Kbas are parameters giving subsurface drainage respectively percolation rate to groundwater for saturated soils. When these parameters increase it will result in higher flow and less water available in the soil for evaporation. CS, CI and CB are related to retention time for surface, subsurface and groundwater flow.

All the seven adjustable parameters are listed in Appendix B. For the simulations all parameters were kept constant, the only input that changed was the vegetation for the different scenarios.

2.2.2 Precipitation and discharge data

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

To calculate the evapotranspiration additional data regarding air temperature, sunshine hours, windspeed, relative humidity and atmospheric pressure is needed. Three meteorological stations were considered in the study and the data was provided by Centro de Previsão de Tempo e Estudos Climáticos (CPTEC). Two stations were located within the river basin and one, Araxa, north of the basin.

Monthly averages were calculated for all meteorological variables of the three stations in earlier works by Pereira et al. (Submitted) and were given as input in the hydrological model. The HPPs and meteorological stations can be seen in Figure 12.

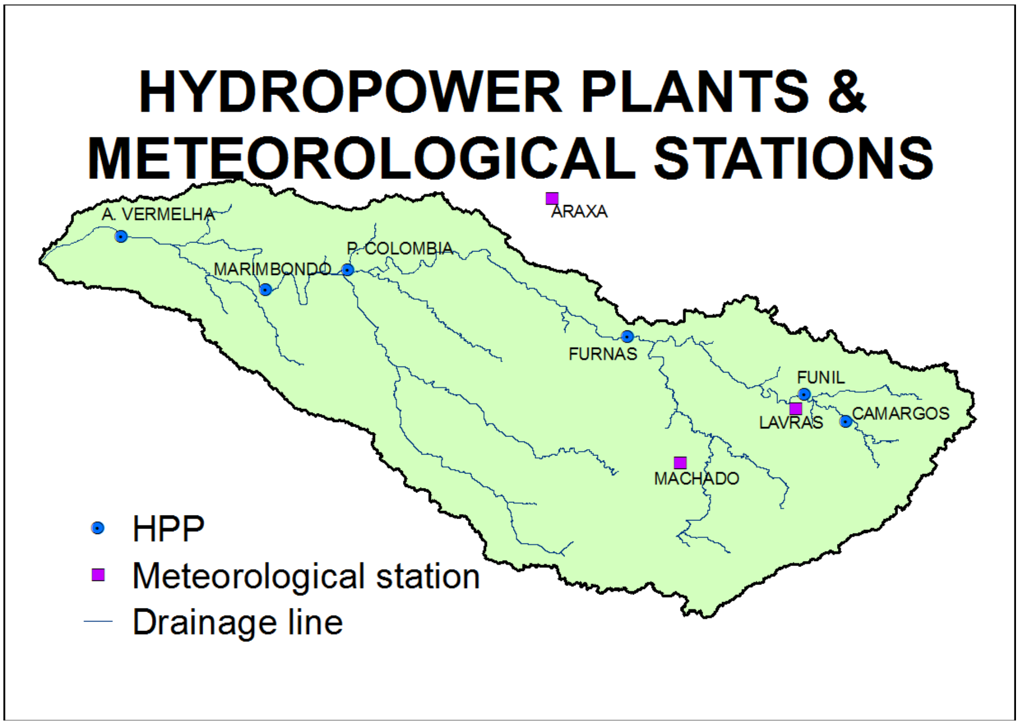

Figure 12: Map over hydropower plants and meteorological stations in Rio Grande basin.

2.3 Output files and data adaptation

For every scenario, the MGP-IPH model generated two output files with information about discharge and evapotranspiration rate. The discharge file contained daily runoff (m^3/s) from the catchment cells contributing to the HPPs over a 20-year simulation period. This data was processed to generate hydrographs. In order to reduce the amount of data and make the hydrographs easier to read, only the control scenario was plotted and the time period was reduced to 5 years.

Relative changes in discharge between control and expansion scenarios were also investigated. These changes were calculated and the result was plotted in graphs over same time period as the hydrographs. 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. As for the discharge, relative changes in total evapotranspiration for the entire simulation period were summarized and presented in tables.

3 Results and discussion

3.1 HPP Camargos

HPP Camargos is situated in sub basin 1 (Fig. 13), which belongs to the eastern, mountainous part of Rio Grande basin. The soil in this area is mainly shallow and a majority, roughly 77%, of the area consists of pasture. Apart from pasture, the area in the basin is made up by 18% forest, 12% agriculture land and 4% water. Almost all of the land in the basin is situated at an altitude above 900 MASL.

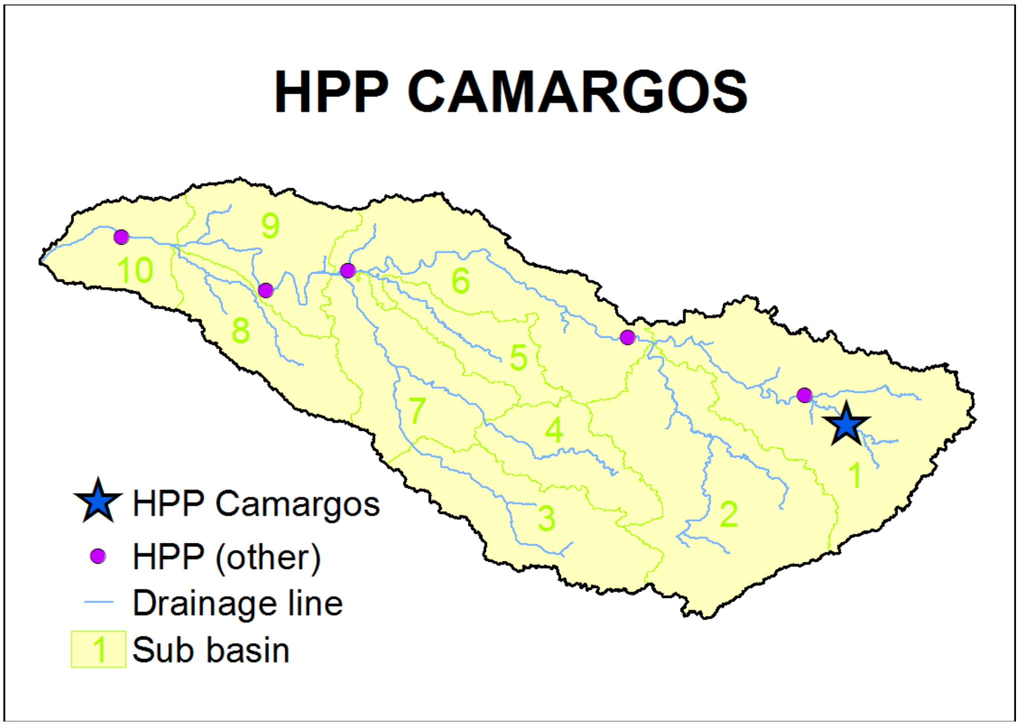

Figure 13: Map showing location of HPP Camargos.

Figure 14 presents the hydrograph at Camargos for a 5-year period. In the hydrograph, the Rio Grande basins two seasons with hot rainy summers and cold, dry winters can be seen clearly. In the beginning of the year, during the austral summer, several storms occur and the discharge is high. This storm period lasts until May, when the winter period starts, with no significant peaks and with a gradually decreasing baseflow. The discharge continues to decrease until October when the summer period once again starts.

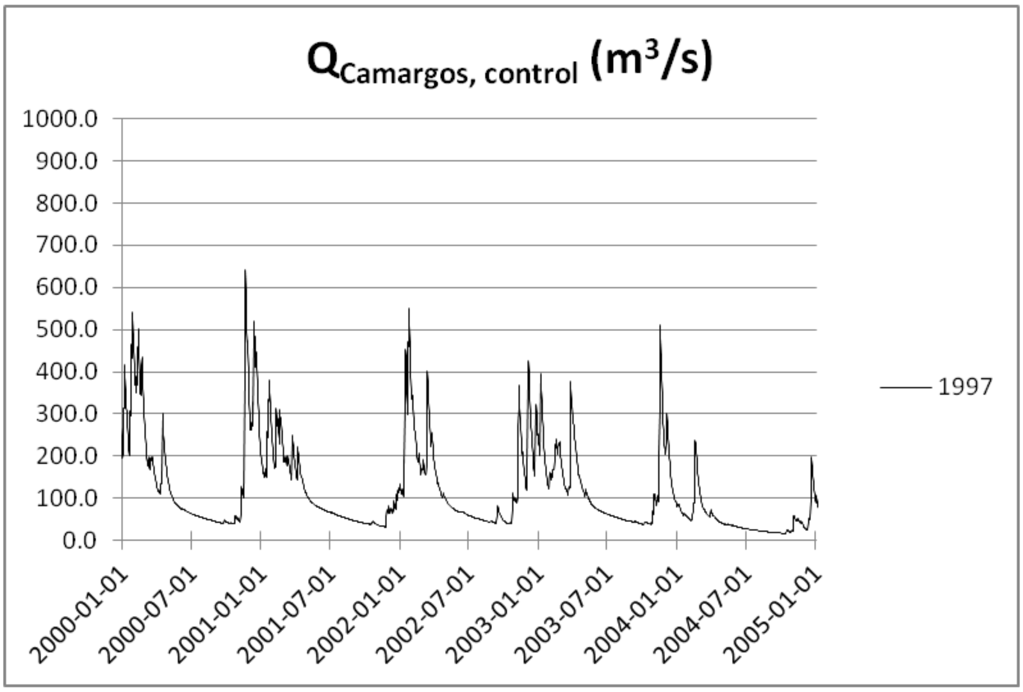

Figure 14: Discharge at HPP Camargos over a 5-year simulation period (2000-2005).

3.1.1 Expansion scenarios

Figure 15 shows the relative changes in discharge at Camargos, it can be seen that only one expansion scenario, 340-1100, differentiates from the control scenario. In the beginning of the year, the relative change in discharge for scenario 340-1100 gradually decreases. After harvest in May there is a minor increase in relative discharge for almost all years in the graphs, which is caused by the decrease in evapotranspiration that occurs after harvest. The big change in relative discharge from February to June is, however, caused by the colder and dryer climate. When the austral winter period starts the discharge is about 10% lower for scenario 340-1100 than it is for the control scenario. During the austral winter months the change in discharge is fairly constant until October when it starts to increase. In the end of the year the discharge is fully recovered and at some point it is even larger than the control scenario.

The general decrease in discharge for expansion scenario 340-1100 during the simulation period can be explained by sugarcane being a fast growing species that consumes large amounts of water. The recovery in discharge for 340-1100 coincides with the storm period in the hydrograph for Camargos. This recovery is not unexpected as the converted sugarcane has lower soil water storage than original pasture and forest. Lower soil water storage will saturate the soil faster and result in more surface runoff during storms.

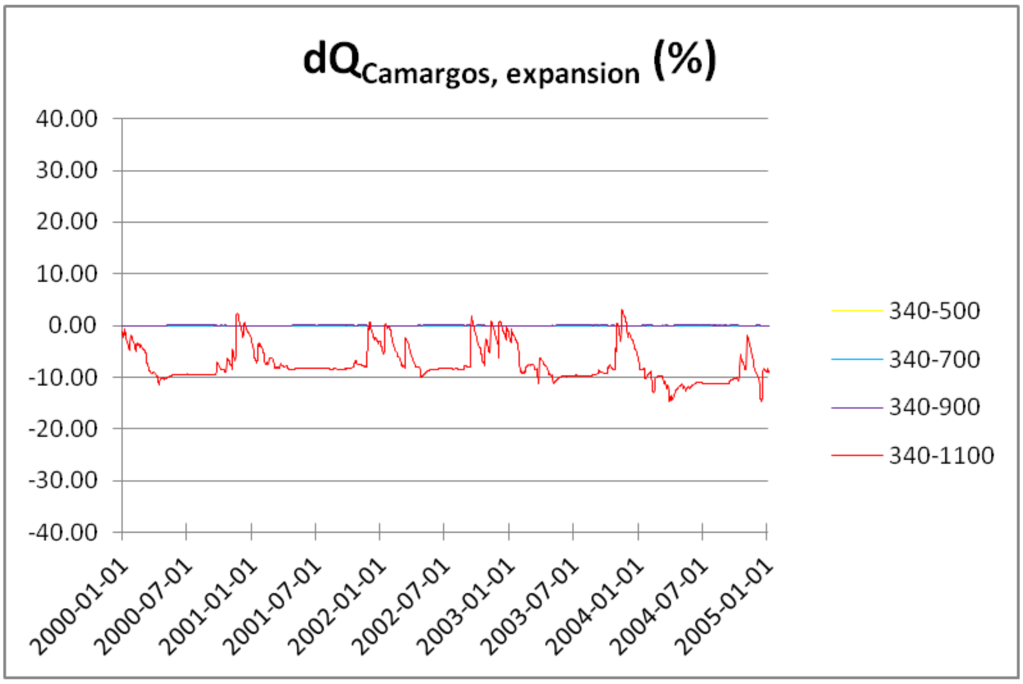

Figure 15: Relative changes in discharge at HPP Camargos for expansion scenarios over a 5-year simulation period (2000-2005).

Table 2 confirms that 340-1100 is the only scenario that has significant impact on discharge at Camargos. Total change in volume over the 20-year simulation period is -6.2%. A barely noticeable decrease can also be seen for scenario 340-900 which originates from mountain valleys below 900 MASL.

Table 2: Relative changes in total volume at HPP Camargos for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-500	0	0
340-700	0	0
340-900	$-7.0*10^5$	0.0
340-1100	$-3.9*10^9$	-6.2

In Figure 16 the change in evapotranspiration is plotted for the area upstream Camargos. As expected, the only scenario that contributes to a significant change in evapotranspiration is scenario 340-1100.

The evapotranspiration line in the graph clearly corresponds to sugarcanes marked annual cycle. In the beginning of the year, the evapotranspiration was about 10% higher for scenario 340-1100 compared to the control scenario. In May, after sugarcane harvest, the relative change in evapotranspiration is -40%. The evapotranspiration from scenario 340-1100 is lower than the control scenario until the end of September when the ratoon crops start to grow. After some large peaks in the beginning of October the relative change in evapotranspiration stabilizes and fluctuates around +10% for the rest of the year.

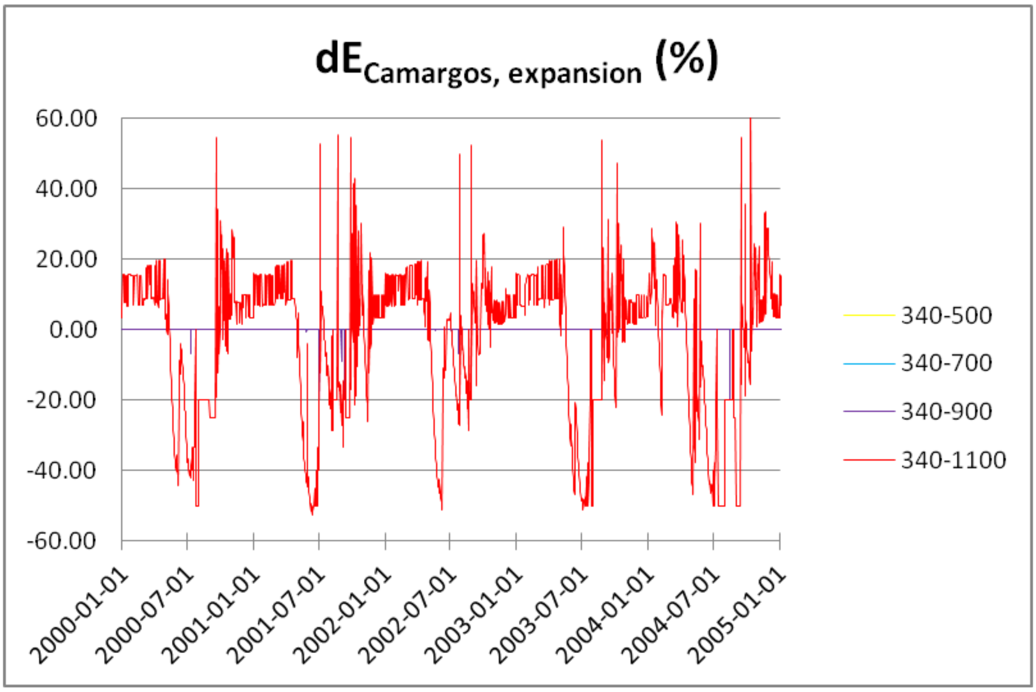

Figure 16: Relative changes in evapotranspiration at HPP Camargos for expansion scenarios over a 5-year simulation period (2000-2005).

The changes in evapotranspiration for the entire simulation period are summarized in Table 3. As the evapotranspiration graph indicated, the only scenario that affects Camargos is 340-1100. This scenario results in 754 mm more evapotranspiration over a 20-year period, which corresponds to a 5.4% increase.

Table 3: Relative changes in total evapotranspiration at HPP Camargos for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-500	0	0.0
340-700	0	0.0
340-900	0	0.0
340-1100	754	5.4

3.1.2 Realistic scenarios

The realistic scenarios do not affect the discharge at Camargos, as can be seen in Fig. 17. This is expected as the area upstream Camargos is situated at such high altitude that it would not be suitable for sugarcane cultivation.

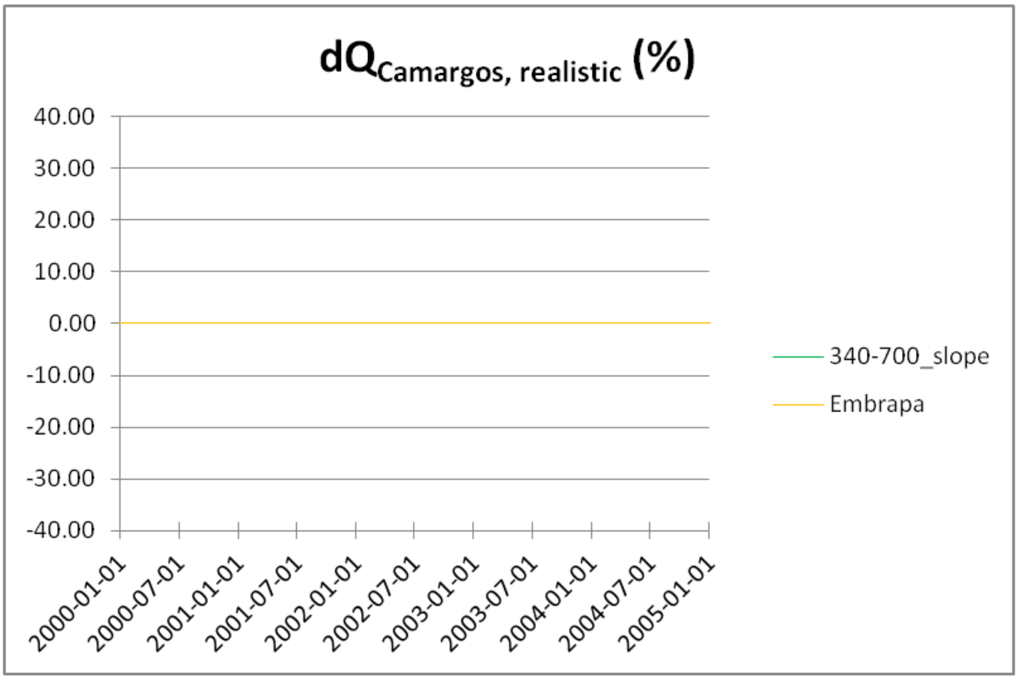

Figure 17: Relative changes in discharge at HPP Camargos for realistic scenarios over a 5-year simulation period (2000-2005). The changes are so small that they are hard to see in the graphs.

Even if the graph indicates that there are no impacts on discharge for the realistic scenarios at Camargos, Table 4 shows a small increase in discharge for the Embrapa scenario. This volume is minimal and the increase can be explained by two land use units that are converted from shallow soil/pasture and shallow soil/forest to shallow soil/sugarcane. Pasture and forest in combination of shallow soil have a larger soil water capacity than sugarcane on shallow soil, thus the surface runoff increases. As can be seen in Table 4, the evapotranspiration for the Embrapa scenario is 0, and therefore there is no reduction for it in the soil water balance, and consequently the discharge becomes positive.

Table 4: Relative changes in total volume at HPP Camargos for realistic scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-700_slope	0	0.0
Embrapa	$2.9*10^4$	0.0

The evapotranspiration is unaltered for the two realistic scenarios at Camargos. Neither figure 18 nor table 5 show any signs of changes in evapotranspiration for the area upstream Camargos.

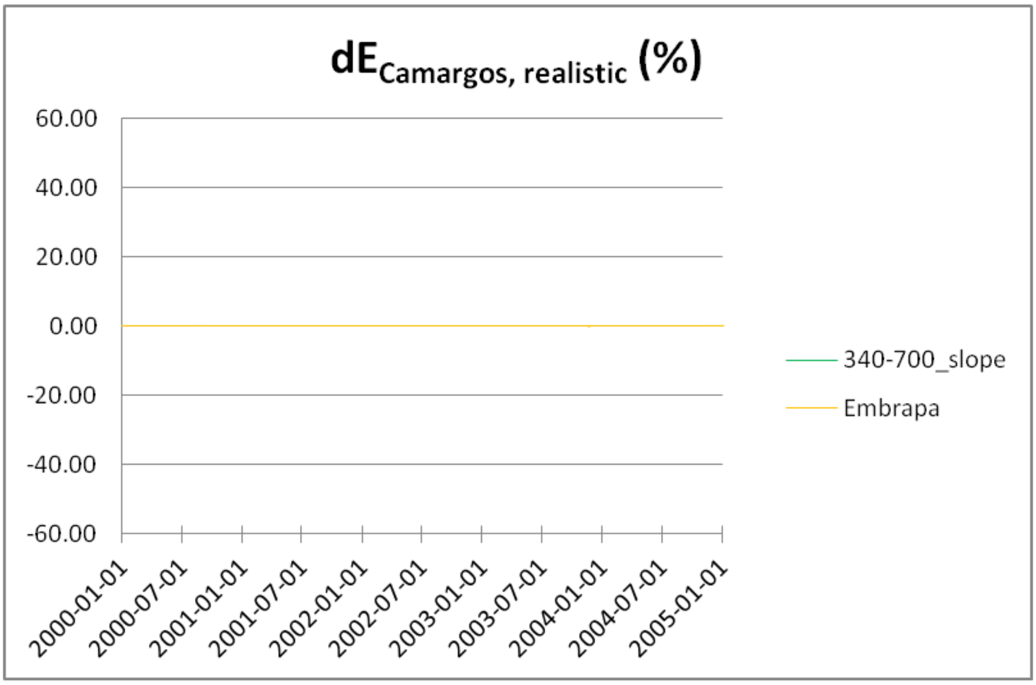

Figure 18: Relative changes in evapotranspiration at HPP Camargos for realistic scenarios, 5-year simulation period (2000-2005). The scenarios were not affected by the sugarcane expansion.

Table 5: Relative changes in evapotranspiration at HPP Camargos for realistic scenarios, 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-700_slope	0	0.0
Embrapa	0	0.0

3.2 HPP Funil

Funil is located downstream of Camargos but in sub basin 1. Besides receiving discharge from Camargos this station receives water from two tributaries to the north and south of the Rio Grande River. The tributaries collect water from both deep and shallow soils, unlike Camargos where almost all soil was shallow.

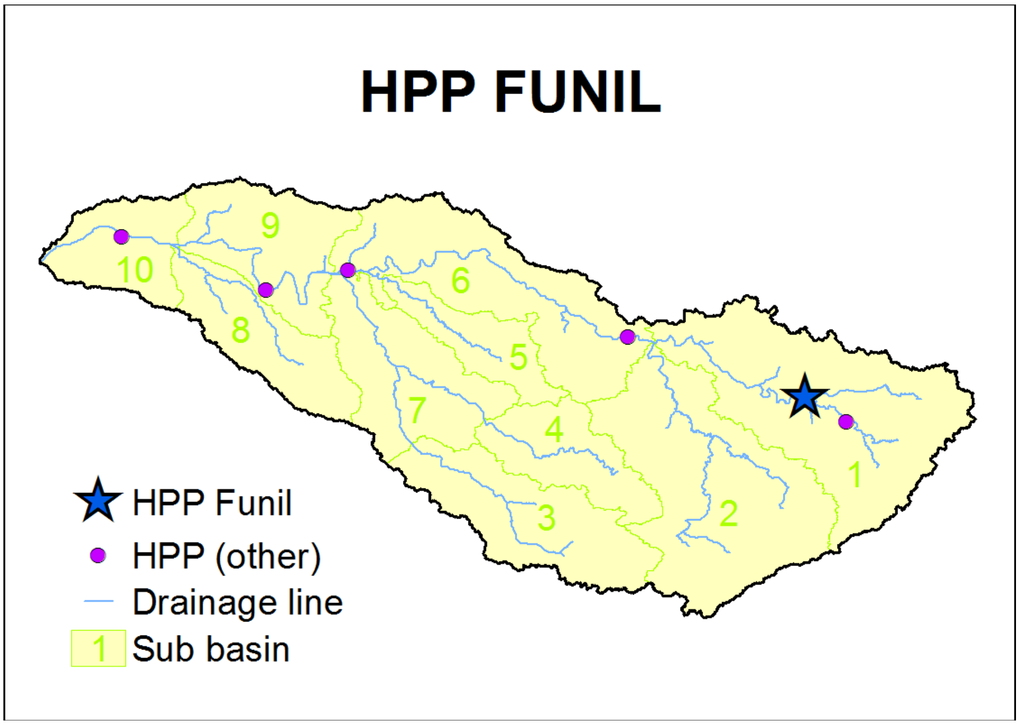

Figure 19: Map showing location of HPP Funil.

The hydrograph for the control scenario at Funil seems almost identical with the hydrograph for Camargos with the exception that the discharge is more than twice as large for the former.

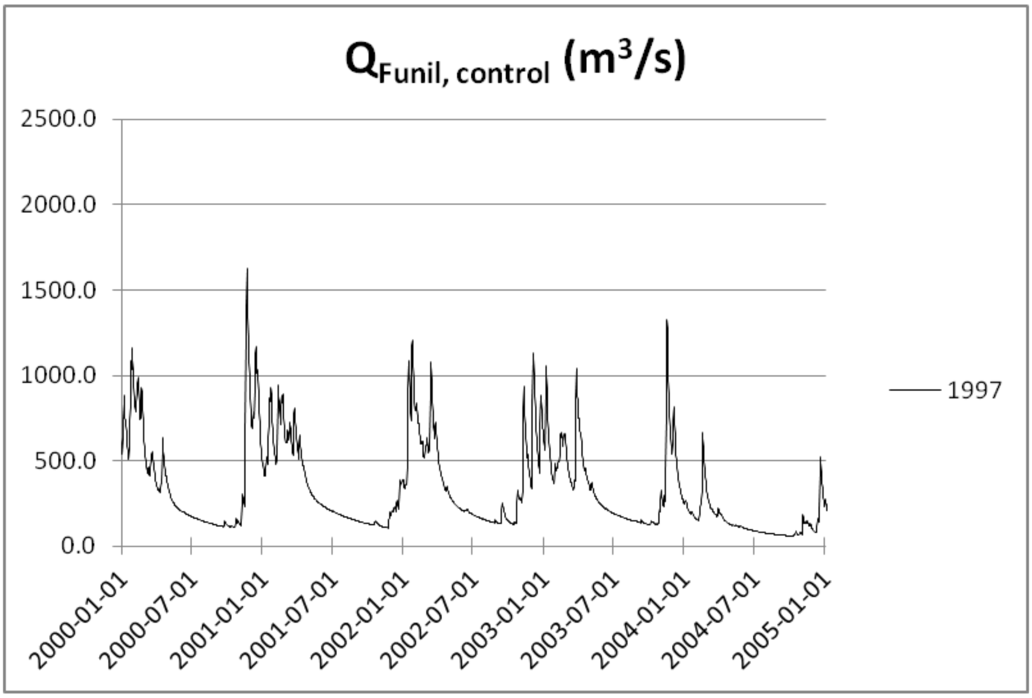

Figure 20: Discharge at HPP Funil over a 5-year simulation period (2000-2005).

3.2.1 Expansion scenarios

As can be seen in Figure 21, the relative discharge for scenario 340-1100 has decreased even more at Funil compared to Camargos. During the southern hemisphere winters, the discharge for scenario 340-1100 is up to 20% lower than the control scenario. The larger decrease at Funil than Camargos is explained by a larger part of the area upstream of the HPP being affected by the sugarcane expansion. The sugarcane expansion also affects scenario 340-900. The changes in discharge for this scenario is however small and lack significant peaks.

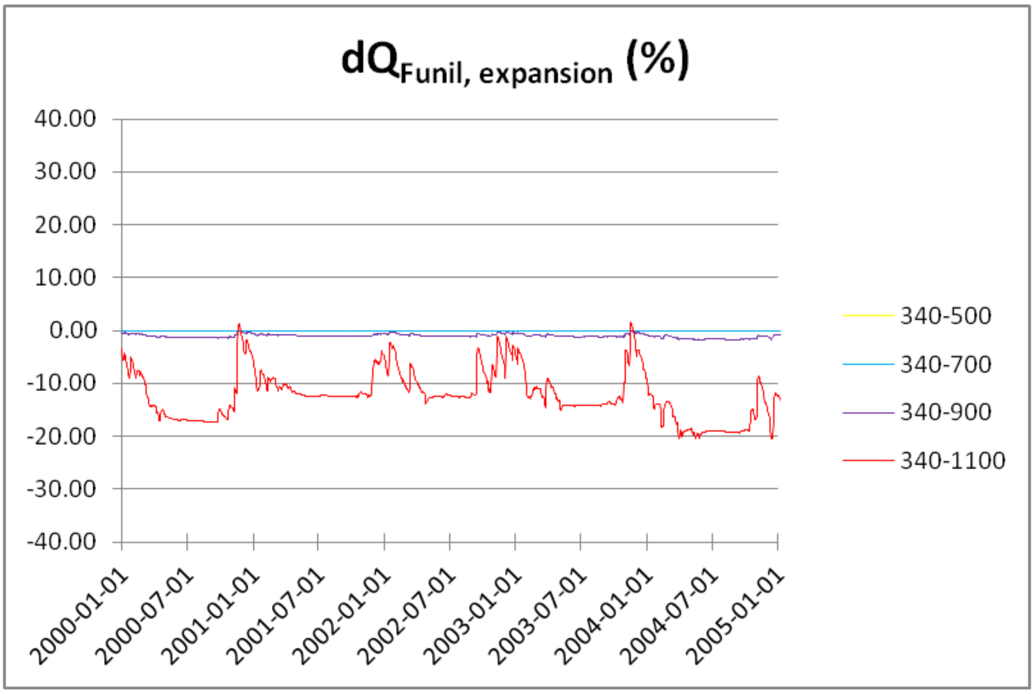

Figure 21: Relative changes in discharge at HPP Funil for expansion scenarios over a 5-year simulation period (2000-2005).

The discharge at Funil for the entire simulation period has decreased as well. In Table 6 it can be seen that the decrease is 10.8% for scenario 340-1100 and 0.8% for 340-900. The discharge for scenario 340-500 and 340-700 is unaffected as the elevation of the river basin is higher than 700 MASL.

Table 6: Relative changes in total volume at HPP Funil for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-500	0	0.0
340-700	0	0.0
340-900	$-1.5*10^9$	-0.8
340-1100	$-1.8*10^{10}$	-10.8

Figure 22 shows changes in evapotranspiration for the area upstream Funil. As with Camargos, the change in evapotranspiration upstream Funil corresponds to the sugarcanes marked annual cycle. It is significantly higher from October to April, and after harvesting in May it decreases. The evapotranspiration for scenario 340-1100 is generally higher at Funil compared to Camargos.

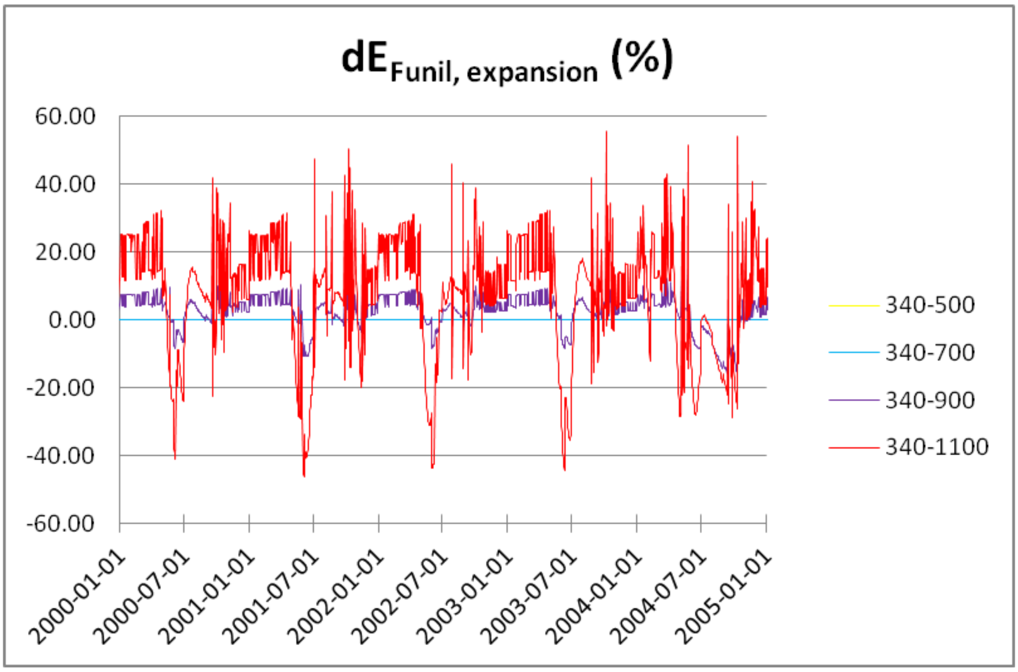

Figure 22: Relative changes in evapotranspiration at HPP Funil for expansion scenarios over a 5-year simulation period (2000-2005).

When comparing the evapotranspiration for the two stations it can also be noted that the amplitude of the peaks are smaller at Funil compared to Camargos. Worth noticing is that at Camargos the evapotranspiration was varying between -20 to -40%, with the exception of some peaks, for the whole period between May and October. Whereas for the Funil basin there are negative peaks until July when the evapotranspiration starts to increase and become positive around mid-July. The smaller peaks at Funil are probably related to the fact that more of the area upstream of the HPP has lower soil water storage. Lower soil water storage will reduce the amount of water able to evaporate.

For the scenario 340-900 there is a change in evapotranspiration for the area upstream of Funil. The evapotranspiration line is, however, lower and the amplitude smaller for the peaks compared to 340-1100. None of the other expansion scenarios stretch far enough up the river basin to affect the evapotranspiration at Funil.

Tables 7 summarize the change in evapotranspiration at Funil for the entire simulation period. For scenario 340-900 the evapotranspiration increases up to 3.3%, and for the scenario 340-900 there is an increase by 9%.

Table 7: Relative changes in total evapotranspiration at HPP Funil for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-500	0	0.0
340-700	0	0.0
340-900	464	3.3
340-1100	1347	9.0

3.2.2 Realistic Scenarios

Embrapa is the only one of the two realistic scenarios that affects the discharge at Funil. The change is small but in Fig. 23 it can be seen that the discharge line is fluctuating just below zero. According to Table 8 the total change in volume for Embrapa is -0.7% for the entire simulation period.

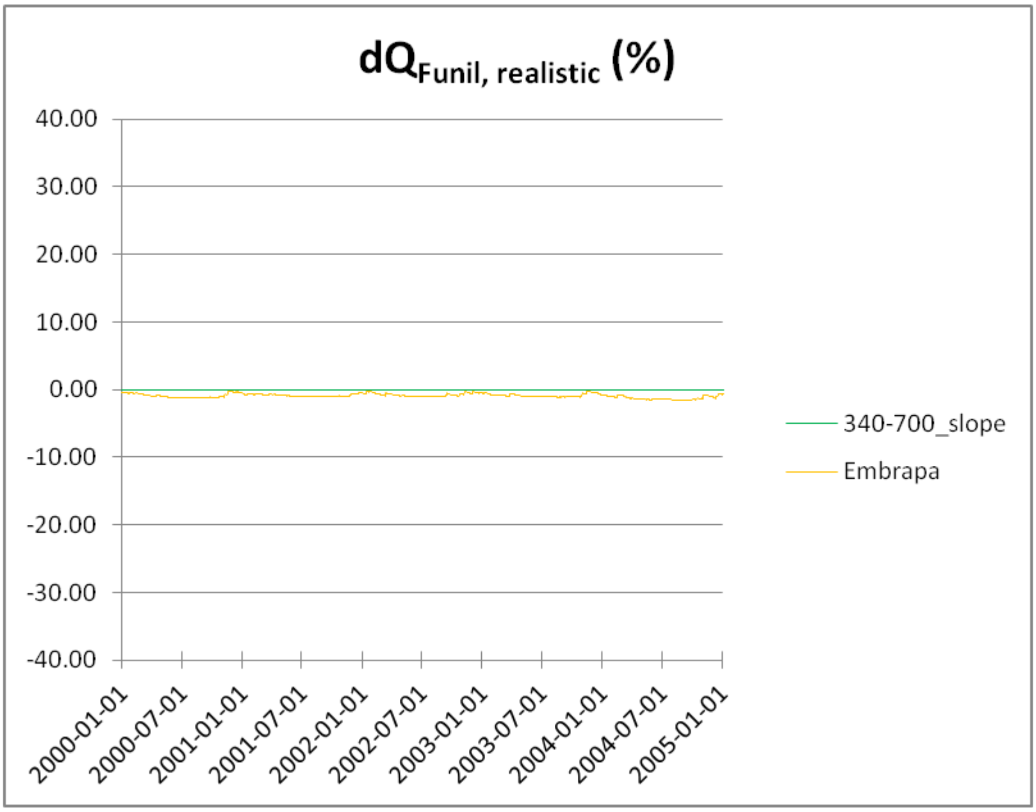

Figure 23: Relative changes in discharge at HPP Funil for realistic scenarios over a 5-year simulation period (2000-2005). The 340-700 scenario is not affected by the sugarcane expansion.

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Table 8: Relative changes in total volume at HPP Funil for realistic scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-700_slope	0	0.0
Embrapa	$-1.3*10^9$	-0.7

The evapotranspiration is unchanged for scenario 340-700_slope at Funil. For the Embrapa scenario, the evapotranspiration line fluctuates around +5% until May, which can be seen in Fig. 24. In May it decreases to -6% but recover most of it until end of July, followed by another decrease before it recovers to +5% for the rest of the year. The change in evapotranspiration corresponds to growth cycle of the sugarcane, but also with the hydrograph. The small decrease in evapotranspiration in May can be explained by the fact that the draught period starts then, which can be seen in the hydrograph as the discharge decrease. In July the sugarcane has regained some of their height and the albedo and leaf area index (LAI) is increasing, which results in higher evapotranspiration. The total change in evapotranspiration for the simulation period is +2.4% (Table 9).

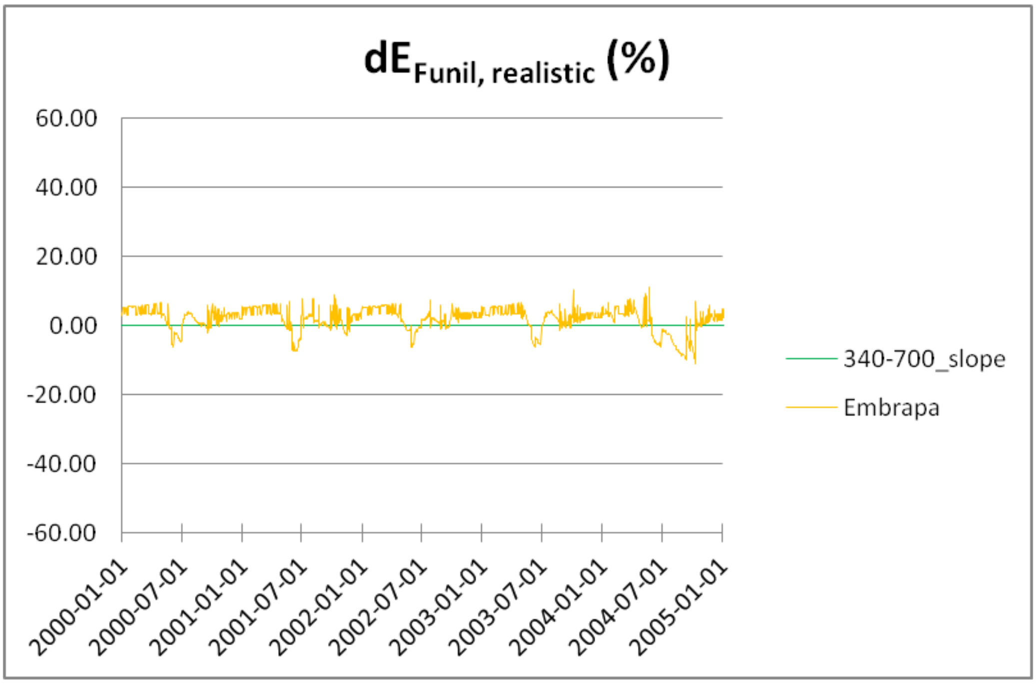

Figure 24: Relative changes in evapotranspiration at HPP Funil for realistic scenarios, 5-year simulation period (2000-2005). The 340-700_slope scenario was not affected by the sugarcane expansion.

Table 9: Relative changes in evapotranspiration at HPP Funil for realistic scenarios, 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-700_slope	0	0.0
Embrapa	340	2.4

3.3 HPP Furnas

HPP Furnas is located eastern part of sub basin 6 and receives runoff from sub basin 1 and 2 (Fig. 25). A large part, about 68%, of sub basin 2 is made up by pasture where the major part is grown on deep soils. Forest in combination with deep or shallow soil is also a significant part of the sub basin, representing 22% of the area. The rest of the sub basin is made up by 4% water, 4% agriculture and 2% sugarcane. Approximately 60% of the soil is deep, in contrast to a little bit more than 30% in sub basin 1.

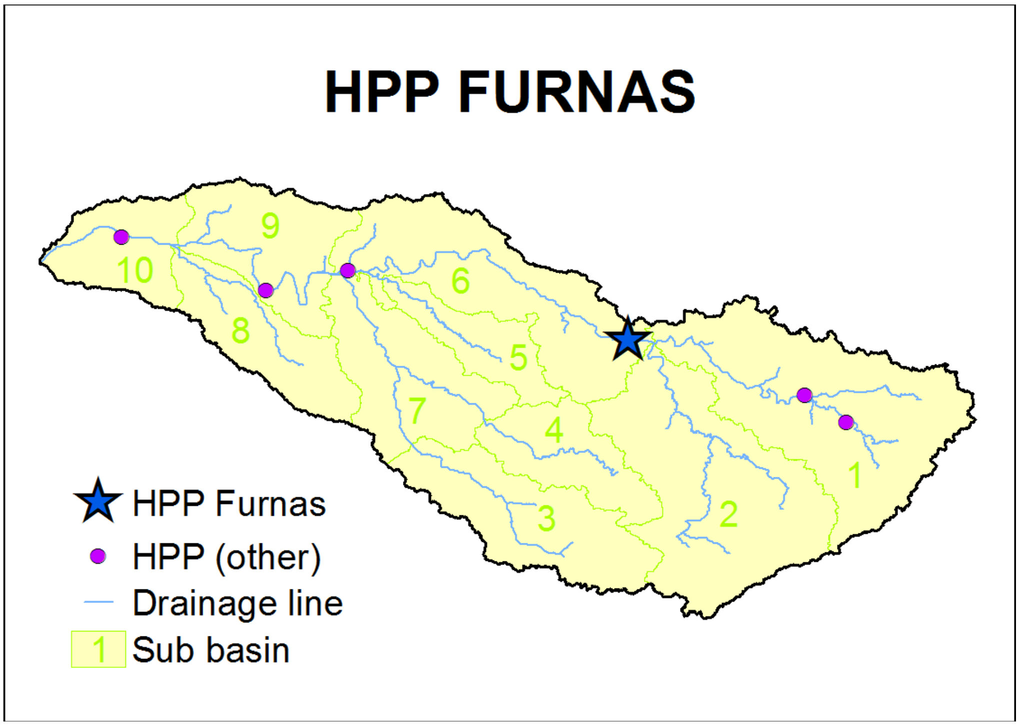

Figure 25: Map showing location of HPP Furnas.

The hydrograph for Furnas, Figure 26, differentiates slightly from the hydrographs for Camargos and Funil. Apart from handling more discharge, some peaks have changed in amplitude in relation to surrounding peaks. This can be explained by the larger amount of the deep soils in the Furnas river basin as the larger soil water storage give less surface runoff during storms and thereby a more even hydrograph. The large peaks in the end of 2000 and 2003 at Funil are reduced in amplitude and do not distinguish from other peaks anymore.

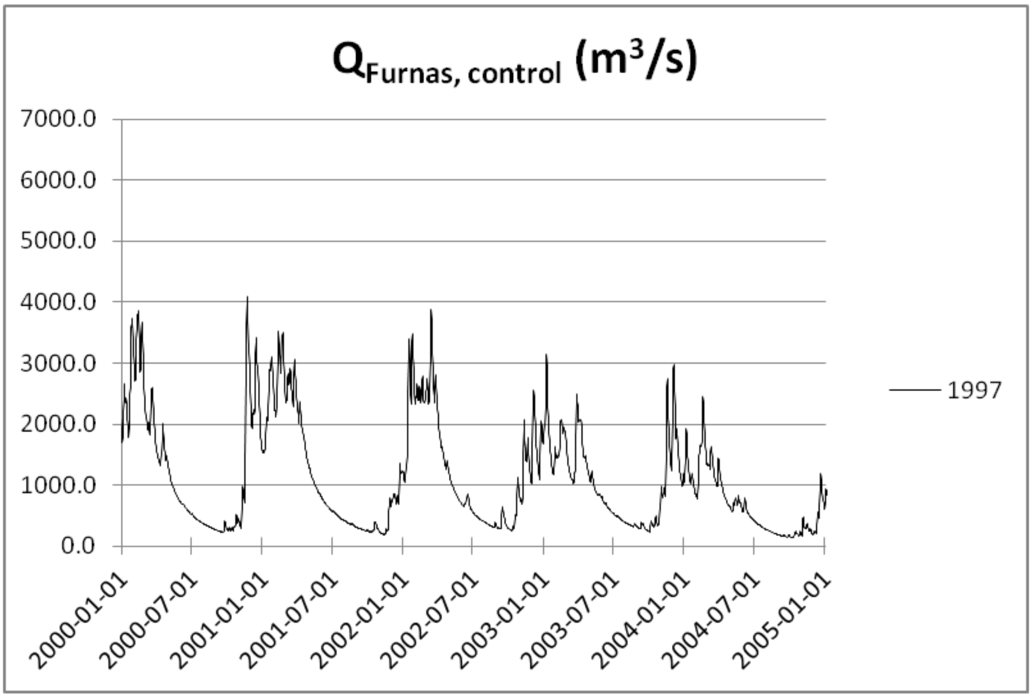

Figure 26: Discharge at HPP Furnas over a 5-year simulation period (2000-2005).

3.3.1 Expansion scenarios

Figure 27 presents changes in discharge at the HPP Furnas for the expansion scenarios. The decrease in discharge for scenario 340-1100 seems to be somewhat similar at Furnas as it was at Funil. The decrease at Funil was faster and then held constant while the decrease is more gradual at Furnas.

For scenario 340-900 the discharge has decreased at HPP Furnas significantly more than it did at HPP Funil. The discharge line for 340-900 has also more apparent peaks at Furnas. Scenario 340-900 lacks however the increase in discharge during storm period that scenario 340-1100 has. This is probably related to a larger part of the sugarcane converted for scenario 340-1100 is on deep soils which have same soil water storage as pasture on deep soils. For scenario 340-900 more shallow soils are converted to deep soils which result in lower soil water budget and hence more surface runoff.

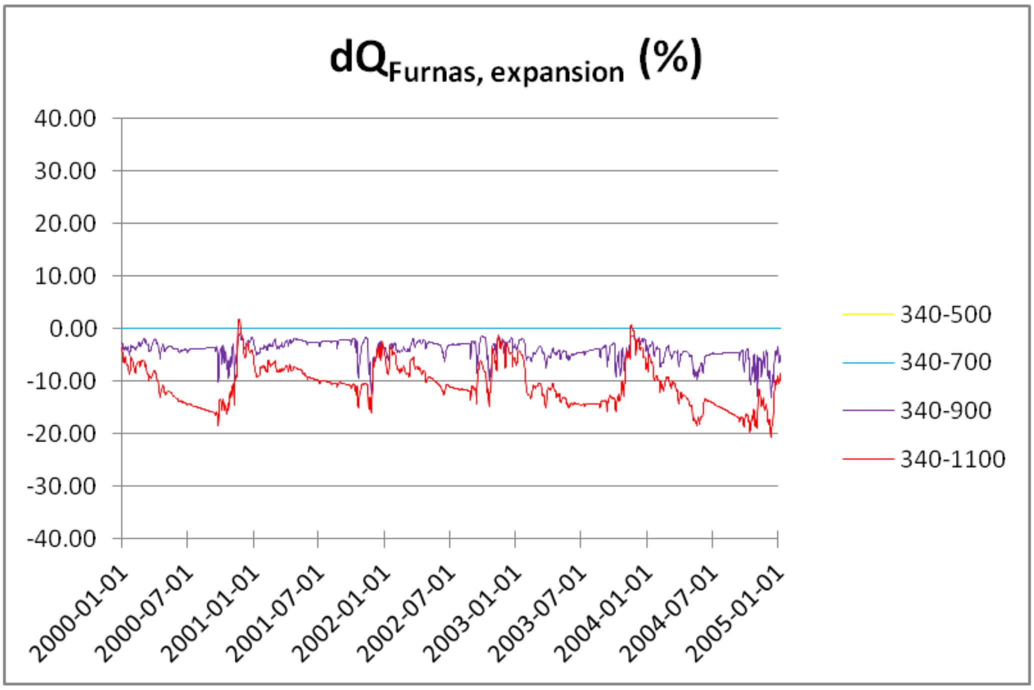

Figure 27: Relative changes in discharge at HPP Furnas for expansion scenarios over a 5-year simulation period (2000-2005).

In Table 10 the changes in volume at Furnas for the total simulation period is presented. For scenario 340-1100 the total volume decreases at Furnas with 9.3% which is less than for Funil. The reason for scenario 340-1100 is affecting Furnas to a lesser extent than Funil is probably related to a larger portion of area upstream is deep soil for the former. In sub basin 2 more than half of the original land converted to sugarcane is grown on deep soils.

The total change in volume for scenario 340-900 at Furnas is -3.9%. For 340-700 there is a barely noticeable decrease and for 340-500 there is no decrease at all.

Table 10: Relative changes in total volume at HPP Furnas for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-500	0	0.0
340-700	$-9.3*10^4$	0.0
340-900	$-2.4*10^{10}$	-3.9
340-1100	$-5.4*10^{10}$	-9.3

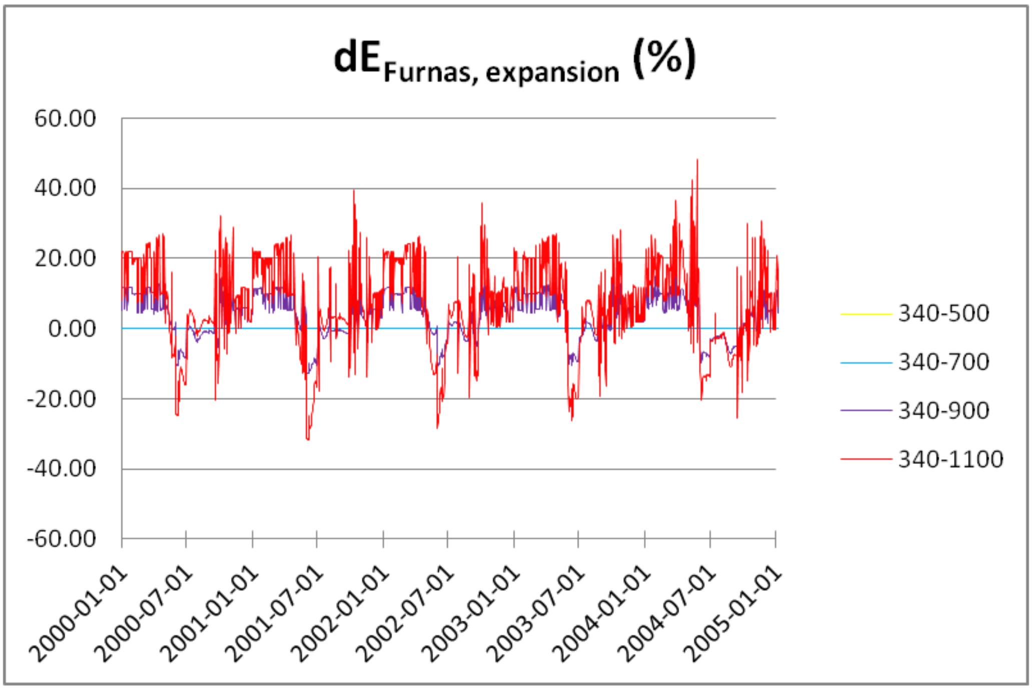

Figure 28: Relative changes in evapotranspiration at HPP Furnas for expansion scenarios over a 5-year simulation period (2000-2005).

Scenario 340-900 does not show the same reduction of peaks. The absence can be explained by fact that the sugarcane conversion is done mostly on pasture on shallow soil for scenario 340-1100 while more pasture on deep soil is converted for 340-900. Pasture and sugarcane growing on deep soil has the same infiltration rate according to our model but shallow pasture has smaller infiltration rate than sugarcane on shallow soil. Thus, 340-900 gives more surface runoff and lower evapotranspiration peaks than scenario 340-1100.

The changes in evapotranspiration at Furnas are summarized in Table 11. For scenario 340-1100 the increase is 7.1% that is, as the graph above indicated smaller than increase for Funil.

Table 11: Relative changes in total evapotranspiration at HPP Furnas for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-500	0	0.0
340-700	0	0.0
340-900	553	4.1
340-1100	992	7.1

3.3.2 Realistic Scenarios

For the realistic scenario the discharge at HPP Furnas is still unchanged for scenario 340-700_slope. For the Embrapa scenario the decrease is a bit larger compared to Funil (Fig. 29). For the whole simulation period the change in total volume for Embrapa decreases with 1.8% (Table 12).

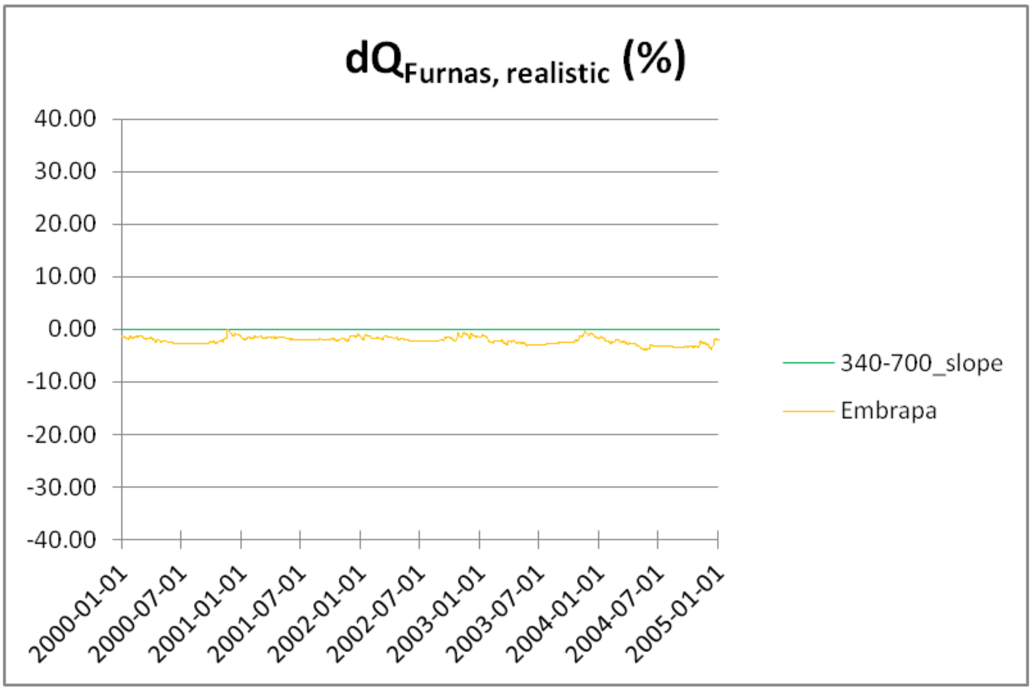

Figure 29: Relative changes in discharge at HPP Furnas for realistic scenarios over a 5-year simulation period (2000-2005). The 340-700-slope scenario was not affected by the sugarcane expansion.

Table 12: Relative changes in total volume at HPP Furnas for realistic scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-700_slope	0	0.0
Embrapa	$-1.1*10^{10}$	-1.8

The change in evapotranspiration at Furnas is similar to Funil for the realistic scenarios. Scenario 340-700_slope is still unchanged and the discharge line for Furnas, in Figure 30, follows the same pattern and amplitude as Funil. The total change in evapotranspiration for the simulation period is +2.6% (Table 13).

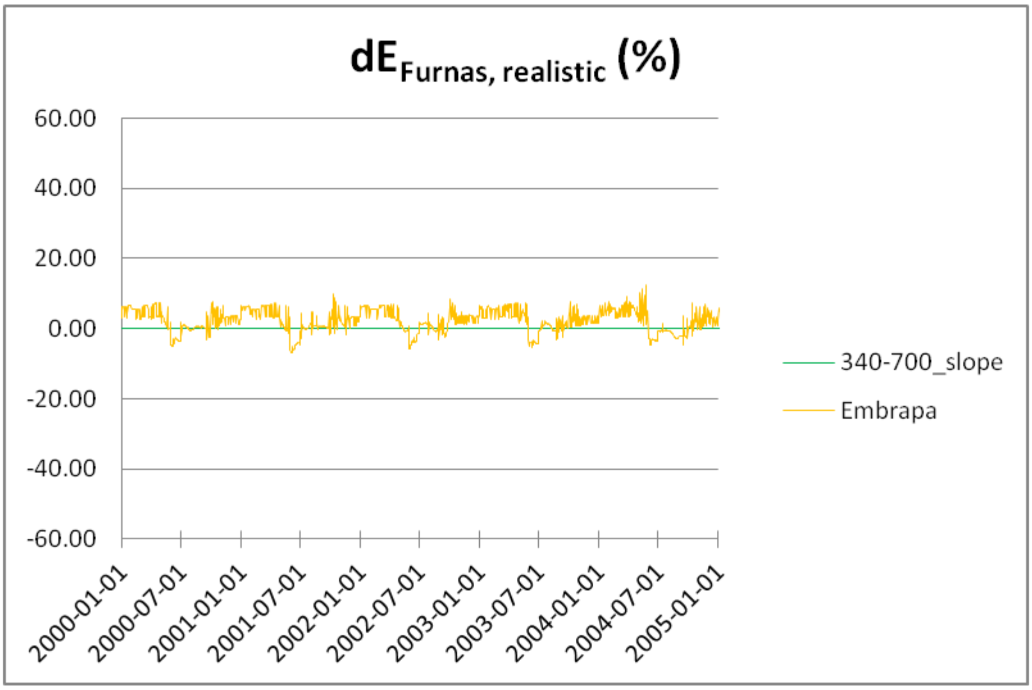

Figure 30: Relative changes in evapotranspiration at HPP Furnas for realistic scenarios, 5-year simulation period (2000-2005). The 340-700_slope scenario was not affected by the sugarcane expansion.

Table 13: Relative changes in evapotranspiration at HPP Furnas for realistic scenarios, 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-700_slope	0	0.0
Embrapa	339	2.6

3.4 HPP P. Colombia

HPP P. Colombia is located in the western part of sub basin 6 (Fig. 31). It receives water from sub basin 1, 2, 5 and 6. Sub basin 5 consists of approximately 41% pasture, 24% agriculture, 22% sugarcane and 14% forest. Almost all of the land in sub basin 5 is categorized as deep soils.

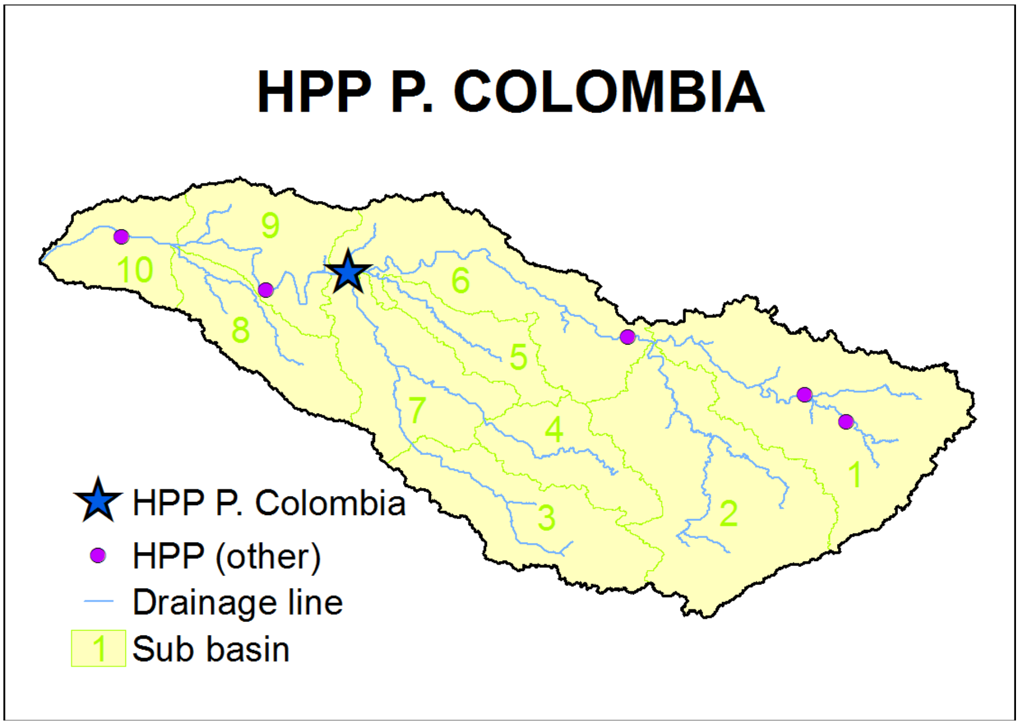

Figure 31: Map showing location of HPP P. Colombia.

For sub basin 6 the land use consists of 52% pasture. Forest and agriculture is made up by 18% each. Around 5% of the area is made up by water. More than 60% of the soil is categorized as deep in the sub basin, where pasture with deep soil makes up the largest fraction with 33 % for the control scenario. The most noticeable difference between sub basin 1 & 2 and sub basin 5 & 6 is that the amount of agriculture is much larger in 5 and 6, with 18-23 % compared to 4-12 %. Sub basin 1, 2, 5 and 6 are made up of mostly of deep soils, and pasture is the most common vegetation in the basin. The amount of pasture is approximately between 40% and 60% for the sub basins.

The hydrograph for P. Colombia can be seen in figure 32.

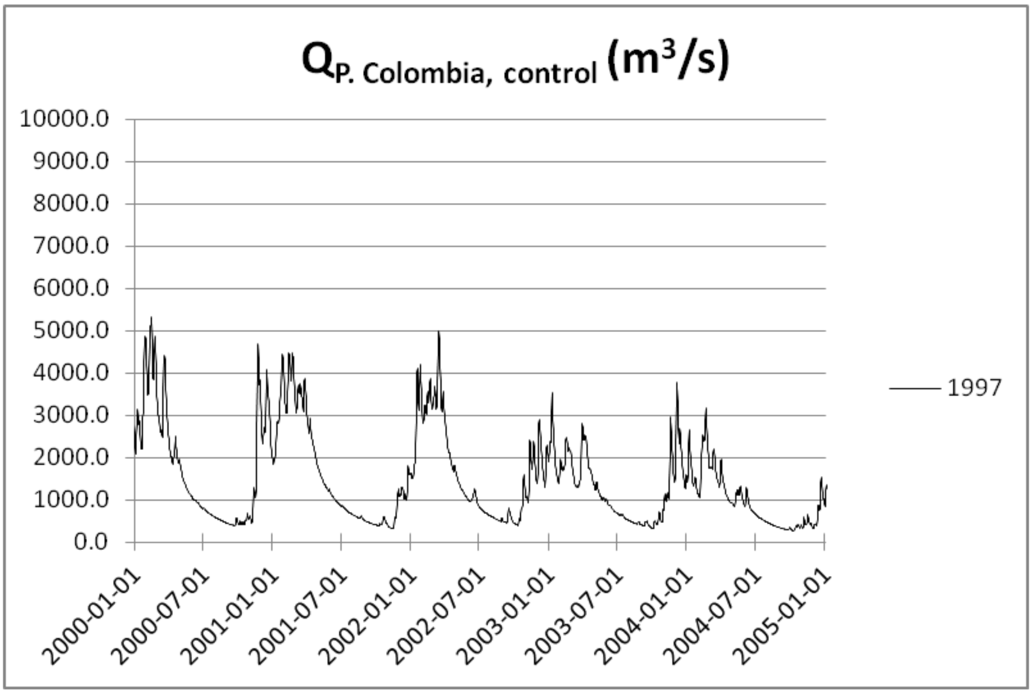

Figure 32: Discharge at HPP P. Colombia over a 5-year simulation period (2000-2005).

3.4.1 Expansion scenarios

P. Colombia is the first station for which all expansion scenarios affect the discharge. In the graph, Figure 33, scenario 340-1100 and 340-900 does not in general differentiate much from Furnas. Even though scenario 340-700 and 340-500 affects the discharge at P. Colombia, the changes are small. Both scenarios fluctuate around zero but scenario 340-700 has larger and more distinct peaks while 340-500 has a more flat discharge line.

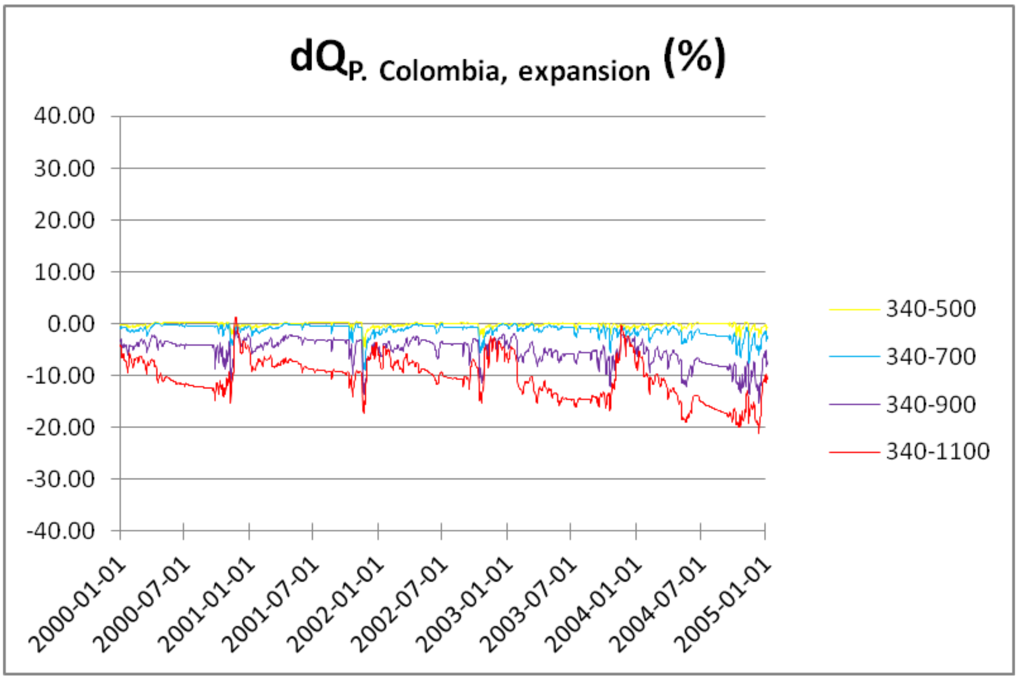

Figure 33: Relative changes in discharge at HPP P. Colombia for expansion scenarios over a 5-year simulation period (2000-2005).

All scenarios at P. Colombia show a decrease in total discharge volume over the simulation period compared to Furnas. Scenario 340-1100 and 340-900 decrease the discharge with 9.4% and 4.9% respectively. For scenario 340-700 the change is -1.1% and for 340-500 it is -0.2%, see Table 14.

Table 14: Relative changes in total volume at HPP P. Colombia for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m³)	dV (%)
340-500	$-2.1*10^{9}$	-0.2
340-700	$-9.7*10^{9}$	-1.1
340-900	$-4.0*10^{10}$	-4.9
340-1100	$-7.4*10^{10}$	-9.4

The evapotranspiration for scenario 340-1100 continue to show small differences compared to the river basins for the HPPs upstream. The amplitude of the peaks have somewhat decreased compared to Furnas. For scenario 340-900 there is no noticeable difference between the evapotranspiration line for P. Colombia and Furnas. Scenario 340-700 and 340-500 show a small increase in evapotranspiration, Fig 34.

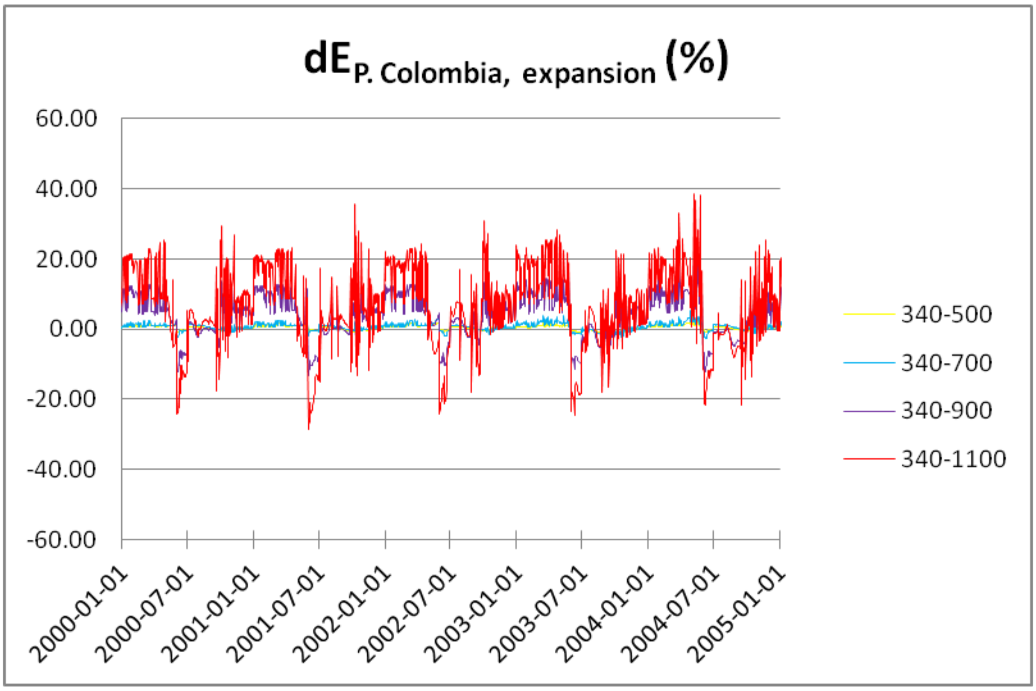

Figure 34: Relative changes in evapotranspiration at HPP P. Colombia for expansion scenarios over a 5-year simulation period (2000-2005).

Table 15 summarizes the changes in evapotranspiration at P. Colombia. The evapotranspiration increased with 6.7% for 340-1100 and 4.2% for 340-900 for the whole simulation period. The changes for scenario 340-700 and 340-500 were +0.8% and +0.5% respectively.

Table 15: Relative changes in total evapotranspiration at HPP P. Colombia for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-500	70	0.5
340-700	103	0.8
340-900	582	4.2
340-1100	953	6.7

3.4.2 Realistic scenarios

In figure 35 it can be seen that both realistic scenarios have impact on the discharge at P. Colombia. The graphs for the two scenarios differentiate somewhat from each other. The discharge line for scenario 340-700_slope is close to zero for most of the time but have large distinct peaks during storm period. For the Embrapa scenario, the discharge gradually decreases from the beginning of the year to October. From October, the discharge recovers before the year is over. For the whole simulation period the decrease in discharge is 1.1% for 340-700_slope and 2.5% for Embrapa (Table 16).

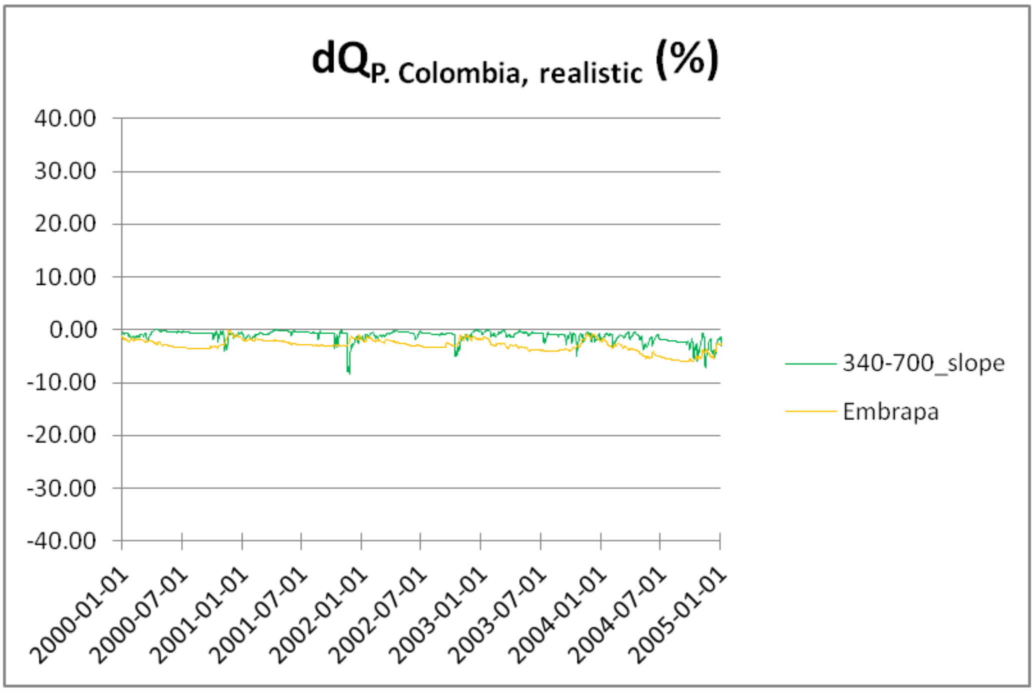

Figure 35: Relative changes in discharge at HPP P. Colombia for realistic scenarios over a 5-year simulation period (2000-2005).

Table 16: Relative changes in total volume at HPP P. Colombia for realistic scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-700_slope	$-9.3*10^9$	-1.1
Embrapa	$-2.0*10^{10}$	-2.5

Scenario 340-700_slope evapotranspiration show small variations for the simulation period see Fig. 36. During most of the simulation period the change in evapotranspiration is balanced just above zero. The change in evapotranspiration for Embrapa scenario seems to be similar as for Furnas. For the whole simulation period the increase is 0.7% for 340-700_slope and 2.5% for Embrapa scenario (Table 17).

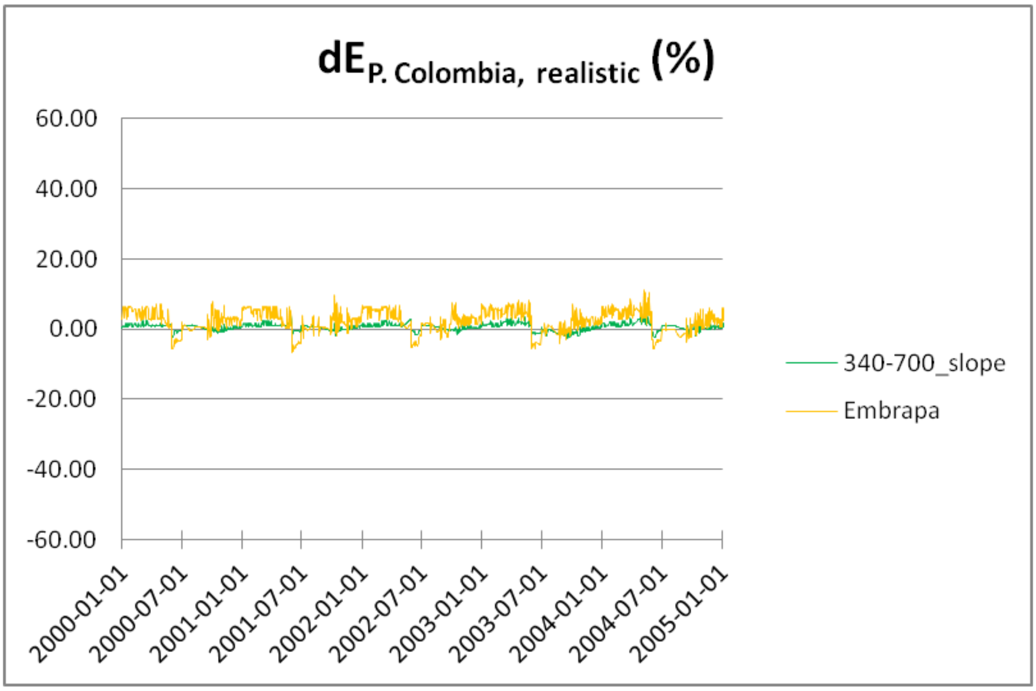

Figure 36: Relative changes in evapotranspiration at HPP P. Colombia for realistic scenarios, 5-year simulation period (2000-2005).

Table 17: Relative changes in evapotranspiration at HPP P. Colombia for realistic scenarios, 5-year simulation period (2000-2005).

Scenario	dE(mm)	dE (%)
340-700_slope	97	0.7
Embrapa	335	2.5

3.5 HPP Marimbondo

HPP Marimbondo is located in middle of sub basin 8 (Fig 37). Apart from half of sub basin 8 it receives runoff from 1, 2, 3, 4, 5, 6 and 7. Sub basin 3 constitutes of around 43% pasture, 27% percent sugarcane, 16% agriculture and 13% forest. Sub basin 4 is made up by 48% pasture, 21% sugarcane, 16% agriculture, 14% forest and 1% water. For sub basin 7 the area is made up by 46% sugarcane, 23% agriculture, 19% pasture, 11% forest and 1% water. Lastly, sub basin 8 composed by 36% pasture, 32% agriculture, 18% forest, 8% sugarcane and 5% water.

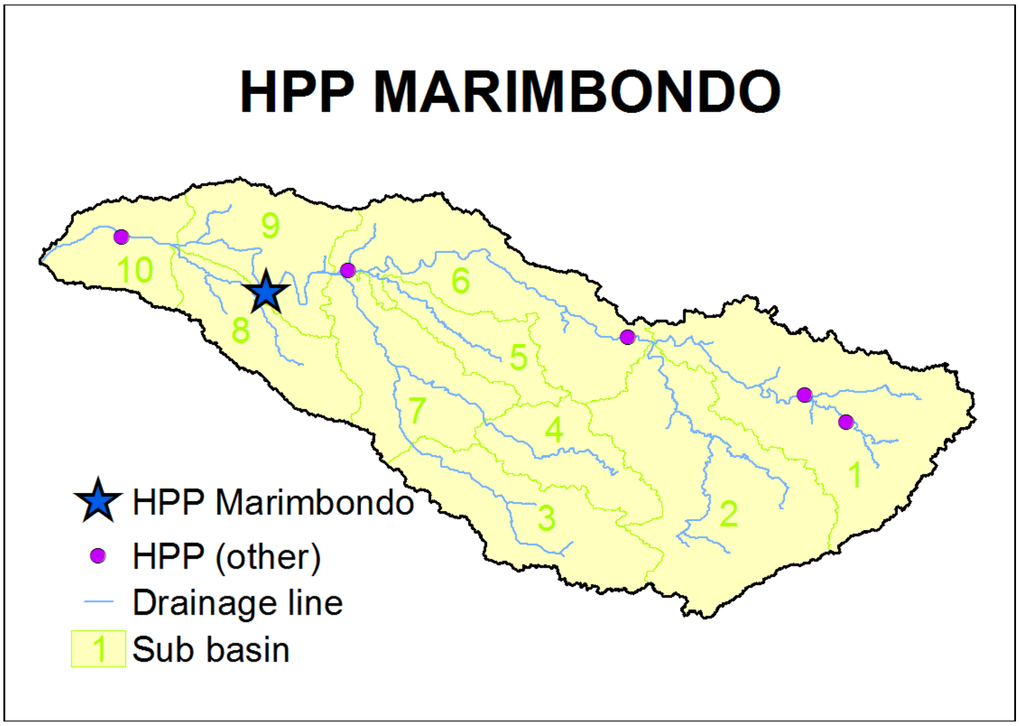

Figure 37: Map showing location of HPP Marimbondo.

The hydrograph for Marimbondo for the years 2000-2005 can be seen in figure 38.

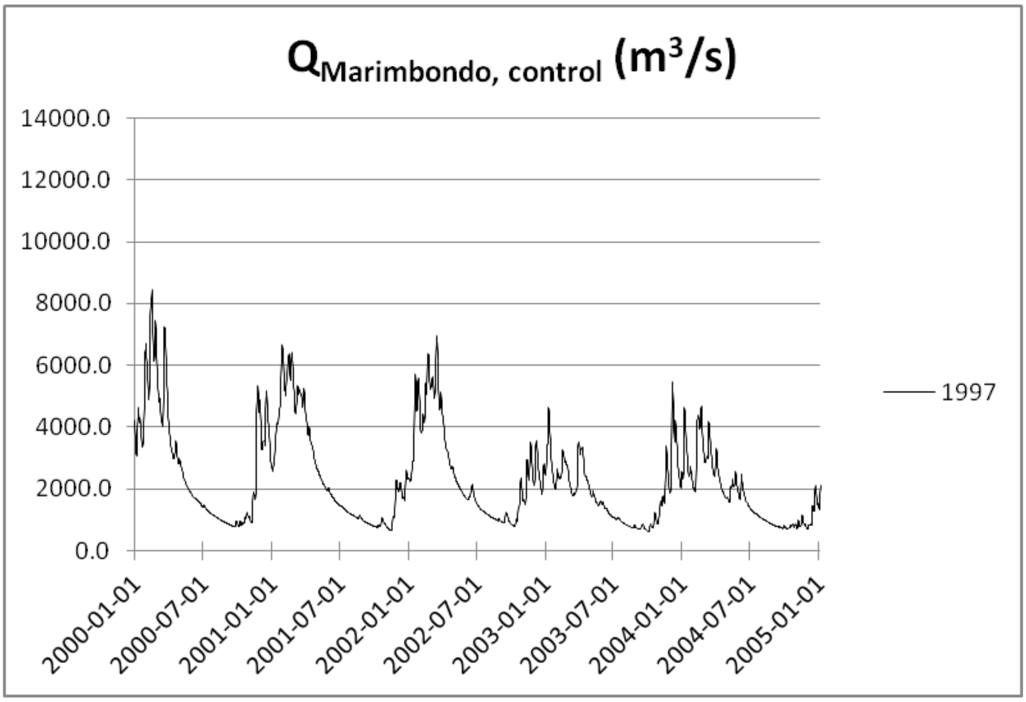

Figure 38: Discharge at HPP Marimbondo over a 5-year simulation period (2000-2005).

3.5.1 Expansion scenarios

The scenarios impact on discharge at Marimbondo is seen in figure 39. Compared to P. Colombia the change in discharge for the expansion scenarios is significantly smaller at Marimbondo. This is most apparent for scenario 340-1100 where the change in discharge varies between -5% and -10% for most of the time period at Marimbondo. For P. Colombia the change in discharge was around -10% but decreased all the way down to -20% in the end of 2004. The explanation for this is Rio Grande subsidiaries Pardo and Mogi-Gaucu contributes to Marimbondo. Pardo and Mogi-Guaco receives runoff from sub basins 3,4 and 7 where a large fraction of the vegetation consists of sugarcane and agriculture in the control scenario. Hence the percentage of sugarcane in all sub basins contributing to Marimbondo becomes smaller than it was for Porto Colombia.

For scenario 340-900, the difference between P. Colombia and Marimbondo is not as apparent as for 340-1100. However, the impact is still smaller at Marimbondo which is, just like for scenario 340-1100, most noticeable in the end 2004. For scenario 340-700 and 340-500, the change in discharge is similar at Marimbondo as it is at P. Colombia.

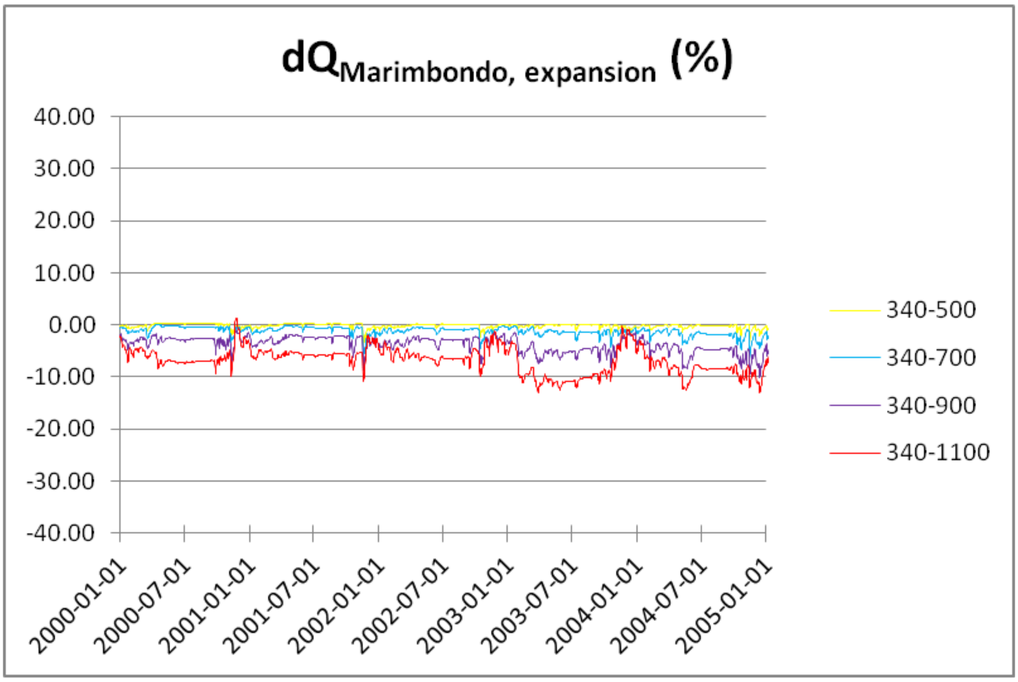

Figure 39: Relative changes in discharge at HPP Marimbondo for expansion scenarios over a 5-year simulation period (2000-2005).

Table 18 gives the change in discharge for the entire simulation period. Scenario 340-1100 decreases the discharge with 6.4% while 340-900 decreases it with 3.7%. For scenario 340-700 and 340-500 the change in discharge is -1.2% and -0.2% respectively.

Table 18: Relative changes in total volume at HPP Marimbondo for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-500	$-3.3*10^9$	-0.2
340-700	$-1.6*10^{10}$	-1.2
340-900	$-4.9*10^{10}$	-3.7
340-1100	$-8.3*10^{10}$	-6.4

The graph describing changes in evapotranspiration for Marimbondo (Fig 40) seems to be similar to the graph for P. Colombia. As shown in Table 15 and Table 19 there is almost no change in evapotranspiration between P. Colombia and Marimbondo. For scenario 340-1100 and 340-900, the increase in evapotranspiration is 6.7% and 4.2% respectively. Scenario 340-700 shows an increase by 0.8% while the increase for 340_500 is 0.5%.

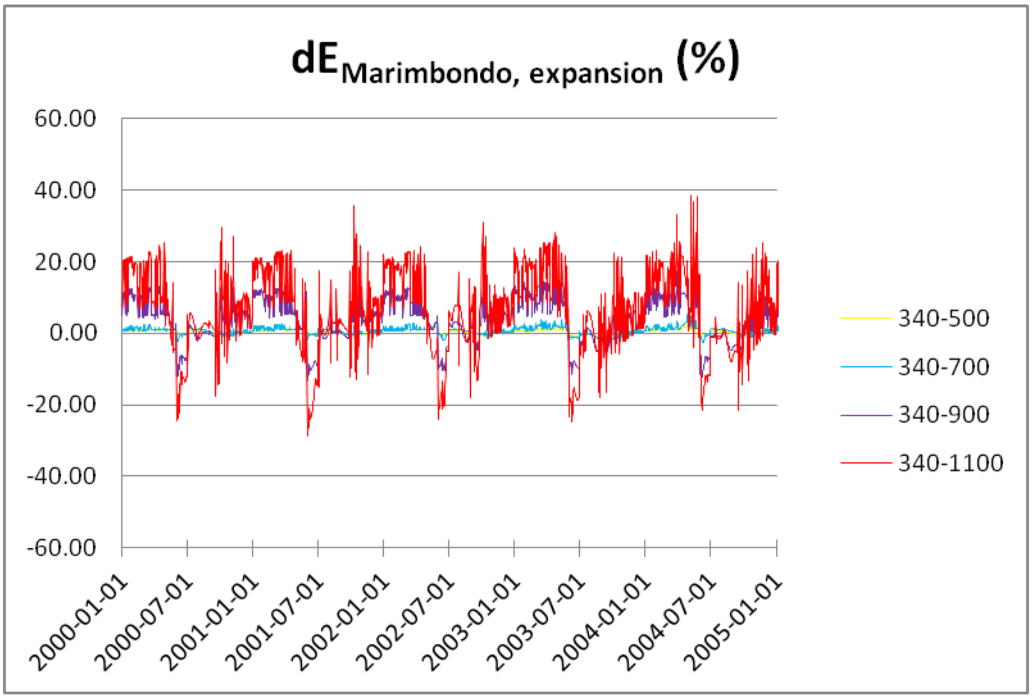

Figure 40: Relative changes in evapotranspiration at HPP Marimbondo for expansion scenarios over a 5-year simulation period (2000-2005).

Table 19: Relative changes in total evapotranspiration at HPP Marimbondo for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-500	49	0.5
340-700	72	0.8
340-900	404	4.2
340-1100	662	6.7

3.5.2 Realistic scenarios

The impact for the realistic scenarios on Marimbondo is, as for the expansion scenarios, somewhat smaller than for P. Colombia. For scenario 340-700_slope the discharge line follows fairly well the one for P. Colombia with the exception that the large peaks are smaller. Most noticeable is the large peak in the end of 2001 at P. Colombia which is about half the size at Marimbondo. The discharge line for Embrapa scenario is a bit higher and the peaks are even flatter if compared with P. Colombia. The change in volume for scenario 340-700_slope and Embrapa is -1.2% and -2.0% respectively (Table 20).

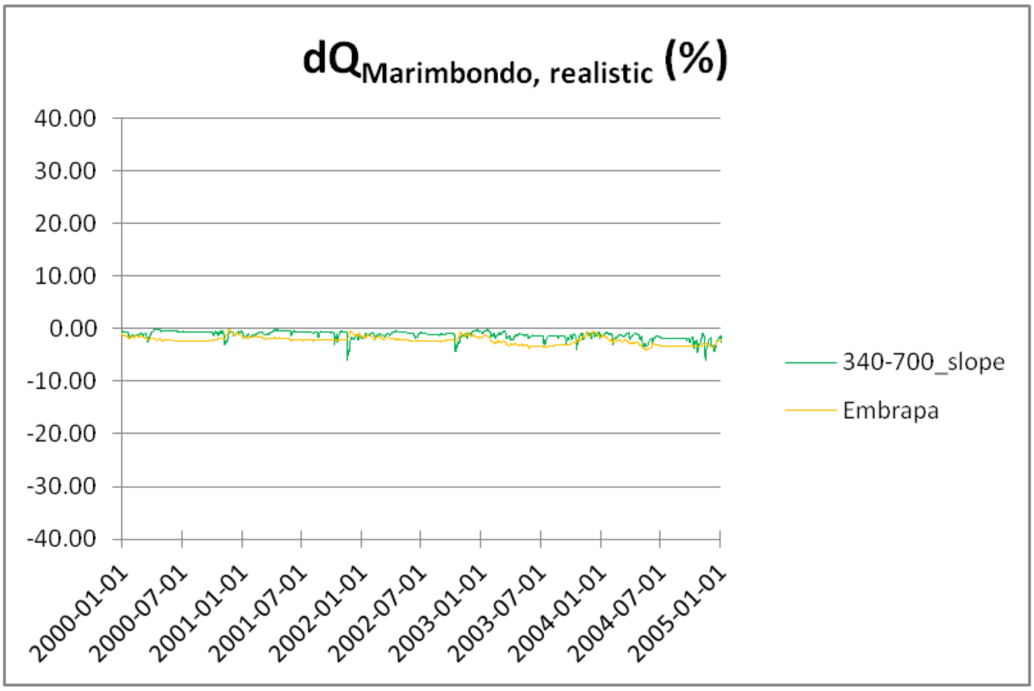

Figure 41: Relative changes in discharge at HPP Marimbondo for realistic scenarios over a 5-year simulation period (2000-2005).

Table 20: Relative changes in total volume at HPP Marimbondo for realistic scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-700_slope	$-1.7*10^{10}$	-1.2
Embrapa	$-2.7*10^{10}$	-2.0

Like the expansion scenarios, the realistic scenarios seem to have changed evapotranspiration for Marimbondo as much as for P. Colombia. The evapotranspiration line for 340-700_slope and Embrapa seem to be identical for the both HPPs (Fig 42). Scenario 340-700_slope increase the evapotranspiration with 0.7%. For the scenario Embrapa, the increase is 2.5%, see table 21.

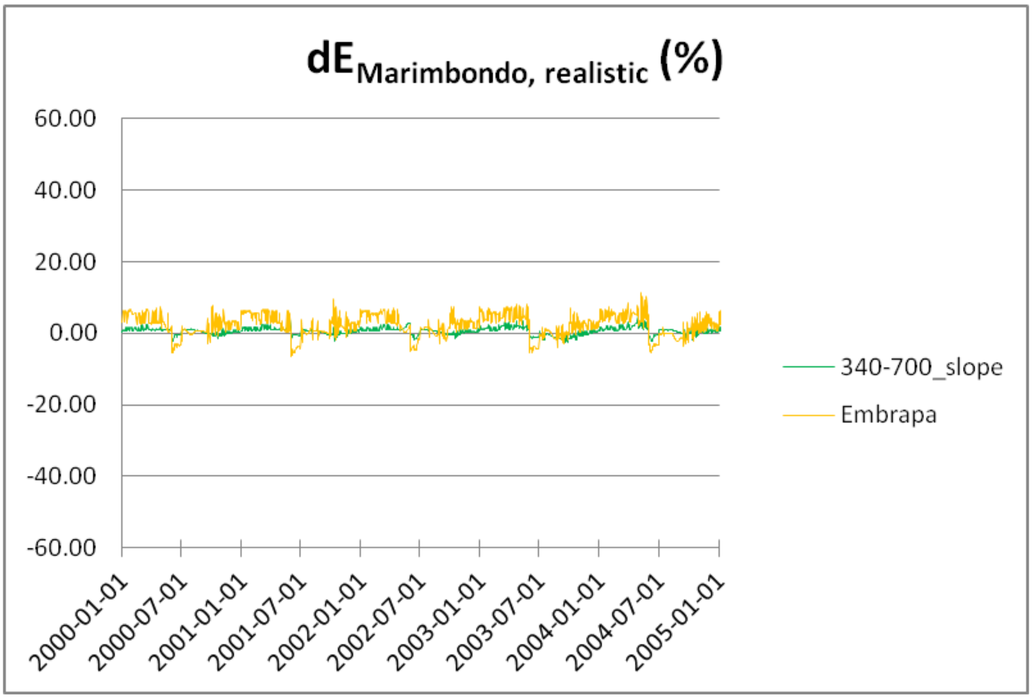

Figure 42: Relative changes in evapotranspiration at HPP Marimbondo for realistic scenarios, 5-year simulation period (2000-2005).

Table 21: Relative changes in evapotranspiration at HPP Marimbondo for realistic scenarios, 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-700_slope	67	0.7
Embrapa	233	2.5

3.6 HPP A. Vermelha

HPP A. Vermelha is the last station in Rio Grande basin. As can be seen in figure 43 it is located close to the outlet of Rio Grande basin, in sub basin 10. It receives runoff from all sub basins in Rio Grande, 1-10. Sub basin 9 consists of 37% pasture, 36% agriculture, 16% forest and 11% sugarcane. For sub basin 10 the land use is made up by 38% pasture, 31% agriculture, 16% forest and 6% sugarcane.

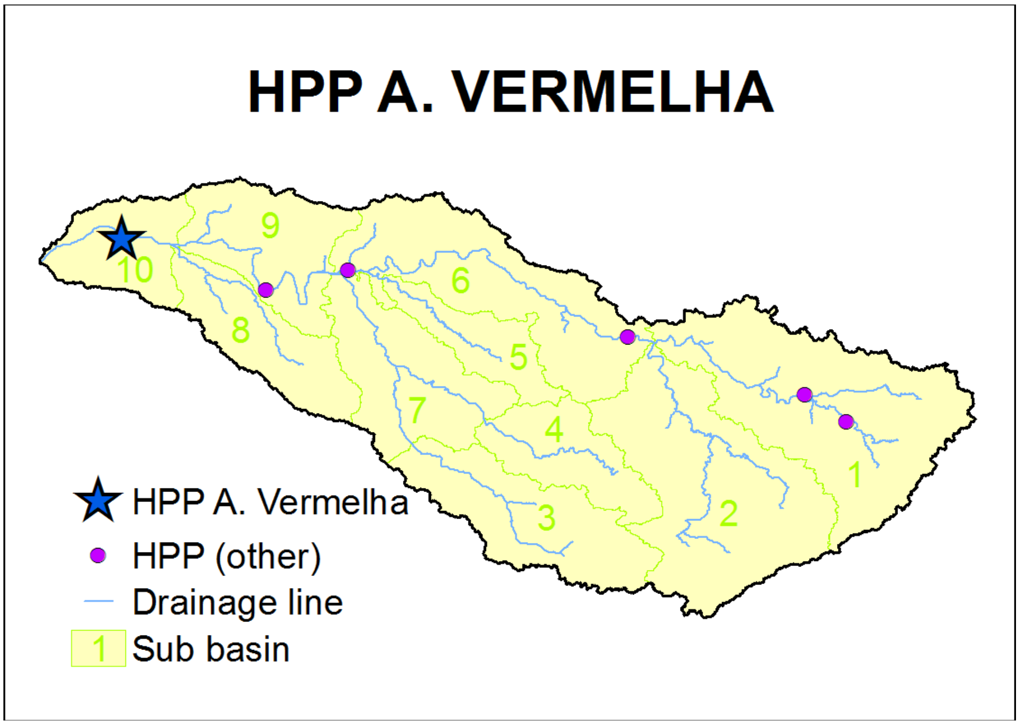

Figure 43: Map showing location of HPP A. Vermelha.

The hydrograph for A. Vermelha can be seen in figure 44 below.

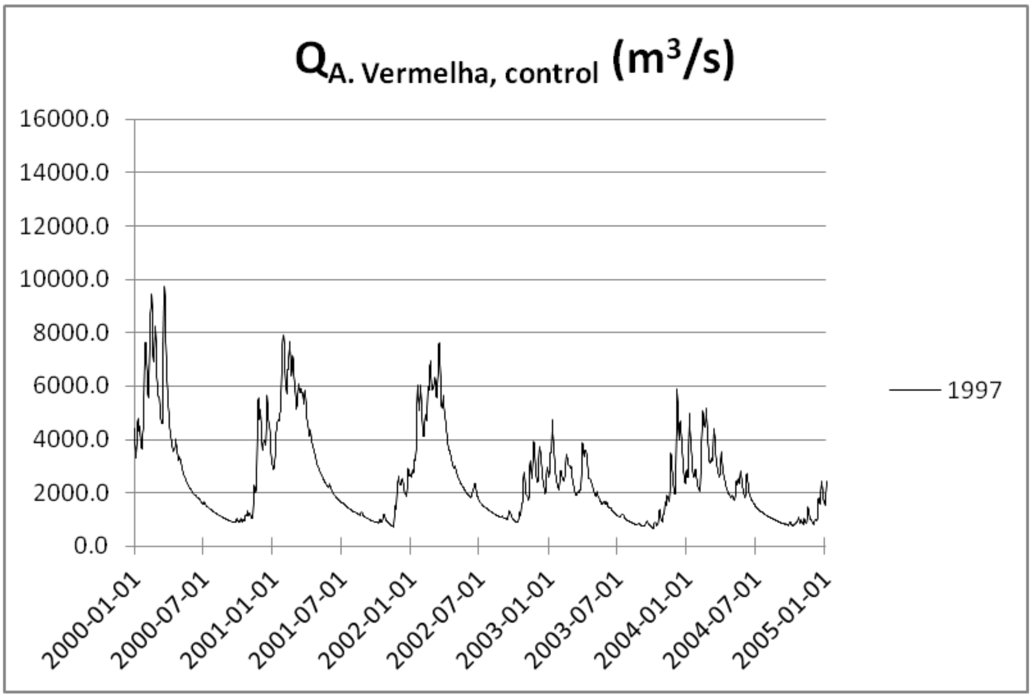

Figure 44: Discharge at HPP A. Vermelha over a 5-year simulation period (2000-2005).

3.6.1 Expansion scenarios

The change in discharge at A. Vermelha is shown in figure 45. The result for the 340-1100 scenario is similar to that of HPP Marimbondo. In general, the discharge line follows each other at the two stations with the difference that the peaks are larger at A. Vermelha. This is probably related to lower soil water storage, which causes more surface runoff. For scenario 340-900 the difference between the two stations even smaller as the peaks has not increased in amplitude at A. Vermelha compared with Marimbondo. Scenarios 340-700 and 340-500 have decreased slightly more at A. Vermelha compared to Marimbondo.

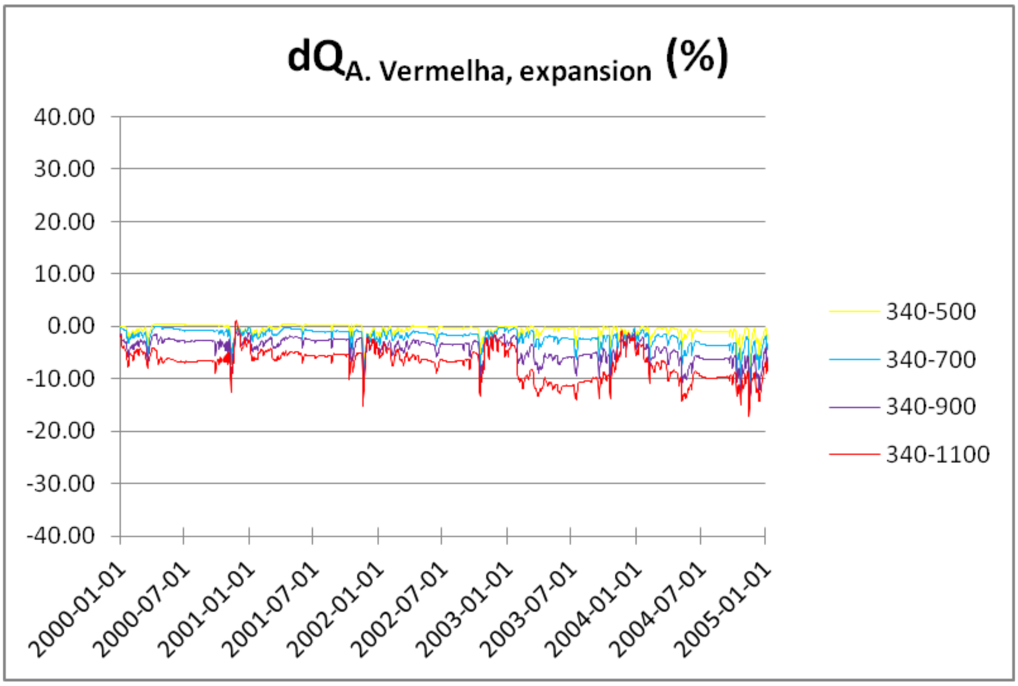

Figure 45: Relative changes in discharge at HPP A. Vermelha for expansion scenarios over a 5-year simulation period (2000-2005).

In table 22 it can be seen that the change in total volume for scenario 340-1100 at A. Vermelha has decreased with 6.7%. For scenario 340-900 and 340-700 the decrease in volume is 4.3% and 2.0% respectively. Finally, scenario 340-500 decreased with 0.8%.

Table 22: Relative changes in total volume at HPP A. Vermelha for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-500	$-1.2*10^{10}$	-0.8
340-700	$-3.1*10^{10}$	-2.0
340-900	$-6.3*10^{10}$	-4.3
340-1100	$-9.7*10^{10}$	-6.7

In Figure 46, the change in evapotranspiration for scenario 340-1100 is lower at A. Vermelha compared to Marimbondo. Even though the evapotranspiration line is lower for A. Vermelha the amplitude of the peaks has increased. For scenario 340-900, the amplitude of the peaks is a bit larger but apart from that the change in evapotranspiration seems to be similar to A. Vermelha. Scenario 340-700 and 340-500 have in contrast to the scenarios mentioned increased in evapotranspiration. Both the evapotranspiration line and the amplitude of the peaks are significant larger for A. Vermelha compared to Marimbondo.

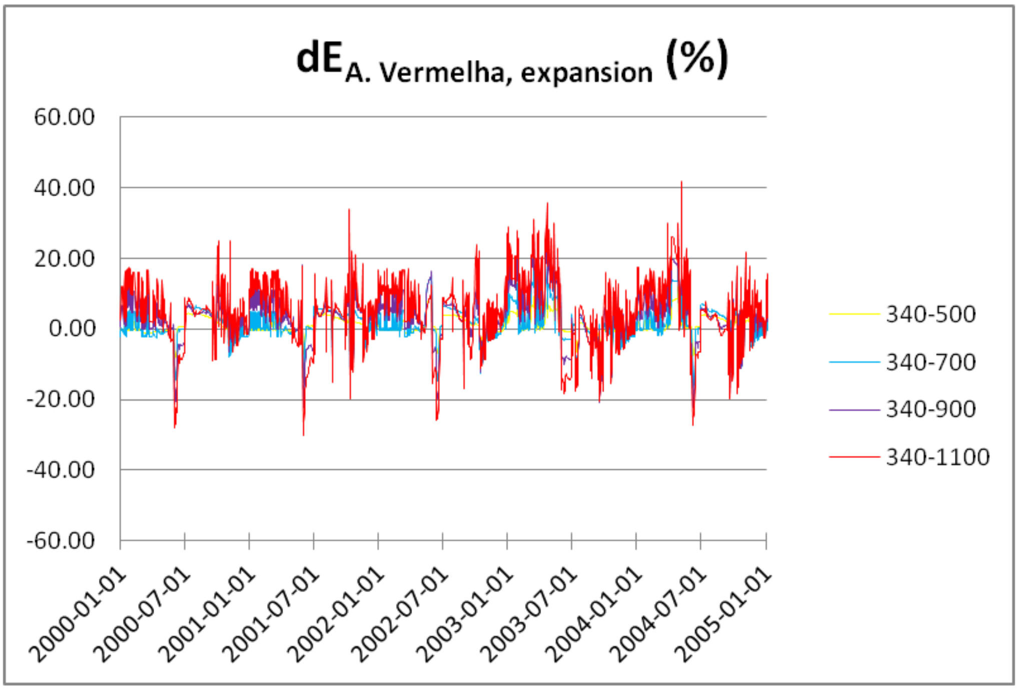

Figure 46: Relative changes in evapotranspiration at HPP A. Vermelha for expansion scenarios over a 5-year simulation period (2000-2005).

Table 23 confirms what the graph above indicated. The change in evapotranspiration for the entire period is +4.9%, which is less than the change for Marimbondo. Scenario 340-900, 340-700 and 340-500 has increased the discharge more at A. Vermelha compared to Marimbondo. The changes for these scenarios were +3.5%, +1.4% and +0.8%.

Table 23: Relative changes in total evapotranspiration at HPP A. Vermelha for expansion scenarios over a 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-500	105	0.8
340-700	192	1.4
340-900	493	3.5
340-1100	710	4.9

3.6.2 Realistic scenarios

The relative change in discharge for HPP Agua Vermelha for the realistic scenarios is shown in figure 47 below. The discharge 340-700_slope for A. Vermelha decreased significant compared with Marimbondo. At Marimbondo most peaks did not fall lower than -5% while it's not uncommon for peaks at A. Vermelha to reach -10%. The changes for Embrapa scenario is not as apparent as it is for 340-700_slope. The discharge line is slightly lower at A. Vermelha than it is for Marimbondo. In addition, the differences between minimum and maximum peaks are larger for A. Vermelha. For the simulation period the change in volume was -2.0% for scenario 340-700_slope and -2.3% for Embrapa, see table 24.

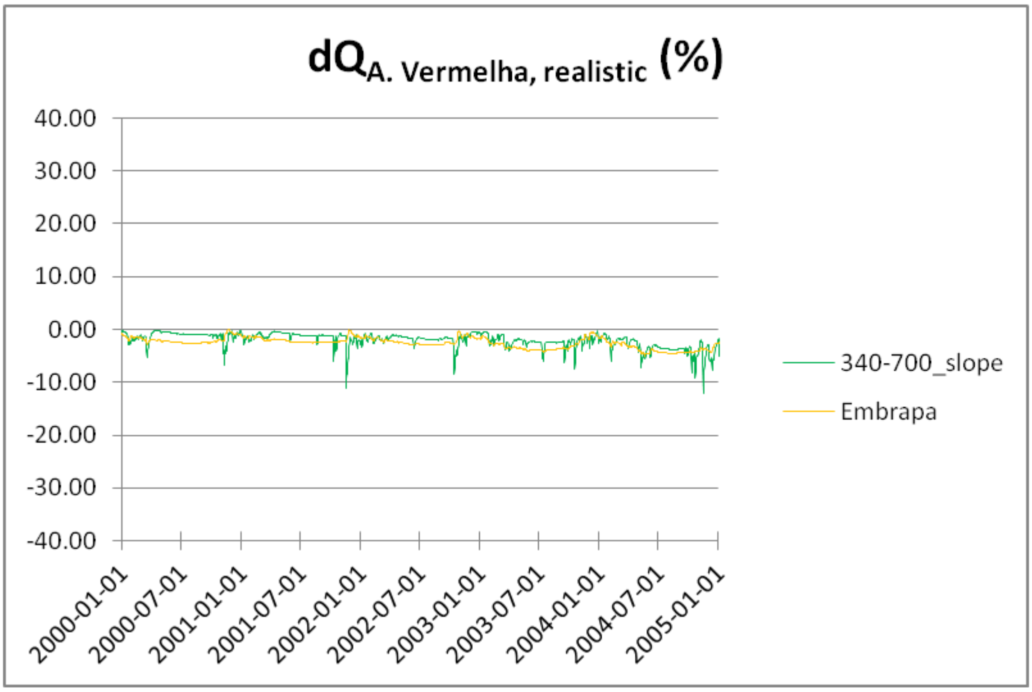

Figure 47: Relative changes in discharge at HPP A. Vermelha for realistic scenarios over a 5-year simulation period (2000-2005).

Table 24: Relative changes in total volume at HPP A. Vermelha for realistic scenarios over a 20-year simulation period (1990-2010).

Scenario	dV (m^3)	dV (%)
340-700_slope	$-3.1*10^{10}$	-2.0
Embrapa	$-3.5*10^{10}$	-2.3

The changes in evapotranspiration, for the two realistic scenarios, differentiate between A. Vermelha and Marimbondo. At A. Vermelha the amplitude of the peaks is significantly larger which is most noticeable for scenario 340-700_slope (Fig 48). For scenario 340-700_slope, the evapotranspiration line is flat while at A. Vermelha the peaks are clearly visible and the most extreme peaks are larger than for Embrapa scenario. The change in evapotranspiration for the whole simulation period is +1.4% for scenario 340-700_slope and +2.2% for Embrapa scenario (Table 25).

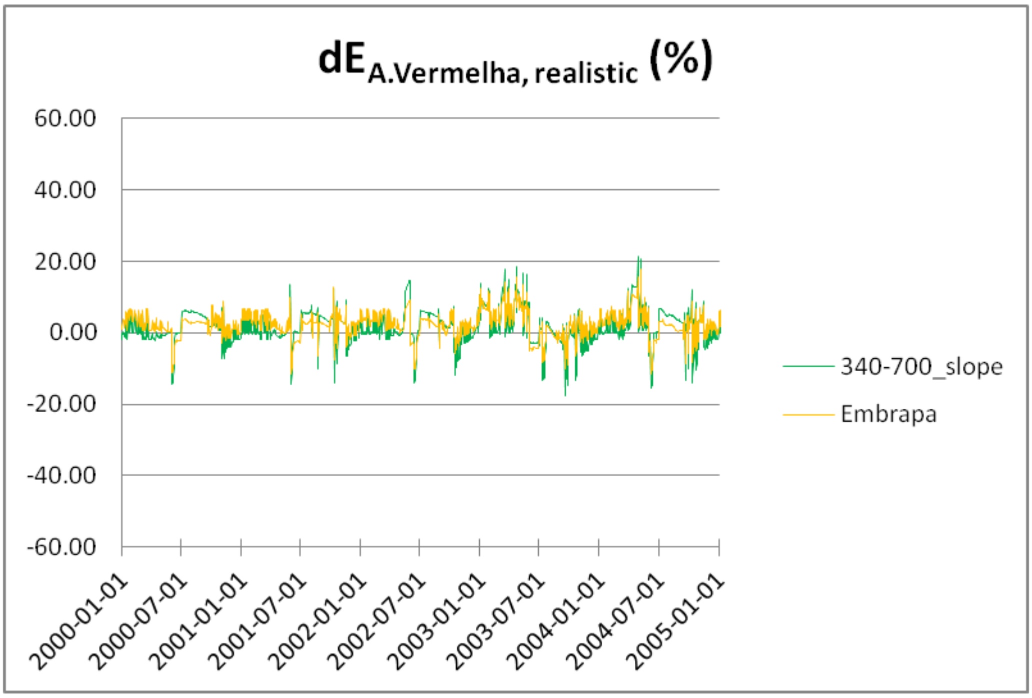

Figure 48: Relative changes in evapotranspiration at HPP A. Vermelha for realistic scenarios, 5-year simulation period (2000-2005).

Table 25: Relative changes in evapotranspiration at HPP A. Vermelha for realistic scenarios, 20-year simulation period (1990-2010).

Scenario	dE(mm)	dE (%)
340-700_slope	194	1.4
Embrapa	312	2.2

4 Conclusions

The results from this study have shown that sugarcane expansion in the Rio Grande basin have significant impact on hydrology and local climate. Gradually expanding sugarcane in the river basin resulted in a very clear trend of decreased surface runoff and increased evapotranspiration. These 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%. This implies that Rio Grande basin is very sensitive for sugarcane related land use changes. However, compared with Nóbrega et al. (2011) study on climate change impact on runoff it seems like Rio Grande basin is more sensitive for the latter.

It also seems as the eastern part of Rio Grande basin is more sensitive for land use changes compared to the western side. In the eastern mountainous part, the vegetation mainly consists of pasture while in the western parts agricultural land becomes more common. Converting pasture to sugarcane gives a higher evapotranspiration rate compared to conversion from agricultural land. The increased evapotranspiration rate will reduce surface runoff. Hence, the impact on discharge for the hydropower plants situated in eastern parts of Rio Grande basin is more severe than for the HPPs located in the west.

The changes in surface runoff and evapotranspiration rate for the sugarcane converted land are not constant over the entire simulation period. The decrease in runoff is greater during the austral winter but recover most of the loss during the storms in the summer. The soil water capacity for sugarcane on shallow soil is the same, or lower, than for the other vegetation types on shallow soil. This actually increases the runoff during the rainy summer months, as the soil can store less water, which can be seen in the results for the HPPs in the eastern part of the basin. As a result the discharge increases in the summer months due to the heavy rainfalls, and decreases during the winter when the evapotranspiration increases. This seasonal variation is unfortunate as the decrease coincide with the dry winter season that lowers the already low reservoirs. Therefore, even if the decrease in runoff for the total simulation period is small it could increase the risk for droughts significantly.

The change in evapotranspiration rate for the sugarcane scenarios is not constant throughout the simulation period. Effects of the sugarcanes marked annual cycle can be clearly seen in the evapotranspiration graphs. From being larger than the control scenario in the beginning of the year the evapotranspiration rapidly decrease and become significantly lower after the sugarcane harvest. However, the evapotranspiration recovers to the same level it was at before harvest when new crops start to grow. The effect of the harvest period on runoff can best be seen at the hydropower plants in the eastern part of the river basins (HPP Camargos, HPP Funil and HPP Furnas). After harvest in May there is a minor increase in relative discharge for almost all years in the graphs, which is caused by the decrease in evapotranspiration that occurs after harvest. The big change in relative discharge from February to June is, however, caused by the colder and dryer climate.

For a likely future scenario, the largest changes in runoff occurred at HPP P. Colombia where the discharge decreased with 2.5%. The evapotranspiration for the realistic future scenario increased most for the area upstream HPP Furnas with 2.6%. Considering how sensitive the hydrology in Rio Grande basin is where only a small precipitation deficit caused severe draught and energy crisis in 2001 it can be assumed that the ongoing sugarcane expansion will cause some damage on the hydropower generation.

Our recommendation to the people responsible for planning new sugarcane plantations in Rio Grande would be to focus on making agriculture more effective and converting agricultural to sugarcane on lands that becomes left over from this process rather than expand over pasture. For future projects it would be interesting to continue evaluate sugarcane expansion together with climate changes effects on surface runoff as these two phenomena seems to counteract each other.

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Appendix A. MGB-IPH fixed parameters

Table 26: Complete list of the fixed parameters for the MGB-IPH model adopted according to Collishonn (2007). The fixed parameters are albedo, leaf area index, height of trees and canopy resistance. Values of the fixed parameters are given for each land use combination. The nine land use combination are shallow pasture, deep pasture, shallow sugarcane, shallow agriculture, shallow forest, deep agriculture, deep forest, deep sugarcane and water.

Albedo

Land/Soil	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Pasture_shallow	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Pasture_deep	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Sugarcane_shallow	0.28	0.28	0.29	0.31	0.31	0.24	0.25	0.25	0.25	0.27	0.27	0.27
Agricult_shallow	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Forest_shallow	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Agriculture_deep	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Forest_deep	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Sugarcane_deep	0.28	0.28	0.29	0.31	0.31	0.24	0.25	0.25	0.25	0.27	0.27	0.27
Water	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Leaf area index

Land/Soil	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Pasture_shallow	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Pasture_deep	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Sugarcane_shallow	7.00	7.00	8.00	9.00	9.00	3.00	5.00	5.00	5.00	6.00	6.00	6.00
Agricult_shallow	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Forest_shallow	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Agricult_deep	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Forest_deep	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Sugarcane_deep	7.00	7.00	8.00	9.00	9.00	3.00	5.00	5.00	5.00	6.00	6.00	6.00
Water	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Height of trees

Land/Soil	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Pasture_shallow	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Pasture_deep	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Sugarcane_shallow	3.60	3.60	3.80	3.80	3.80	0.50	1.20	1.20	1.20	2.80	2.80	2.80
Agricult_shallow	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Forest_shallow	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Agricult_deep	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Forest_deep	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Sugarcane_deep	3.60	3.60	3.80	3.80	3.80	0.50	1.20	1.20	1.20	2.80	2.80	2.80
Water	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

Canopy resistance

Land/Soil	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Pasture_shallow	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Pasture_deep	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Sugarcane_shallow	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Agricult_shallow	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Forest_shallow	100	100	100	100	100	100	100	100	100	100	100	100
Agricult_deep	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Forest_deep	100	100	100	100	100	100	100	100	100	100	100	100
Sugarcane_deep	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Water	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix B. MGB-IPH adjustable parameters

Table 27: Complete list of the adjustable parameters for the MGB-IPH model calibrated by Pereira et al. (Submitted). The parameters were calibrated for each land use combination and sub basin using trial and error method. The adjustable parameters are maximum water storage in soil (Wm), GRU parameter b (b), drainage rates of water to groundwater for saturated soils (Kbas), drainage rates of water to subsurface flow for saturated soils (Kint), surface flow retention time (CS), subsurface flow retention time (CI) and groundwater flow retention time (CB). Values for parameter XL, CAP and Wc were adopted and not calibrated. The nine land use combination are shallow pasture, deep pasture, shallow sugarcane, shallow agriculture, shallow forest, deep agricultur, deep forest, deep sugarcane and water.

```
Sub basin 1;3-10
Land/Soil                Wm      b    Kbas    Kint      XL     CAP      Wc
Pasture_shallow       150.0   0.15    0.05    8.00    0.60    0.00    0.05
Pasture_deep          900.0   0.15    0.05    8.00    0.60    0.00    0.05
Sugarcane_shallow     125.0   0.15    0.05    8.00    0.60    0.00    0.05
Agriculture_shallow   125.0   0.15    0.05    8.00    0.60    0.00    0.05
Forest_shallow        220.0   0.15    0.05    8.00    0.60    0.00    0.05
Agriculture_deep      950.0   0.15    0.05    8.00    0.60    0.00    0.05
Forest_deep          1100.0   0.15    0.05    8.00    0.60    0.00    0.05
Sugarcane_deep        900.0   0.15    0.05    8.00    0.60    0.00    0.05
Water                   0.0   0.00    0.00    0.00    0.00    0.00    0.00
CS            12.00
CI           200.00
CB          3200.00
QB_M3/SKM2     0.0100

Sub basin 2
Land/Soil                Wm      b    Kbas    Kint      XL     CAP      Wc
Pasture_shallow       150.0   0.15    0.05    8.00    0.60    0.00    0.05
Pasture_deep          900.0   0.15    0.05    8.00    0.60    0.00    0.05
Sugarcane_shallow     125.0   0.15    0.05    8.00    0.60    0.00    0.05
Agriculture_shallow   125.0   0.15    0.05    8.00    0.60    0.00    0.05
Forest_shallow        220.0   0.15    0.05    8.00    0.60    0.00    0.05
Agriculture_deep      950.0   0.15    0.05    8.00    0.60    0.00    0.05
Forest_deep          1100.0   0.15    0.05    8.00    0.60    0.00    0.05
Sugarcane_deep        900.0   0.15    0.05    8.00    0.60    0.00    0.05
Water                   0.0   0.00    0.00    0.00    0.00    0.00    0.00
CS            14.00
CI            50.00
CB          7000.00
QB_M3/SKM2     0.0100
```

Appendix C. Land use distribution for scenarios

Table 28: Land use distribution for the generated control, expansion and realistic scenarios. The land use is described in percentage for each of the ten sub basins. The nine land use combinations are shallow sugarcane, deep sugarcane, shallow pasture, deep pasture, shallow forest, deep forest, shallow agriculture, deep agriculture and water.

Sub basin 1

Scenario	Sugarcane		Pasture		Forest		Agriculture		Water
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	0.1	0.1	51.4	25.9	11.5	6.5	0.6	0.3	3.7
340-500	0.1	0.1	51.4	25.9	11.5	6.5	0.6	0.3	3.7
340-700	0.1	0.1	51.4	25.9	11.5	6.5	0.6	0.3	3.7
340-900	12.3	11.1	41.9	17.9	9.4	4.6	0.4	0.1	2.3
340-1100	46.9	31.5	12.9	1.7	4.2	0.5	0.2	0.0	2.1
340-700_s	0.1	0.1	51.4	25.9	11.5	6.5	0.6	0.3	3.7
Embrapa	6.2	7.9	46.4	19.5	10.5	5.3	0.5	0.2	3.5

Sub basin 2

Scenario	Sugarcane		Pasture		Forest		Agriculture		Water
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	0.4	1.6	23.6	45.5	8.8	12.5	1.7	2.2	3.8
340-500	0.4	1.6	23.6	45.5	8.8	12.5	1.7	2.2	3.8
340-700	0.4	1.6	23.6	45.5	8.8	12.5	1.7	2.2	3.8
340-900	10.7	28.8	15.1	23.0	7.6	9.4	1.4	1.4	2.7
340-1100	23.8	51.0	5.8	6.2	4.6	4.9	0.6	0.4	2.7
340-700_s	0.4	1.6	23.6	45.5	8.8	12.5	1.7	2.2	3.8
Embrapa	3.6	11.0	20.7	37.2	8.5	11.7	1.6	2.0	3.7

Sub basin 3

Scenario	Sugarcane		Pasture		Forest		Agriculture		Water
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	6.6	21.1	15.0	27.6	5.0	7.9	3.6	12.9	0.3
340-500	6.6	21.3	15.0	27.5	5.0	7.9	3.6	12.8	0.3
340-700	12.4	52.1	12.3	10.9	4.3	3.4	1.1	3.3	0.1
340-900	19.5	64.7	7.0	3.2	3.0	1.4	0.7	0.4	0.0
340-1100	24.3	67.8	3.8	1.1	1.7	0.7	0.3	0.1	0.0
340-700_s	12.0	49.6	12.6	12.1	4.4	4.0	1.2	4.0	0.1
Embrapa	9.8	40.4	12.9	14.8	4.6	5.2	2.9	9.1	0.2

Sub basin 4

Scenario	**Sugarcane**		**Pasture**		**Forest**		**Agriculture**		**Water**
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	2.8	18.3	26.9	21.4	8.6	5.5	5.1	10.6	0.7
340-500	2.8	18.4	26.9	21.4	8.6	5.5	5.1	10.5	0.7
340-700	6.0	39.2	24.9	10.5	8.2	2.8	4.5	3.4	0.6
340-900	20.2	48.7	15.5	5.3	5.7	1.3	2.3	0.5	0.4
340-1100	30.4	52.6	8.9	2.4	3.4	0.7	1.1	0.2	0.4
340-700_s	5.5	36.8	25.2	11.5	8.3	3.4	4.6	4.1	0.6
Embrapa	10.0	30.1	21.7	13.9	7.9	3.9	4.0	7.9	0.6

Sub basin 5

Scenario	**Sugarcane**		**Pasture**		**Forest**		**Agriculture**		**Water**
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	0.5	21.1	6.5	34.3	2.8	10.8	2.2	21.4	0.3
340-500	0.5	22.0	6.5	34.2	2.8	10.5	2.2	21.1	0.2
340-700	6.3	25.5	1.2	2.1	2.5	14.8	8.0	39.6	0.1
340-900	9.0	68.9	1.8	10.0	0.7	3.5	0.6	5.5	0.0
340-1100	11.5	86.3	0.3	0.6	0.1	0.4	0.1	0.5	0.0
340-700_s	1.0	38.4	6.4	25.9	2.6	8.3	2.1	15.2	0.1
Embrapa	2.1	46.7	5.5	19.1	2.6	7.3	1.9	14.6	0.1

Sub basin 6

Scenario	**Sugarcane**		**Pasture**		**Forest**		**Agriculture**		**Water**
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	0.5	6.5	19.2	33.0	6.9	11.0	4.6	13.2	5.1
340-500	0.5	9.9	19.2	31.8	6.9	10.5	4.6	12.6	4.1
340-700	4.1	30.5	17.5	21.8	6.1	7.1	3.7	6.6	2.6
340-900	17.6	51.5	9.5	9.3	3.2	2.8	1.4	2.4	2.4
340-1100	26.8	62.8	3.4	2.1	0.9	0.7	0.4	0.5	2.4
340-700_s	3.5	28.1	17.8	22.8	6.3	7.9	3.8	7.1	2.8
Embrapa	9.2	31.2	13.8	17.5	5.5	7.5	2.6	7.7	5.0

Sub basin 7

Scenario	Sugarcane		Pasture		Forest		Agriculture		Water
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	2.2	43.7	2.5	16.4	1.3	9.7	2.4	20.9	0.8
340-500	2.2	58.4	2.5	12.3	1.3	5.4	2.4	15.3	0.2
340-700	8.4	88.9	0.0	0.9	0.0	0.2	0.0	1.6	0.0
340-900	8.4	91.4	0.0	0.0	0.0	0.1	0.0	0.1	0.0
340-1100	8.4	91.4	0.0	0.0	0.0	0.1	0.0	0.1	0.0
340-700_s	8.4	88.3	0.0	1.0	0.0	0.4	0.0	1.8	0.1
Embrapa	5.1	61.6	1.3	9.4	0.7	5.9	1.4	14.0	0.6

Sub basin 8

Scenario	Sugarcane		Pasture		Forest		Agriculture		Water
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	0.7	6.8	6.9	29.5	4.7	13.6	8.2	24.2	5.4
340-500	0.8	43.3	6.9	16.3	4.7	5.9	8.1	12.2	1.7
340-700	19.3	77.0	0.7	0.4	0.2	0.2	0.4	0.3	1.6
340-900	20.6	77.6	0.0	0.1	0.0	0.1	0.0	0.1	1.6
340-1100	20.6	77.6	0.0	0.1	0.0	0.1	0.0	0.1	1.6
340-700_s	16.4	75.2	1.4	0.8	1.2	0.7	1.5	0.8	1.9
Embrapa	12.4	49.5	2.2	10.5	3.0	5.5	2.9	8.8	5.2

Sub basin 9

Scenario	Sugarcane		Pasture		Forest		Agriculture		Water
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	6.0	5.4	17.1	19.8	7.4	8.1	18.6	17.0	0.7
340-500	11.7	32.3	14.7	8.8	5.8	2.5	16.7	7.2	0.3
340-700	48.8	50.5	0.1	0.1	0.1	0.1	0.1	0.1	0.2
340-900	48.9	50.5	0.0	0.1	0.0	0.1	0.0	0.1	0.2
340-1100	48.9	50.5	0.0	0.1	0.0	0.1	0.0	0.1	0.2
340-700_s	47.8	49.8	0.5	0.2	0.3	0.4	0.5	0.3	0.2
Embrapa	27.1	37.7	8.0	5.2	3.5	2.5	10.3	5.1	0.6

Sub basin 10

Scenario	Sugarcane		Pasture		Forest		Agriculture		Water
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep	
1993	2.4	3.9	15.7	22.3	5.4	11.0	11.0	20.4	7.9
340-500	32.0	54.0	1.6	1.7	0.4	0.9	0.8	1.7	6.8
340-700	34.5	57.9	0.1	0.1	0.1	0.2	0.1	0.2	6.8
340-900	34.5	57.9	0.1	0.1	0.1	0.2	0.1	0.2	6.8
340-1100	34.5	57.9	0.1	0.1	0.1	0.2	0.1	0.2	6.8
340-700_s	34.2	57.6	0.2	0.2	0.2	0.2	0.2	0.2	6.9
Embrapa	28.0	45.5	2.2	3.7	1.5	3.8	2.9	4.7	7.7