Water scarcity effects of the expansion of sugarcane in the Parana basin in Brazil

Master Thesis

MSc Energy Science

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Abstract

Biofuel is an important renewable fuel in the energy transition, especially in the transport sector. Bioethanol demand is rising, which means that the land use for biofuel crops such as sugarcane is increasing. Brazilian sugarcane-based bioethanol is a major source of biofuel. It is expected that Brazilian bioethanol production will increase, and thus sugarcane expansion is likely to occur, especially in the Parana basin in south east Brazil. Biofuel increase is associated with risks, such as food competition and increased water consumption. This thesis investigates what the impact of expansion scenarios would be on water scarcity by the year 2030. Land use projections for 2030 are adapted for use in the hydrological model PCR-GLOBWB, which is run over a period of 30 years in various scenarios. These are analyzed based on discharge and sampling points, which are reported chronologically, seasonally, and in flow duration curves. Water scarcity is analyzed based on river flow reduction. According to the findings, tenfold expansion of non-irrigated Brazilian sugarcane will not result in water scarcity in the Parana basin. When irrigation is fully applied however, a doubling of sugarcane production just touches the low water scarcity border (>20% flow reduction), a tripling causes low water scarcity (20-30%), a fivefold increase results in moderate water scarcity (30-40%) and a tenfold increase leads to severe water scarcity (>40%). This indicates that for water scarcity projections, the irrigated area is more important than the expanded area. From a perspective of avoiding water scarcity, it is better for policies to focus on limiting irrigation than on limiting sugarcane expansion. For the near future, the likely expansion within Parana for the year 2030 is expected to double or (optimistically) triple. With irrigation remaining low (25% across Brazil, including the dry north east), these expansions will likely cause low to no water scarcity. This allows for a doubling or even tripling of current bioethanol production. Although it remains important to assess water scarcity, it will likely not be the main limitation to bioethanol expansion.

Word of thanks

First and foremost, I would like to thank Dr. Birka Wicka, for your supervision, great feedback and patience. Sincere gratitude also goes out to Dr. Edwin Sutanudjaja and Judith Verstegen, thank you for freeing up your time, interest in my project and your help with the modelling.

For motivation I would like to thank Viola, for motivation when I was down, and my housemates for constantly reminding me that I would never finish this project. Also a great thanks to Eva, for her excellent review. The combination of your trust and mockery made this thesis much more fun to write.

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1.0 Introduction

In an effort to combat climate change, alternative sources of energy are being exploited across the globe. Bioenergy is expected to have an important role as a renewable energy source for all types of applications: electricity generation, heating but also as a low-carbon fuel in the transport sector (IEA, 2013). Projections of the potential contributions of biomass to the TPES (Total Primary Energy Supply) in 2050 vary between 130-270 EJ (exajoule), which is 15-25% of TPES (Beringer, Lucht, & Schaphoff, 2011; IEA, 2013). Bioenergy has a relevant role to play in the energy transition as a whole, but might be specifically vital in the transport sector as biofuel[1]. The transport sector currently predominantly uses liquid fuels, which makes fossil fuels difficult to replace. The Brazilian sugarcane based bio-ethanol industry is a major contributor to the global biofuel production and has continuously grown over the last years (UNICA, 2015). Brazil also has the world's largest potential for expansion in agriculture (Alexandratos & Bruinsma, 2012), and will likely increase its bioethanol production to meet demand of both national and international markets (de Souza Ferreira Filho & Horridge, 2014; IEA, 2013). This expansion is likely to occur in the Parana basin, the south-east region of Brazil surrounding Sao Paolo (CANASAT, 2013; CONAB, 2008; Verstegen et al., 2015).

Expansion of biofuel production is associated with risks, such as competition on food security, deforestation and water scarcity (Gheewala, Berndes, & Jewitt, 2011; Rathmann, Szklo, & Schaeffer, 2010). This thesis will further investigate the relation between biofuel land use expansion and water scarcity risks. Many studies have discussed the relation between water and bioenergy qualitatively (Carlton et al., 2014; Gheewala et al., 2011; SIWI, 2012, 2014). Interesting is the notion of Gheewhala et al., (2001), which is that within biofuel-research, the focus is typically on land use, and water use is only taking into account implicitly. This means that water limitations are taken as a condition; the crop can only grow when water is present. However, this does not take into account that as a result, that water will no longer be present downstream. Sugarcane uses more water than short plants such as grass or small crops (See Appendix 7.3). In Brazil, sugarcane expansion happens at the cost of grassland and croplands, thus water use increases when sugarcane production is expanded (Adami et al., 2012) (See Appendix 7.3). This increase in water use might cause water scarcity[2]. When crop evaporation increases locally due to sugarcane expansion, downstream water availability decreases, risking water scarcity (Berndes, 2002).

Berndes (2002) projects that by 2075 evapotranspiration from energy crops could globally become as large as the current evapotranspiration from cropland, which might lead to water scarcity situations. The Berndes (2002) projection is a rough global estimate, not a precise analysis per basin. Other water scarcity research focusses on water efficiency, calculating Water Footprints (WF), the amount of water required to produce a certain amount of (energy) crops (Scarpare et al., 2015). WFs are useful in assessing the total water use on a certain crop, within a country, and are a good indicator of the water efficiency, but cannot indicate water scarcity. This is because WFs do not include the spatiotemporal aspect of water use, nor the relation with water availability. Using global hydrological models, various spatiotemporal studies have been performed on water resources. Hoekstra and colleagues (2012) in a global study found Brazil to have no water scarcity issues (except for the North-East) up to the recent past. Similar studies have been performed using the WATCH-model globally, or a SWAT

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[1] For further information on the difference between biofuel and bioenergy see Appendix 5.1

[2] Within this thesis water scarcity definitions from (Hoekstra et al., 2012) are used: a decrease of river flow >20% (See methods 2.4)

model for the Mississippi region (Yano, Hanasaki, Itsubo, & Oki, 2015) (Deb, Tuppad, Daggupati, Srinivasan, & Varma, 2015). However none of these studies make projections for the future. What is currently missing is a spatiotemporally explicit study, which uses expected land use changes to project hydrological changes. The objective of this thesis is to see whether, and to what extent, sugarcane expansion will lead to water scarcity.

In spite of Brazil's average abundance of fresh water availability (12% of global fresh water) (Hoekstra, Mekonnen, Chapagain, Mathews, & Richter, 2012), locally, shortages can exist temporarily. Historically, water scarcity occurred predominantly in the North-East, but in 2014 and 2015 droughts have had major impacts on the SPMA (Sao Paulo Metropolis Area) (Escobar, 2015). Many possible reasons for this sudden shortage are proposed such as: lacking water management, an increase of water demand and decreased precipitation (Nazareno & Laurance, 2015). Interestingly, the SPMA and the vast majority of Brazilian sugarcane production share the same catchment area; the Parana basin (Hoekstra et al., 2012). The SPMA uses a series of canals, pumps and reservoirs to obtain water from its surroundings (e.g. the Cantareira system) and is dependent on the availability of surface water in that area (Hoekstra et al., 2012).

The implementation of irrigation in the expanded regions, could further exacerbate the risk for water scarcity. In the past, the sugarcane surrounding Sao Paulo has been practically non-irrigated, as irrigation did not give enough benefit to be economically viable (Matioli, 1998). Most of the sugarcane grown in the Parana basin, grows rain-fed, without any irrigation (Moreira, 2007). In 2006 only 1.7 Mha (Mega hectare) of 8.5Mha Brazilian sugarcane was irrigated (FAO, 2006), mostly in the dry North-East (Anselmi, 2000; Hoekstra et al., 2012). If expansion of sugarcane production will happen in dry areas, irrigation will likely become more prevalent. About 70% of the Brazilian lands suitable for sugarcane cultivation are localized in regions with high water deficits (Christofidis, 2006). Increase in irrigation can have a serious effect on water availability. The north end of the Paraná basin, in an area close to Brasilia, has shown a 40-70% decrease in river flow compared to 1970 (Lorz et al., 2011). Lorz and colleagues indicate that they presume this to be due to increased irrigation, but do not provide with proof of that statement. From 2006 to 2010, irrigation in the Parana basin increased from $120m^3/s$ to $320m^3/s$, which was the main driver for the 50% increase in water withdrawal. (Scarpare et al., 2015). The bio-ethanol demand driven sugarcane expansions might lead to further stress on the water supply, potentially causing water scarcity.

The objective of thesis is to quantify the potential effect of sugarcane expansion on water scarcity, by combing land use projections with a hydrological model. Various land use scenarios that have been projected by Verstegen et al., (2015) will be used as potential expansion scenarios. The modelled area will be the Paraná basin. The focus will be on the occurrence of water scarcity, using river flow as the primary indicator (see methods 2.4). The research questions are as follows:

How will the expansion of sugarcane-land-use in 2030 affect the instances of hydrological drought in the Parana basin, Brazil?

1. Which land use projections lead to water scarcity?
2. What is the effect of irrigation on water scarcity in the various projections?
3. What is the effect of changes in key parameters (Kc, precipitation, rooting depth, dep1factor, Leaf Area Index) on the results?

In order to obtain answers to these questions the hydrological model PCR-GLOBWB will be used. This model is adapted to the requirements of this study, and used to evaluate the water scarcity effects of the sugarcane land use projections made by Verstegen et al., (2015) with a PLUC model. This will calculate the river flows for a scenario with various sugarcane scenarios. In the second question the effect of irrigation will be treated. The last question will be a sensitivity analysis on the first two questions, analyzing other scenarios by varying input data.

The report will be structured as follows. First comes the methods section, which shows the study area, briefly explains PCR-GLOBWB, the drought definitions, high-lights the adaptations made, explains the measure point procedure, reports the used scenarios and explains the analysis of the results. Then the results of the model runs are given in the Results sections, which will also contain some discussion of these results. Next is the discussion of the results and that of the method used. The report is closed with the conclusion. In the back additionally the references and the appendices can be found, these are referred to throughout the report for additional explanation.

2.0 Method & input data

2.1 Overview

This section will give an overview of the method. The method is structured as follows: the study area is shown in section 2.2, and the drought definitions are covered in section 2.3. After that section 2.4 covers the basics functioning of the used hydrological model PCR-GLOBWB. Section 2.5 discusses how PCR-GLOBWB has been adapted specifically for this study. The various scenarios that tested are discussed in section 2.6, which also includes the input data for these scenarios. Section 2.7 discusses how the data obtained and how these are analyzed in the results (section 3).

In order to assess whether sugarcane expansion will exacerbate water scarcity in the Parana basin, the hydrological effects of sugarcane expansion have to be calculated spatiotemporally explicit, from which predictions on water scarcity can be derived. Figure 1 shows the inputs (Scenarios of vegetation maps & settings), being processed in the adapted PCR-GLOBWB model over a 30 year period. From these scenarios resulting in hydrographs, which are used to assess water scarcity.

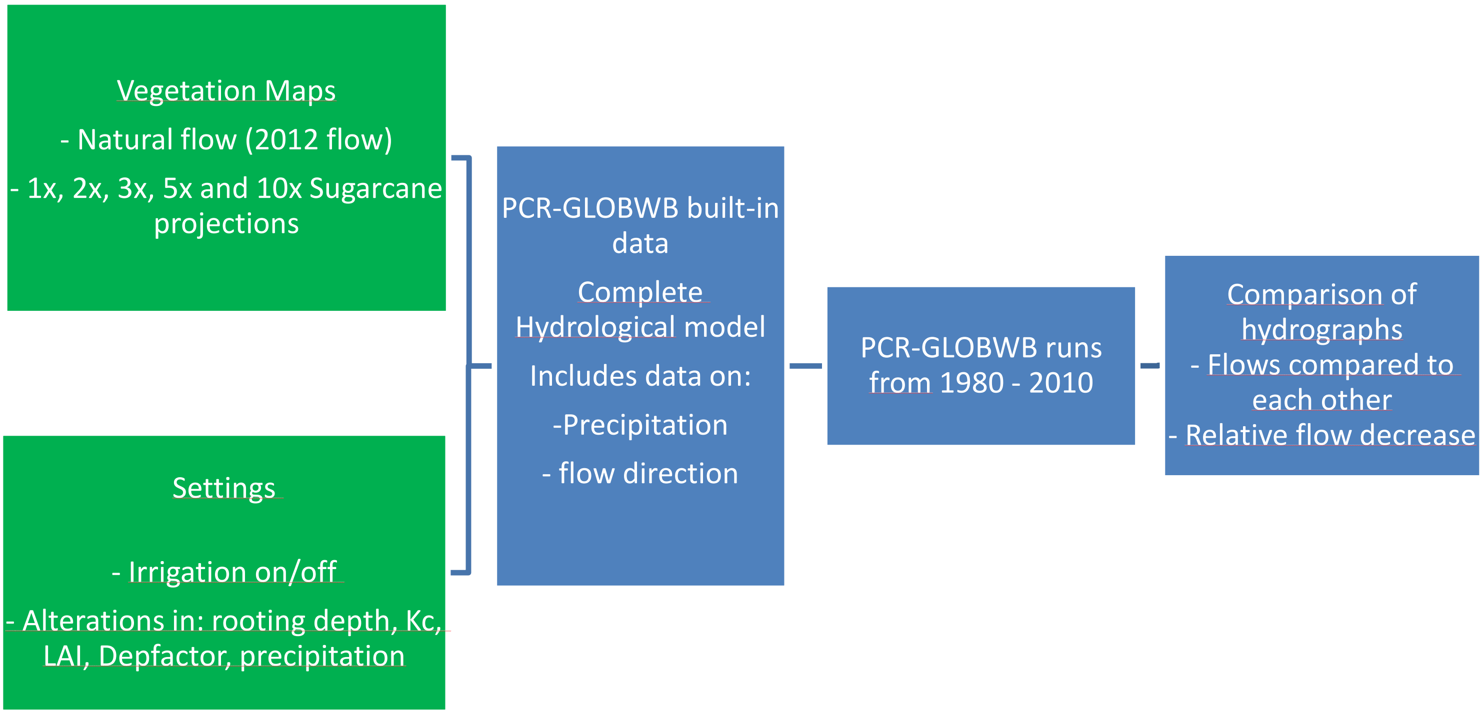


Figure 1. Research steps taken in running PCR-GLOBWB to assess water scarcity due to land use change. Input is given in green, after which the standard hydrological model is represented in blue. The hydrographs resulting from each scenario are compared to provide with answers for the research questions.

2.2 Study area

The area study area is the Parana basin, situated in the south-east of Brazil, but also crossing borders into Uruguay, Paraguay, Bolivia and Argentina. The Parana basin covers a large share of the south-east region of Brazil, the heart of the Brazilian sugarcane production (CANASAT, 2013). Figure 2 shows an overlay of South America, the 2012 vegetation map and the Parana basin. Additionally the measuring points for discharge and sampling have been included (more information on this can be found in section 2.7., additional another overlays and vegetation maps of other projections in section 2.6).

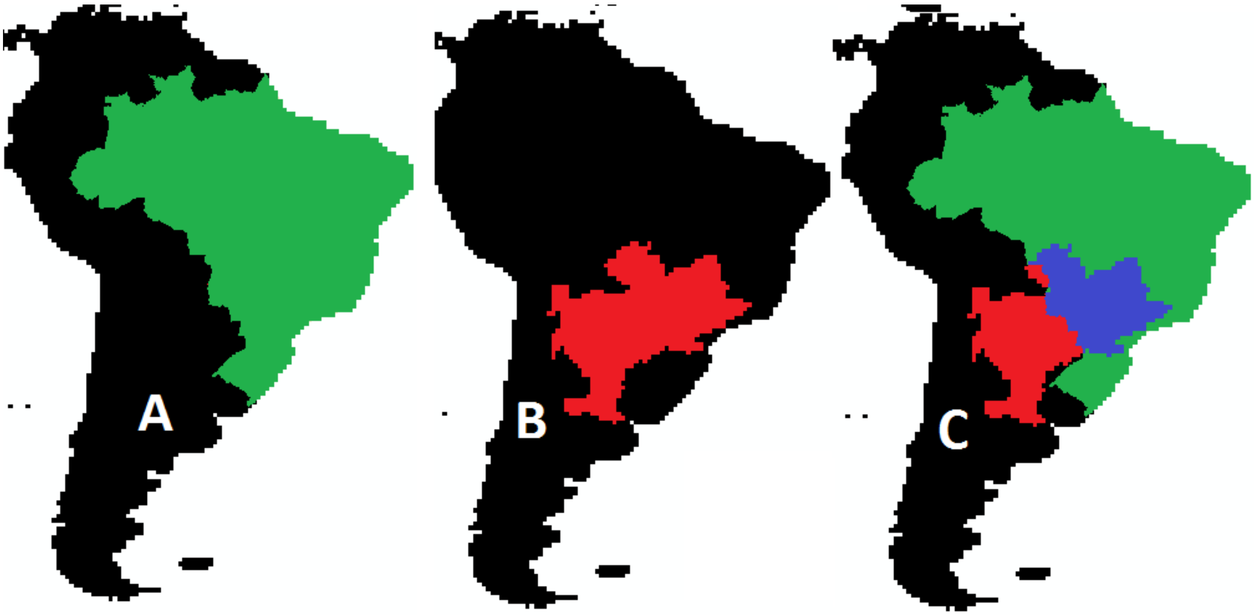


Figure 2. Outlining of the study area. South America (black), Brazil (green), Parana basin (red), the study area (blue). Figure 2A shows the outline of Brazil. Figure 2B shows the outline of the Parana basin. Figure 2C combines the outlines of 2A&2B, resulting in the study area: the Brazilian part of the Parana basin.

2.3 Water scarcity definitions

2.3.1 Available water scarcity definitions

Water scarcity is difficult to measure and define. Water availability can be dependent on lots of factors such as (but not exclusive); precipitation, land coverage, local basin geography and human extraction. Water scarcity could be defined based on many factors such as (but not exclusive); groundwater tables, reservoir levels, or river flows. Multiple of these outputs could be used as a definition, for example when reservoirs reach critical levels, ground water plummets below a certain debts, or rivers reach a critically low flow. An easy to measure option to define water scarcity is the water barrier concept, which is defined as the absolute availability of water per capita (Falkenmark, 1989). For a country-wide scale, water withdrawal as a percentage of supply is used as an indicator for water scarcity (Raskin, Hansen, & Margolis, 1996). This is called the use-to-resource ratio, where 25% of water withdrawn indicates water stress (Raskin et al., 1996). However such a large scale and general approach is not a sufficient scope to properly gauge water scarcity per location. Hoekstra et al., (2012) argue to not count water withdrawal, but specifically water consumption, as return flows should be taken into account and lessen the scarcity. To measure water consumption the gross river flow can be measured, as all recycled flows return to the surface water.

2.3.2 Water scarcity definition for this study

The results of this research are analyzed based on the gross river flow of Rio Parana. Hereby we use river flow reduction guidelines given by (Hoekstra et al., 2012; Richter, Davis, Apse, & Konrad, 2012); which relates river flow to water scarcity. We are using this indicator for two reasons: Firstly, it's a strong indicator used to measure prolonged hydrological droughts, especially when taking irrigation into account (Wanders, 2015). Secondly it is the only indicator which can fairly distinguish between the irrigated scenarios and non-irrigated scenarios, which soil moisture (skewed by irrigation) and precipitation (equal in both scenarios) cannot. In this case the gross river flow of the baseline (natural flow scenario see 2.5.3) is compared to the gross flow of the scenario, resulting in the relative decrease in flow. The larger the decrease in flow, the larger the water scarcity situation. The damage threshold for environmental damage (due to flow change) is 80%, hence the first 20% reduction in abstraction can be considered to be relatively damage-free. A flow reduction of 20-30% is considered low water scarcity, 30-40% moderate water scarcity and >40% severe water scarcity.

2.4 A brief explanation of PCR-GLOBWB

PCR-GLOBWB is a grid based hydrological model, which uses stacked grids to simulate hydrological flows. In PCR-GLOBWB areas are divided into separate same-sized cells. These cells are treated as homogenous entities. The cell size decides the spatial resolution: the smaller the cell, the higher the resolution and the more detailed maps can be displayed. To provide the model with information, input from databases can be inserted into the model as a grid layer, giving an input for each individual cell. At any time moment a cell might have an abundance of water (exceeding soil saturation point, appendix 5.3.4). Because PCR-GLOBWB is a leaky bucket model, this will result in the abundant water being transport to a downstream cell (Van Beek & Bierkens, 2009). To decide in which direction the water flows, a slope grid is created out of an altitude grid, using altitudes of neighboring cells to dictate that slope of the cell. This slope grid can then be transformed to a flow direction grid, which is used to decide upon the direction of the run-off (Van Beek & Bierkens, 2009). Similarly soil-type dictates the variables for the soil-water storage grid, which in turn dictates how much water is stored in the soil, how much is directed to the ground water and how much is run-off. This is an example of how PCRaster functions, by combining information from layered grids, where complex grid are created, by combining information from other grids. By using multiple grids PCR-GLOBWB creates a model of a hydrological system. Figure 3 gives a sketch of the type of real-life streams that are taken into account within PCR-GLOBWB. The specific formulas, grid operations and calculations that support the model are extensively described in Wada et al. (2014).

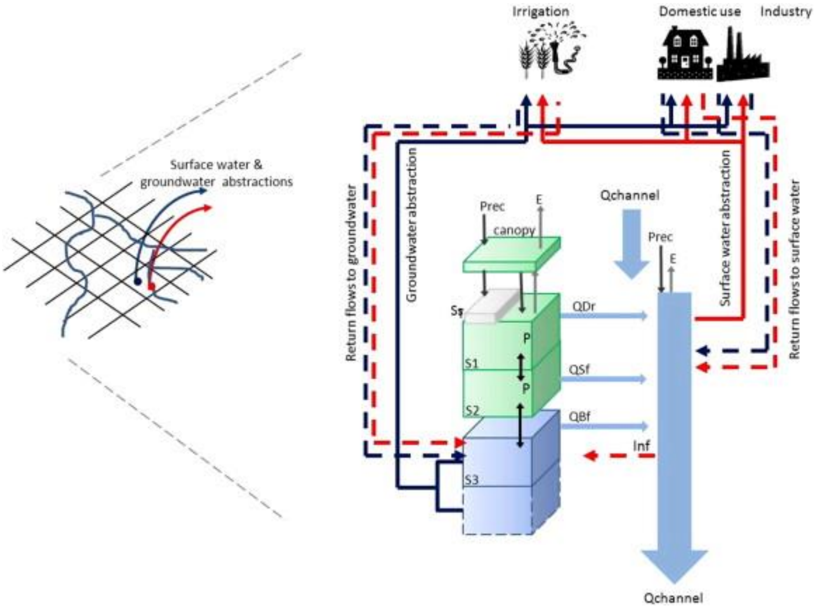


Figure 3. An overview of the flows in the PCR-GLOBWB hydrological model (de Graaf, van Beek, Wada, & Bierkens, 2014) The center of the figure (the stacked soil layer) shows a single cell. This cell receives water in the form of precipitation or irrigation, and loses water as run-off, evaporation, domestic, industrial or agricultural abstractions. Return flows are also modelled, such as treated waste water flowing back into rivers, or irrigation water seeping back into the ground water. The left side of the picture indicates how each of those cells fit into a larger whole, and how flows between cells are incorporated (by surface water flow towards other cells in the form of Qchannel).

2.5 Application and modification of PCR-GLOBWB in this study

2.5.1 Including the sugarcane cell

PCR-GLOBWB currently does not distinguish between sugarcane and other crops. The current version only distinguishes between general land types such as forest, short (grassland, including pasture and all rain-fed crops), (non-)paddy irrigation and city area (Wada et al., 2014). As a crop, sugarcane would typically be grouped as short, however it uses relatively large amounts of water compared to other regular agricultural crops (See Appendix 7.3). The FAO indicates that it uses roughly 30% more water than grassland under the same circumstances (FAO, 1986). In order to use PCR-GLOBWB to measure the change in water use, it is imperative to distinguish sugarcane from the average rain-fed crops. This new land-use type needs to be put into PCR-GLOBWB, which requires the vegetation phenology parameters: cover factor, interception capacity, rooting depth and crop coefficient (see table 4, section 2.6).

2.5.2 Altering the land use maps

Land use projections have been obtained from Verstegen et al., (2015). The 2012 land use, is used for the natural flow scenario (see 2.5.3). The other maps are land use projections, with larger amounts of sugarcane. The projections (1x, 2x, 3x, 5x and 10x) are created with a land use model (PLUC) which uses bioethanol demand as an input and attributes land use according to suitability for cane production. Because PLUC expansion is based on regions and production is predominantly within Parana, most of the modelled expansion is by default found there. The names of the maps reflect the land use given an increase in demand for bio-ethanol destined sugarcane. This does not automatically mean that the associated land mass is equal to that as there is also some "sugar"-sugarcane, which PLUC counts separately. Therefore the 1x scenario and the 2012 scenarios are not equal, with 1x actually having more sugarcane land, but equal ethanol production. The land use maps are shown in figure 4 (section 2.4). Initially the Verstegen maps were projected in South America Albers Equal Area (5x5km grid) and classified 11 different land uses. Using ArcGIS the maps have been reprojected to WGS_1984 (0.5 degree) on which the standard PCR-GLOBWB model runs. Additionally the 11 land categories have been brought back to three: Sugarcane, short (rangelands, grass and shrub, croplands, planted pasture, urban, abandoned, bare soil and water) and tall (natural forest and planted forest). This is done because PCR-GLOBWB already describes the characteristics of short and tall crops. The decision to include urban areas and water into the "short"-category has been made due to the relatively low dedicated area. Additionally, surface water and reservoirs are modelled separately within PCR-GLOBWB (and surface area is deducted from the other cells proportionally). The Parana basin stretches beyond Brazil (see Figure 2), the area outside of Brazil is not described by the Verstegen (2015) maps. These areas are covered by the PCR-GLOBWB standard-short/tall vegetation maps.

	Natural (2012)	1x	2x	3x	5x	10x
Cane area (m^2)	8.9E+10	1.4E+11	2.7E+11	4.1E+11	6.8E+11	1.2E+12
Cane area (Mh)	8.9	13.7	27.3	40.9	68.1	124.1
Ethanol (mln L)	23901	23901	47802	71703	119505	239010

Table 1. Size of the area of sugarcane cultivation in each of the scenarios. For the maps see figure 4.

2.5.3 Resolution

The cell resolution is chosen to be at 0.5 degree scale. A model is only valid if cells are of such size that each cell can be considered homogenous; within one cell properties should be fairly similar. Therefore, the maximum tolerable size depends on the variation of land coverage. Large fields, forests and cities could be counted as one cell, whereas smaller patch-like agriculture would require smaller cell-size. Given high resolution input data, smaller cell size would allow for a potential higher level of accuracy. Ideally a higher resolution would be used to give higher levels of detail, however not all data is available at this higher resolution. Increasing the resolution by dividing larger cells into smaller (identical) cells gives a false resolution. Additionally it would require more complex calculation (0.05 grids require 10^2 times more computational power). Because PCRaster relies on stacked grids for its model function, all grid cells need to be of equal size. Much of the data in the standard version of PCR-GLOBWB is in a 0.5 degree resolution, which is therefore limiting. PCRaster has already been run with a 0.5 degree scale, and this also the scale planned for this research (Van Beek, Wada, & Bierkens, 2011; Y Wada, Wisser, & Bierkens, 2014). This way, only the land use maps from Verstegen and colleagues (2015) have to be converted.

2.5.4 Precipitation

PCR-GLOBWB uses a built in model as an input for precipitation. This uses precipitation data from 1980-2010. Additionally, it can adjust these data for climate scenarios, such as the IPCC's Representative Concentration Pathways (RCPs) (Van Vuuren et al., 2011). Using the average climate scenario The AIM scenario (RCP 6.0, assuming 700ppm CO_2 by 2100) would result in a global warming of 3.5 °C and an average decrease of precipitation by 9% (Van Vuuren et al., 2011; Yoshihide Wada et al., 2013). This climate data has been obtained from the ERA Interim reanalysis, with precipitation corrected with GPCP (Global Precipitation Climatology Project) (Dee et al., 2011; GPCP, 2011). 9% increase/decrease will be used as a sensitivity analysis using it as an average increase and decrease of precipitation.

2.5.5 Irrigation

Next to modelling the natural hydrological cycle, the model also needs to incorporate manmade changes to the cycle, such as artificial reservoirs, interconnectivity and transport between reservoirs/basins or blue water extractions/additions. Primary examples of this in the Parana Basin are hydro dams, municipal water supply (such as the Cantareira system), industrial extractions and irrigation, which PCR-GLOBWB includes. PCR-GLOBWB has the option to assume automatic irrigation; whenever precipitation is insufficient, surface water is applied. This option will be used within this study for the irrigated scenarios. This means that surface water is automatically abstracted on a daily basis whenever soil water falls short of the maximum evaporation demand (see section 7.3.4). Such estimates have been made by similar studies before at 60, 80 and 100% of maximum irrigation demand (Döll, Müller Schmied, Schuh, Portmann, & Eicker, 2014). In this study only scenarios with 0% (non-irri) and 100% irrigation (irri) are used. Given that Parana is a relatively wet region, compared to global average, therefore the 100% irrigation option is considered to be a fair estimate. This has a downside that all agriculture is modelled to be fully and optimally irrigated. In the real world, farmers might consider the costs of irrigation too high, which will lead to losses in production, the model does not include that possibility. On the other side, irrigation might be applied wrong, applying too much or irrigation right before precipitation (due to imperfect information). These distorting effects will be relatively small in the rain-fed areas, where precipitation is plenty, but might be larger when assessing plantations in drier areas.

2.5.6 Timescale

The goal of this research is to analyze the effects of the land use change that is projected to occur for 2030. In order to get an indication of the hydrological situation in 2030, we alter the land use towards the expect values in 2030 and then run the model over time. Ideally the precipitation data of 2010 to 2040 would be used, but those are unknown and projections are highly insecure. Because this thesis focusses on water scarcity due to land use change and not precipitation, historical precipitation data will be used as a proxy. This is not ideal, and to compensate for the possible inaccuracy a sensitivity analysis is performed on precipitation (see 2.5.5). The reason to use a 30 year period is twofold. Firstly hydrological effects may lag behind, for example when ground water is gradually depleted, which results in effects only being displayed later. Therefore this model runs over a period of 30 years, to properly adjust to the land use change. Secondly a 30 year period provides with a more varied precipitation pattern and thus more data to analyze (inter-annual variation). The land use is set from the start (at expected 2030 condition per scenario), although in reality the land use change would happen gradually. This has two reasons: First of all this is done to provide with enough time for the hydrological situation to balance out (as explained above) and secondly this is done for simplicity, avoiding the necessity of an annual land map. The hydrological starting conditions, which indicate how much water is where (in which cell, in which soil layer etc) are taken for the year 2000, after which 10 spin-up years (repeats of the first year: 1980) are performed to balance out the system, which starts in a balanced 1980 state. This is mainly done to simplify calculations, alternatively just starting the model and using many more spin-up years would yield similar results, but take more time.

2.6 Scenarios & Input data

2.6.1 Sugarcane input maps

Land use maps are taken and created by Verstegen et al., (2015). Maps from 2012 and projections of 2030 of 1x-10x current biofuel-intended sugarcane, were available for use. 1x is the business as usual scenario (no expansion of biofuel-destined sugarcane, only expansion of sugarcane for the sugar industry). 2x contains a doubling and 3x a tripling, etc. The 10x scenario is not expected for the 2030 scenario but is interesting to analyze nonetheless (for optional expansion even further down in the future). In both the 5x and the 10x scenarios substantial sugarcane expansion takes place outside of the Parana basin, and thus outside the scope of this study. The natural flow map is the map of the situation in 2012. The maps shown in Figure 4 are the maps used as input for the respective scenarios (see 2.6.3, Table 4).

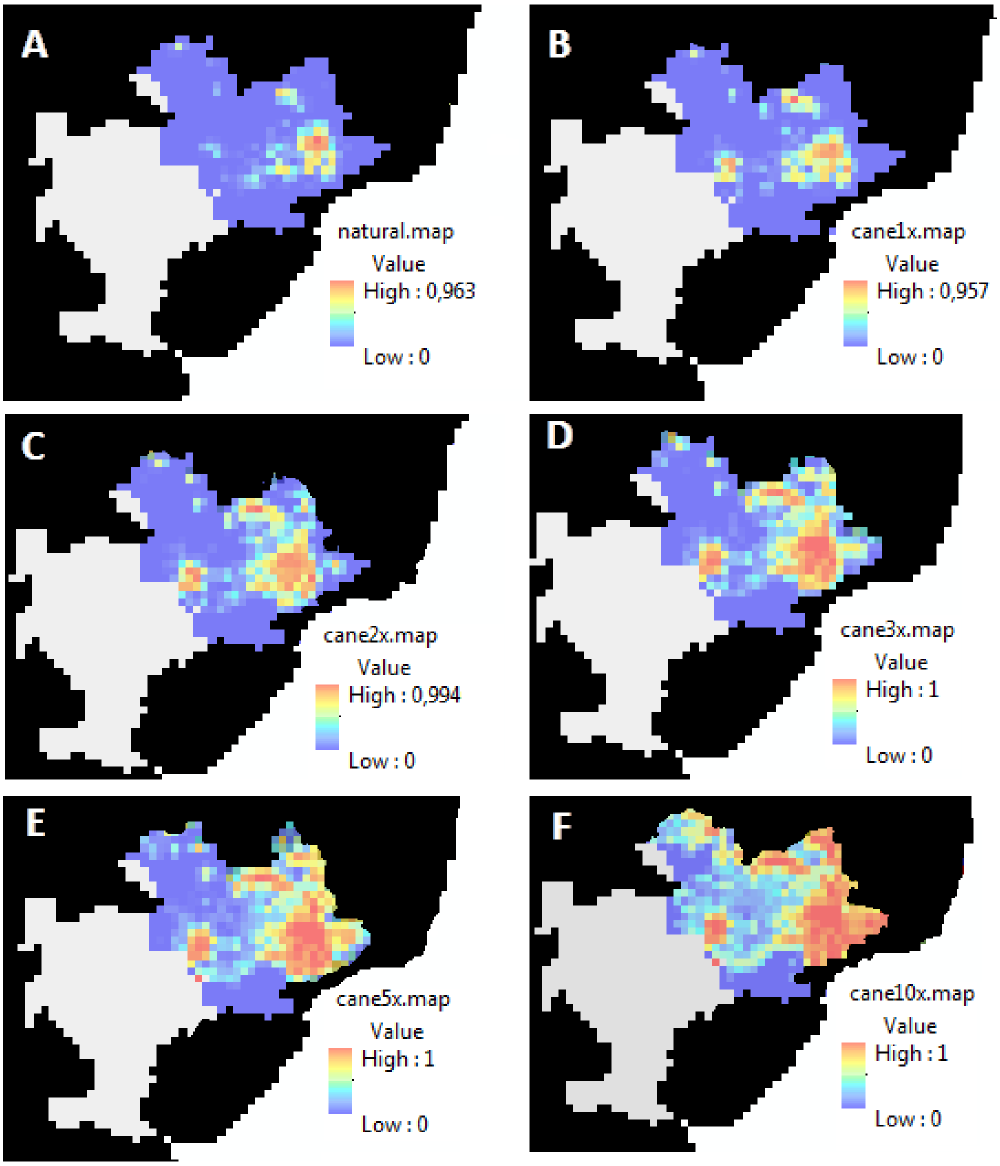


Figure 4. Various sugarcane cover projections for The Parana basin. Only the cane in the Brazilian part of the basin is analyzed (see Figure 3). The coloring indicates the fraction of the cell covered in sugarcane (Blue being 0% and red 100%). Figure A: Sugarcane cover fraction in 2012. B-F, projections for various cane scenarios: B:1x, C:2x, D:3x, E:5x, F:10x

2.6.2 Baseline scenario and Business as Usual scenario

To answer the research questions statements about water scarcity have to be made. To use our water scarcity definition (section 2.3) of relative river flow we need to measure river flow compared to the baseline. The baseline is the natural flow scenario (2012 map). This flow scenario is not a natural scenario as the entire area has been used for agriculture for a long time, but it is the most neutral option available (see discussion 4.3). Cane1x (non-irrigated) can be considered a business as usual scenario (no increased sugar cane production for bio-ethanol production). For the definition of water scarcity the natural flow scenario will be used (which is the strictest criterion as it has the highest flow, thus the relative flows will be lower).

2.6.3 Other inputs

PCR-GLOBWB is sensitivity to more variables than merely land use. RQ 2 and 3 investigate the effects of these other factors. RQ 2 focusses on the effect of irrigation, all projected scenarios (1x, 2x, 3x, 5x and 10x) are also tested with a 100% irrigation option as described in section 2.3.5. Additionally a high and low range of other input variables (Kc, LAI, dep1factor, rooting depth) are put in scenarios and tested in combination with the 3x sugarcane map. 3x is chosen as a moderate map, containing high, yet reasonable amounts of sugarcane attributed land mass (2x or 4x would also have been suitable). Because of the introduction of the sugarcane field to the model, only the crop variables of sugarcane are being varied in the sensitivity analysis. Crop phenology factors of the "tall" and "short" vegetation types in PCR-GLOBWB, might have some uncertainty, but that is beyond the scope of this research. Rooting depth and dep1factor are variables dependent on soil moisture and are thus tested with and without irrigation. The various scenarios are specified in table 4. Table 2 & 3 give the Kc and LAI input values, these influence evaporation (see section 7.3)

	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
Kc low	0.45	0.75	0.9	1	1.05	1.05	1.05	1.05	1.05	1.05	0.8	0.6
Kc normal	0.5	0.8	0.95	1.1	1.25	1.25	1.25	1.25	1.25	1.25	0.9	0.7
Kc high	0.6	0.85	1	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.05	0.75

Table 2. Kc values per month for the normal, high and low scenario (da Silva et al., 2012; FAOc, 2015)

	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
LAI low	0.83	1.42	1.77	2.02	2.21	2.36	2.49	2.61	2.71	2.80	2.88	2.96
LAI normal	1.66	2.84	3.54	4.03	4.41	4.72	4.99	5.22	5.42	5.60	5.76	5.91
LAI high	2.49	4.27	5.31	6.05	6.62	7.09	7.48	7.82	8.13	8.40	8.64	8.87

Table 3. LAI values per month for the normal, high and low scenarios (da Silva et al., 2012)

	Scenario name	Land use map	Irrigation	Kc	Rooting Depth	Dep1Factor	LAI	Precipitation alteration factor
Baseline	Natural flow	2012 land use	No	Normal	1	0.65	Normal	-
Non-irrigated base scenarios	1xnonirri	1xcane	No	Normal	1	0.65	Normal	-
	2xnonirri	2xcane	No	Normal	1	0.65	Normal	-
	3xnonirri	3xcane	No	Normal	1	0.65	Normal	-
	5xnonirri	5xcane	No	Normal	1	0.65	Normal	-
	10xnonirri	10xcane	No	Normal	1	0.65	Normal	-
irrigated base scenarios	1xirri	1xcane	Yes	Normal	1	0.65	Normal	-
	2xirri	2xcane	Yes	Normal	1	0.65	Normal	-
	3xirri	3xcane	Yes	Normal	1	0.65	Normal	-
	5xirri	5xcane	Yes	Normal	1	0.65	Normal	-
	10xirri	10xcane	Yes	Normal	1	0.65	Normal	-
Kc sensitivity (Max exvaporation, see section 7.3)	3xKcHigh	3xcane	Yes	High	1	0.65	Normal	-
	3xKcLow	3xcane	Yes	Low	1	0.65	Normal	-
	3xLAIHigh	3xcane	Yes	High	1	0.65	High	-
	3xLAIlow	3xcane	Yes	Low	1	0.65	Low	-
Dep1factor sensitivity (How easy can water be abstracted from soil, see section 7.3.3)	3xDep1factorHighirri	3xcane	yes	Normal	1	0.8	Normal	-
	3xDep1factorLowirri	3xcane	yes	Normal	1	0.5	Normal	-
	3xDep1factorHighnonirri	3xcane	No	Normal	1	0.8	Normal	-
	3xDep1factorLownonirri	3xcane	No	Normal	1	0.5	Normal	-
Rooting depth sensitivity analysis (Which soil layers can be reached for abstraction, see section 7.3.4)	3xRootinghighirri	3xcane	Yes	Normal	1.5	0.65	Normal	-
	3xRootingslowirri	3xcane	Yes	Normal	0.6	0.65	Normal	-
	3xRootingshighnonirri	3xcane	No	Normal	1.5	0.65	Normal	-
	3xRootingslownonirri	3xcane	No	Normal	0.6	0.65	Normal	-
Meteo sensitivity analysis	3xMeteo1.09	3xcane	Yes	Normal	1	0.65	Normal	*1.09
	3xMeteo0.91	3xcane	Yes	Normal	1	0.65	Normal	*0.91

Table 4. All scenarios with specific alterations to the model. For values for KC and LAI, see Table 2&3. For explanation on how LAI, KC, rooting depth and dep1factor

2.7 Measuring points and baselines

2.7.1 Measuring points

In order to extract data from the scenarios measuring points have to be selected. As our drought indicator is based on river discharge, we need to measure river discharge in the region. Preferably this is done on a river which encompasses the area which contains mostly sugarcane, yet has a large enough basin to capture most of the area. Measuring at the mouth of the Parana (in Argentina), would result in less distinct hydrographs as the rest of the basin also drains there. Therefor to limit our data to only include data from the study area (the Brazilian part of Parana), the measure point is taken in the Rio Parana (Red, -54.25,-24.25). At these coordinates this big river leaves Brazil, having collect the water from the main sugarcane area. Any changes in agricultural water use due to sugarcane expansion in the study area will be best visible here, because it has both a large flow and it incorporates the most important part of the study area (see Figure 5). Additionally, precipitation, evaporation, direct run-off and irrigation are sampled at various locations. These locations are chosen randomly across the basin. The sample points (green, see table 5) are averaged out to give an indication of the average values within the basin.

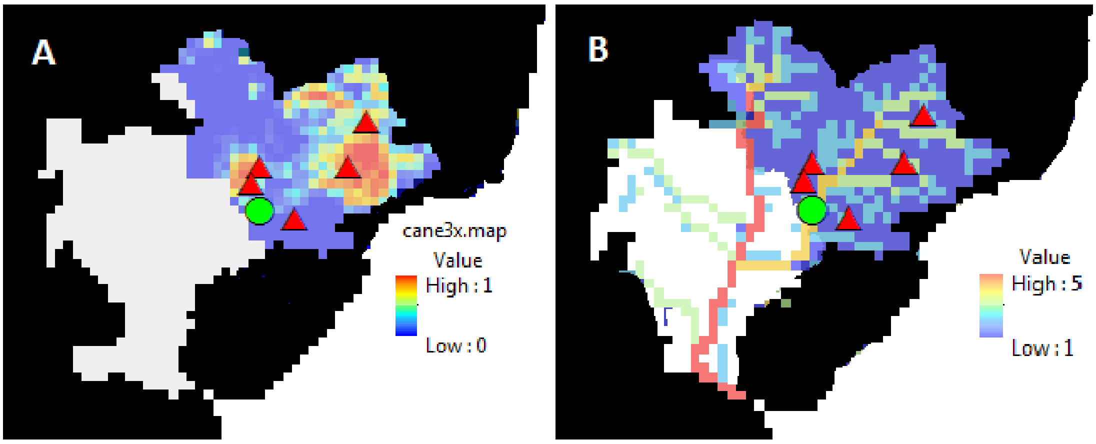


Figure 5. Red triangles indicate the sampling points, the green circle the discharge point. A, overlay of the Parana basin with the 3x cane map. The legend indicates the sugarcane cover fraction (from blue (0%) to red (100%)). A shows that the sampling points A, B, C & D are in the main sugarcane areas. B, overlay of the Parana basin with the flow direction map. Red line gives the primary river, orange, green and blue give "lower level" river which end in the higher level rivers. B shows that the discharge point (green circle) is the discharge collection point for the main sugarcane area.

	Measured	Map Symbol	Lon	Lat
Discharge Point	Discharge	Green circle	-52.25	-24.75
Sample A	Sampling of Precipitation, Evaporation, Direct Run-off and Irrigation	Red triangle	-49.25	-21.75
Sample B			-54.25	-21.75
Sample C			-48.25	-19.25
Sample D			-54.75	-22.75
Sample E			-52.25	-24.75

Table 5. An overview of the measuring points indicating the points where discharge and the sampling are measured.

2.7.2 Abstraction of data

PCR-GLOBWB stores output data in NCfile, these are maps for each time frame. Output tabs were made for various points (see table 5) so that data from individual cells could be measured. Discharge, precipitation, evaporation, direct run-off and irrigation were each sampled and exported to Microsoft Excel for further analysis.

2.8 Analysis of results

The analysis of the results are ordered per research question. Analysis is performed on both discharge and the sample point data (See Table 5). This data is displayed d in various ways: chronologically, based on flow duration and seasonally, as done in Wada, Van Beek, & Bierkens (2011). The combination of research questions, used maps, data type and method of display is illustrated in Table 6. In chronological display, the monthly flows (discharge at Rio Parana, table 5) are shown ordered on time. The flow duration curve is a display of the flow moments ordered from high to low, the percentage indicating which percentage of flows is higher than that specific discharge value. This means that at the 50% margin (x-axis), 50% of all reported flow moments (y-axis) were higher than the flow moment at that point. The 0% point indicates that no flows were high that that flow, which means that that was the highest flow point. Oppositely, the 100% point indicates that all flows moments were higher than in that moment, which means that that flow is the lowest. Flow duration curves are then inter-compared (calculating the relative decrease compared to the baseline). Here each value is divided by the value with the same rank order (highest flow to highest flow).
High flow moments do not necessarily occur at the same time in two different scenarios. When comparing two flow order scenarios, you are not necessarily comparing two flow moments which occurred at the same time. Instead two flows with the same "flow-order" are compared, wettest to wettest, and driest to driest moment. This is done for two reasons. First of all it splits the analysis in low and high flow moments, and thus it can be seen where the biggest difference occurs. Additionally, it simplifies the analysis, the comparison of two relatively smooth curves is easier than that of two chronological discharge moments. The seasonal analysis is performed by graphing monthly discharges over the years (Jan 1980, Jan 1981 etc.), additionally the data each month is averaged over 31 years. This also done for the sampling points (reporting precipitation, evaporation, direct run-off and irrigation).

	Data		Method of display			
	Maps	Data measured	Chronological	Flow duration	Seasonal	Seasonal Average
RQ1 & RQ 2	1,2,3,5,10x Non-Irrigated & Irrigated	Discharge	All maps	All maps	-	-
RQ3	3xsensitivityMaps	Discharge	-	3xIrri	-	-
Balancing explanation	1,2,3,5,10x Non-Irrigated & Irrigated	Discharge	All maps	All maps	1x, 3x, 5x (irri)	1x, 3x, 5x (irri)
		Sample Points	-	-	3x	3x

Table 6. An overview of the data and the types of analysis performed. Maps, measured data and analysis types are shown per research question.

Research Question 1: Which scenarios will lead to water scarcity?

To answer RQ1, we need to analyze the 1x, 2x, 3x, 5x and 10x scenarios, both irrigated and non-irrigated. Those are then analyzed, using the flow duration curves to assess the decrease in stream volume. As described in section 2.3, water scarcity will be analyzed by comparing the flow decrease relative to the baseline.

Research Question 2: What is the effect of irrigation?

To answer the second question, we need to analyze the difference between the irrigated and the non-irrigated scenarios. This is calculated by comparing the decrease of discharge from the non-irrigated flow duration curve to the irrigated flow duration curve of the same scenario. This results in a percentage flow decrease, which is solely attributable to application of irrigation.

Research Question 3: How robust are the results for changes in key parameters (Kc, precipitation, rooting depth, dep1factor, Leaf Area Index) on the results?

Research question 3 deals with the sensitivity analysis. Here all the scenarios with alternative phenological and metereological data are compared. This is done only on size-ordered analysis (not chronologically or seasonally) to give a brief indication of how sensitive the model is to potential variation of that input factor. Overview of the scenarios for the sensitivity analysis and the ranges used for the key parameters are shown in Table 4.

3.0 Results & Discussion

The results are ordered in the following way. First graphs are given for chronological discharge, both for rain-fed and irrigated scenarios. Secondly, the monthly flows are ordered from large to small, graphed and compared to each other. This way the high and low flow moments can be analyzed. After that, flows are compared to the natural flow and displayed as %-based flow decrease. These flow decreases are then compared to the flow-based water scarcity indicators.

3.1 Chronological monthly river discharge at Rio Parana

In order to analyze drought situations, river flow is modelled. Various scenarios are then compared to the baseline (Natural flow 2012) and the business as usual scenario (cane1xnonirri). Flow varies both seasonally and cross-seasonally. Figure 6A displays the average monthly river flow over time. At first sight the differences in discharge are hard to observe as the lines are very close. The difference is largest between the 10xcane scenario and the natural flow, with the other scenarios fitting in between. Interestingly the differences in discharge seem to be largest at the high discharge peaks and much smaller during low-flow periods (for a clearer view see 6C). In the next chapter these flows will be analyzed ordered on flow-volume where this difference is easier to observe. Figure 2 displays the average monthly river flow overtime for the irrigated scenarios. Unlike the non-irrigated scenarios, the differences in discharge are sizeable. Again it can be observed that the difference in the positive peaks is much larger than the differences during low flow volume. This will be quantified during the next chapter. Important to note is that in spite of the full irrigation option at 10xcane scenario, the river never runs dry (at a monthly average level). Figure 6C shows a zoom in of 3 years of river flows both irrigated and non-irrigated scenarios, to illustrate the differences between the flows in the various scenarios. Here it clearer to see that the differences between the flows are larger during the high flow moments. Section 3.3 covers describes various theories of why this would be the case.

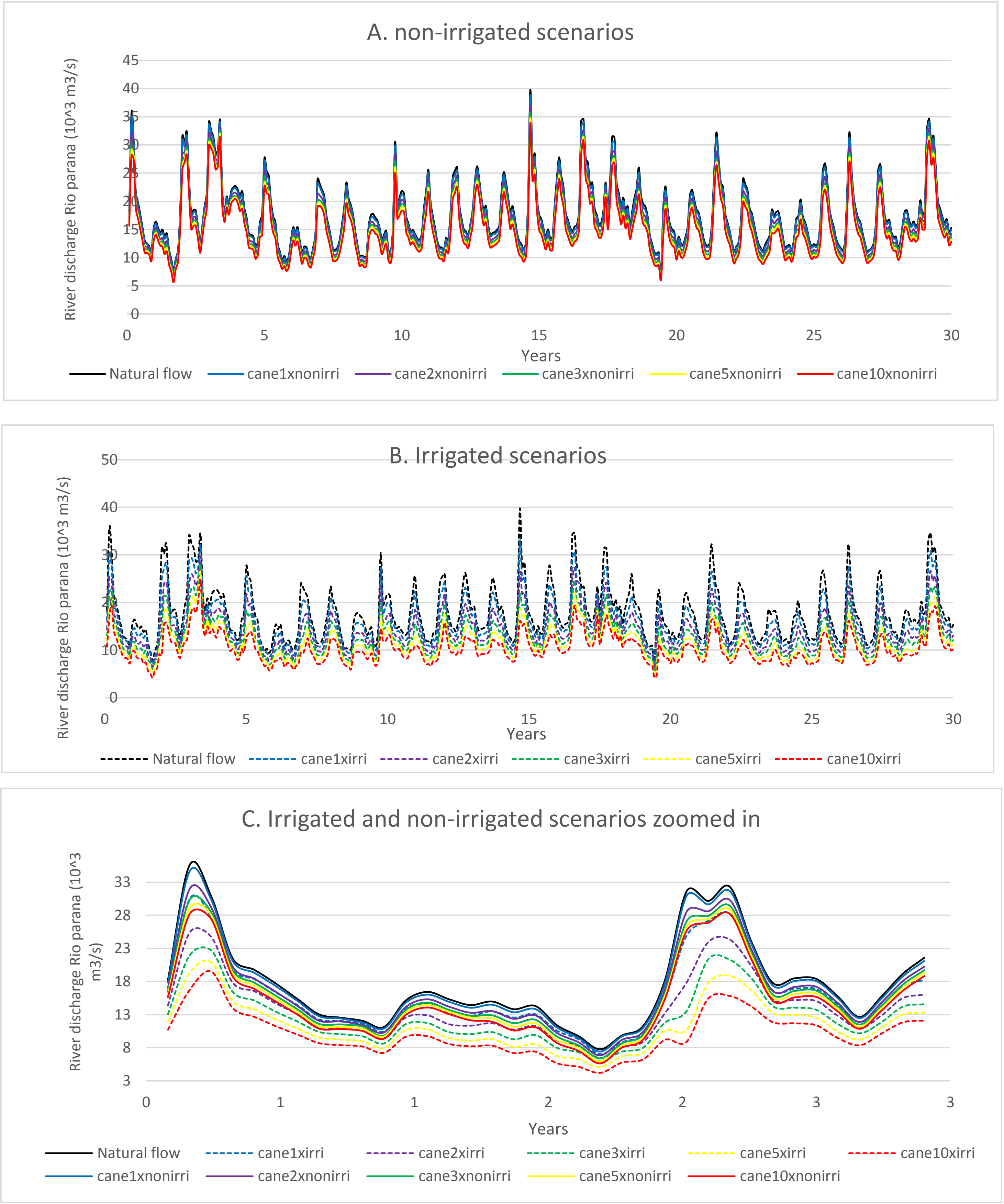


Figure 6. Chronological hydrographs of the non-irrigated (A), irrigated (B) and a zoom in of both scenarios (C).

3.2 River discharge ordered from high to low flow

In this chapter river discharge from various scenarios is compared to the natural flow. In order to do this, the flows are ordered from high to low flow months. The percentage indicates the % of highest flows that are graphed (0-10% indicates the 10% highest flow moments). High flow moments do not necessarily occur at the same time in two different scenarios, thus when comparing two scenarios, you are not necessarily comparing two flow moments which occurred at the same time. Instead two flows with the same "flow-order" are compared, wettest to wettest, and driest to driest moment. This is done for two reasons. First of all it splits the analysis in low and high flow moments, and thus it can be seen where the biggest difference occurs. Additionally, it simplifies the analysis, the comparison of two relatively smooth curves is easier than that of two chronological discharge moments.

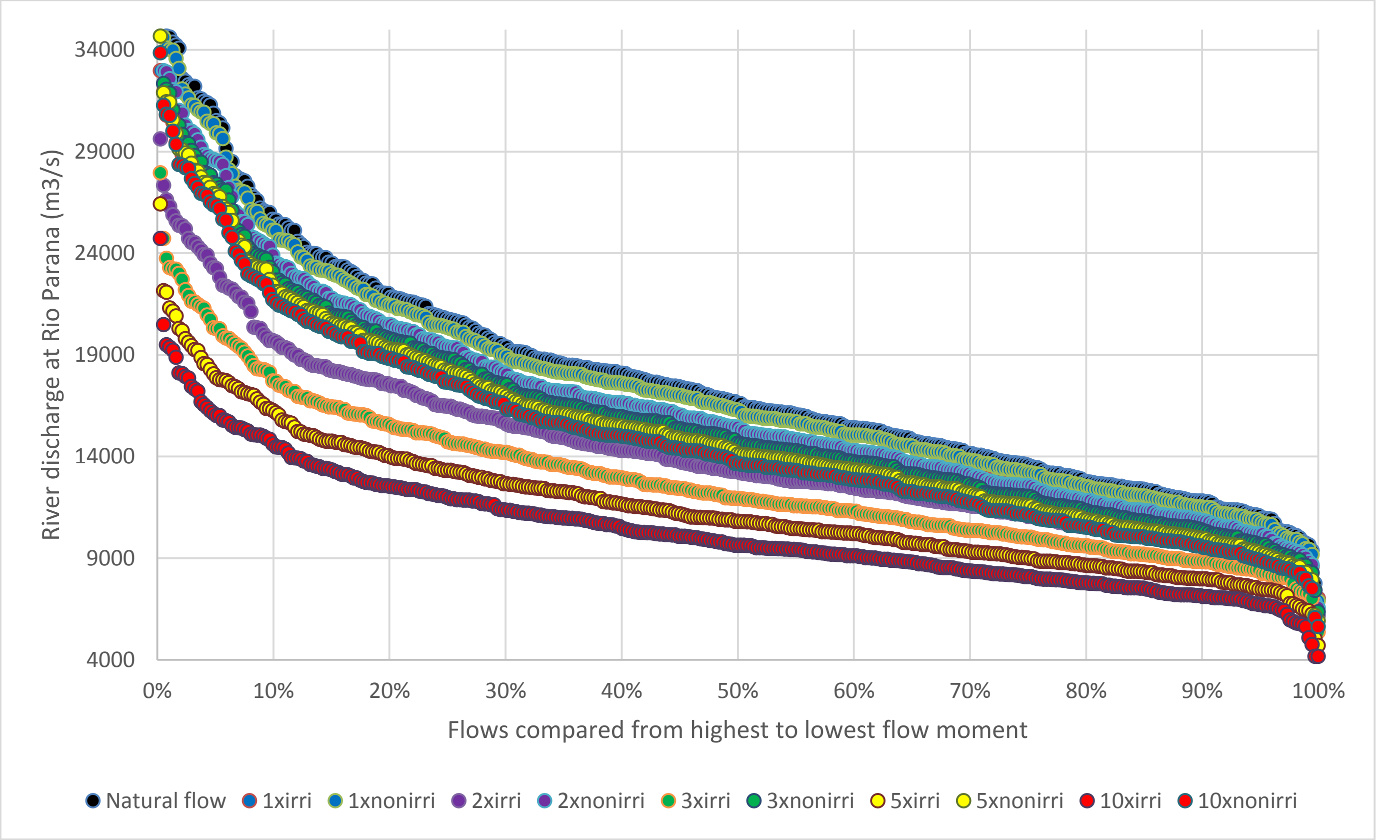
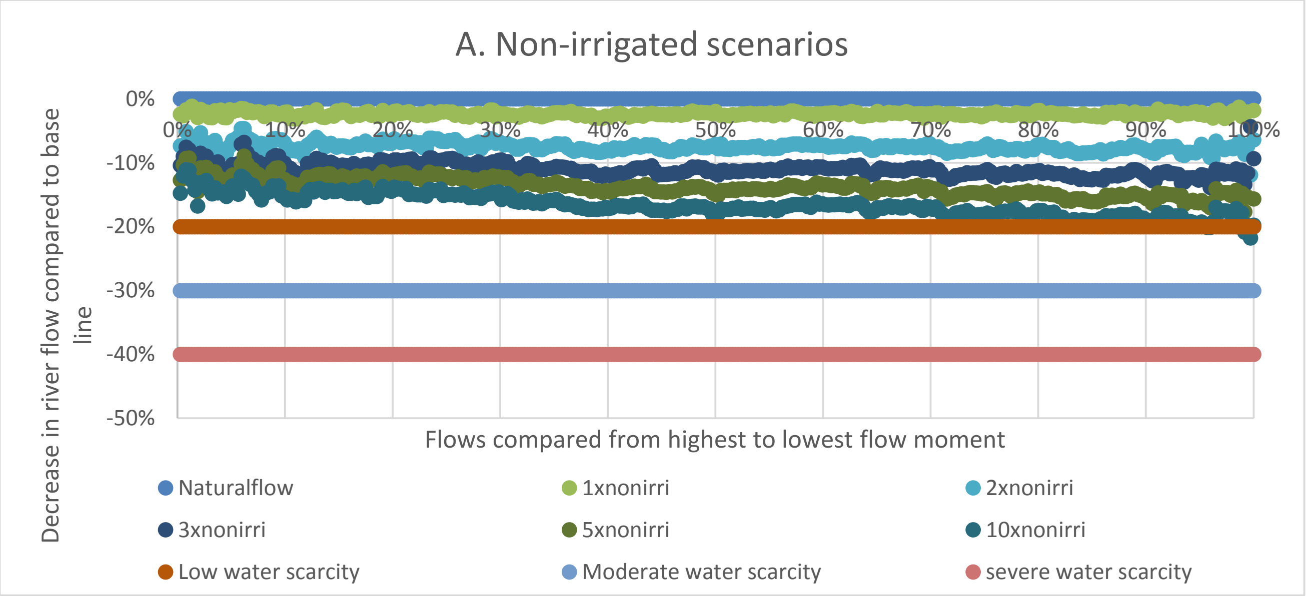


Figure 7. Flow moments from all scenarios, ordered from large to small. The percentage on the x-axis indicates the % of highest flow moment (0% being the highest, 100% the highest and 50% the mean).

Figure 7 shows the ordered monthly average discharge of the Rio Parana. It can be seen that also in the ordered flow graph, the irrigated scenarios result in lower flows than the non-irrigated scenarios. Additionally it can be observed that the absolute flow differences between the scenarios are larger at the high flow moments compared to the low-flow moments. This is most clear when looking at the difference between the Natural flow and the 10xirri scenario, at the high flow side this is 15000 m^3/s, and at the low side only 5000 m^3/s. This is somewhat unexpected, as it was expected that expansion of irrigated sugarcane would make an especially large difference during the dry period. Oppositely, the expansion seems to have a stabilizing effect on river flow, mainly decreasing flow peaks (as could also be seen in Figure 6, also see section 3.3).

3.3 Drought analysis

In the following part the flows are analyzed for drought risk. Flows are analyzed using their flow volume relative to the natural flow. Drought indicators are given at 0-20 (no water scarcity) 20-30% (low water scarcity), 30-40% (some water scarcity) and >40% (high water scarcity).



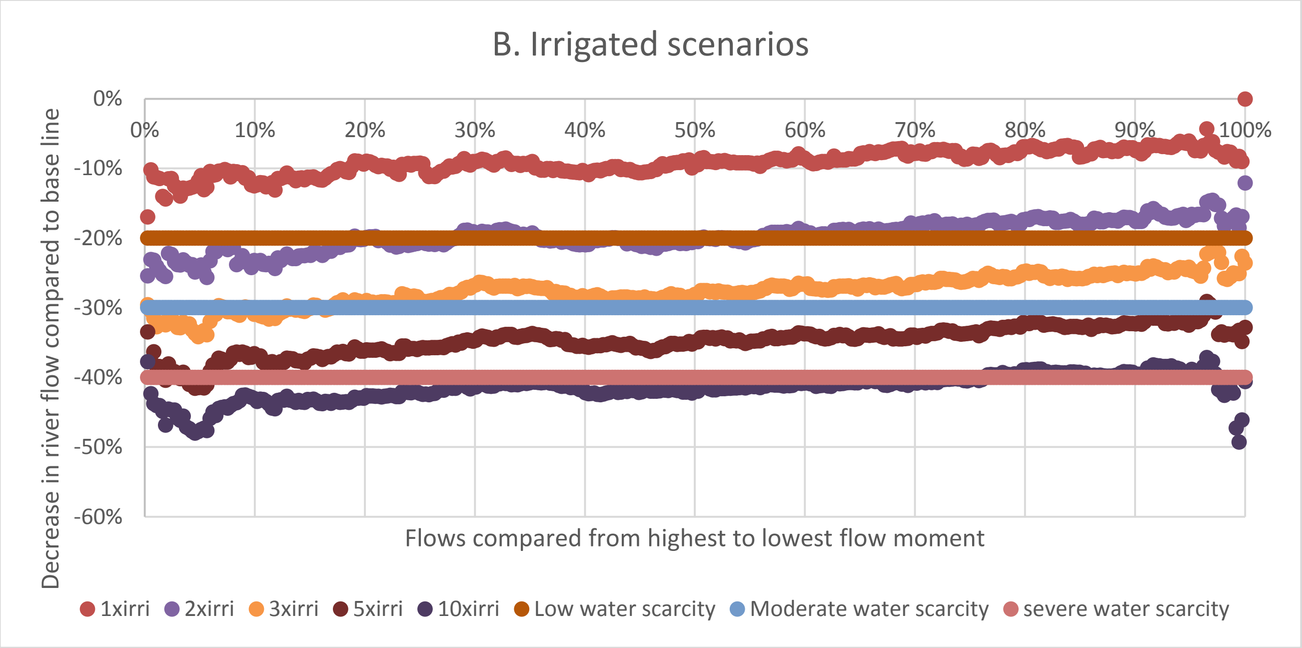


Figure 8. Shows the relative river flow decreases per scenario compared to the baseline for both the non-irrigated (A) and the irrigated (B) scenarios. These scenarios are compared to the water scarcity indicators.

Figure 8A shows the decrease in river discharge of the non-irrigated scenarios relative to the natural flow scenario. The more sugarcane is planted, the stronger the decrease. Only the 10xnonirri scenario breaches the 20% border (and only very slightly: 2 months over a 30 year period). This indicates that based on this data and monthly averages none of the non-irrigated scenarios would lead to water scarcity on a catchment level. Although the absolute differences in flow were lower on the low-end flows, the relative differences are higher. This means that for non-irrigated scenarios the (small) impact is largest during the most critical periods (where flow is already low). However the difference is small, and hardly breaches water scarcity boundaries.

Figure 8B shows the decrease in river discharge of the irrigated scenarios relative to the natural flow scenario. The more sugarcane is planted, the stronger the decrease. The 1xirri scenario is well within the 20% border. The 2xirri scenario is hovers around the -20% scenario, below it on the high flow end, but above at the low flow end. The 3xirri scenario has a similar pattern over the -30% (some water scarcity) border. The 5xirri scenario ranges between -30 and -40% (severe water scarcity) and the 10xirri goes well under the 40% border for most of its high flow moments.

In general the relative flow decrease is lower at the lower flow side. This is an interesting result, as it means that the impacts of irrigated cane on water scarcity is lower during the most critical flow periods. Initially it was hypothesized that the irrigation would result in an especially large impact during drier periods. During periods with lacking precipitation additional abstraction can be made from surface water, resulting in decreased flow. However this is not what is observed: the relative difference at the low flow is actually lower in the irrigated scenarios. Somehow expansion of irrigated sugarcane has a balancing effect on river flow as it decreases peaks.

This might be explained by the fact that the modelled irrigation system has perfect foresight of precipitation. This means that irrigation is only applied during longer dry periods and not when precipitation will fall in the period directly following. Additionally, a main difference between the natural and the cane scenarios is the expansion of the cane area. This not only results in higher use (due to Kc), it also results in larger potential useable soil moisture (due to deeper rooting). This means that soil moisture levels can be depleted further, resulting in a larger potential storage of precipitation. The primary theory is that sugarcane might act similar to how forests act: stabilizing river flow (Brown, Zhang, McMahon, Western, & Vertessy, 2005; Farley, Jobbágy, & Jackson, 2005; Sun et al., 2006). Deep rooting results in high amount of TAW (Total Available Water, see 7.3.4), which acts as a storage for water, and as a reservoir during periods of high precipitation. This would explain both the relatively large difference during water abundance (is stored in the emptied soil) and the relatively small difference during scarcity periods (can live of the water stored in soil).If this would be the case, then this could be tested as a part of the sensitivity analysis, which (amongst others) tests the effect of changing the rooting depth (see section 3.4).

3.4 The effect of irrigation

In sections 3.1 – 3.3 it already became clear that irrigation has a very large effect on discharge. All irrigated scenarios (except for 1x) had lower discharge than all of the non-irrigated scenarios. A doubling of sugarcane with under full irrigation will have a stronger effect than a ten-fold expansion without irrigation. Figure 9 shows how much of the discharge increase can be attributed to the use of irrigation. It shows that the difference in discharge becomes larger with more sugarcane expansion, e.g. the effect of irrigation on discharge is larger when a larger area is irrigated. When looking back at Figure 8A and 8B it can be seen that water scarcity is much more affected by the amount of cane irrigated, than by the total amount of sugarcane expansion. Thus when projecting water scarcity for the area, the amount of irrigation is vital information.

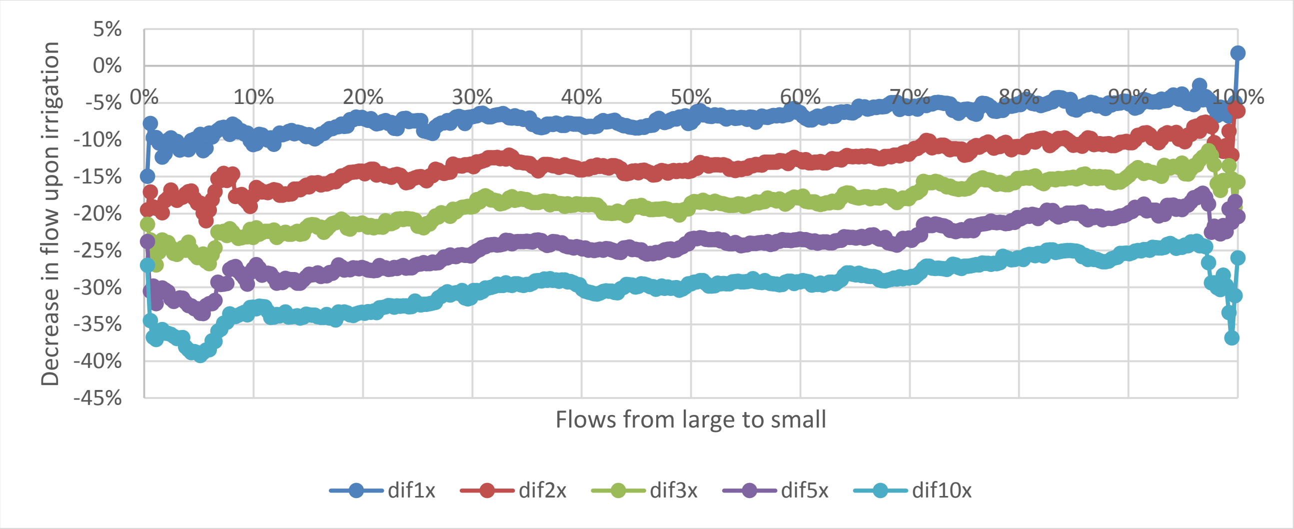


Figure 9. Shows the relative difference between the irrigated and the non-irrigated scenarios. On the y-axis is the decrease in flow occurring due to application of irrigation. The effect is larger in the scenarios with a higher amount of sugarcane.

3.5 Sensitivity Analysis

In this section, the effect of changes in various input variables are assessed. This has three functions. First of all, it tests which variables the model is most sensitive to. In future studies, extra focus can then be put on obtaining accurate data for variables that have a high sensitivity (such as precipitation, see Figure 10). Values with low sensitivity are not as important to obtain accurately, as they do not affect the model as much. Secondly, it can be used as an experiment to test hypotheses, for example the rooting-hypothesis postulated in section 3.4. Lastly, it can be used as a control for the model, to check whether it behaves as it should (for example, increasing Kc should make a change, otherwise Kc would not be incorporated properly).

Figure 10 indicates that the model is extremely sensitive to changes in precipitation. A 9% increase or decrease results in a 25% increase or decrease of discharge. This means that it is extremely important to use accurate precipitation numbers, as any error in the output will be amplified almost three times in the input. This was to be expected, as not all of the precipitation becomes discharge: a share of the precipitation evaporates or percolates into the groundwater. As evaporation is restricted by Kc, an increase in precipitation is expected to result in an even larger increase in discharge because evaporation is likely already maxed out (in irrigated scenarios).

Figure 11 shows that the model is somewhat sensitive to changes in the Kc. The changes indicated in table 2 result in a 5% decrease in discharge, whereas a decrease results in a much larger flow of roughly 12%. This is roughly the expected order of magnitude.

Variations of the leaf area index (LAI) result in very low changes in discharge (<<1%). The effect was measurable but the model is hardly sensitive to variations in LAI, the difference is so small that it is not graphed. Variation of up to 50% is used in the LAI sensitivity (see Table 3), which is in turn used to calculate Interception Capacity (IC), but no relevant impact was found.

Alterations in rooting depth and dep1factor had absolutely no effect on river discharge. This is highly peculiar. Rooting depth decides whether a certain soil-water layer can be reached, and dep1factor decides how easily that water is abstracted from that layer. The only situation in which the model could lead to absolutely no difference in discharge between these two would be if the soil would be constantly saturated above a point of effortless extraction (see Appendix 7.3.4). For the irrigated scenarios, this would be a possible explanation as the soils are wetted above that point (100% irrigation ensuring that rooting depth and dep1factor are irrelevant). However, in the non-irrigated no effect was found either. This is problematic because non-irrigated scenarios have higher discharge (and thus lower evaporation), which can only be limited by the availability of water (all other variables are equal). The fact that non-irrigated scenarios have higher evaporation means that non-irrigated scenarios must be limited in terms of water availability, at least some point in time. Something is either wrong in the adaptation of the model (altered rooting depth and dep1factor in the initial conditions might not link to the model correctly) or something does not connect in the model itself (rooting depth and dep1factor not functioning). For more on this see section 4.2.

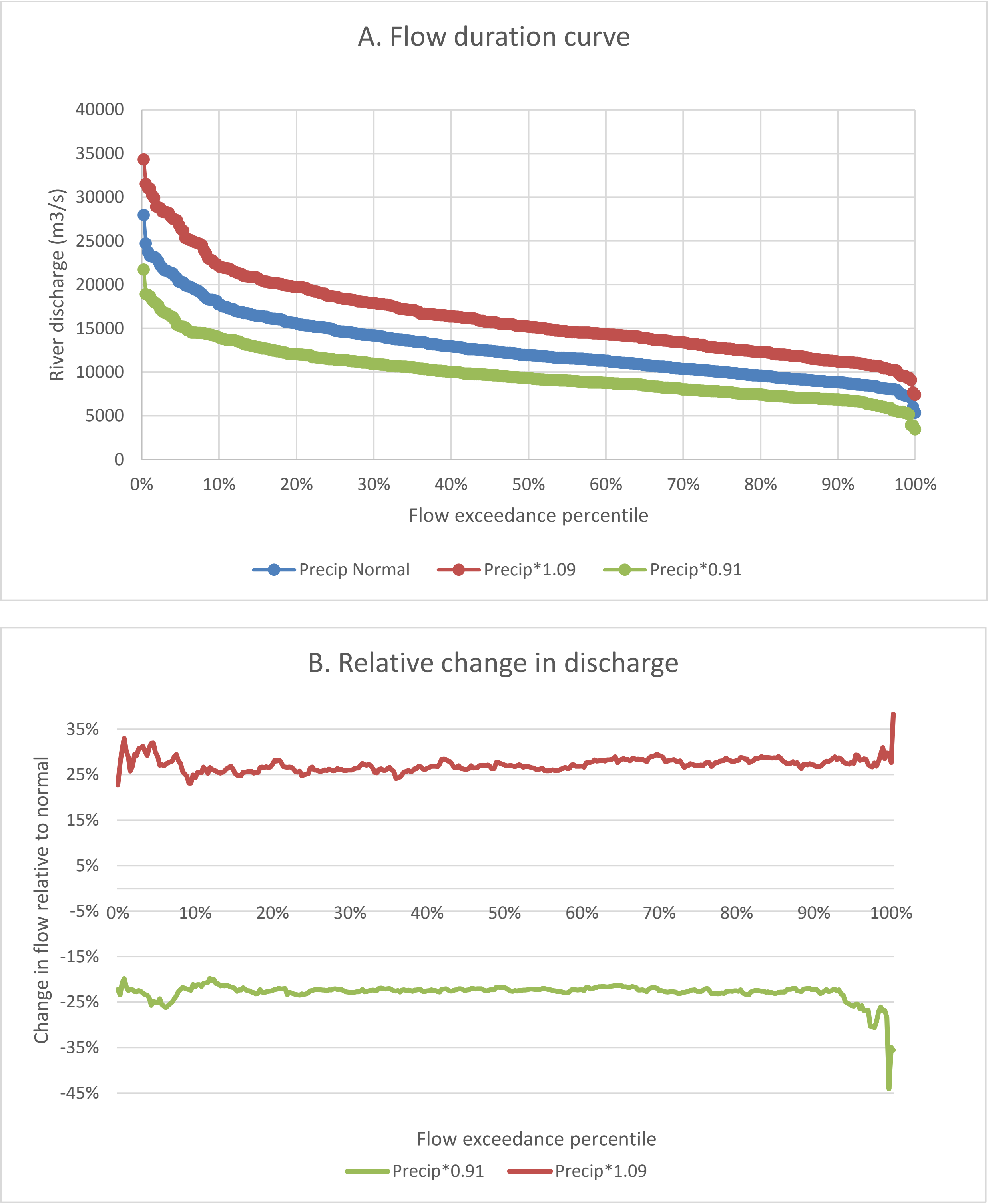


Figure 10. Sensitivity of precipitation. Showing a flow duration curve (A) and relative change in discharge (B) of the irrigated 3x scenario with altered precipitation (See table 4: 3xMeteo1.09 & 3xMeteo0.91 scenarios).

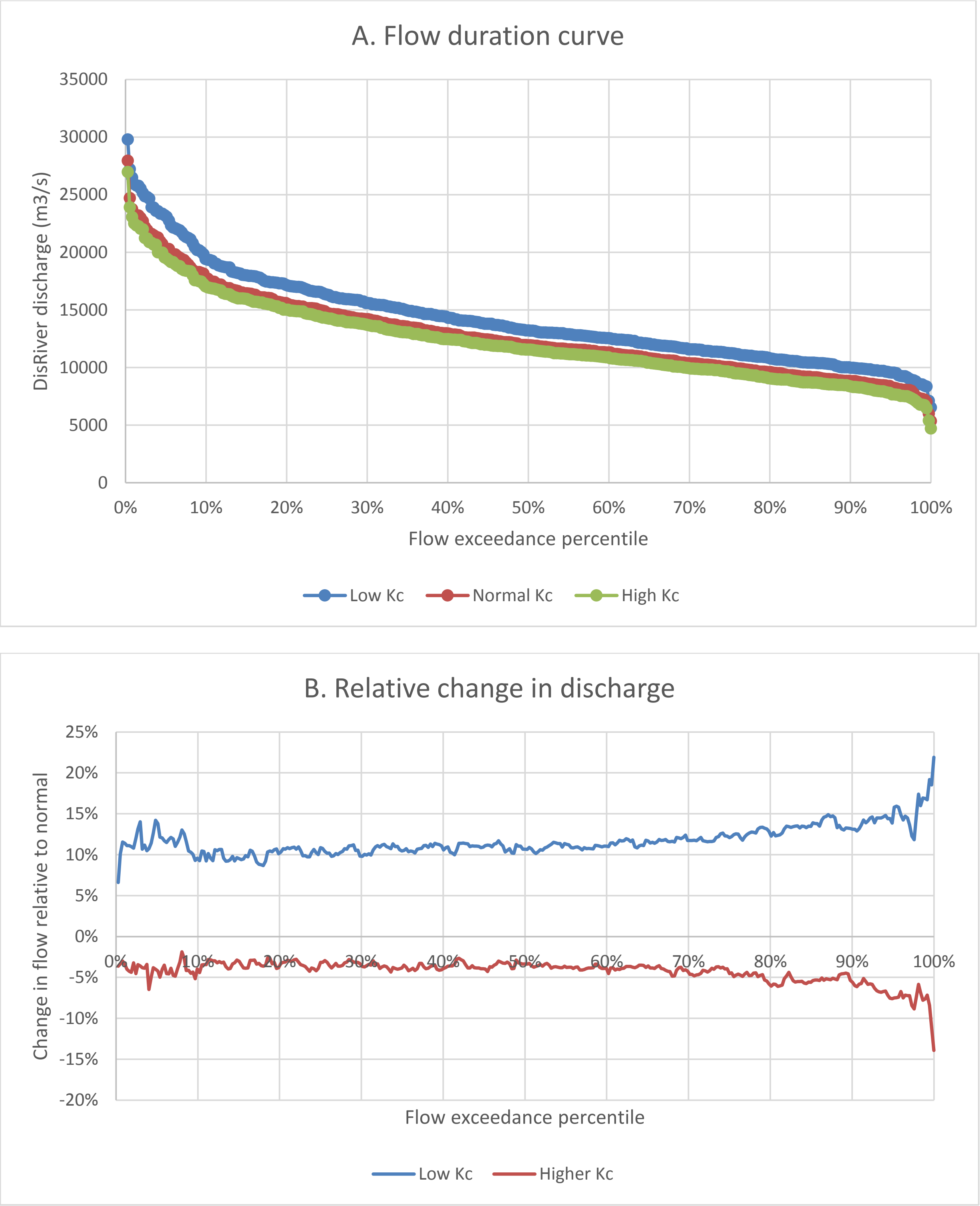


Figure 11. Sensitivity of Crop coefficient (Kc). Showing a flow duration curve (A) and relative change in discharge (B) of the irrigated 3x scenario with altered Kc (See table 4: 3xKchigh, 3xIrri, 3xKclow scenarios).

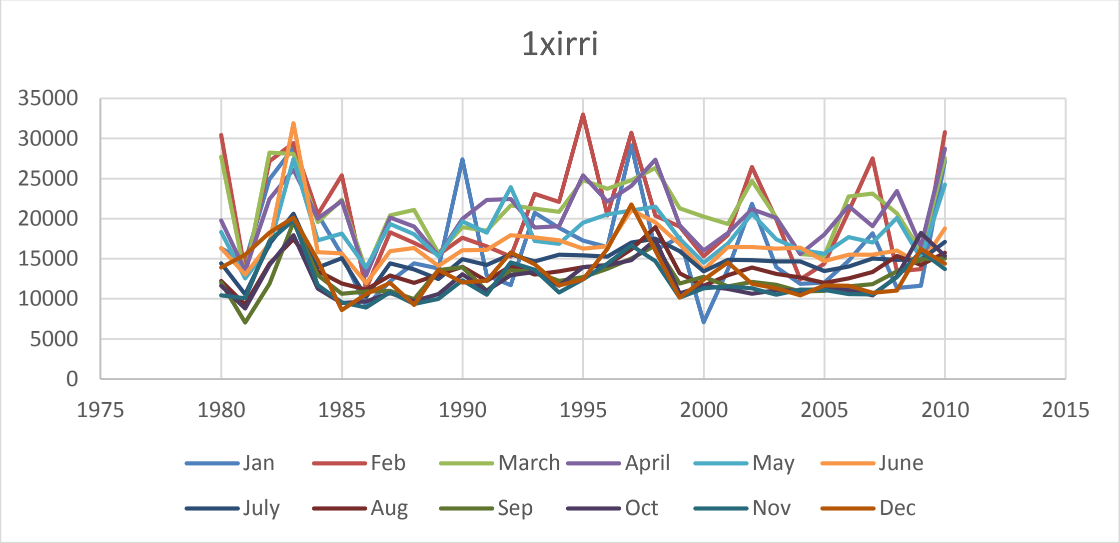
3.6 Seasonality

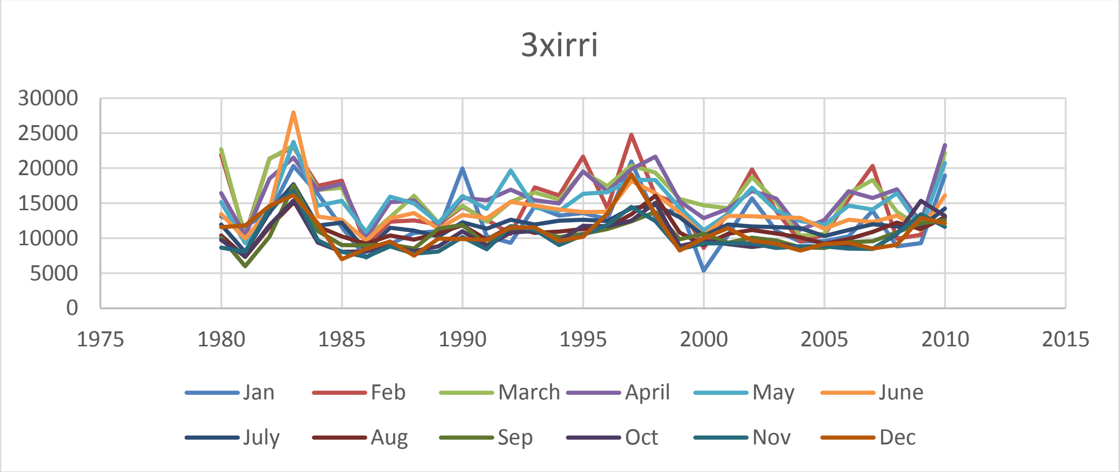
This section provides contextualization for the results found so far. When analyzing the various sugarcane scenarios, it was noticed how sugarcane expansion had a balancing effect on river flow. This was especially the case for the irrigated sugarcane scenarios, which is precisely the opposite of what was expected. In section 3.4 it was postulated that the sugarcane forest-like phenology (deep roots) could be the cause of this. However, the sensitivity analysis indicates that the model is insensitive to changes in the rooting depth and dep1factor. So this theory might work in practice, but within this execution of the model and these results, the theory of water storage does not work, as the model is not sensitive to changes in rooting depth.

A much simpler explanation can be found in the seasonality of precipitation and water. Sugarcane grows so well in Brazil because the precipitation pattern matches the sugarcane water demand. An increase of the amount of sugarcane results in more evaporation following the sugarcane pattern (Kc, see figure 14). When evaporation matches the precipitation better, variations in discharge decrease, resulting in stabilized flow. This means that sugarcane does not actively abstract more water during wet periods, but instead that the high precipitation periods in Brazil simply match the water requirements (Kc) of sugarcane. Figure 12 shows the discharge per month of the study period for 1x, 3x and 5x irrigated sugarcane. The harvest months (June, July, and August) tend to be much drier than the growing period (December, January and February), which coincides with the water requirements of sugarcane (which are low during ripening and harvesting, see appendix 7.3.2).

Figure 13 shows the precipitation, irrigation, direct discharge, evaporation and calculated soil storage, taken from the sample points in the 3xirri scenario (see table 5). This data is graphed chronologically. These graphs are used to exemplify the water fluxes of a typical cell in the basin. What is clearly noticeable is that the variation in precipitation is very large between months. Soil storage is similarly variable, this is because soil storage has been defined based on the other fluxes (see section 2.8). Likely, the variation in soil storage is an indirect effect of the variation in precipitation. Evaporation seems to vary rather predictably (with the season and the Kc as expected, as can be seen in Figure 14). It is also clear that the magnitude of precipitation, evaporation and soil storage is far greater than that of direct run-off or irrigation. This explains the sensitivity of changes in precipitation for discharge: the small change in precipitation, is a relatively large volume of water compared to the regular direct-runoff flux (which forms discharge combined with other cells).

The least noticeable variable is irrigation, which is barely present at all, with less than a millimeter per month on average. Compared to the direct run-off this is also lower than expected. All direct run-off forms the discharge of the basin, and all irrigation forms the difference between the irrigated and the non-irrigated scenarios. Therefore within the cells (which should be a proxy for the basin), the irrigation should be roughly 25% of the direct run-off (as basin-wide a 3x scenario has 25% less discharge). The sampling points have 18 times more direct-runoff than irrigation, this is likely because of the low amount of sampling points (only 5), which form a poor representation of the basin's average soil fluxes. Discussion section 4.2 continues on this point.





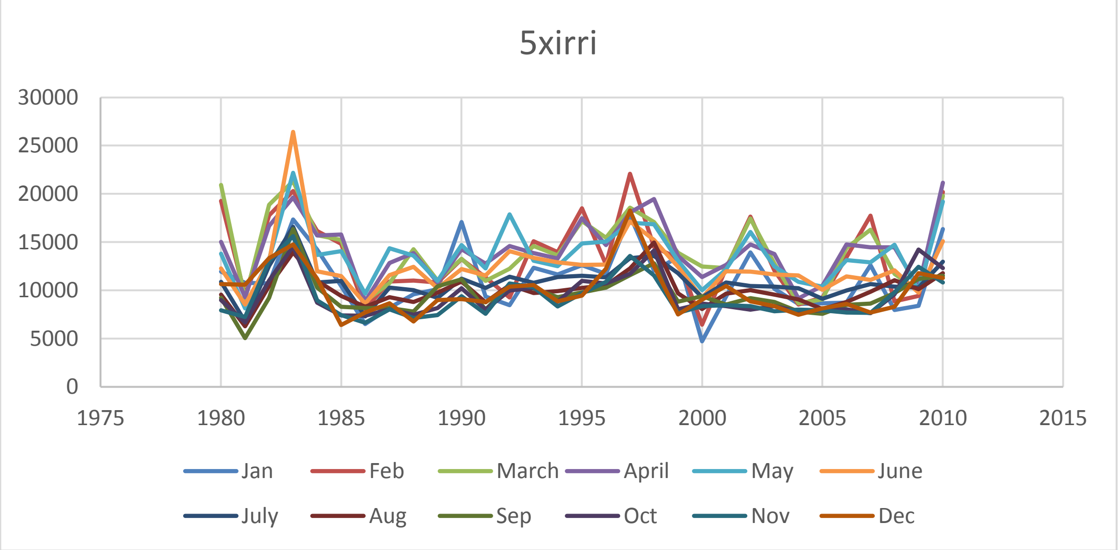


Figure 12. Seasonal discharge differences for irrigated 1x, 3x and 5x scenarios.

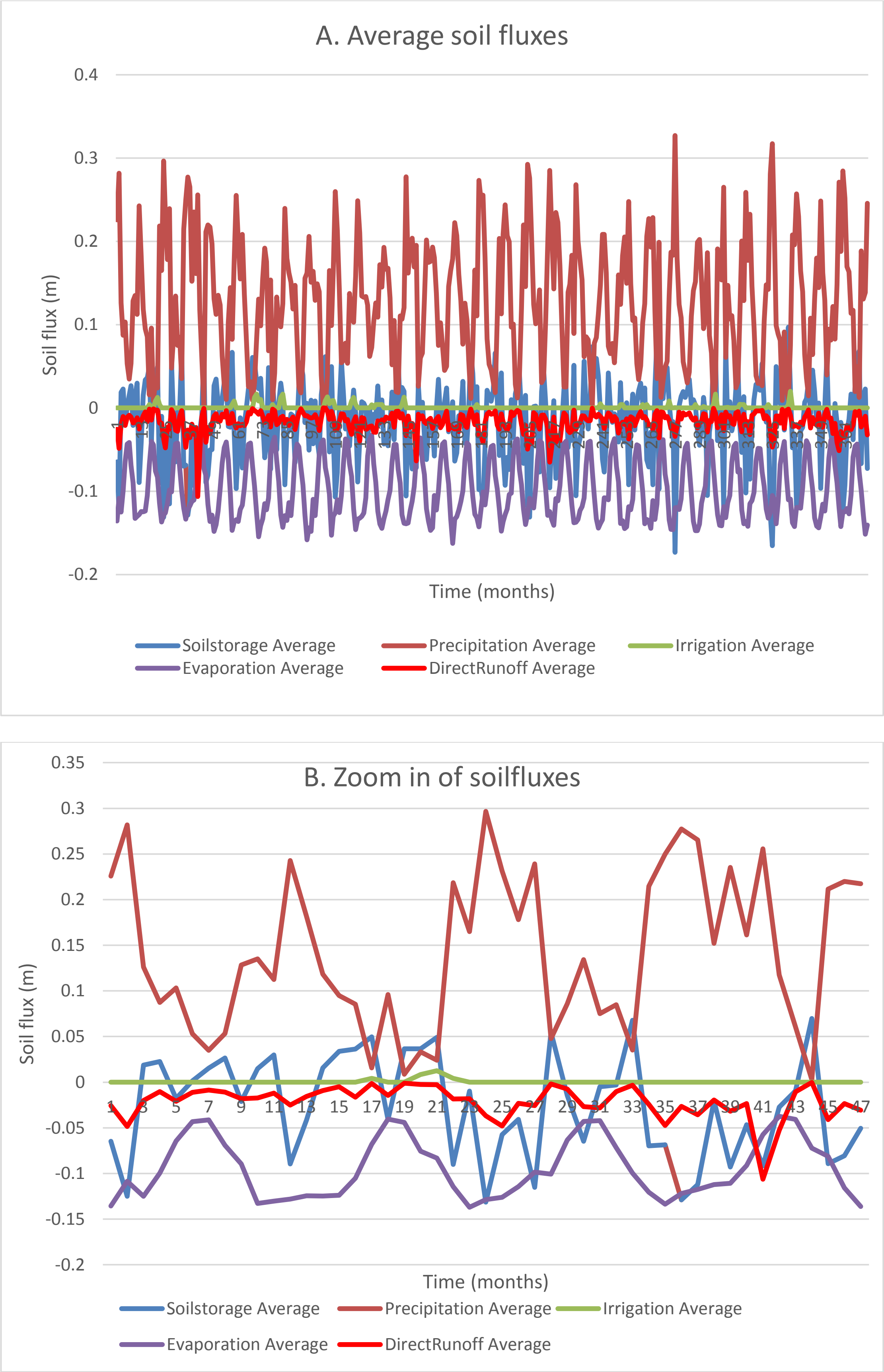


Figure 13. Averages of soil fluxes noting soil storage, precipitation, irrigation, evaporation and direct runoff for the full period (A) and for the first 4 years (B).

Figure 14 shows the relative fractions of the average annual hydrological fluxes. Each flow is divided by its own average, this is to compare the patterns of the fluxes (not the magnitude). The three discharge measures (1x, 3x and 5x) have a similar pattern, with 1x being more extreme (higher discharge around March, lower discharge around October), than 3x, and 5x is even more moderate. This shows that the flow balancing effect mentioned throughout sections 3.1-3.4 is a seasonally driven. Secondly, the Kc, the evaporation, and the precipitation also follow a very similar pattern. This makes sense, as Kc heavily influences evaporation. As has been previously noted, precipitation also nicely coincides with the Kc. With increased expansion of sugarcane, more of the area in the basin is covered in sugarcane, thus, the share of crops with a Kc that matches the precipitation pattern increases. The improved fit of precipitation and evaporation, main drivers for water supply and demand, leads to a decreased variation in the run off, and thus the discharge. This is the reason that cane expansions have a stabilizing effect on river flow.

Irrigation (which is very small in total magnitude, as is visible in Figure 13) occurs almost exclusively from September to November. This also the period during which evaporation is relatively below precipitation in that period (unlike from December to June). As has been discussed earlier in this section, the reliability of the irrigation data is not very high, therefore an erroneous indication of seasonality might be given. The main difference between the irrigated and non-irrigated scenarios occurs during the wetter periods. The application of irrigation is the only factor separating the scenarios, which means that irrigation is occurring more during wet periods than dry periods. Indeed, Figure 14 shows that the months that are most irrigated are in fact months that have reasonably high precipitation. Although the irrigation period coincides with the low discharge period, it is unlikely that these are causally connected: after all, increasing the irrigation mainly affects the high discharge periods. An explanation for the seasonal effect of irrigation on discharge can be found in flow delays.

Precipitation that falls within the basin is not directly converted to discharge at the measuring point, instead it takes time for the water to reach the measuring point. Discharge seasonality is therefore expected to lag behind precipitation. Figure 14 shows that the peak precipitation (December) precedes the peak in river discharge (March) by three months. Similarly irrigation occurring in September to December will only affect discharge three months later, outside of the low flow period. What happens in the basin (sample points) does not directly translate to river discharge (discharge point). This might explain the seasonality of irrigation. However, it must be noted that the reliability of the irrigation data remains low, due to a limitation in the amount of sampling points (See section 4.2 for suggestions to improve this in future research).

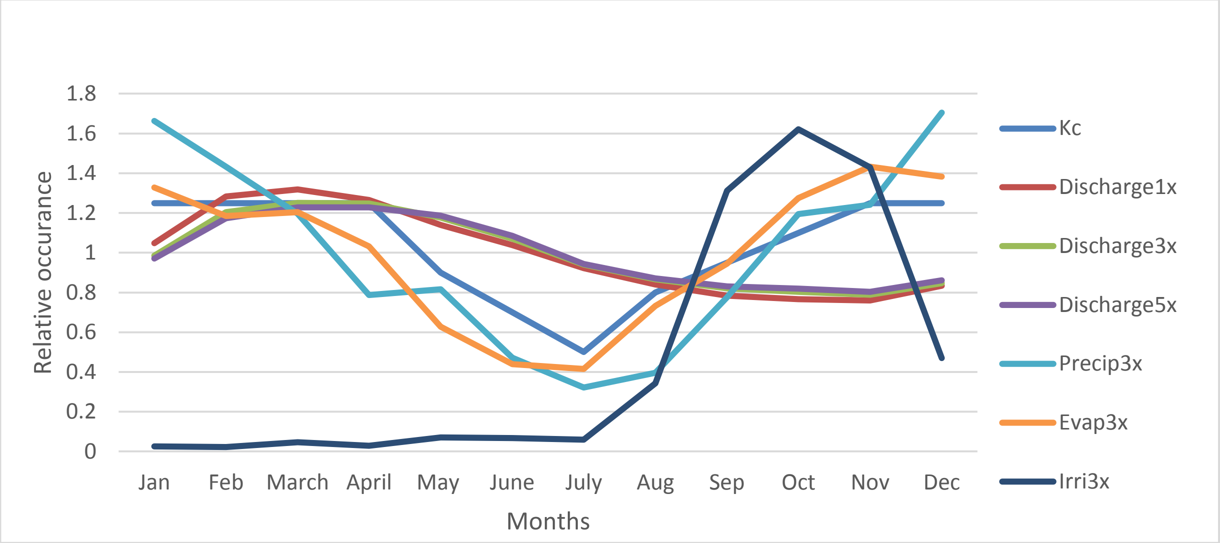


Figure 14. Averaged seasonal water fluxes of the 3x irrigated scenario, compared to the Kc and the discharge of 1xirri, 3xirri and 5xirri scenarios. Data is displayed as a relative fraction (divided over their own average).

4.0 Suggestions for future research

This section will discuss how the methods used in this study can be improved in future studies. To that purpose, it will focus on three subjects: the input, the model and the drought indicators.

4.1 Limitations of the input

A major limitation of this study is the lack of spatio-temporally specific information on irrigation. Instead of real irrigation information, a "modelled"-irrigation is used, which automatically optimizes surface water abstraction. This results in two main problems. Firstly, this irrigation system has perfect predictability, which means that it will only irrigate as much as needed until the next rainfall. In reality, this cannot be predicted, and irrigation might occur the day before it rains. This will lead to a (small) underestimation of water consumption. Secondly, it is now assumed that either all or none of the cane is irrigated, whereas in reality it is roughly a quarter (although a large share of that is in the north east). This second effect is much more dominant, as it currently leads to a major overestimation of consumption when assuming a fully irrigated scenario, and a large underestimation when it is not taken into account at all. In order to accurately assess how much decrease in discharge a certain expansion will cause, it is more important to know the extent to which it is irrigated, than the extent of the expansion.

A second limitation is the specificity of precipitation input. The precipitation of 1980-2010 might be a proxy for future precipitation, but a whole range of different future scenarios are possible. A nice addition would be to use short term precipitation projections, or at least data including the 2014-2015 droughts surrounding Sao Paulo (Escobar, 2015). Additionally, specific projections could be used, instead of just increasing or decreasing with 9%. This would allow for incorporation of increased variation, which might give a more complete picture of possible future outcomes.

A third improvement would be to obtain region-specific Kc values for sugarcane, or even better, direct information on all the water fluxes (evaporation, ground percolation, et cetera) at the basin level in various sub-areas and under various growth schemes. However, because the discharge results are not too sensitive to alterations in Kc, this has much less priority than the precipitation data.

Initially, this study had planned to also incorporate industrial and municipal water abstractions in the scenario analysis. Although they were activated in the initial conditions, running the model with debug showed that other abstractions were not taken into account. This is unfortunate as the combination of other abstractions can exacerbate water scarcity, especially in combination with high expansion irrigated scenarios. However, industrial extractions are expected to relative minor compared to fully irrigated scenarios. In 2006, industrial abstractions (150 m^3/s) were higher than irrigation (100 m^3/s). By 2010 irrigation tripled (300 m^3/s), being 50% higher than industrial extractions (200 m^3/s) and growing much faster (Scarpare et al., 2015). However, this is still less than 1% of the flow in the basin, for both irrigation and industrial abstraction. Comparatively, the 1x irrigated scenario already consumes 10% of the basin flow. The potential expansion of water abstraction by irrigation is much larger than that of industry.

Lastly, it is important to take into account that currently only land use is assessed. The land attribution model PLUC has made the implicit assumption that all land results in equal yields. In reality, the most suitable lands, to which cane will likely be expanded first, has a higher yield than the less suitable lands. In this study, scenarios are named after the amount of land attributed to cane production. For the water consumption the land use (and irrigation practice) is most important, but for the production of ethanol yield matters more. Therefore, it is worth considering that even though the 10x scenario has 10x more land allocated, it is unlikely to produce 10x as much cane. Similarly, the irrigated lands are expected to produce more cane than the non-irrigated lands. The effects of yield (and irrigation on yield) have not been accounted for within this thesis. Likewise changes in processing efficiency of cane are not accounted for. Developments in that field are very relevant for final sugarcane output (thus altering the data given in Table 1), but are outside of the scope of this study.

4.2 Limitations of the model

This section discusses what additional analyses could have been performed within the model, but have not been conducted in the study due to time constraints. The first aspect entails the reporting of the soil interactions. Currently, soil fluxes (Sample points, section 2.7) are calculated from the other reported variables. However, PCR-GLOBWB can report these variables directly from the model. Future research should take care to implement this, as it results in more precise data for the soil fluxes.

Additionally, accufluxes (accumulated fluxes) could have been reported, or extracted from the existing output files. An accuflux can report the fluxes of all cell within a basin, which allows for a flux analysis of the whole basin. This would be a much better version of the sample point analysis, as accuflux is a sample point analysis of all points in the catchment. Next to being more accurate, it would also have been a more time efficient method of reporting the data. Using this method both the average annual impact and the the seasonal effect of irrigation could be assessed more accurately.

When using accufluxes, it would also be easier to identify smaller catchments, comparing those with high and low sugarcane content (within one basin). Discharge could also be measured at various points. In this study discharge was only measured at the drainage point of the main study area, however sub-drains within the area could also be analyzed, as well as the drainage point of the whole Parana basin. This would give additional information on the water scarcity situations more locally (sub-basins) or more generally (throughout the rest of Parana). Analysis of sub-basins might prove especially interesting in combination with higher resolution data, which could properly locate sub-rivers and streams.

Lastly would be the investigation and reimplementation of the rooting depth and the dep1factor in the model. Section 3.5 already mentions the peculiarity of the absence of any effect in discharge when altering these variables. Especially in a non-irrigated scenario, which has a very clear difference from an irrigated scenario, soil moisture uptake is limiting. Any time that a variable is limiting, a change should at least be noticeable. This was not the case for alterations in the rooting depth and dep1factor, which resulted in absolutely no change. This indicates a mistake in the model set-up, or the model as a whole. In order to clarify this, the part of the model which describes Dep1factor and rooting depth should be re-evaluated. Future research should definitely focus on resolving this problem in PCR-GLOBWB.

4.3 Limitations of the indicators

The last point of discussion concerns the method with which water scarcity is measured. The results of this method are very dependent on the chosen baseline. This underlines the principle problem of this method: since flow volumes are variable over history, it is difficult to pinpoint a fair natural flow. Additionally, the level of this natural flow also matters. Certain very wet areas (such as Parana) might be much less affected by a 40% decrease in flow than areas where water availability is already limiting in the baseline scenario.

A 20% reduction in average flow is considered to be harmless to the environment, but can already cause a fairly serious decreases in production for downstream hydro dams (which will have a 20% decrease in electricity production). The 20% is mainly based on local ecosystem damage, which might however not be the most relevant parameter in an area that has a sugarcane mono-culture (e.g., large parts of Parana in a 5-10x scenario). The definition of water scarcity and the complexity of the potential damage makes it very hard to decide when scarcity becomes truly problematic. For future research, it is therefore also recommended to take into account other drought metrics to obtain a more complete understanding of the problem.

5.0 Conclusions

This study investigated how the expansion of sugarcane would affect water scarcity situations in the Parana basin in Brazil. In order to answer this general research question more accurately, it has been divided into various sub questions, which are each discussed below.

The first research question asked which of the scenarios would cause water scarcity. It has been shown that none of the non-irrigated scenarios cause water scarcity (Section 3.3, Figure 8). This is different for the irrigated scenarios, here only the 1x scenario does not cause water scarcity. The 2x scenario causes low water scarcity, the 3x causes low to some water scarcity, the 5x scenario causes moderate water scarcity and the 10x scenario results in severe water scarcity. Although river flow was severely limited, the river did not come close to running dry, as none of the scenarios caused the river to decrease below 50% flow volume.

The second research question revolves around the effect of irrigation on water scarcity. As can be seen from the answers to the first question, irrigation has a major negative effect on discharge. Whereas none of the expansion scenarios lead to water scarcity, all of the irrigated scenarios (except 1x) do lead to some degree of water scarcity. A 2x irrigated scenario causes more water scarcity than a 10x non-irrigated scenario. Irrigation is therefore extremely important in terms of assessing water scarcity situations. When calculating water scarcity - within the constraints of this study - it is more important to know the size of the area that is irrigated than the total expanded area. When continuing research on water scarcity projections, it is therefore imperative to obtain projections on the extent to which irrigation will be applied. For 2030, land use is not expected to increase beyond 2x or 3x. With irrigation remaining low (25% across Brazil, including the dry north east), these expansions will likely cause low to no water scarcity.

From the analysis of the first two research questions, it became apparent that expansion of irrigated sugarcane had a stabilizing effect on river flow (the decrease was mostly on the high flow side). This was initially hypothesized to be due to the increased rooting depth and perfect irrigation scheme. However, it was shown that the model is insensitive to rooting depth, thereby disproving this hypothesis. The seasonal analysis indicated that the seasonal pattern of sugarcane water requirements (Kc and evaporation) aligns nicely with the precipitation in the area. The additional evaporation caused by sugarcane (due to its higher Kc) is predominantly in the wettest periods, which results in a decrease of flow. Sugarcane expansion results in a more stabilized flow because it fits the precipitation pattern better than the displaced vegetation (mostly grass, Kc <1 year round).

This study shows that expansion of irrigated sugarcane could seriously affect river flow and cause water scarcity. This might be exacerbated by changes in climate, as was shown in the sensitivity analysis on precipitation. The model was highly sensitive to changes in precipitation: a change of 9% resulted in a 25% alteration in river flow. The sensitivity analysis also found that the model is somewhat sensitive to the Kc of sugarcane, but hardly sensitive to its LAI. Strangely, it was discovered that rooting depth and dep1factor (i.e., the ease with which water is absorbed) did not affect river discharge in the irrigated or the non-irrigated scenarios. As has been explained in section 4.2, this indicates that there is a limitation to the way these variables have been modeled within this study. Further investigation of this might lead to very interesting results. For planning of large scale expansion of sugarcane, it is vital to monitor and evaluate irrigation requirements and plans. Areas in which irrigation is required should preferably be avoided. From a perspective of avoiding water scarcity, it is better for policy to focus on limiting irrigation than limiting sugar cane expansion. For the near future, the likely expansion within Parana for the year 2030 is expected to be around 2x, and optimistically 3x, mostly non-irrigated. This would result in an ethanol output of 47802-71703 million liters, not accounting for changes in yield or processing efficiency. Although it remains important to assess water scarcity, it will likely not be the main limitation to bioethanol expansion.

6.0 References

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7.0 Appendices

7.1 Bioenergy and biofuels

Bioenergy is energy derived from biomass. Biomass is non-fossilized material of organic origin(FAO, 2006). This includes agricultural crops and forestry (by)products and wastes, but also manure, microbial matter and organic wastes from households and industry (Gerbens-Leenes, Hoekstra, & van der Meer, 2009). Biomass can be used to provide various forms of bioenergy such as heat (e.g. household traditional biomass, city heating), electricity (e.g. waste incineration, wood pallets), or biofuels (e.g. bioethanol, biodiesel)(Gerbens-Leenes et al., 2009). Biofuels are derived from plants with easily convertible form of energy such as sugar or oil. The first generation involve oily crops (e.g., rapeseed or sunflower), or crops with a high sugar (e.g. sugarcane) or starch (e.g. corn) content. Oils are converted to diesel, whereas sugar is fermented in ethanol. Bioethanol is the largest contributor to the amount of liquid biofuel (Balat & Balat, 2009). These are considered first generation as they use conventional conversion technologies (e.g. fermentation, oil extraction). Second generation biomasses focusses on hydrolysis consequent fermentation of the (ligno) cellulosic fraction of biomass, to produce ethanol. However this technology is still underdeveloped, currently the lignocellulosic part is burned to provide heating and electricity for the conversion processes (Gerbens-Leenes et al., 2009; Schenk et al., 2008). This research will focus only on first generation bioethanol derived from sugarcane.

7.2 Water scarcity definitions

Water scarcity is difficult to measure and define. Water availability can be dependent on lots of factors such as (but not exclusive); precipitation, land coverage, local basin geography and human extraction. Water scarcity could be defined based on many factors such as (but not exclusive); groundwater tables, reservoir levels, or river flows. Multiple of these outputs could be used as a definition, for example when reservoirs reach critical levels, ground water plummets below a certain debts, or rivers reach a critically low flow. An easy to measure option to define water scarcity is the water barrier concept, which is defined as the absolute availability of water per capita (Falkenmark, 1989). For a country-wide scale, water withdrawal as a percentage of supply is used as an indicator for water scarcity (Raskin et al., 1996). This is called the use-to-resource ratio, where 25% of water withdrawn indicates water stress (Raskin et al., 1996). However such a large scale and general approach is not a sufficient scope to properly gauge water scarcity per location. Hoekstra et al., (2012) argue to not count water withdrawal, but specifically water consumption, as return flows should be taken into account and lessen the scarcity. To measure water consumption the relative river flow can be measured, as all recycled flows return to the surface water. When river flow is lower than 80% of its unabstracted flow water is considered scarce (Richter et al., 2012). The level of 20% decrease in river flow is used as it is considered a borderline where ecosystem damage occurs (Hoekstra et al., 2012; Richter et al., 2012). On the downside, the river flow definition of water scarcity is only complete if only surface water is abstracted as it does not measure local groundwater abstractions.

7.3 Water use of crops: Evapotranspiration and Penman-Monteith

Sugar cane requires water to grow. During growth, water is taken up by roots and transpired through the stomata of a plant. In field conditions water will also directly evaporate from the soil, without directly contributing to plant growth. This combined water use is called evapotranspiration, and it can be estimated by the Penman-Monteith equation (FAOa, 2015).

The Penman-Monteith (PM) form of the combination equation is:

$$\lambda ET = \frac{\Delta (R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)}$$

R_n is net solar irradiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapor pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapor pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances (FAOa, 2015).

7.3.1 FAO Penman-Monteith

Evaporation of water requires energy. All of the terms in PM describe sources of possible energy transfer. These parameters are measure for various sources, such as solar irradiation (Rn), heat from the surrounding soil or air (cp, G), or by turbulent transfer (rs, ra, γ, Δ) (Monteith, 1965). The height of these parameters is set for a hypothetical reference crop to provide with a reference evapotranspiration (ET_0) in a certain area. This reference crop is defined at an assumed height of 12 cm, a surface resistance of 70 s/m and an albedo of 0.23, which resembles the evapotranspiration growing grass at adequate availability of water (FAOb, 2015). This calculation of ET_0 is known as the FAO Penman-Monteith method. Using this method, only available climatic data has to be filled in to obtain the ET_0.

$$ET_o = \frac{0.408\Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}$$

ET_o reference evapotranspiration (mm day^{-1}), R_n net radiation at the crop surface (MJ m^{-2} day^{-1}), G soil heat flux density (MJ m^{-2} day^{-1}), T mean daily air temperature at 2 m height (°C), u_2 wind speed at 2 m height (m s^{-1}), e_s saturation vapour pressure (kPa), e_a actual vapour pressure (kPa), e_s - e_a saturation vapor pressure deficit (kPa), Δ slope vapour pressure curve (kPa $°C^{-1}$), γ psychrometric constant (kPa $°C^{-1}$) (FAOb, 2015). In order to determine the ET_o in a certain area you will need the R_n, G, γ,T, u_2, e_s, e_a, and Δ within that area. However, ET_0 is only the reference evapotranspiration, different types of crops will have a higher evaporation than low grass. The amount of water consumed by the crop is dependent on a range of variables including crop type, growing phase, climate and the method of irrigation (Zotarelli, Dukes, Romero, Migliaccio, & Morgan, 2014).

7.3.2 ET_c and crop coefficient K_c

In order to determine the crop specific evapotranspiration (ET_c) the ET_0 needs to be multiplied with the crop characteristic coefficient (K_c). Following

$ET_c = K_c \, ET_o$

ET_c crop evapotranspiration (mm/d),
K_c crop coefficient (dimensionless),
ET_o reference crop evapotranspiration (mm/d).

Kc is generally higher for taller crops, and lower for shorter crops. Kc is also generally higher at high wind (high u_2) speed and arid conditions (high e_s - e_a) , whereas low wind speeds and high humidity will lead to a lower Kc (See Figure 3). However, under similar conditions of humidity sugar cane is likely to have a higher Kc compared to other (shorter) crops (FAO, 1986). Kc varies furthermore over the growing season (generally starting low, reaching a plateau and then decreasing). ET_c indicates the evapotranspiration for a specific crop, per growing stage, under specific climate conditions assuming enough water is present (FAOc, 2015).

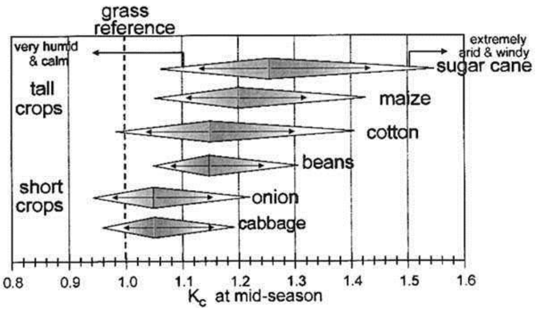

Figure 2 Kc for various crops, under different climate conditions, compared to grass reference (FAO website c)

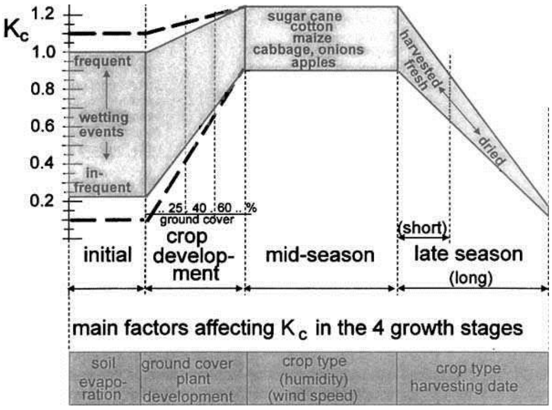

Figure 3 K_c for various crops in various stages of plant development (FAO website c)

7.3.3 Stress conditions

ET_c is a measure of water production under optimal circumstances. In the field circumstances are not necessarily always optimal. Shortage of water will decrease the evapotranspiration, which has negative consequences for growth (FAOd, 2015). Amongst with other stress effects such toxicity (e.g. salinity) water shortage (measured as K_w water stress coefficient) forms the total stress factor (K_s), which is a fraction (0-1) indicating the extent to which the crop evapotranspires at its potential. This is incorporated with the total formula as follows

$ET_{c\ adj} = ET_0 * K_c * K_s$

$ET_{c\ adj}$ = Adjusted evapotranspiration
ET_0 = reference evapotranspiration
K_c = crop coefficient
K_s = Stress coefficient (With K_s consisting of $K_w * K_{s1} * K_{s\ etc}$)

7.3.4 Water stress

Water stress occurs when plants are limited in their water take up from the soil. Soils are supplied with water by either precipitation or irrigation. A heavy rainfall will fully saturate a soil, consequently a soil will drain till field capacity, which is the amount of water a soil can hold against gravity. Crops growing in this soil will gradually take up the water in the root zone, until the water is held so strong by soils that the roots can no longer extract it. This is called the wilting point. The difference between the fully saturated soil (maximum) and the wilting point (minimum) makes for the total available water (TAW) (FAOd, 2015). Rooting depth positively influences the TAW, because plants with deeper roots have access to deeper layers of soil.

$TAW = 1000\ (\theta_{FC} - \theta_{WP}) * Z_r$

TAW = Total available soil water in the root zone (mm)
θ_{FC} = Water content at field capacity (m^3/m^3)[3]
θ_{WP} = Water content at wilting point (m^3/m^3)
Z_r =Rooting depth (m)

Sufficiently wetted soils yield water at the rate of atmospheric evaporation demands. The wilting points indicates that absolute maximum level of water that the plant can take from the soil, yet already before this point is reached water uptake is reduced. This threshold is reached as soon as atmospheric demands (ET_c) exceed the actual water uptake, resulting in (partial) water stress. Readily Available Water (RAW) is the part of the TAW that can be taken up without experiencing water stress (FAOd, 2015).

$RAW = p * TAW$

RAW = Readily Available Water (mm)
TAW = Total Available Water (mm)
P = average fraction of TAW that can be depleted without water stress occurring

At an ET_c of 5 mm/day, the p for sugarcane is 0.65, which is high compared to most crops (typically 0.5) (FAOd, 2015). This means that in similar soils sugarcane has a relatively large water reserve, and if wetting is infrequent, it has more water to its disposal (due to other crops being limited in the extraction of the water at an earlier stage). Values for p are lower when the ET_c is higher because the total transport demand

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[3] Dimensionless factor, indicated as a (m^3/m^3) by the FAO.

will be higher, and thus the limits of soil-root transport will be reached earlier. When the frequency of wetting is low or possibly limiting, as can happen in rain fed agriculture, the deep roots of sugarcane allow a higher $ET_{c\ adj}$ compared to crops with lower p values, and thus a higher water use.

7.3.5 Land use change

When sugarcane production is expanded (outside of productivity increases), additional land is required. This land will have different vegetation growing on it prior to the sugarcane growth. This different vegetation can have a different Kc, and thus a different total evapotranspiration. If the Kc is higher, the evapotranspiration is higher and the land will use more water than before. Brazilian sugarcane plantations typically expand into cropland or grasslands (Adami et al., 2012). The direct land use change (dLUC) is for 99% on grasslands or croplands (Adami et al., 2012). Some argue that as a result of the decrease of pastures and agricultural lands, an expansion at the cost of forest or Cerrado occurs (Lapola et al., 2010). This would be an indirect land use change (iLUC); even though the fields where sugar cane growth occurs were not originally Cerrado, the final effect is a decrease in Cerrado. However, Verstegen and colleagues (2015) argue that the magnitude of the sugarcane based iLUC is uncertain. Because this thesis aims at taking into account the spatial temporal perspective, it is very difficult to consider iLUC water use, because these are not spatiotemporally set. The primary reason for this is that iLUC could occur outside of basin area, or within an area of the basin where water is abundant, and thus not cause a problem.

Grassland (ET_0, thus Kc = 1) and basic cropland (Kc 1.05-1.20) typically have a lower Kc value than sugarcane (Kc 1.25) (FAOc, 2015) this means that the areas to which sugarcane is currently expanding (grass and crop), will have increased evapotranspiration. In order to understand how that effects local hydrology a basic explanation of the water cycle is given in the next section.

7.4 Hydrological cycle

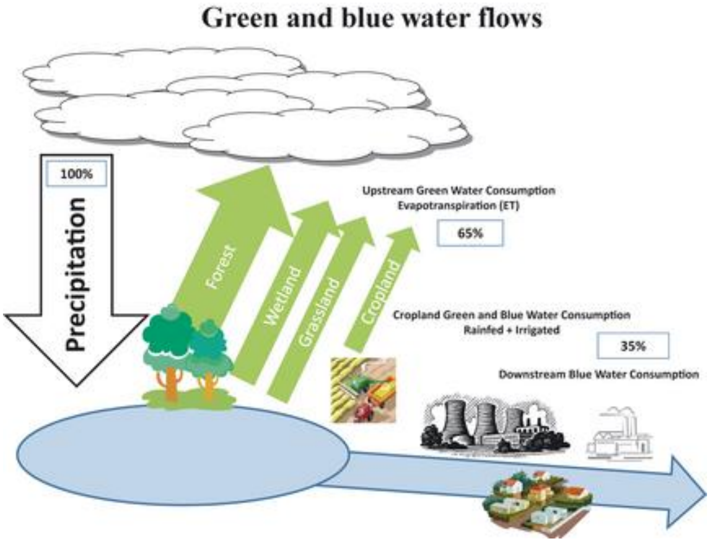

Figure 4 Illustration of interactions P, ET and R (Ellison et al., 2012)

Figure 5 gives a very concise illustration of the water cycle. The water cycle starts with P (from oceanic evaporation) falling on the land. The combination of ground evaporation and plant stomata transpiration is called evapotranspiration (ET). In agriculture ET is the productive part of the water, it enables crop growth. The non-ET water adds runs off (R) as blue water and can be used downstream (Ellison, N Futter, & Bishop, 2012).

P = ET + R

P = Precipitation
ET = Evapotranspiration
R= Run-Off

This equation tends to stigmatize ET as "wasted" water, as it is not added to the surface water in the form of R and thus cannot be used downstream. Forests, which have high ET, are then mainly seen as consumers. However as a large part of ET become P again, this leaves with an incomplete picture (Ellison et al., 2012). In fact P is composed the part of ET and OE (Oceanic Evaporation) that falls on land, thus when ET changes, P changes with it, which alters ET in return. Any increase in ET, will lead to an increase in P, which can once more be used. However, not all P falls back in the same basin, or at all on land, thus some ET is lost to the cycle, however a part of it is recycled as useful P.

P = ET(P) + OE

P = Precipitation
ET(P) = Evapotranspiration as a function of precipitation
OE = Oceanic evaporation

From this it is important to note that green water can cycle various times, hence a decrease in ET, will result in a lesser increase of R. Because of the difference between a decrease in ET and a decrease in R these water types need to be distinguished. Mekonnen & Hoekstra (2011) have coined the part of water that will turn into ET green water as it is associated with plant growth. Alternatively, Run-off (R) will seep into the groundwater table or flow through canals and finally end up into rivers, for downstream use. Water extractions from the surface water for is called blue water consumption. Not all R is useful as it might be polluted with agrochemicals, such fertilizer, or various pollutants emitted by industry or municipal use. Such water use is called “grey”-water consumption and is defined as the amount of water needed to dilute the pollutant to safe concentrations (Mekonnen & Hoekstra, 2011). Typically forests have high levels of evapotranspiration, and therefore little run-off. Yet due to the recycling mentioned above, this ET will partially come down again a P. Forests have been classified both as high users and producers, whereas in the hydrological system they are both (Ellison et al., 2012). However, from a same basin only perspective (not counting the ET that falls as P outside of the basin) forests consume blue water. This has been put forth by a range of studies, all indicating increased flow after deforestation and decreased flows in afforestation and reforestation projects (Brown et al., 2005; Farley et al., 2005; Sun et al., 2006). This thesis will focus on the in-basin changes to the hydrological cycle, seeing what the effect of the (sugarcane land use change-driven) increase in evaporation is on water availability and drought.

7.5 Water use and population growth 1993-2013

Water use in 10^9/year	Industry	Municipal	Recycled	Total	Population	population/total water use	Relative increase in pop/water
1993-1997	10	11,5	1	20,5	164,4	0,12	1,00
2003-2007	10	16,2	2,5	23,7	188	0,13	1,01
2008-2013	12,7	17,2	3,1	26,8	200	0,13	1,06

Water use from (AQUASTAT, 2012), population from (Worldbank, 2015). Population to water use seems fairly equal (slightly inclining in the last period, but low enough to consider it linear for the scope and accuracy of this research).

7.6.1 Other models

Several other models have made assessments of global water stress (Vörösmarty, Green, Salisbury, & Lammers, 2000), continental runoff (Nijssen, O’Donnell, Lettenmaier, Lohmann, & Wood, 2001), or future estimates of continental runoff (Milly, Dunne, & Vecchia, 2005). Sheffield and Wood (2007) modelled soil moisture fields and global droughts, and Güntner and colleagues (2007) modelled continental water storage (Gunkel et al., 2007; Sheffield & Wood, 2007; Van Beek & Bierkens, 2009). Other models such as SWAT might be used in a similar fashion (Deb et al., 2015; Gassman, Reyes, Green, & Arnold, 2007), or the Watch model (Yano et al., 2015). The models used in those studies are similar to PCR-GLOBWB. It is not the only model that would be capable of performing such calculations, but it does have the advantage of having certain required streams build in, such as manmade water extractions. Additionally, it is present at the department of the UU, which means it is directly accessible to the researcher. Although the vast majority of the model required for this research has already been developed, some adaptations are still required.