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# Hydrologic Impacts of Biofuel Expansion in the Ivinhema Basin, Brazil

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# Hydrologic Impacts of Biofuel Expansion in the Ivinhema Basin, Brazil

**by**

**Jesse Madden Libra, B.S.**

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## Dedication

This thesis is dedicated to my family, for all their love and support over the last three years.

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# Abstract

## Hydrologic Impacts of Biofuel Expansion in the Ivinhema Basin, Brazil

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The University of Texas at Austin, 2015

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Brazil produces approximately a quarter of the world's yearly ethanol demand, making it a global leader in biofuel production. The repercussions for local water resources in areas of intensive biofuel expansion, however, remain uncertain. The purpose of this study is to assess the effects of various land-use scenarios on water sustainability in Brazil, specifically the Ivinhema basin. This basin, located in Southern Mato Grosso do Sul, has experienced extensive sugarcane expansion since the mid-1990s -- a trend that is expected to continue in the short to medium term. To achieve the goals of the study, I used the Stockholm Environment Institutes' Water Evaluation and Planning software (WEAP), specifically, the Soil Moisture Method, to model hydrologic processes in the Ivinhema basin from 1990-2013. The study has two parts.

The first part focuses on model calibration in a data poor environment. To circumvent poor data quality, I examined the effects on model accuracy of a number data processing methods for land-use, precipitation, and ethanol production data. A total of 8 different calibration scenarios were run using these different data inputs, which I evaluated for accuracy using Nash-Sutcliffe Model Efficiency coefficients. Those producing the best results were used as a baseline for part two.

The second part of the study uses the baseline model developed in part one to investigate the crop yield and stream flow effects under three different irrigation and ethanol production scenarios. Water consumption for the ethanol production process has little impact on stream flows, with daily demand peaking at 0.7 percent of baseline flows. Irrigation, however, massively reduces flows – when irrigation is limited to only sugarcane, flow reductions of over 60 percent only occurs on 1.98 percent of days, while reductions of up to 100 percent during the dry season. Despite these large flow reductions, sugarcane yield increase from irrigation was only 7-14 percent over the study period.

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# Chapter 1: Brazil and Biofuels

## BIOFUELS AND WATER

Biofuels are widely hailed as a net-zero carbon fuel because biofuel stocks remove carbon from the atmosphere during cultivation; however, the additional energy and water required in the production process skews this balance and raises questions about the environmental efficacy of biofuels.[1] Biofuel production requires large amounts of water, both for cultivation and processing; however, whether the water-footprint of biofuel production has a large environmental impact depends on a number of site-specific variables including crop type, climatic variables, and processing technologies. Because of this, it is important to evaluate the impacts of biofuel production on water availability on a case-by-case basis.

This paper will investigate the impacts of various biofuel production scenarios on surface hydrology in the Ivinhema Basin in Mato Grosso do Sul, Brazil, a basin currently experiencing rapid increases in biofuel stock cultivation and ethanol production. The study covers 1990-2013, using WEAP's Soil Moisture Method to simulate hydrologic processes and land use change within the basin. The first chapter of this study offers background on issues relevant to the paper, such as water consumption in the production of biofuels, Brazilian biofuel production, and the Ivinhema basin itself. The second chapter will detail the data used, and the methods used to calibrate the model. The final chapter looks at the impact of irrigation on crop yields and stream flow in the basin, accounting for increased ethanol production due to sugarcane irrigation.

## Crop Water Requirements of biofuels

Cultivation is by far the most water-intensive stage of biofuel production. In the United States, evapotranspiration requirements range from 500 – 4000 L of water per L of ethanol produced, which is 50 – 2000 times the amount of water used in the processing stage (on average 2 – 10 L of water per L of ethanol).[2] Because evapotranspiration represents the highest water cost in the biofuel production chain, this study aims to evaluate the yield benefits of sugarcane irrigation versus the water costs.

### *Evapotranspiration and Crop Water Coefficients*

The water required to maximize yields is equal to the *maximum evapotranspiration* ($ET_c$) and represents the crop's evapotranspiration in mm/day. This value depends on two variables: the *reference crop evapotranspiration* ($ET_o$) and the *crop water coefficient* ($K_c$).

$$ETc = (ET_o)(K_c) \qquad \text{Equation 1.1}$$

$ET_o$ is the amount of water in mm/day that a reference crop requires for evapotranspiration, in this case switchgrass. $ET_o$ is dependent on climatic variables, such as temperature, humidity, wind speed, and cloud cover, and accounts for climatic variation in evapotranspiration rates.[3] Climates that generate the highest $ET_o$ values are those that are hot, dry, windy, and sunny. $ET_o$ values used were calculated using the Penman Monteith Method by the University of Texas Energy Institute as part of the Integrated Modeling of Land Use, Water, and Energy Nexus of Brazilian Biofuels Expansion under Climate Change project, funded by the BMUB.[4]

$K_c$ is a factor relative to the reference crop used to determine $ET_o$ that accounts for biological variation in evapotranspiration rates between crops. It varies depending on crop type and growth stage. Crops with larger leaf area tend to have higher $K_c$ values; therefore, fully matured crops tend to have higher $K_c$ values than those in early growth stages. The time a given crop spends in a given growth-stage is dependent on climate, with growth stages being shorter in warmer climates. General estimates of $K_c$ can be used as a relative indicator of crop water needs in a given area. Table 1.1 shows the $K_c$ values for the crops used in this study, while Table 1.2 shows growth periods for each crop. Figure 1.1 shows describes the seasons and the general shape of Kc values over a plant's growth cycle. These values will be revisited in Chapter 2.

| | Initial $K_c$ | Mid-season $K_c$ | Late season $K_c$ |
|---|---|---|---|
| Sugarcane | 0.5 | 1.2 | 0.65 |
| Corn | 0.3 | 1.2 | 0.5 |
| Soybeans | 0.5 | 1.15 | 0.5 |

Table 1.1: Crop $K_c$ for different growth stages.

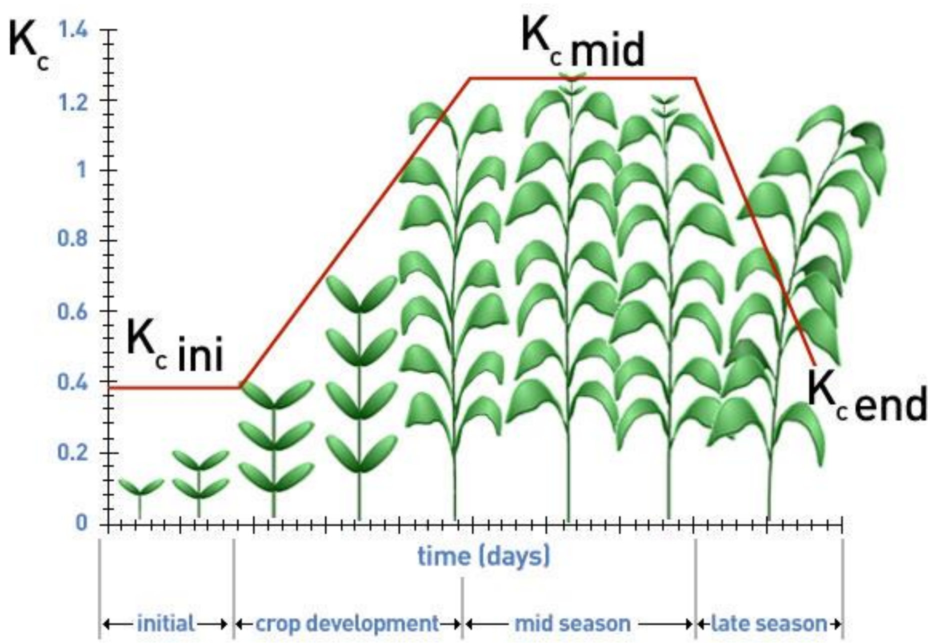



Figure 1.1: Example of crop growth stages and $K_c$ values.

| | Initial (days) | Mid-season (days) | Late season (days) | Stage 3 (days) (days) |
|---|---|---|---|---|
| Sugarcane | 30 | 95 | 180 | 60 |
| Corn | 20 | 35 | 40 | 30 |
| Soybeans | 15 | 15 | 40 | 15 |

Table 1.2: Days in each growth stage for crops used in this study

These variables are used to calculate the $ET_c$ for various crops. Yields are maximized if a crop's evapotranspiration level is equal to $ET_c$; however, this situation is rare. If soil water moisture is insufficient to provide a crop's root system with the enough water to meet its evapotranspiration requirement, the evapotranspiration will be less than $ET_c$ and yields will be lower. This actual evapotranspiration ($ET_a$) depends on soil moisture and rooting depth, and was calculated by WEAP for this study. WEAP calculates the $ET_a$ using equation 1.2:

$$ET_a = ET_0 * K_c * \frac{5z_1 - 2z_1^2}{3} \qquad \text{Equation 1.2}$$

where $z_1$ = the relative soil water storage as a fraction of the total effective storage of the root zone.

The ratio of $ET_a$ to $ET_c$ can be used to estimate actual crop yields relative to maximum crop yields, or the yield obtained if crops experienced ideal soil moisture throughout all growing periods (Equation 1.3).[5] Chapter 3 of this study will use this equation to examine the effects of irrigation on yields.

$$\frac{Y_a}{Y_m} = (1 - K_y\left(1 - \frac{ET_a}{ET_c}\right)) \qquad \text{Equation 1.3}$$

Even crops with relatively low crop water requirements ($K_c$) can alter hydrologic processes. For example, a study modeling the Iowa River Basin found that stream flows decreased by 1.2 – 3.2 percent when more land was dedicated to corn cultivation for ethanol production.[6] This is purely due to increased evapotranspiration, not a change in irrigation, which this study will investigate. Due to the heavy dependence of both $K_c$ and $ET_o$ on climatic factors and the importance of the local hydrological cycle in evaluating impact, evaluation of the extent to which hydrological processes alter in a given area must occur on a case-by-case basis. Despite higher efficiencies, water consumption and contamination are still concerns.

### ETHANOL PRODUCTION IN BRAZIL

In 2011, Brazil was the world's largest producer of sugarcane, with more than 50 percent of this production going to ethanol.[7] The country has a long history of ethanol production with research on ethanol beginning in the 1920s and ethanol blending required by law by 1931.[8] In 1973, the first oil crisis shocked the Brazilian economy and the government responded by creating the National Alcohol Program, also known as Proalcool. This program mandated ethanol blending levels in gasoline and subsidized sugarcane production and processing resulting in a large investment in research and development in sugarcane cultivation. In the early 2000s, sugarcane cultivation for ethanol rose rapidly as a result of two events: 1) the introduction of flex-fuel cars to the Brazilian market and, 2) a government mandate requiring a 25 percent blend in 2007. By 2008, sugarcane ethanol represented 17 percent of the country's energy consumption in the transportation sector.[9] An ethanol shortage in 2011 forced a reduction in the mandated blend, briefly reducing it to 18 percent, but has continued to raise it since. In September 2014, the mandate was raised to 27.5 percent.

Sugarcane ethanol production in Brazil requires less land, energy, and water per liter of ethanol produced than corn ethanol in the United States. The energy balance – the ratio of energy contained in a volume of ethanol to the energy required to produce that volume – of sugarcane ethanol is estimated to be around 9 in Brazil, while ethanol in the U.S. from corn feedstock averages about 1.3.[10] This difference is due to differences in both the physical properties of the feedstock and processing technologies used. Brazilian ethanol production is also far more efficient than the U.S. when it comes to land use – Brazil produces about 7,000 L of ethanol/ha.year, while the U.S. produces only 3,500 L of ethanol per ha/year.[11] Additionally, sugarcane produced in the Southwest regions of the country use virtually no irrigation and the water withdrawn for industrial processes is almost entirely treated and reused within the ethanol plant.[12] This is significant when compared to ethanol production in the Midwestern United States, where water use in processing alone requires 3-4 gallons of water per gallon of ethanol produced.[13] Despite the increased efficiency, growing ethanol production in Brazil continues to raise concerns about the effect sugarcane expansion on the environment, specifically water quantity and quality.

IVINHEMA BASIN

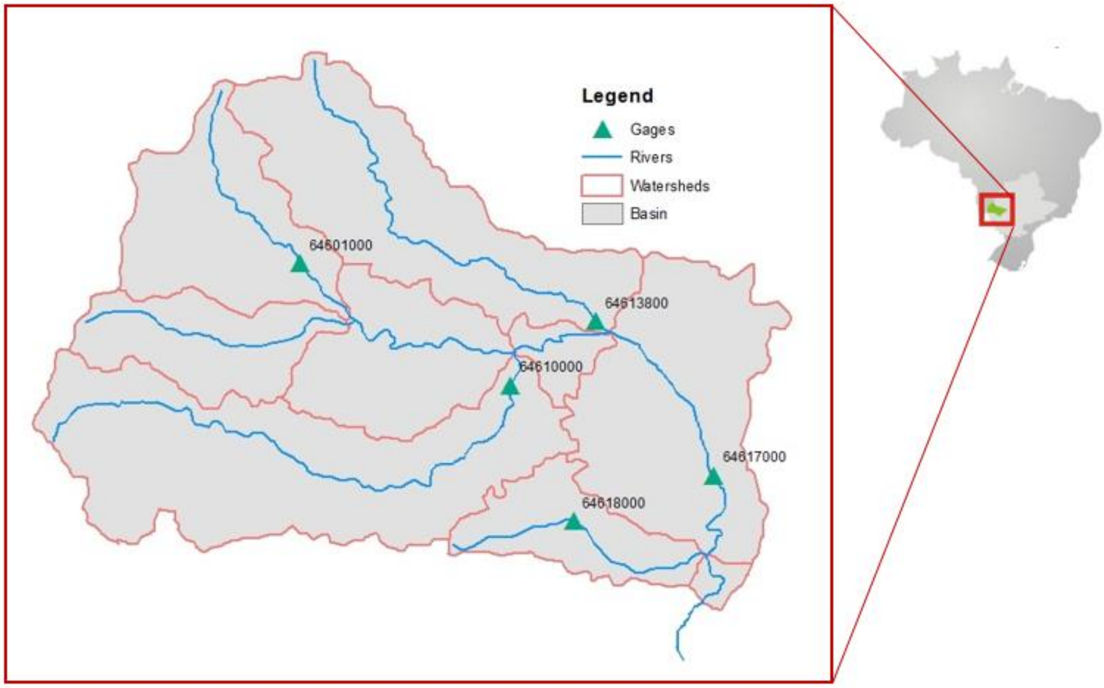



Figure 1.2: Location of the Ivinhema basin, showing sub-watersheds, rivers, and flow gauges.

The Ivinhema basin covers about 46,400 square kilometers in the southern part of Mato Grosso do Sul (Figure 1.2) and is part of the larger Paraná River basin – the sugarcane cultivation center of Brazil. The basin has been experiencing rapid expansion of sugarcane cultivation, with the number of hectares under sugarcane cultivation increasing by a factor of eight between 2000 and 2013, from 50,000 hectares to 400,000 hectares, with a number of ethanol mills popping up over the same period. This rapid expansion poses a number of questions for water resources in the basin.

**Climate and Topography**

The basin consists of six rivers: the Vacaria, Brilhante, Santa Maria, Dourados, Ivinhema and Guirai, representing nine separate catchments. (Figure 2.1)

The basin's climatic and topographic characteristics are overall well-suited to sugarcane production. Rainfall in the area is high in the spring and summer (November – March) averaging 5.27 mm per day, while winter (June – September) is far drier, averaging 2.25 mm per day. Average yearly rainfall over the study period was 1420 mm, while sugarcane requires 1500 – 2500 mm over the course of the yearlong growing period.[14] While this is less than the ideal water requirement, it is close enough to allow for sugarcane cultivation without irrigation.

Temperature in the basin fluctuates approximately 10 degrees throughout the year, ranging from 17 to 27 degrees Celsius.[15] Sugarcane thrives in air temperatures ranging from 22 to 30 degree, which is close to yearly temperatures throughout most of the year in the Ivinhema.

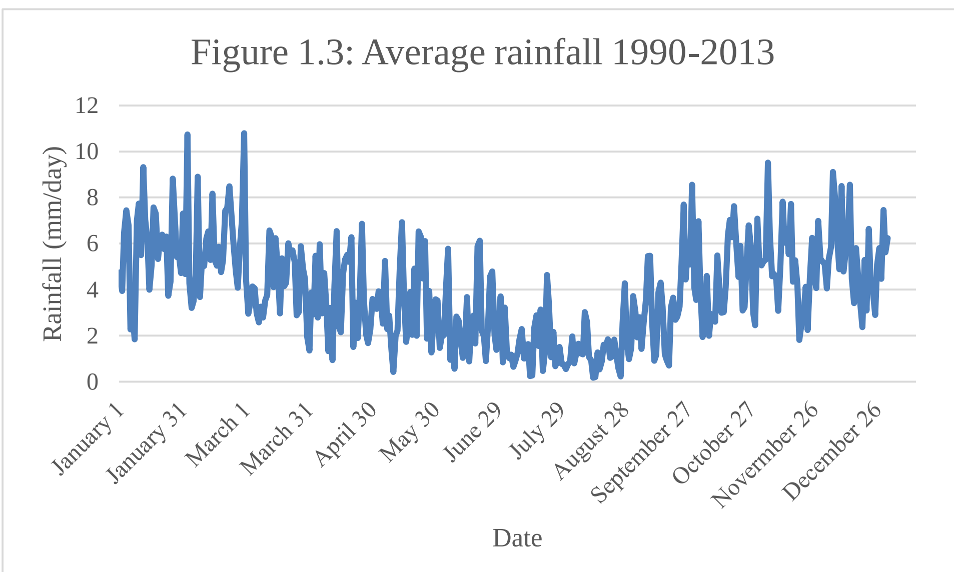



Figure 1.3. Average daily rainfall over the study period. Average daily rainfall is higher in the spring and summer months (November- March) and lower in the winter (June – September).

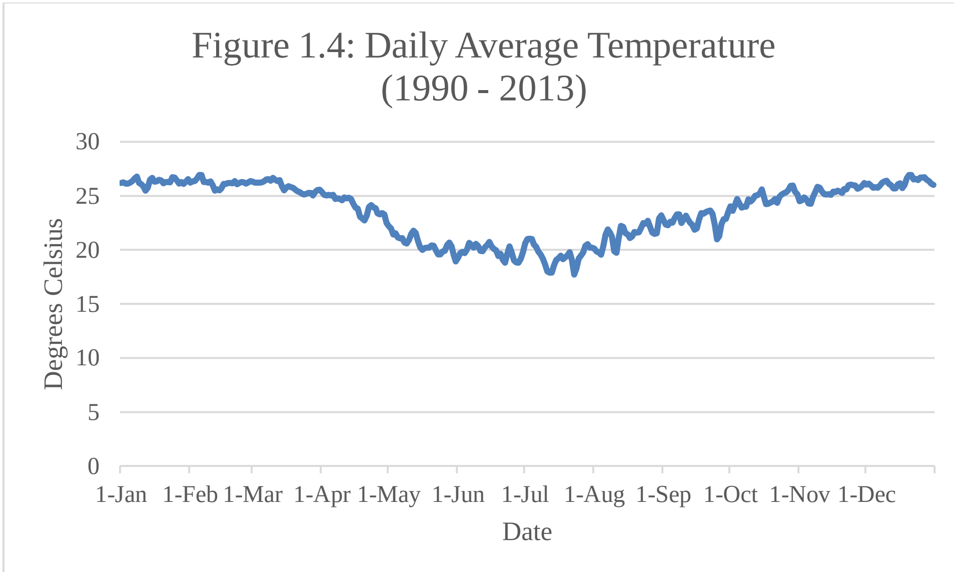



Figure 1.4: Average daily temperature over the study period. Temperature peaks December – February, and is the lowest June – August.

Most of the sugarcane production in the Ivinhema basin takes place in the western portion of the basin. This difference reflects a number of physical differences between the west and east basin, primarily soil permeability. Soil in the upper basin is dominated by semi-permeable purple latosols, while the east is primarily highly permeable red latosols. Latosols are soils typically found under tropical rainforests with relatively high iron and aluminum oxide content and can range from a few meters to over 20 meters in depth. Higher permeability makes the eastern portion of the basin less fertile due to increased nutrient leaching, and, as a result, sugarcane cultivation occurs more heavily in the western portion of the basin (Figure 1.10). Despite being nutrient poor, soil in booth parts of the basin has a high clay content, allowing it to hold a large amount of water.[16] With the use of agricultural inputs to make up for nutrient deficiencies, the basin is highly suitable for agriculture.

The hydrogeology of the basin also differs from west to east across the basin. Most wells in the western part of the basin are drilled into the Serra Geral, a fractured basalt aquifer. Most groundwater utilized on the eastern side is drawn from the Barrau- Caiuá aquifer, a set of interbedded sandstone formations that covers much of central Brazil.[17]

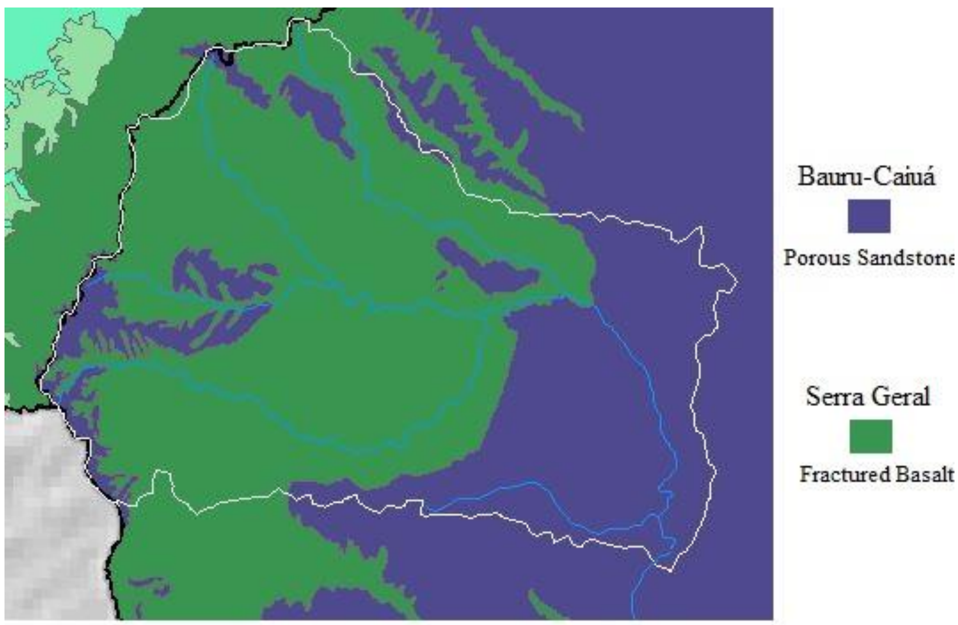



Figure 1.5: Map showing aquifers of the Ivinhema basin, the Serra Geral and the Bauru-Caiuá.

**Economy of Ivinhema**

The Ivinhema basin is predominately rural; there are 22 municipalities in the basin with an average population of 27,300 in 2005. In 2005, there were approximately 432,000 people living in the basin, with the largest municipality, Dourados, making up about 38 percent of the population.

The economy of the Ivinhema basin is dominated by cattle breeding and agricultural production, primarily corn, soybeans, and sugarcane. In 2009, the basin produced approximate 2.7 percent of Brazil's corn and soybean harvest and over 1.73 million heads of cattle.[18] The region is highly favorable for agricultural production due to the climate, soil and advanced infrastructure, including the extension of the Ferroeste Railway from Paraná and the Nova Olimpia Pipeline to the Port of Paranaguá. This gives the area an advantage over northern Mato Grosso, the other sugarcane frontier in the country.[19] Low prices for land and transportation have spurred agricultural expansion in the basin.

Sugarcane cultivation, in particular, has expanded significantly over the last decade and a half, moving from 50,000 hectares in 2002 to nearly 400,000 hectares in 2012 (Figure 1.9). Production has also increased significantly in terms of weight, with the basin producing a little over 4 million tonnes of sugarcane in 2002 to over 27 million tonnes in 2012.[20] According to Biosul, the biofuel producer association in Mato Grosso do Sul, the basin is currently home to ten ethanol plants.

Figure 1.6: Map of Ivinhema municipalities.

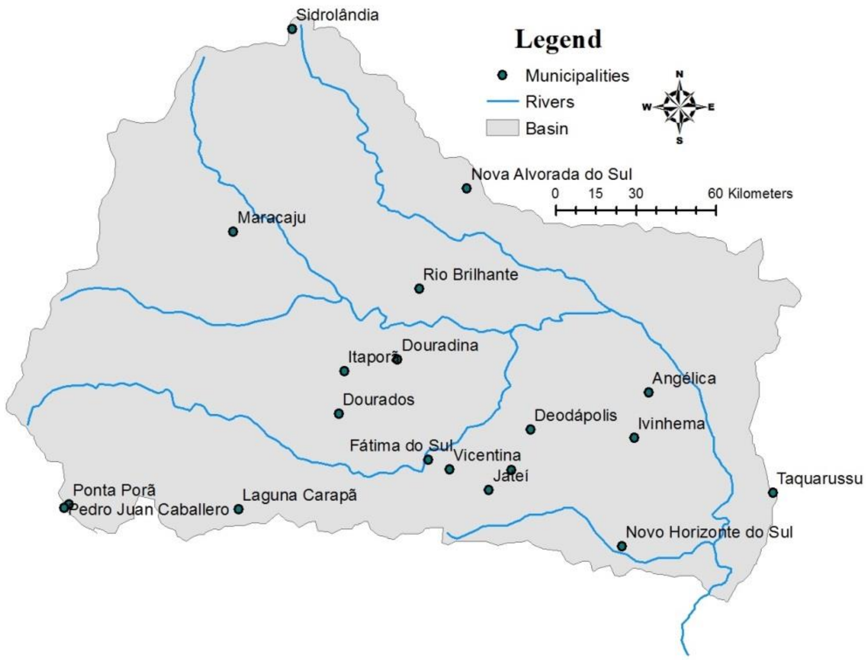
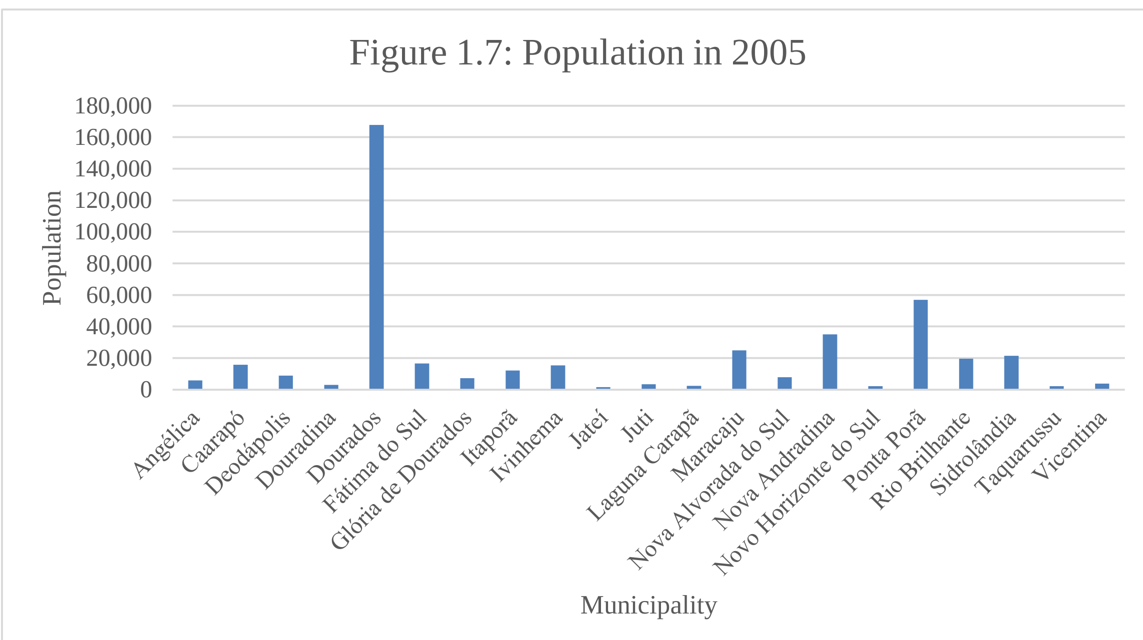



Figure 1.7: Population in Ivinhema municipalities.



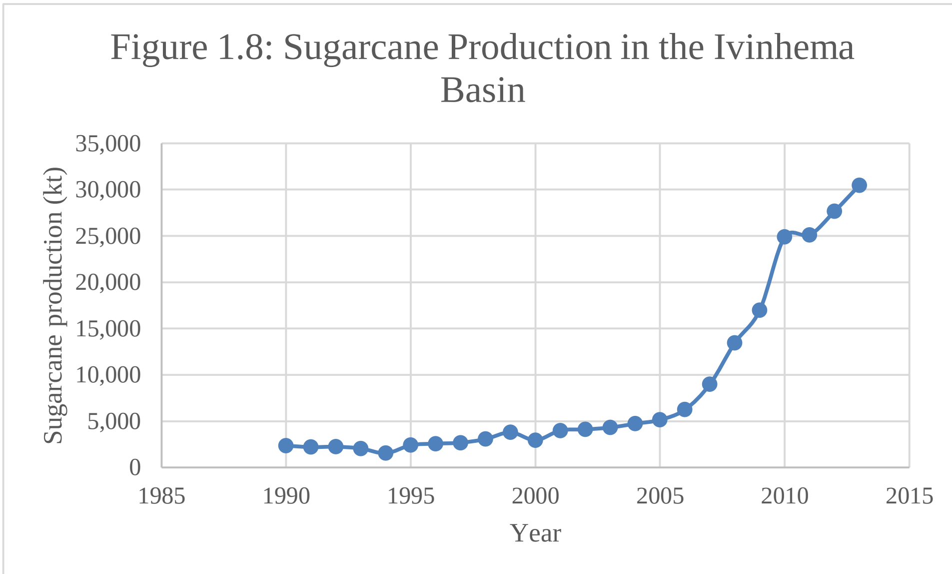



Figure 1.8: Sugarcane production in the Ivinhema basin in kilotonnes

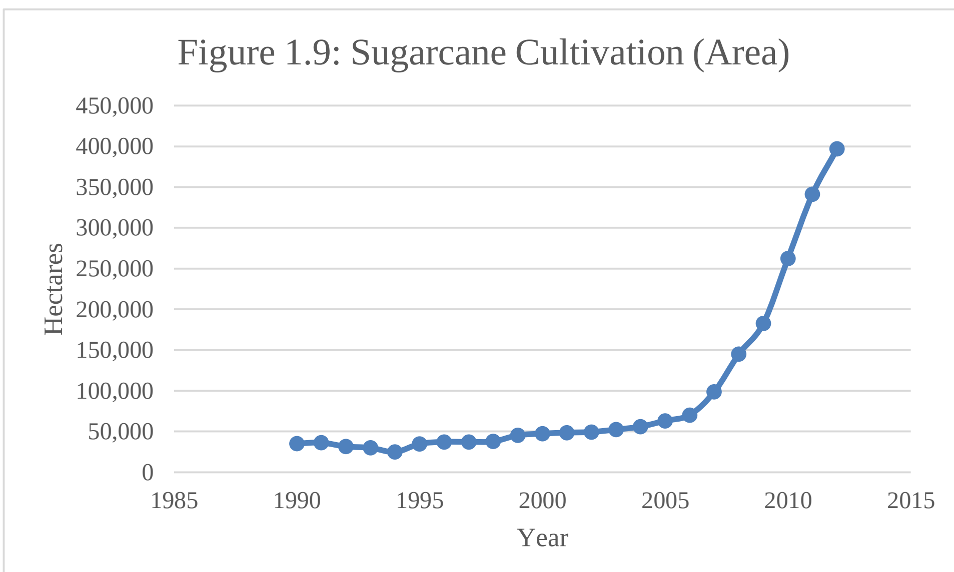



Figure 1.9: Area (hectares) under sugarcane cultivation in the Ivinhema basin.

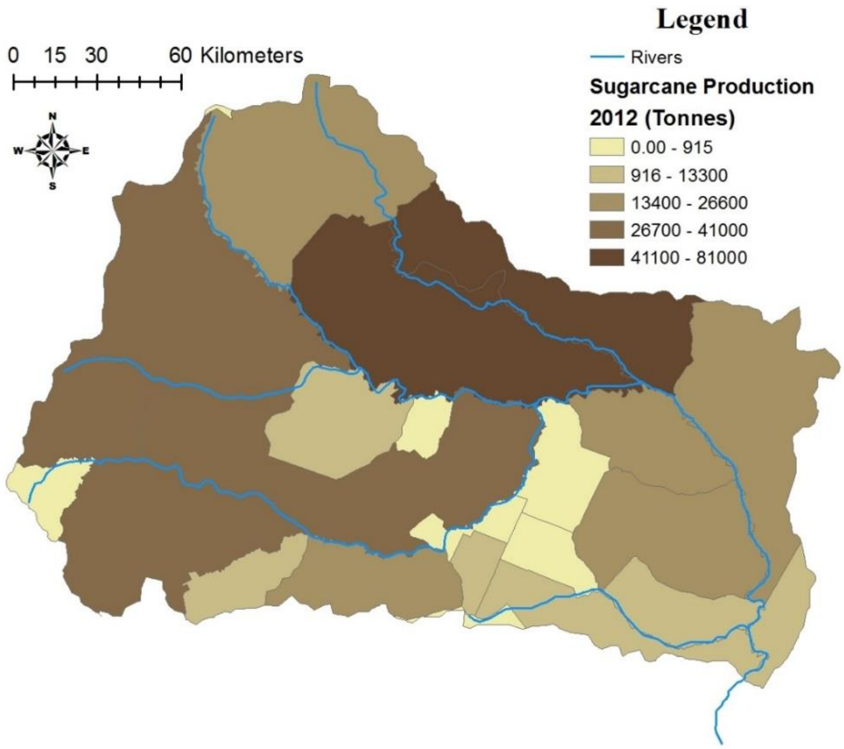



Figure 1.10: Area under sugarcane production in 2012 by municipality.

**Objectives of this Study**

Biofuel production requires large amounts of water, both for cultivation and processing; however, whether the water-footprint of biofuel production in the Ivinhema basin will have a large environmental impact depends on a number of site-specific variables including, climatic variables, production levels, and planting practices. The rapid increase in sugarcane cultivation over the last 10 years could have major impacts on water balance in the basin, especially if that sugarcane is irrigated to optimize yield. This study 1) attempts to mimic current processes occurring in the Ivinhima basin, for which there are large data gaps, and 2) investigates the impacts of various crop irrigation scenarios on stream flows and crop yields in the Ivinhema basin.

Chapter 2 will describe the development of a basin model using the Stockholm Environment Institute's Water Evaluation and Planning (WEAP) software. The study covers 1990-2013, using WEAP's Soil Moisture Method to simulate hydrologic processes and land use change within the basin. Chapter 2 details the model development process, including data used and the model calibration process. Chapter 3 will use the model described in Chapter 2 to explore three different irrigation and ethanol production scenarios, focusing on the effect of those scenarios on crop yields and stream flows.

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# Chapter 2: Methods

## Introduction

This section describes the model development process, starting with an explanation of the data used and the process through which those data were entered into the Stockholm Environment Institute's Water Evaluation and Planning (WEAP) modeling software. It describes and justifies the basin model assumptions and the initial model calibration process. Lastly, this section examines different calibration scenarios, with the objective of assessing the importance of different design variables on model accuracy and establishing the most appropriate values to those design variables that are unknown. These calibration scenarios, numbered 1, 2, 3 and 4, depending on the design variable examined, are evaluated for flow accuracy using the Nash-Sutcliffe Model Efficiency Coefficient.

## Data

Most of the data used in this study were sourced from Brazilian governmental agencies. Crop scheduling and cultivation data from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística) or IBGE, was used for corn, soybeans, and sugarcane.[21] Sugarcane $K_c$ values for each crop stage were sourced from IBGE, while $K_c$ values for crop stages for corn, soybeans, and grass were sourced from the United Nation's Food and Agriculture Organization (FAO).[22] [23]

The vast majority of the hydrological data – including stream flows, municipal water demand, and precipitation data – were sourced from the National Water Agency (Agéncia Nacional de Águas) or ANA.[24] [25] Due to the poor quality of the ANA precipitation dataset, precipitation data developed by the University of Texas' Energy Institute (EI) was also used.[26]

| Data | Data Source |
|---|---|
| Precipitation data | ANA and EI |
| Flow data | ANA |
| Municipal demand | ANA |
| Crop production | IBGE |
| Crop area planted | IBGE |
| Crop scheduling | IBGE |
| $K_c$ (corn, soy, grass) | FAO |
| $K_c$ (sugarcane) | SUCRE Power point* |

Table 2.1: Datasets and sources, primarily from Brazilian government agencies.

**Gridded Precipitation Data**

This study investigates two primary precipitation sources, ANA precipitation data from gauge stations and a gridded climate model produced by the University of Texas's Energy Institute. The grid's creators used actual precipitation data from Brazil's National Institute of Meteorology (INMET) and ANA to interpolate a 0.25° by 0.25° grid of precipitation data points. Outliers were removed from the actual INMET and ANA data by eliminating daily precipitation values greater than 450 mm. Xavier et al. then calculated the grid data by combining the six nearest gauge stations to each grid point via inverse distance weighing. Equation 2.1 shows the weight calculation of each precipitation point that went into the grid points.

$$W_g = \frac{1}{d_g} \quad \text{(Equation 2.1)}$$

$W_g$ = gauge weight

$d_g$ = distance of the gauge from the grid point

**Comparison of Precipitation Data**

This study looks at three different precipitation design input scenarios: the arithmetic mean of all EI grid data points in each catchment (Scenario 1A: Grid), the arithmetic mean of all rain gauges in each catchment (Scenario 1B: ANA mean), and data from the central most ANA gauge in each catchment (Scenario 1C: ANA one). Overall, the gridded precipitation data produced by EI is similar to both the ANA datasets; however it is slightly skewed (see Figure 2.2, Figure 2.3). EI's gridded precipitation data has less variation than either ANA precipitation dataset, having far fewer days with zero precipitation, and days with high rainfall measurements consistently lower than the high rainfall measurements for the actual ANA data. The ANA mean dataset, in turn, is less extreme than the ANA one dataset.

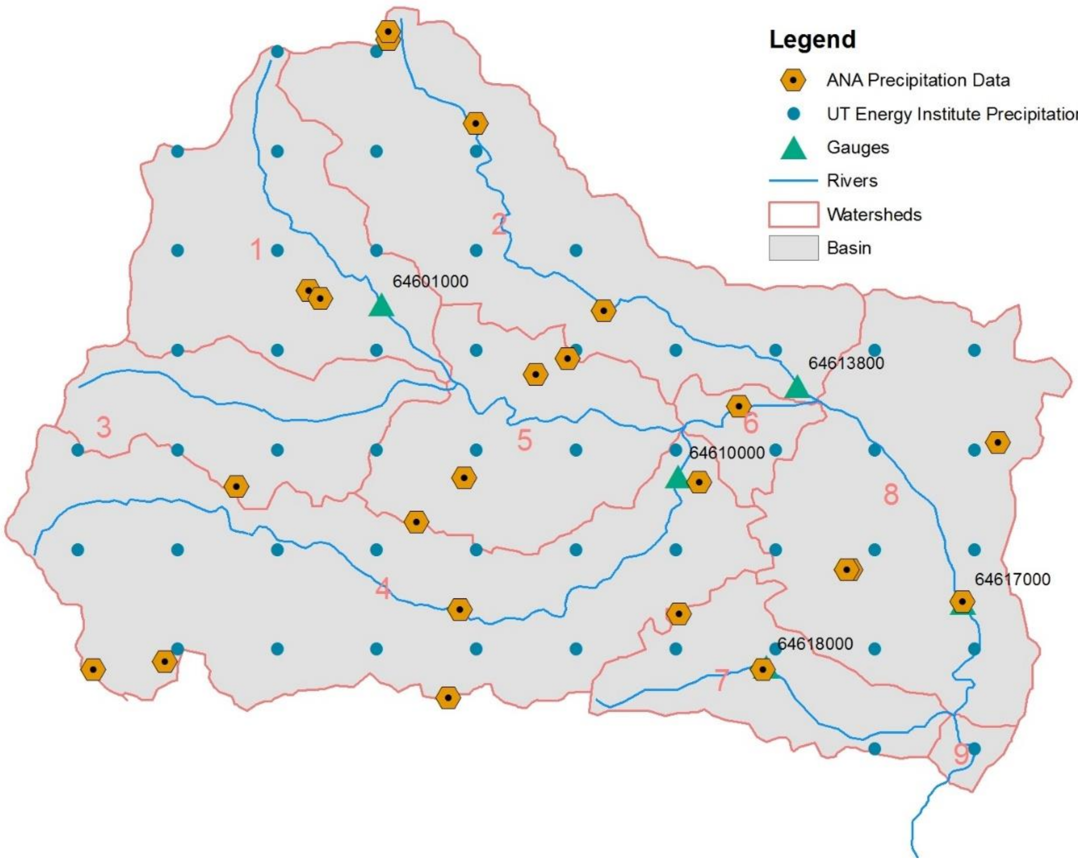



Figure 2.1: The Ivinhema basin, with rivers, watersheds (catchments), and all data collection points used in this study: ANA precipitation data stations, flow gauge stations, and EI grid data points.

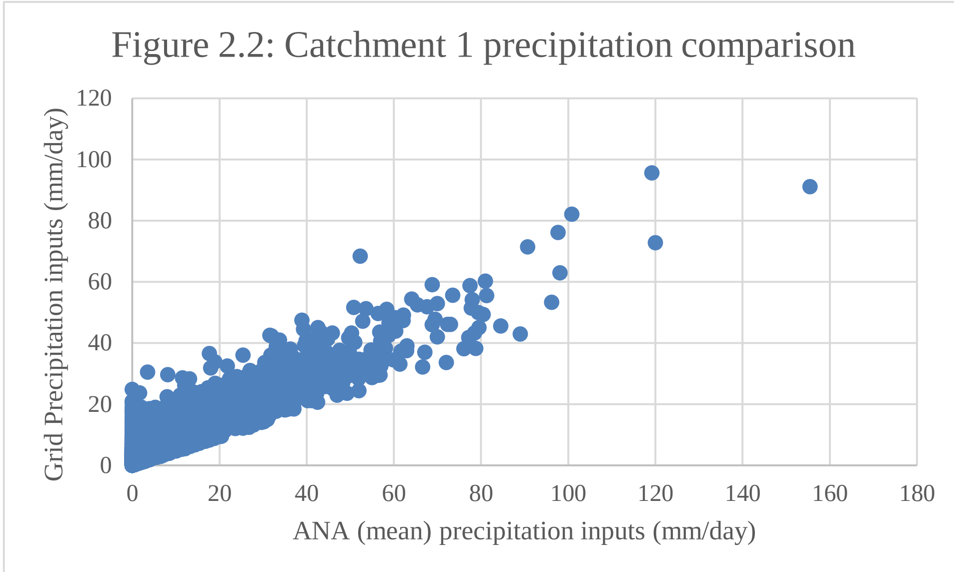



Figure 2.2: A daily comparison of ANA mean inputs and EI Grid Data shows the Grid data to be slightly skewed, with values consistently lower than actual values on any given day.

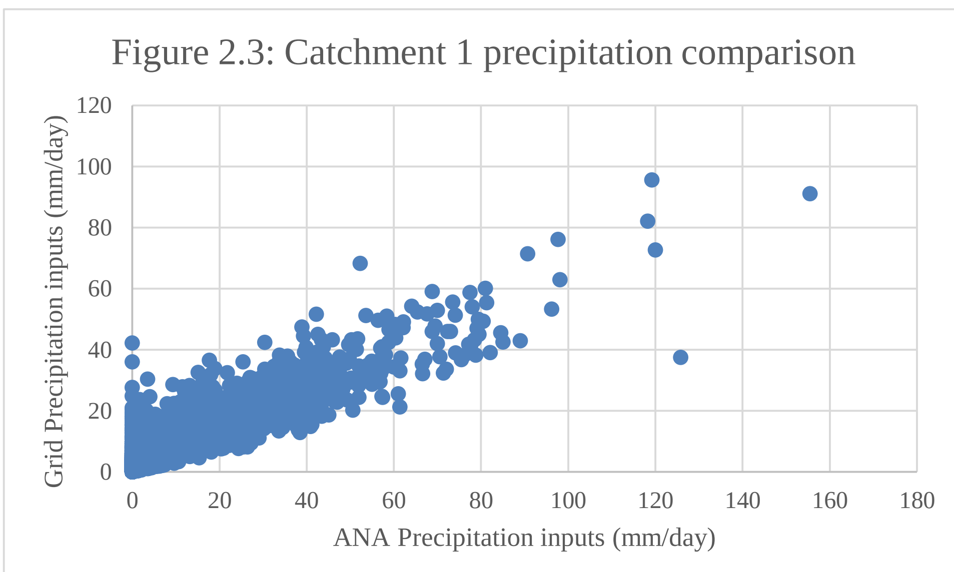



Figure 2.3: A daily comparison of ANA inputs (one gauge) and EI Grid Data shows the Grid data to be slightly skewed, with values consistently lower than actual values on any given day, and has more variability than the mean data (Figure 2.2).

The reduction in extreme precipitation values (both high and low) in the gridded data set is likely due to the interpolation process, during which neighboring gauges dampen both high and low values. This effect is also seen when comparing the ANA mean data to the ANA one data, with the averaging process once again curbing extreme values.

Due to the abundance of low or no rainfall days, the higher rainfall values on the low end of the spectrum for the EI Grid data result in higher total rainfall over the time-period (1990 – 2013) when compared to actual data. For Catchment 1, the difference amounts to .983 meters over the 23-year period, or about 0.117 mm per day. A similar trend is observed throughout the seven other catchments in the Ivinhema basin.

Despite the skew of the data, the model using the grid precipitation data yielded more accurate flows than the ANA datasets during the calibration process. This could be due to a number of reasons. First, the model accuracy in this study is judged based on the amount of variation between the modeled and actual flows versus the variation in the actual flows. Less extreme precipitation trends result in less sporadic flow activity, resulting in similar flows levels but less day-to-day variation. This decreases the sum of variation between the model and actual flows over time and improves the apparent accuracy of the model. Second, there are much fewer actual rain gauges than grid points, so although the interpolated data does not perfectly reflect actual flows, it does so better than actual data, which is geographically and temporally incomplete.

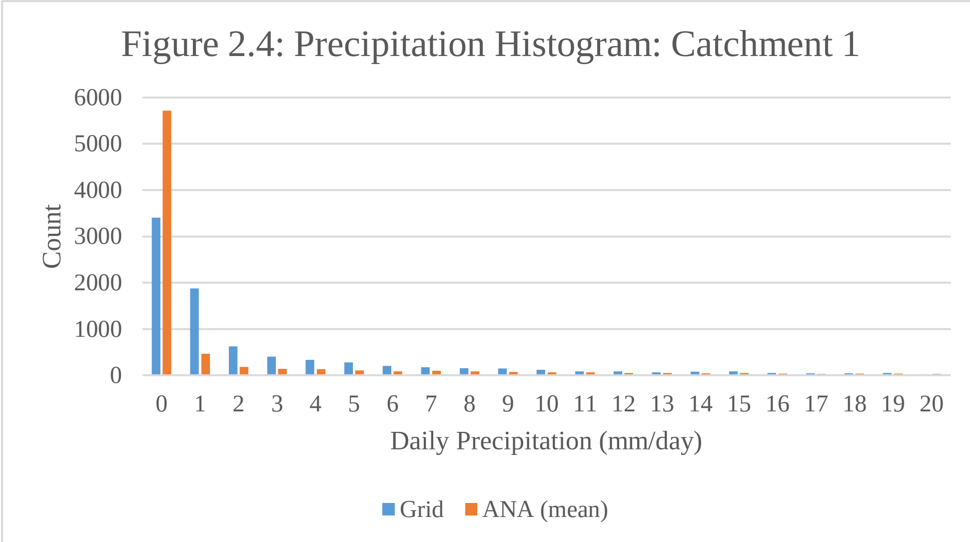



Figure 2.4: A histogram comparison of daily precipitation data in catchment 1 from 1990 - 2013 totaling 8,766 data points for each dataset (EI Grid data versus mean ANA data).

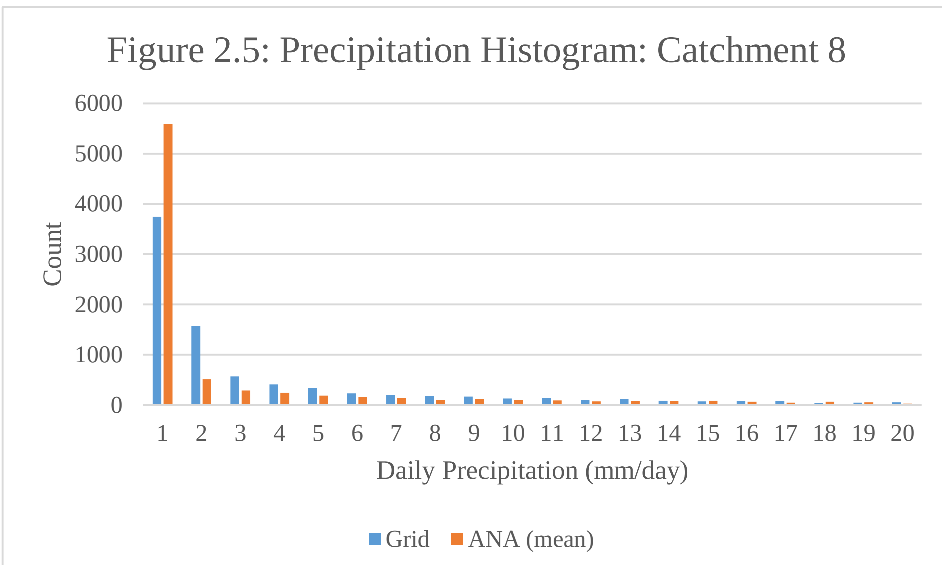



Figure 2.5: A histogram comparison of catchment 8 precipitation data from 1990 -2013 totally 8,766 data points for each dataset (EI Grid data versus mean ANA data).

The most significant difference between the grid and actual data is the amount of missing data points. The Grid data have no missing data points because it was constructed to estimate precipitation data even when the nearest gauge station was missing values. The ANA data, however, have large data gaps. For example, 22 percent of the values for the ANA precipitation data in Catchment 6 are missing. On average, catchments have no mean data for approximately 7 percent of the ANA mean precipitation inputs, which means that, on average, 614 days were missing data for all ANA stations within a given catchment. Across the entire basin, there are 5,533 data points for which no mean precipitation data could be calculated, or approximately 7.8 percent (Figure 2.8). The ANA one dataset is even more deficient because the likelihood of a missing value is even higher than when stations are averaged. For catchment 1, there were 882 missing data points (~10 percent) when using one ANA data station, and 711 missing data points (~8.1 percent) when using the average over the entire catchment.

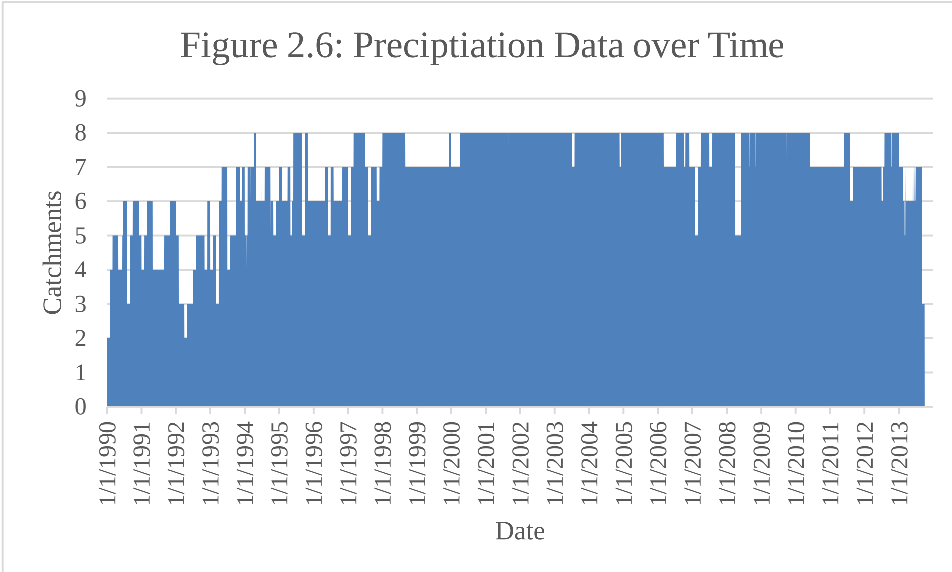



Figure 2.6: Figure 2.6 shows the number of catchments with insufficient input precipitation data to calculate the mean values used in scenario 1B (ANA mean).

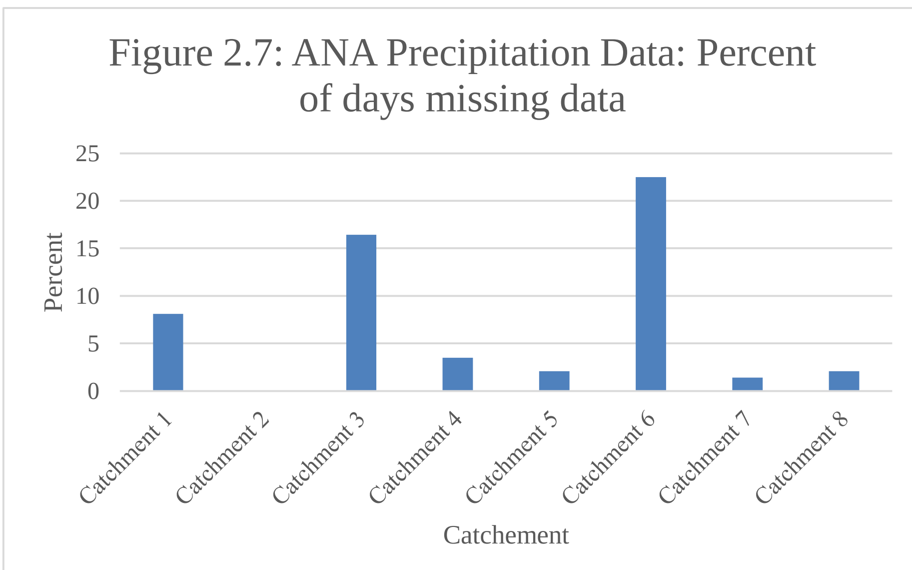



Figure 2.7: The percent of days, by catchment, for which it is not possible to calculate a mean value for ANA precipitation (input for scenario 1B).

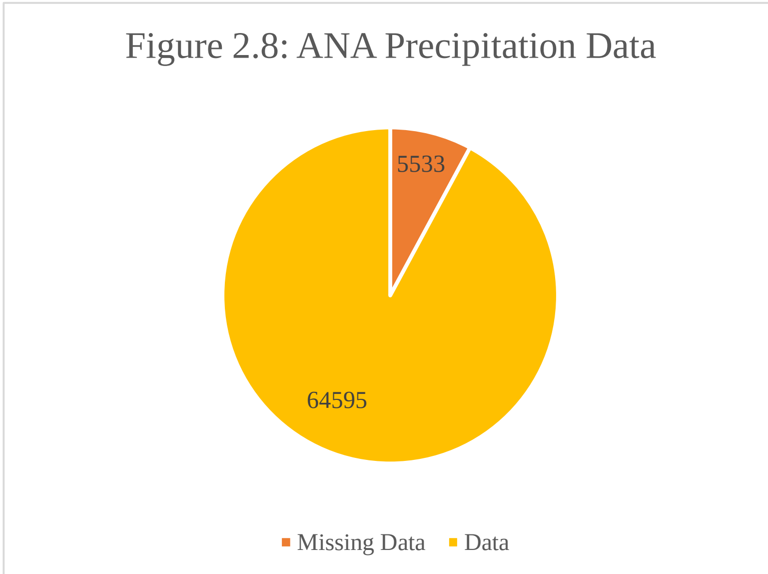



Figure 2.8: The count and proportion of missing ANA precipitation data throughout the basin used for scenario 1B (ANA mean) over the study period.

**Data Preparation: Precipitation Data**

As mentioned in the previous section, this study examines the impact of precipitation inputs on model flow outputs by looking at three different scenarios for precipitation inputs (Table 2.2).

| Scenario Group 1 | Precipitation Data |
|---|---|
| 1A | EI Interpolated Grid |
| 1B | ANA (mean of gauges) |
| 1C | ANA (one gauge) |

Table 2.2: Precipitation Scenarios evaluated in the calibration scenarios.

WEAP only allows precipitation inputs to have one daily time series per catchment, so for precipitation scenarios A and B, this time series was calculated by averaging precipitation gauges over the catchment areas (Equation 2.2). For example, if a catchment had four ANA gauges, the input for that catchment under Scenario B would be the sum of these gauges divided by four.

$$p_{catchment} = \frac{1}{n}\sum_{i=1}^{n} p_i \qquad \text{(Equation 2.2)}$$

By contrast, precipitation inputs for Scenario C represent the data from one gauge. These gauges were chosen based on geographic location within the catchment and the amount of data available from the gauge, with the ideal gauge being centrally located within the catchment and having all precipitation values from 1990-2013. Figure 2.9 shows the gauges chosen for Scenario C. Catchment 9 has no ANA precipitation gauges and is at the bottom of the basin, so it was excluded from further analysis.

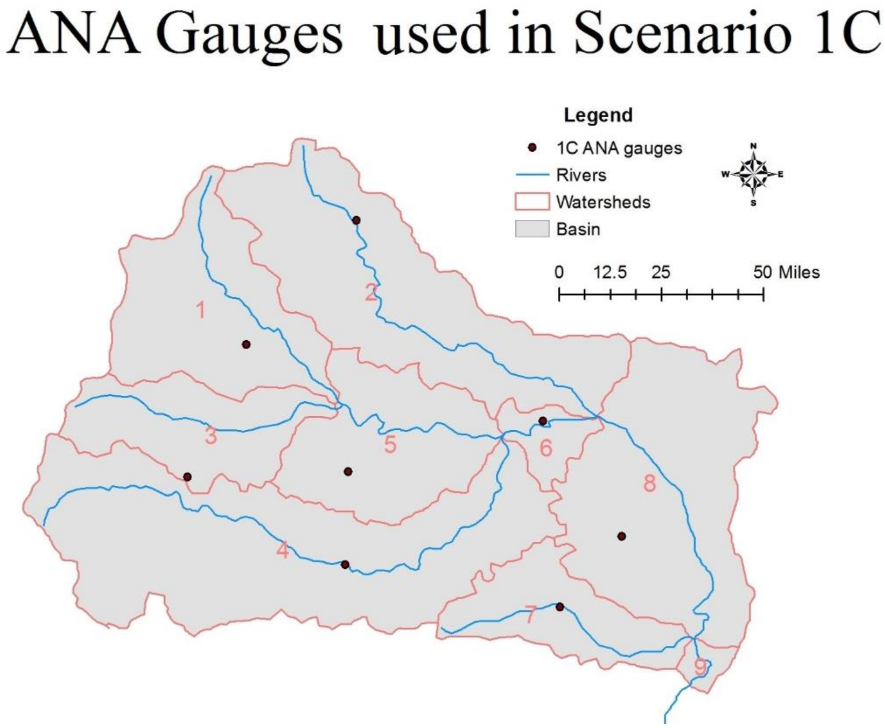



Figure 2.9: ANA precipitation data points used in scenario 1C.

## Flow Data

Five rivers in the Ivinhema Basin have flow gauge data: the Brilhante, Vacaria, Ivinhema, Dourados, and Guirai. The Santa Maria has no flow gauges so calibration analysis was not possible (Figure 2.1).

The available flow data is not complete – in fact, every gauge used to check modeled flows is missing more than 20 percent of its daily flow data. The accuracy of the model was assessed using Nash-Sutcliffe Model Efficiency Coefficients (see the Model Calibration Section), and in order to accurately assess model accuracy and maintain the comparability of these coefficients across rivers, the Nash-Sutcliffe calculations exclude periods with missing flow data for any of the five gauges. As a result, the Nash-Sutcliffe Coefficients shown in the Calibration Scenario section of this chapter are only measuring model accuracy for periods that show five gauges with data in Figure 2.10. This lessens the impact of missing flow data on Nash-Sutcliffe values; however, the faulty gauges could contribute to poor modeling results for some waterways. This issue will be explored further in the Calibration Scenario Section.

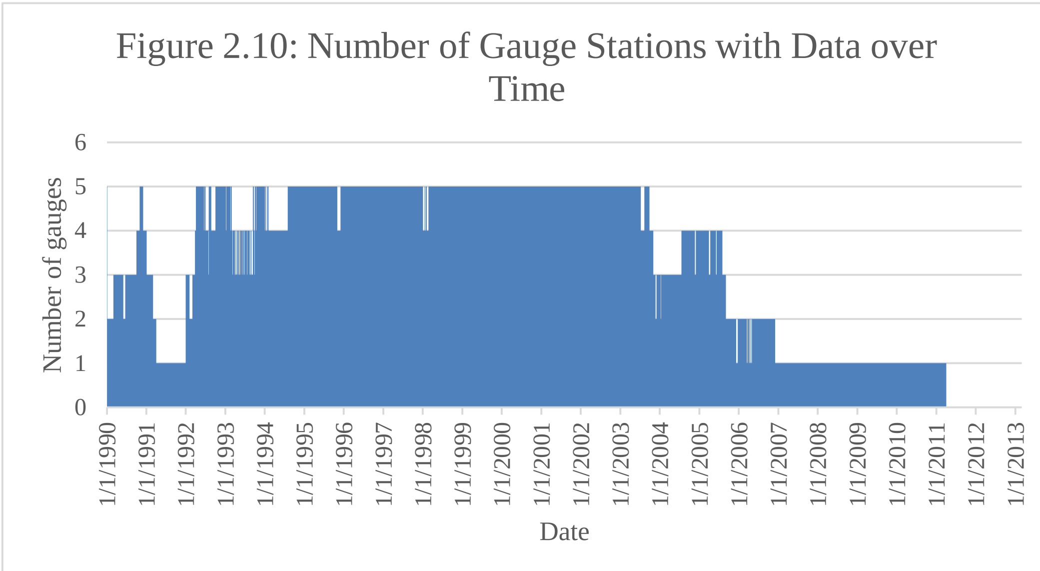



Figure 2.10: The number of gauges, out of the five gauges used in this study, with flow data over time.

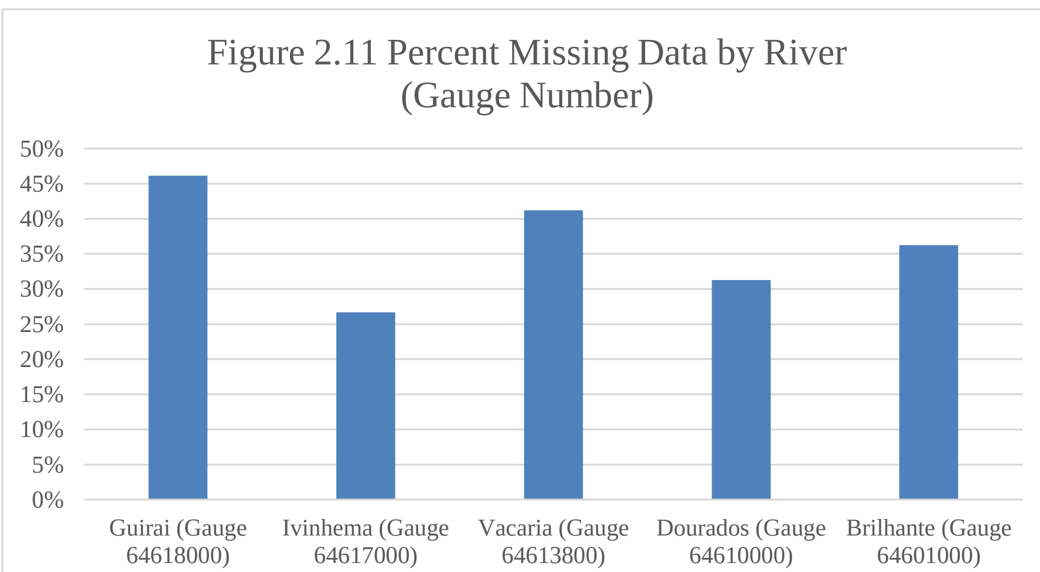



Figure 2.11: The above graph shows the percent of days missing data by river, with Guirai having the most and Ivinhema having the least.

**Land Use Data**

Land use data for this study were derived from IBGE's agricultural production statistics for the three dominant crops in the Ivinhema basin: corn, soybeans, and sugarcane.[27] WEAP requires data to be amalgamated at the catchment level; however, IBGE agricultural production data is only available at the municipal level (Figure 2.13, Figure 2.14). To remedy this, an area-weighted method was used to calculate the land area percent of each catchment under crop cultivation. The area each municipality contributes to each catchment was calculated as a percentage. Land use values from all municipalities within a catchment were then weighted based on these percentages and summed across each catchment. I followed this procedure for all eight catchments for years 1990, 2000, 2008, and 2012 because these years represent major shifts in cultivation trends. The intervals get shorter as time goes on because crop production levels in the Ivinhema basin remained relatively similar throughout the 1990s, and shifted majorly after 2007 (Figure 2.13).

Scenario group 2 examines the effect of drastic land use change on model accuracy, with one scenario assuming the IBGE land cover described above (2A), one assuming one hundred percent sugarcane (2B), and one assuming one hundred percent grass cover (2C).

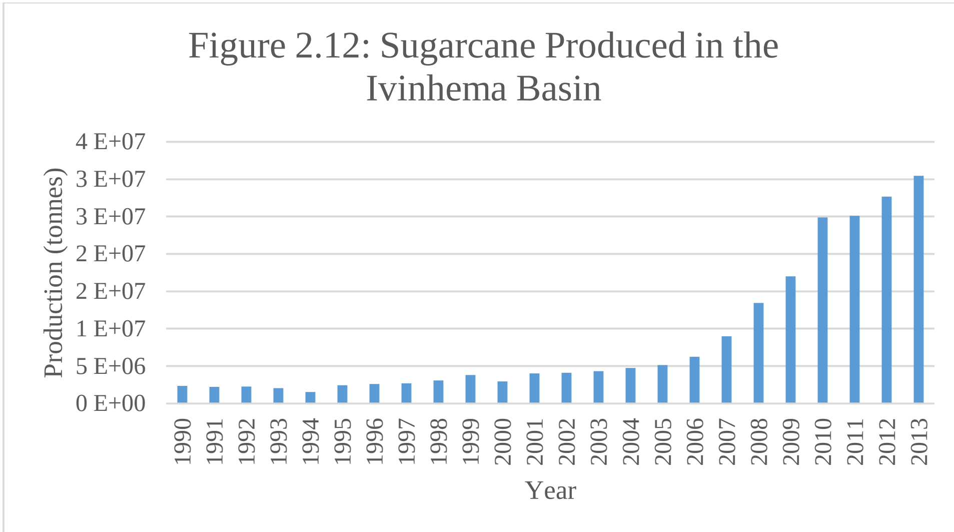



Figure 2.12: Figure 2.13 shows the increase in sugarcane production in the Ivinhema basin over the study period.

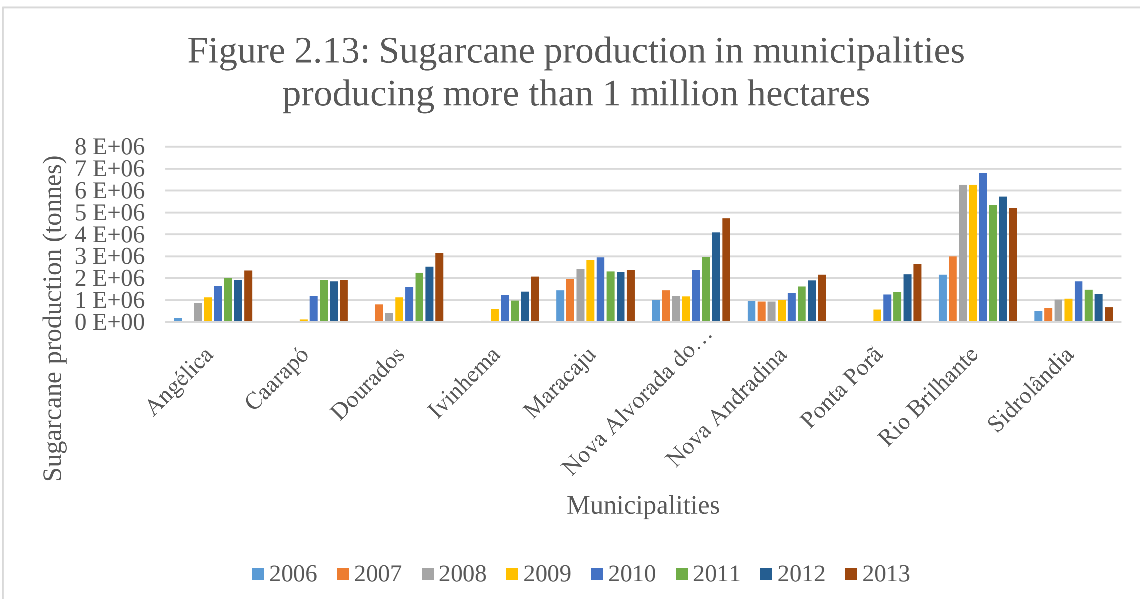



Figure 2.13: Sugarcane cultivation (area cultivated) by municipality 2006 – 2013.

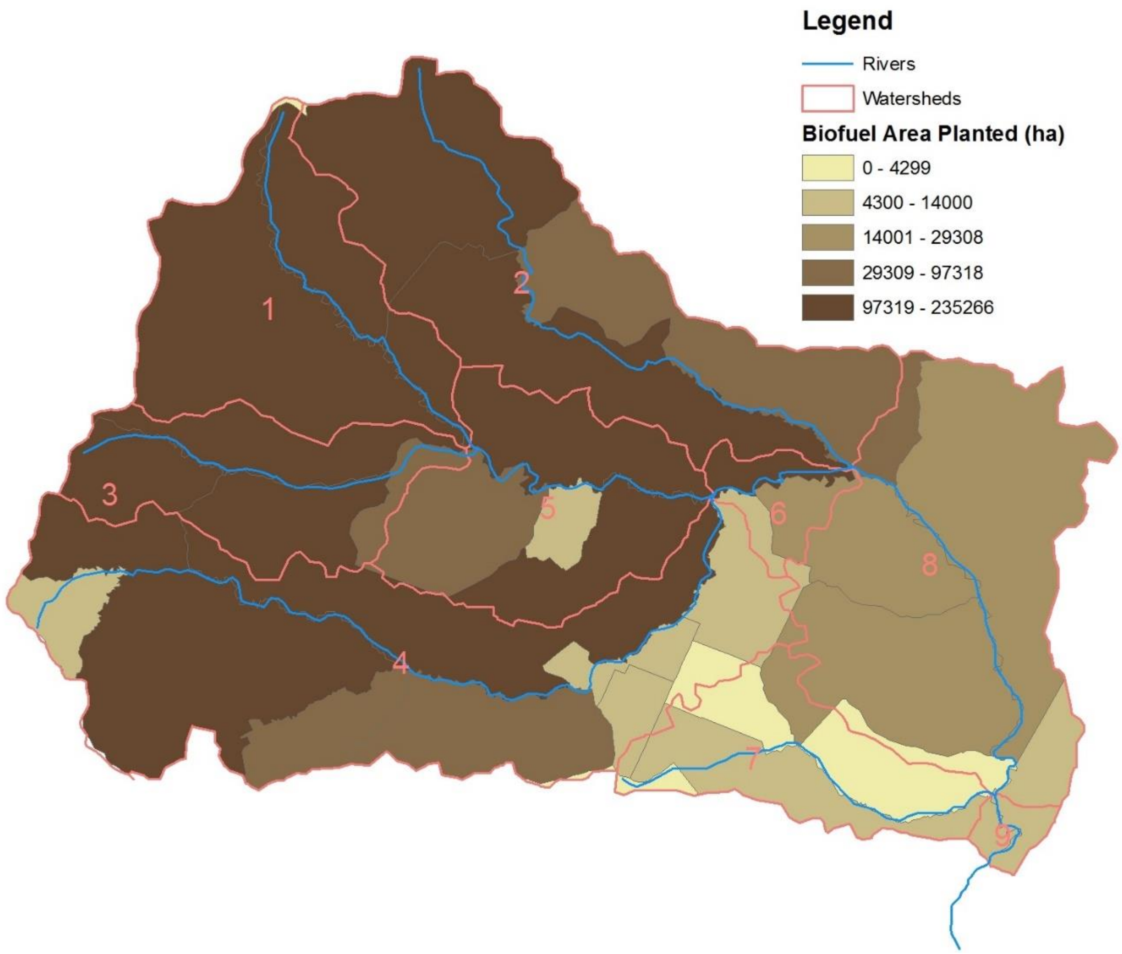



Figure 2.14: Biofuels cultivation by municipality throughout the basin, with rivers and numbered catchments.

## $K_c$ and Crop Scheduling Data

Crop coefficients ($K_c$), as discussed in Chapter 1, take a predictable pattern over the course of a plant's lifetime, starting low and ramping up to a plateau during the peak growth phase and then declining during the last stage of plant growth. Following this pattern, $K_c$ data and crop scheduling data were entered into WEAP for the period 1990-2013.

To capture the growing season accurately, crop planting was staggered throughout the planting season for each crop. Planting periods were sourced from the IBGE and from the Sugarcane Renewable Electricity project out of the Brazilian Bioethanol Science and Technology Laboratory and the CNPEM. It was assumed that the crops were planted in equal proportions every two months throughout the growing season. These values were then averaged across the number of plantings to give one $K_c$ daily time series for each crop. Figures 2.16 – 2.18 show this procedure for each crop, while Figure 2.19 shows the average of each crop. It is important to acknowledge that this method assumes that equal proportions of each crop are planted in each planting period. The effect of staggering crop cultivation (3A) versus assuming all cultivation begins on the first day of the growing season (3B) is explored in the third scenario in the scenario section of this chapter.

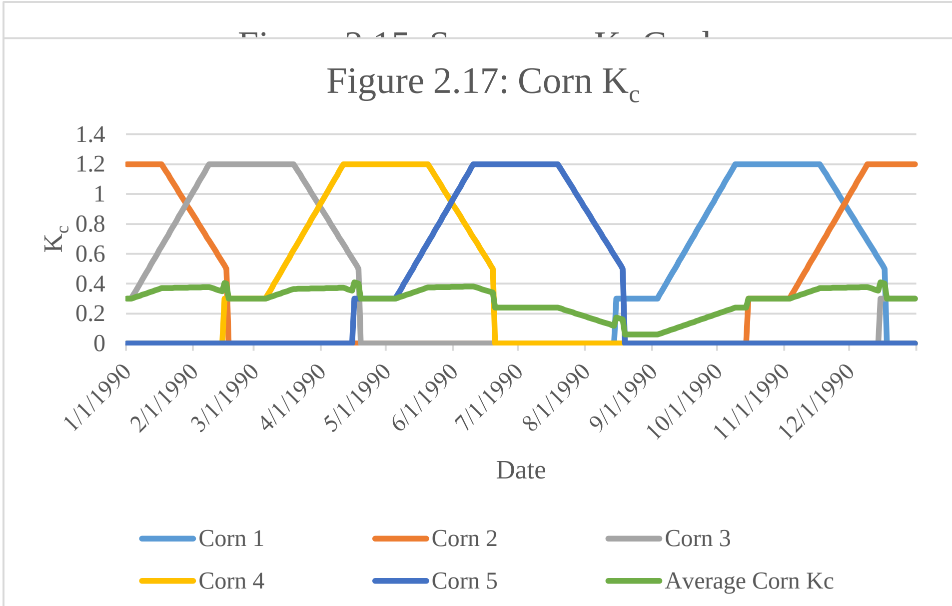
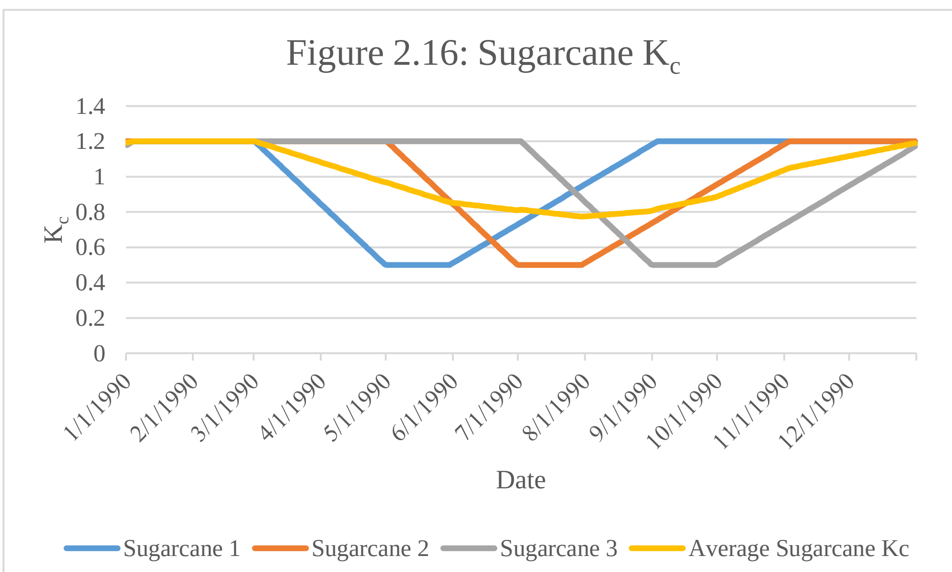



Figure 2.15: Sugarcane $K_c$ over a plant's life cycle.

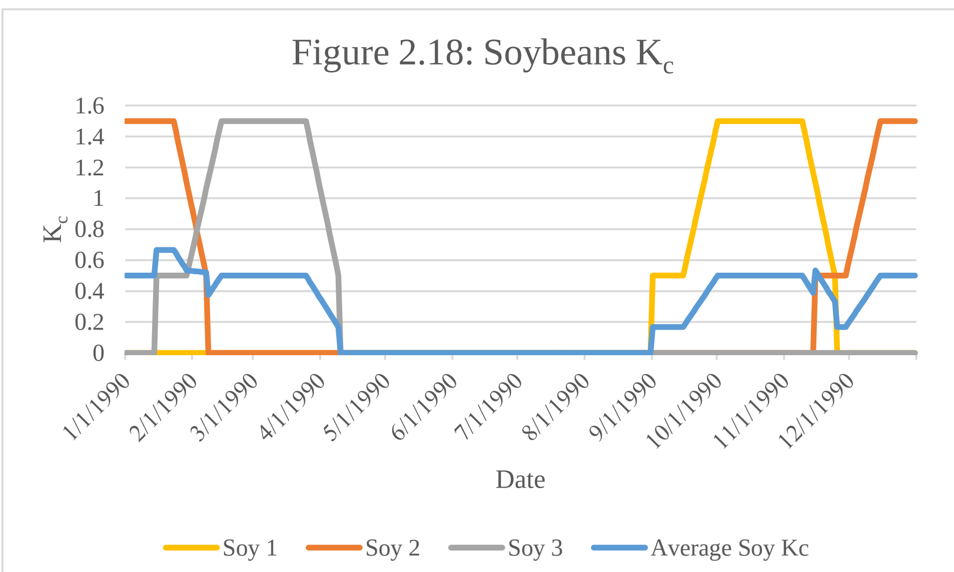
Figure 2.16: Sugarcane $K_c$ values under the staggered scenario, with the average




representing the $K_c$ input for scenario 3A.

Figure 2.17: Corn $K_c$ values under the staggered scenario, with the average representing the inputs for scenario 3A.

Figure 2.18: Soybean $K_c$ values under the staggered scenario, with the average representing the $K_c$ inputs for scenario 3A.



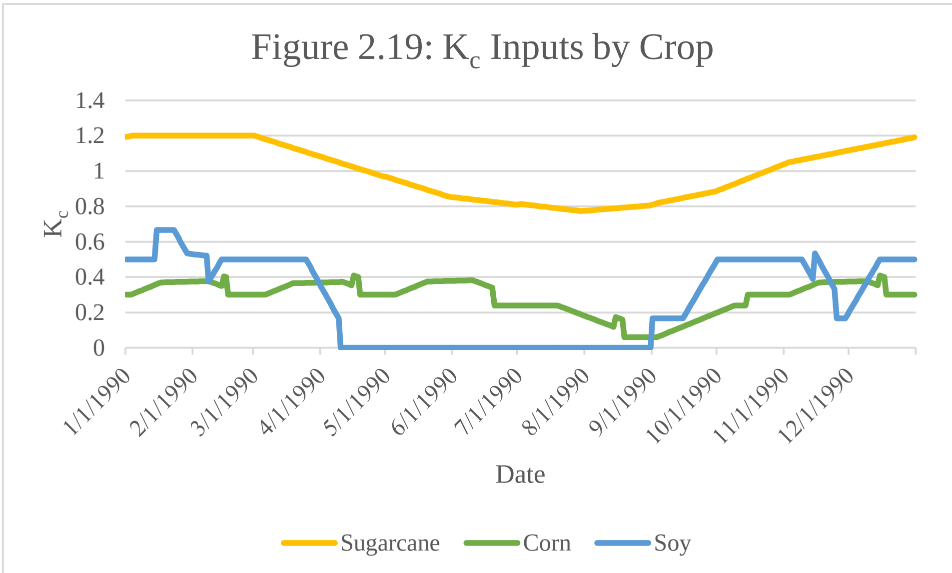



Figure 2.19: Average $K_c$ inputs for each crop, representing the $K_c$ values used in scenario 3A.

### DEMAND ASSUMPTIONS ACROSS SCENARIOS

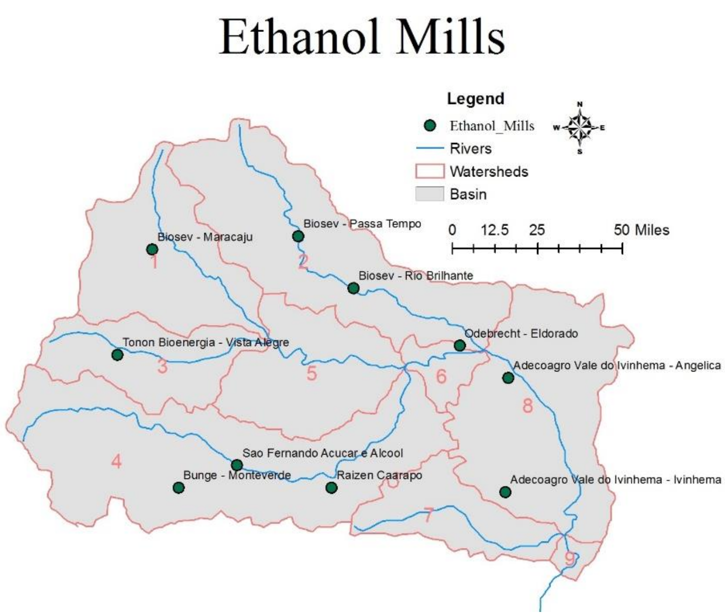
It is important to establish the distinction between consumption and demand in as used in the following section. Demand is the water volume required at a given site, some of which returns to surface water as return flow. Consumption is the amount of water consumed at that demand site, i.e. the volume that does not flow back into the watershed because it has left the basin through evaporation or transpiration. Municipal consumption data was not available, so municipal demand, discussed in this section is significantly larger than actual municipal consumption.

#### Water Consumption for Ethanol Mills

Evapotranspiration makes up the vast majority of water consumed in ethanol production; however, the process of converting sugarcane into ethanol also requires water. In 1997, total water demand during the conversion process was estimated to be 21 $m^3$ per ton of cane, but, due to efficient recycling practices actual water consumption was only around 5.6 $m^3$/t of sugarcane. Technological improvements had lowered water consumption to 1.83 $m^3$/t of sugarcane by 2004.[28] Currently, the water withdrawn for industrial processes is almost entirely treated and reused in the plant itself, resulting in a system that is virtually closed.[29] For the purpose of this study, we assumed water consumption was between 1 and 3 $m^3$/t sugarcane. The 2013/2014 growing season in Mato Grosso do Sol produced 41,496,000 tons of sugarcane, from which it produced 2,230 million liters of ethanol and 1.368 million tons of sugar.[30] Assuming that one ton of sugarcane produces 82 liters of ethanol, this level of ethanol production indicates that approximately 27,195,000 tons of sugarcane was uses as ethanol feedstock, or 65.5 percent of the total harvest.[31] This is slightly higher than the national percentage, which hovers around 55 percent.[32]

For scenario groups 1, 2, and 3, ethanol demand is assumed to be zero; however scenario group 4 examines ethanol demand, comparing consumption rate of 1 $m^3$/t (scenario 4A) to results using a consumption rate of 3 $m^3$/t (scenario 4B). These were both compared with scenario 1-3A, which all have identical inputs are represent no ethanol consumption. A number of calculations had to be made to incorporate ethanol production into the model. To input demand, WEAP requires a total value of water demanding entities, in this case sugarcane production in tonnes being converted to ethanol, and a water usage rate per unit demand. As with the land use data, data on production was only available by municipality, so to obtain catchment level data, sugarcane tonnage at the municipal level was processed using the same methods as catchment land use (described in the Data Section). Approximately 65 percent of sugarcane produced in the Ivinhema basin goes to ethanol production, so each catchment's production value was multiplied by 0.65.[33] It is important to note that many of the ethanol plants in Mato Grosso do Sul, and Ivinhema specifically, have the capacity to produce sugar and ethanol, so assuming all sugarcane is used as feedstock for ethanol production would be inconsistent.[34] Three catchments, 5, 7, and 9, do not have ethanol plants so their sugarcane production was combined with the nearest catchment with the closest ethanol plant. All sugarcane produced within 7 and 9 was assumed to go to catchment 8, while sugarcane in catchment 5 was split evenly between catchment 2 and 4 (Figure 2.20). None of the sugarcane for ethanol processing was assumed to be transported more than 100 km from growth location and processing, and it was assumed that all plants use surface water. This is a reasonable assumption because most of the ethanol plants in the Ivinehema basin are located on streams or rivers.

Figure 2.20: Ethanol Mills in the Ivinhema basin



**Municipal Water Consumption**

| Municipality | Demand (m3/day) | Population |
|---|---|---|
| Sidrolândia | 4665.6 | 21,302 |
| Maracaju | 5356.8 | 24,803 |
| Nova Andradina | 7603.2 | 34,922 |
| Ponta Porã | 13737.6 | 56,803 |
| Dourados | 40089.6 | 167,668 |

Table 2.3: Water demand by in the five most populous counties in the basin.

Water demand throughout the Ivinhema basin averages 0.2144 $m^3$/day per person and populations in the basin are relatively low, with the five largest towns ranging in population from 21,000 – 167,000. Low population densities within the basin mean that municipal water use is a small percentage of the water budget. In fact, total municipal daily water demand for the basin in 2005 was 98,755 $m^3$/day, which amounts to only 0.3 percent of the Ivinhema's average daily flow volume during the study period.

A few important caveats must be considered. The vast majority of water used to meet municipal demand is pumped from groundwater sources, not diverted from surface flows. In fact, all water distribution systems in the basin rely on groundwater except Dourados, the largest town in the basin, which relies on a combination of groundwater and surface water.[35] The surface water that it uses is drawn from the Dourados River; however, the proportion of total water demand that is pulled from surface versus groundwater is unknown. Additionally, ANA's municipal water demand data only has yearly estimates and no seasonal variation, making it impossible to estimate the impact of this demand on flows with any consistency. Finally, as discussed earlier, water consumption is only a small percent of this demand, the rest is returned to the basin as municipal waste. Because the data quality are poor and municipal demand is such a small fraction of basin flows, municipal demand was not incorporated into the scenarios in this study.

**Irrigation**

Most biofuel stock producers do not irrigate their crops, so irrigation demand was not included as a design variable.[36] The next chapter will investigate the irrigation volumes theoretically necessary to optimize sugarcane yields. Sugarcane cultivation requires an estimated 1500 – 2500 mm of water/year.[37] WEAP's soil moisture method allows you to specify the soil moisture content necessary for crop growth and the program will implement irrigation whenever soil moisture falls beneath this level or above the water capacity of the soil. This level, called the *wilting point*, varies from catchment to catchment depending on soil conditions. The wilting points along with the maximum soil water capacities, termed the *field capacity*, are show for each catchment in Table 3.2. All irrigation simulated in this study is sourced from surface water.

**Summary of Basin Demand**

Table 2.4 shows average daily demand estimates in the Ivinhema basin by use, as well as the percentage of average daily Ivinhema flows that each demand category represents. Municipal daily demands were found by summing daily municipal demand in the basin. Ethanol demands were estimated using the total sugarcane grown in a given year, under the assumption that 65 percent of the sugarcane grown goes to ethanol production. A rate of 3 $m^3$/t was assumed as a conservative estimate because data from 1997 suggests common consumption rates of 4 $m^3$/t. Total ethanol demand for each year was then divided by 365. Average daily Ivinhema flow volume for the study period was 31,518,300 $m^3$/day.

The average daily demand across the basin for these activities amount to approximately 0.9 percent of total daily flows in the Ivinhema.

| Demand Source | 2005 average daily use ($m^3$/day) | Percent of average daily Ivinhema flow (%) | 2015 average daily use ($m^3$/day) | Percent of average daily Ivinhema flow (%) |
|---|---|---|---|---|
| Municipal | 98,755.2 | 0.31 | 116,121.6 | 0.37 |
| Ethanol | 27,660.08 | 0.06 | 167,692 | 0.53 |
| Irrigation | 0 | 0 | 0 | 0 |
| **Total** | **126,415.28** | **0.39** | **283,813.6** | **0.9** |

Table 2.4: Total demand and percent of average daily Ivinhema flow by demand source. Municipal demand represents demand not consumption, while ethanol values represent consumption.

## MODEL DEVELOPMENT

To evaluate the validity of the design variables and datasets discussed in the previous section, inputs were put into the Stockholm Environment Institutes' Water Planning and Evaluation software. I chose to use the program's Soil Moisture Method because it is the most detailed method available for measuring land use impacts on stream flows. This method divides each catchment within the larger basin into two soil layers, an upper layer and a bottom layer. By entering in data for a number of soil, land cover, hydrogeological, and climatic parameters, it allows modelers to simulate evapotranspiration, runoff, shallow interflow, soil moisture changes, and baseflow.[38] Modelers assign each catchment a daily time series or individual value for each input parameter. The values used for each parameter are in Appendix 1, along with an explanation of the Soil Moisture Method. Much of the hydrogeological data was not available for this study, so these parameters, specifically Soil Water Capacity and Preferred Flow Direction, were used for model calibration.

### Soil Moisture Method

#### *Two bucket method*

The soil moisture method is a two-bucket method that models hydrologic processes such as evapotranspiration, surface runoff, interflow, and percolation, using the inputs listed in Appendix 1. This method calculates the water balance within each catchment, assuming uniform climate within catchments and taking into account the fraction of each catchment cultivating different crops. WEAP uses Equation 2.3 as the primary water balance equation:

Soil moisture = Precipitation – Evapotranspiration – Surface runoff – interflow – deep percolation

(Equation 2.3)

This balance is calculated by conceptualizing hydrologic processes as part of a top bucket representing the soil zone, and a bottom bucket representing deeper groundwater water. The components of Equation (2.3) are calculated by using a number of input parameters catalogued in Appendix 1. Movement of water between these balanced compartments is represented by percolation, which depends on soil characteristics, i.e. the upper bucket (preferred flow direction, root zone conductivity). When the bottom bucket is 100 percent saturated, the top bucket begins to fill, with runoff occurring only when both buckets are completely saturated. Land use data for each catchment is used to calculate evapotranspiration over time for each catchment.

**Model Calibration**

The calibration process consisted of two stages. The first was a visual calibration, wherein simulated flows were visually compared with actual flow data from each river, with Soil Water Capacity and Preferred Flow Direction being adjusted between runs as the optimization design variables. During this first calibration period, the model was calibrated based on actual rainfall data; however, because there are long periods with missing data this was only done for periods of time with consistent data, including 1994 – 1996, 2000 – 2002 and 2008 – 2009. The calibration period was opened to the full 23 years and calibration continued using the interpolated grid precipitation data. IBGE land use data was used, and $K_c$ values were entered assuming that all crops were planted on the first day of the planting season. Ethanol, irrigation, and municipal demand were assumed to be zero.

Once the model achieved a level of visual accuracy, the Nash-Sutcliffe Model Efficiency Coefficient ($E$) values were calculated using the daily flow results for each run, via Equation 2.4. The numerator in Equation (Y) represents the variance between observed and simulated flows, while the denominator represents the variance within the observed flows. $E$ ranges from -∞ to 1, with a value of 1 indicating no difference between observed and modeled flows. $E$ becomes more negative as variation between the model and observed flows increases relative to the variation within the observed flows. An $E$ of greater than zero indicates that the model emulates the observed values better than using the mean of the actual values. $E$ greater than 0.6 is considered very accurate.

$$E = 1.0 - \frac{\sum_{i=0}^{N}(Qo_i - Qs_i)^2}{\sum_{i=0}^{N}(Qo_i - \overline{Q})^2} \qquad \text{(Equation 2.4)}$$

$Qo_i$ = observed flows
$Qs_i$= modeled flows
$\overline{Q}$= mean of observed flows
N = 278 (monthly data, 1990 – 2013)

To maintain comparability, periods with missing actual flow data for any of the rivers were excluded from the $E$ calculations. Inputs that resulted in the highest $E$ values for various calibration scenario groups are used in Chapter 4 to analyze the effects of irrigation on crop yield and flows.

### CALIBRATION SCENARIOS

| Scenarios | | | |
|---|---|---|---|
| **1** | **2** | **3** | **4** |
| **Precipitation Inputs:** These scenarios use staggered crop scheduling and IBGE Data, with no ethanol demand | **Crop Composition:** These scenarios use staggered crop scheduling and gridded precipitation data, with no ethanol demand | **Crop Scheduling:** These scenarios use IBGE data and gridded precipitation with no ethanol demand | **Ethanol Mill demand:** These scenarios use IBGE data, staggered crop scheduling and gridded precipitation. |
| **A:** EI Grid Data | **A:** IBGE Data | **A:** Staggered scheduling | **A:** 1 $m^3$/ton demand |
| **B:** Average of ANA Stations | **B:** 100 percent sugarcane cover | **B:** All planting at the beginning of the season | **B:** 3 $m^3$/ton demand |
| **C:** 1 ANA Station | **C:** 100 percent grass cover | ----- | ----- |

Table 2.5: Description of inputs for the calibration scenario of Chapter 2.

| **Scenario** | **Precipitation data** | | | **Crop Composition** | | | **Crop Scheduling** | | **Ethanol demand** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | EI Grid | ANA Average | 1 ANA Station | IBGE | 100 % Sugarcane | 100 % Grass | Staggered | All at once | 1 $m^3$/ton demand | 3 $m^3$/ton demand |
| 1A, 2A, 3A | x | | | x | | | x | | | |
| 1B | | x | | x | | | x | | | |
| 1C | | | x | x | | | x | | | |
| 2B | x | | | | x | | | | | |
| 2C | x | | | | | x | x | | | |
| 3B | x | | | x | | | | x | | |
| 4A | x | | | x | | | x | | x | |
| 4B | x | | | x | | | x | | | x |

Table 2.6: Visualization of calibration scenario inputs.

The scenarios examined in the following pages investigate the effects of four types of inputs: precipitation inputs, crop composition, crop scheduling, and ethanol mill demand. Each of these input groups are labeled with numbers (1-4 respectively), while the runs within those groups are labeled with letters (see Table 2.5).

The *E* values across the various input scenarios (1A-4B) show a clear trend across rivers in the basin, regardless of the tested input. Values are consistently high for the Ivinhema, Dourados, and Brilhante Rivers, while the Guirai and the Vacaria rivers exhibit negative values across the board, with actual flows in the Vacaria and the Guirai Rivers exhibiting much more variation on day-to-day basis than the simulated flows. This indicates that there may be issues with the calibration process, which are likely due to issues with gauges within the Gaurai and Vacaria catchments and unknown or unmodeled hydrogeological conditions in these catchments, including aquifer characteristics, baseflow values, soil conductivity, and surface runoff resistance. The assumptions for precipitation inputs (e.g. interpolation and lack of multiple rain gauges) might also severely limit the ability to accurately model stream flows.

## Reasons for Bad *E*

### *Gauge Accuracy and Placement*

Both the Vacaria and the Guirai are missing over 40 percent of their flow gauge data. All periods with missing flow gauge data were excluded from the *E* value calculations, however, periods with suspect data quality were included. For example, measured flows for Guirai exhibit unusual gauge behavior for some periods, showing long periods with no day-to-day change in flows (Figure 2.21). This could be an indication that reported gauge values are inaccurate.

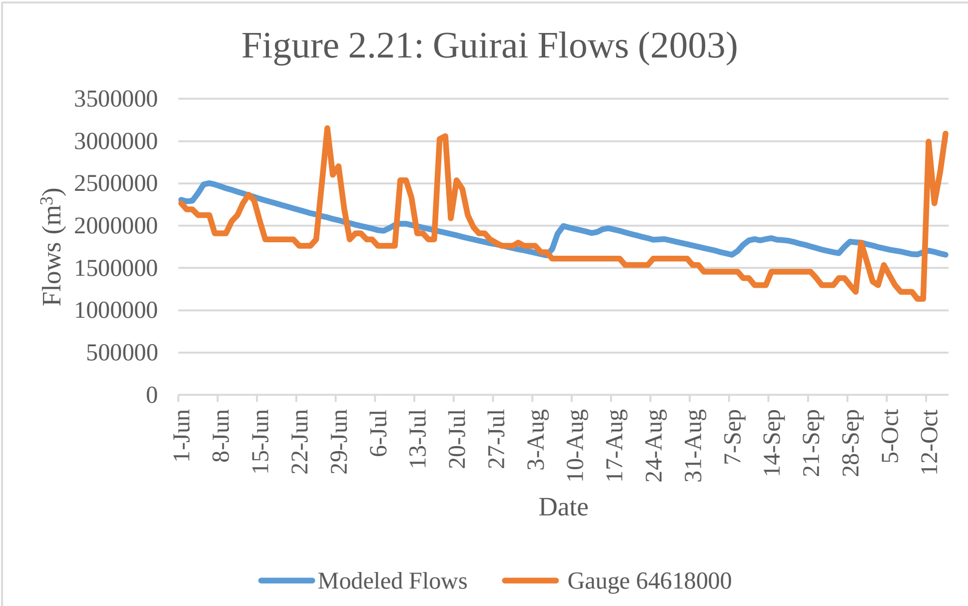



Figure 2.21: Guirai flows: modeled flows versus flows measured at Gauge 64618000 in 2003. The flat output for August and September suggests the possibility of a faulty gauge.

Additionally, the gauge on the Guirai is only half way down the catchment, while the values reported in the model represent total river inflow at the bottom of the catchment. This means that the gauge is only capturing flow volumes incorporating runoff from the upper half of the basin, while the model is predicting flows at the basin's outlet point. This discrepancy could be a large contributor to the low *E* values seen for the Guirai. This is not an issue, however, with the Vacaria, as the gauge on that river is at the base of the catchment.

### ***Geologic and Topographic Unknowns***

There are significant differences across the Ivinhema basin in terms of soil type and groundwater conductivity. Soils in the upper part of the basin, which consists of the Vacaria, Rio Brilhante, and Dourados river catchments, are deep purple latosols, while well-drained dark red latosols make up the bottom half of the basin.[39] This information indicates that there is a difference in soil cover been the upper and lower basin, however, there was no data found concerning conductivity for these soils, so the effects of this difference are ambiguous.

Additionally, the hydrogeology in the region varies between the upper and lower basin. There are two main aquifer groups in the Ivinhema basin, the Bauru-Caiuá Group, which is primarily porous sandstone, and the fractured basalt formations of the Serra Geral (Figure 1.5).[40] While conductivity can be estimated within a range for the Bauru-Caiuá Group, it is notoriously difficult to estimate conductivity within fractured basalts and there is very little information readily available.

Because there was so little available information on near-surface and deep groundwater hydrology, the hydrogeological input parameters required by the model were calibrated to optimize accuracy across catchments. This lack of knowledge could contribute to the poor results seen in the modeled Vacaria and Guirai flows. Strangely, though, this was not a barrier to modeling the Ivinhema, Dourados, or Rio Brilhante moderately successfully. These rivers encompass a wide geographic range, so the discrepancy between their modeled flow accuracy and that of the Guirai and Vacaria is not a result of an obvious difference in hydrogeology between the upper and lower basin. It is possible, however, that these discrepancies are caused by varying conditions within the same aquifer. Additionally, the Vacaria catchment (Catchment 2) straddles the basin's hydrogeologic and soil divide, making it difficult to assign one number to the various hydrological parameters.

## SCENARIO RESULTS

### Scenario Group 1: Precipitation Scenarios

| | Crop Composition | Crop Scheduling | Ethanol demand |
|---|---|---|---|
| **Scenario 1 Inputs** | EI Grid | Staggered | None |

Table 2.7: The above table shows the inputs used in scenario 1 for other design variables.

| River | Scenario 1A: Grid Data | Scenario 1B: ANA Data (Average of Stations per Catchment) | Scenario 1C: ANA Data (Individual Stations) |
|---|---|---|---|
| Dourados | **0.6446** | *-0.0055* | *-0.148* |
| Ivinhema | **0.5233** | **0.4682** | **0.3056** |
| Brilhante | **0.462** | 0.0485 | 0.0485 |
| Vacaria | *-0.7108* | *-0.7246* | *-0.8215* |
| Guirai | *-2.774* | *-3.263* | *-2.079* |

Table 2.8: Nash-Sutcliffe values for various precipitation scenarios representing comparison between daily modeled flows and daily actual flows.

The purpose of this group of scenarios was to analyze the best precipitation input data for future modelling.

Table 2.8 shows the Nash-Sutcliffe values for various precipitation scenarios. As explained earlier, an $E$ value of 1 indicates that there is no difference between the model and the observed flows, while a negative $E$ indicates that the mean of the actual data is a better indicator of the actual data than the modeled flows.

Dourados has the best $E$ for Scenario 1A, but Ivinhema consistently preforms best across scenarios. This is surprising because Ivinhema is the bottom most river in the basin, and all the modeled error in the above reaches should compound in Ivinhema's modeled flows. On the flipside, this could be seen as encouraging because it indicates that the model overall is performing decently.

Scenario 1B and 1C both have *E* values consistently lower than Scenario 1A, likely due to the fact that the ANA data is incomplete. This theory is supported by the fact that, for the Dourados, Ivinhema, and Brilhante rivers, the data shows a consistent pattern of Scenario 1A > Scenario 1B > Scenario 1C. Because 1C represents just one precipitation station, while 1B represents the average across the basin, 1C is more likely to have more missing days of data. This pattern, however, does not hold for Guirai and Vacaria, likely due to modeling issues addressed in the previous section. Overall, A1, the EI Grid dataset produced the most accurate flow results.

**Scenario Group 2: Crop Compositions Scenarios**

| | **Precipitation** | **Crop Scheduling** | **Ethanol demand** |
|---|---|---|---|
| **Scenario 2 Inputs** | EI Grid | Staggered | None |

Table 2.9 Crop Composition Scenario Inputs

| **River** | **Scenario 2A: Crops** | **Scenario 2B: Sugarcane** | **Scenario 2C: Grass** |
|---|---|---|---|
| Dourados | **0.644** | **0.565** | **0.575** |
| Ivinhema | **0.523** | **0.431** | **0.441** |
| Brilhante | **0.462** | **0.396** | **0.394** |
| Vacaria | *-0.711* | *-0.581* | *-0.639* |
| Guirai | *-2.774* | *-2.388* | *-2.71* |

Table 2.10: Nash-Sutcliffe values for various crop composition scenarios representing comparison between daily modeled flows and daily actual flows.

The purpose of this group of scenarios was to assess the impact of using different land use compositions on the accuracy of the model. These scenarios used gridded precipitation and staggered crop inputs. An input of 100 percent land cover in sugarcane was used to represent the extreme end of biofuel expansion, while 100 percent grass cover was used to represent 100 percent grazing.

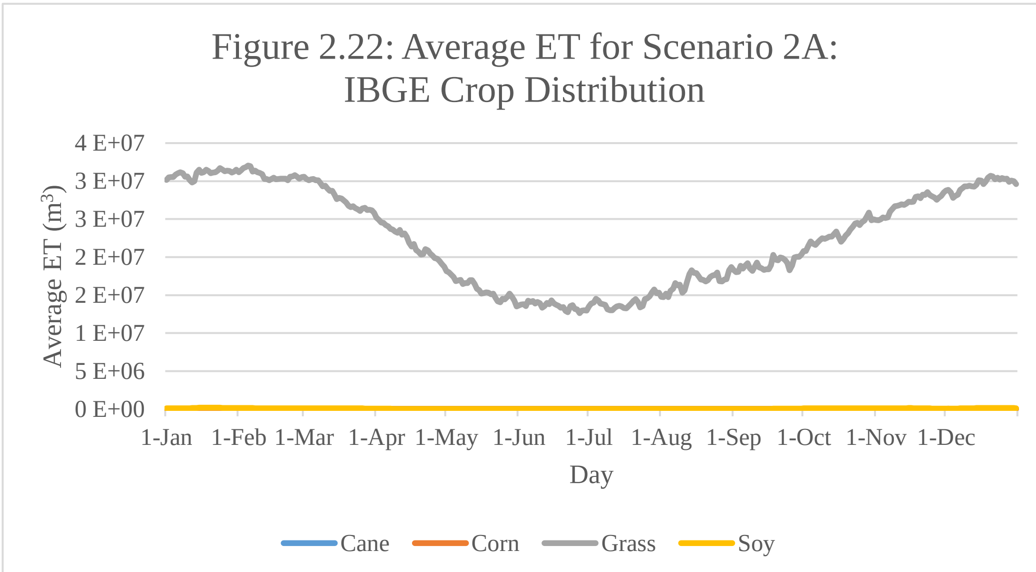



Figure 2.22: Average evapotranspiration for crops in scenario 2A.

*E* values vary substantially between scenarios 2A, 2B, and 2C, indicating land use significantly affects the accuracy of the model. Of these scenarios, scenario 2A produced the best results, while scenario 2C was consistently better than Scenario 2B for the Dourados, Ivinhema, and Brilhante rivers, a trend that is reversed for the Vacaria and Guirai. This is in line with what we would expect – the actual land use data should produce more accurate flows than the other two scenarios, while assuming that one hundred percent of the basin is under sugarcane cultivation should produce the least accurate flows.

Average daily evapotranspiration for each scenario is show by crop in Figures 2.23-2.25. Scenario 2A, the IBGE crop distribution, shows that grass has the highest average evapotranspiration, followed by soybeans, then corn, then sugarcane, with grass contributing over two orders of magnitude more to evapotranspiration than the crops (Table 2.11).

| **Crop** | **Cane** | **Corn** | **Grass** | **Soy** |
|---|---|---|---|---|
| **Average Yearly ET ($m^3$)** | $3.84 \times 10^6$ | $6.61 \times 10^6$ | $8.22 \times 10^9$ | $2.15 \times 10^7$ |

Table 2.11: The above table shows the average yearly evapotranspiration for each crop under scenario 2A.

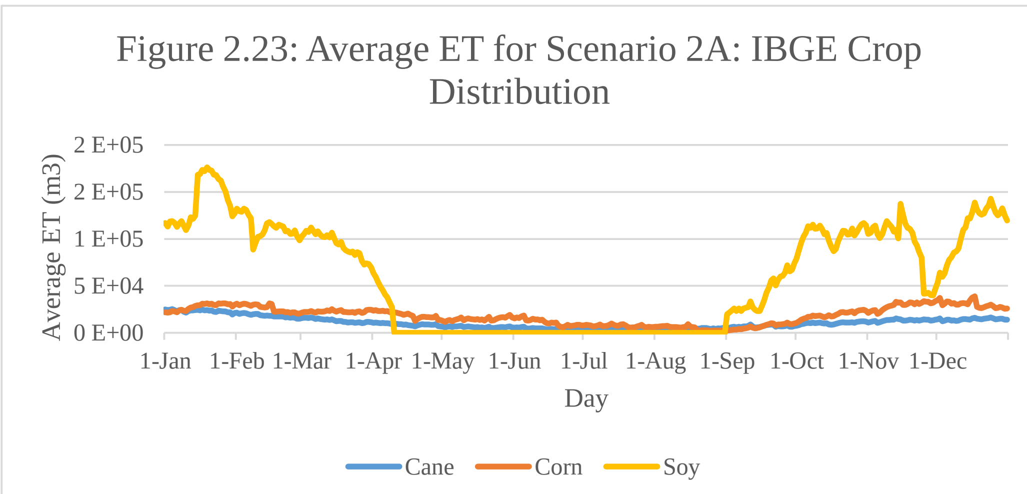



Figure 2.23: Average daily evapotranspiration for cane, corn, and soybeans over the study period.

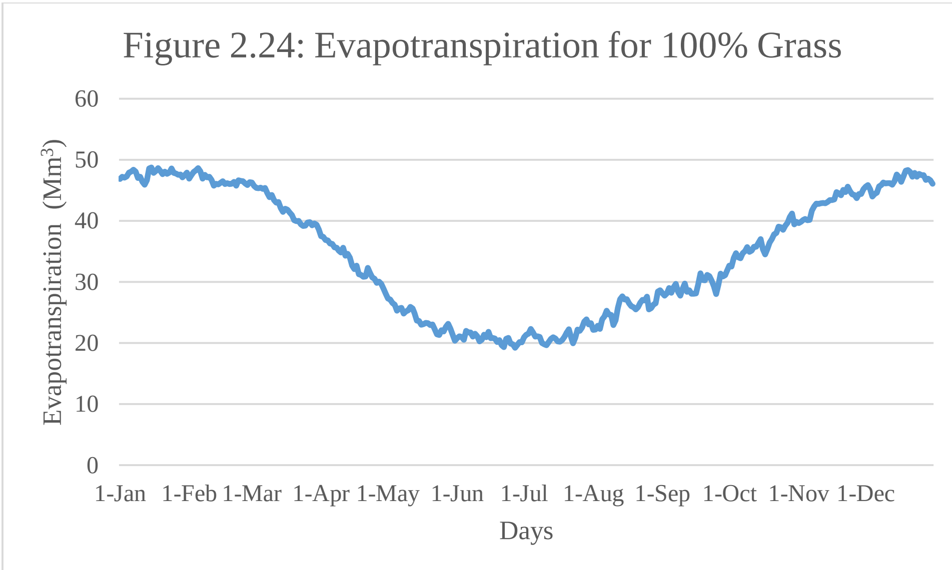



Figure 2.24: Average daily evapotranspiration for scenario 2C over the study period in $m^3$/day.

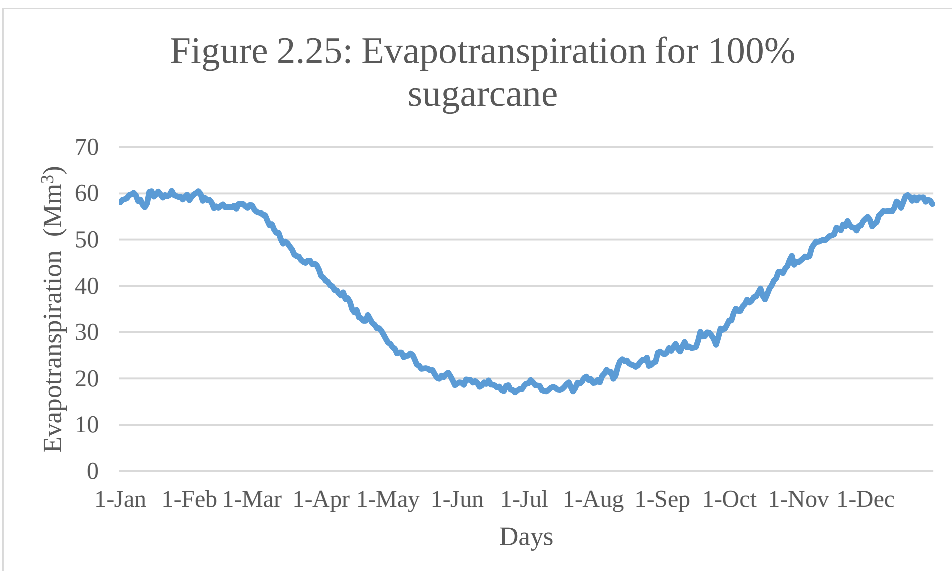



Figure 2.25: Average evapotranspiration for scenario 2B over the study period in $m^3$/day.

**Scenario Group 3: Crop Scheduling Scenarios**

| | Precipitation | Crop Composition | Ethanol demand |
|---|---|---|---|
| Scenario 2 Input | EI Grid | IBGE | None |

Table 2.12: Design variables for scenario group 3

The purpose of this group of scenarios is to test assess the accuracy of using varied planting times versus single planting times for each crop. For the staggered planting times, it was assumed that equal proportions of the crops were planted at each planting time, as explained in the crop scheduling section of this chapter. These scenarios used gridded precipitation inputs and IBGE crop distributions.

*E* values are consistently higher for scenario 3A, except for the Guirai River. This is consistent with expectations because planting for most crops in Mato Grosso do Sul takes place over the course of a few months.

| **Rivers** | **Scenario 3A: Staggered Planting** | **Scenario 3B: Planting all at once** |
|---|---|---|
| Dourados | **0.645** | **0.608** |
| Ivinhema | **0.523** | **0.493** |
| Brilhante | **0.462** | **0.447** |
| Vacaria | *-0.707* | *-0.7716* |
| Guirai | *-2.774* | *-2.754* |

Table 2.13: Nash-Sutcliffe values for various crop scheduling scenarios representing comparison between daily modeled flows and daily actual flows.

**Scenario Group 4: Ethanol Scenarios**

| | **Precipitation** | **Crop Composition** | **Crop Scheduling** |
|---|---|---|---|
| **Scenario 4 Inputs** | EI Grid | IBGE | Staggered |

Table 2.14: Ethanol Scenario Inputs

| **Rivers** | **No Ethanol Demand (Scenarios 1A-3A)** | **Scenario 4A: 1m3/ton** | **Scenario 4B: 3m3/ton** |
|---|---|---|---|
| Dourados | **0.645** | **0.645** | **0.645** |
| Ivinhema | **0.523** | **0.523** | **0.523** |
| Brilhante | **0.462** | **0.462** | **0.462** |
| Vacaria | *-0.707* | *-0.711* | *-0.711* |
| Guirai | *-2.774* | *-2.774* | *-2.774* |

Table 2.15: Nash-Sutcliffe values for various ethanol scenarios representing comparison between daily modeled flows and daily actual flows.

The purpose of the fourth group of scenarios was to test the best ethanol use parameters for the Ivinhema Basin; however, incorporating ethanol demand has little effect on Nash-Sutcliffe values and negligible effects on flows. For this scenario sugarcane production (tonnes) for each municipality was sourced from the IBGE, which were then weighted by area and summed to obtain the production by catchment. This value was then multiplied by 0.65, the average proportion of sugarcane going to ethanol in the basin over time (see Demand Assumptions section). Figure 2.27 shows the delivered ethanol demand in scenario 4A and the Scenario 4B, while Figure 2.28 shows these values as a percent of baseline flows (Scenario 1A). At its highest, the gap between these scenarios is less than 0.3 percent of modeled flows.

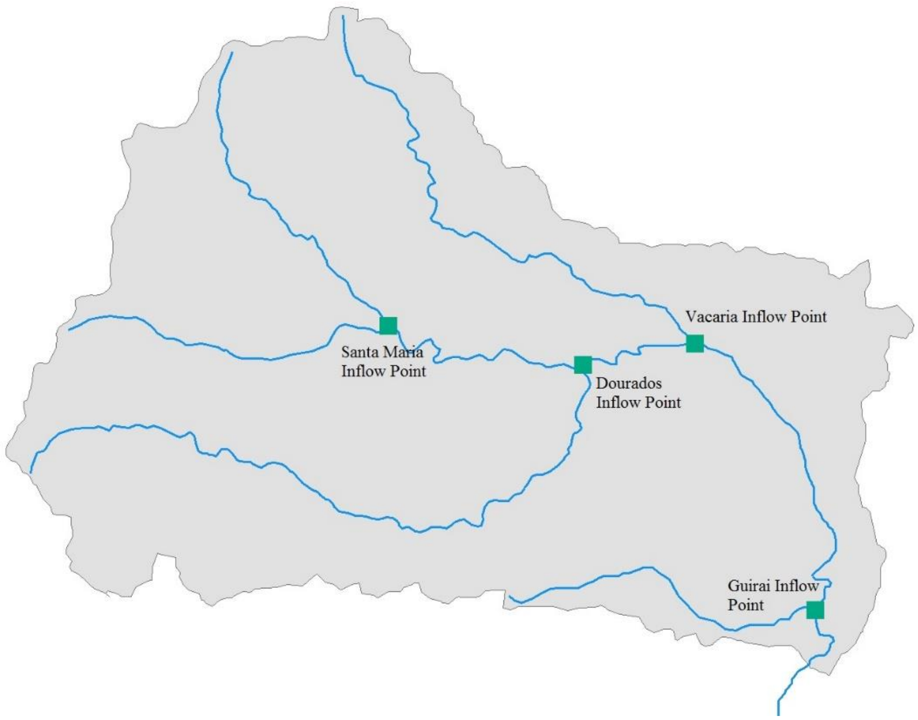



Figure 2.26: Inflow points throughout the basin. The Guirai inflow point is commonly used in this study as a comparison point for flows between scenarios.

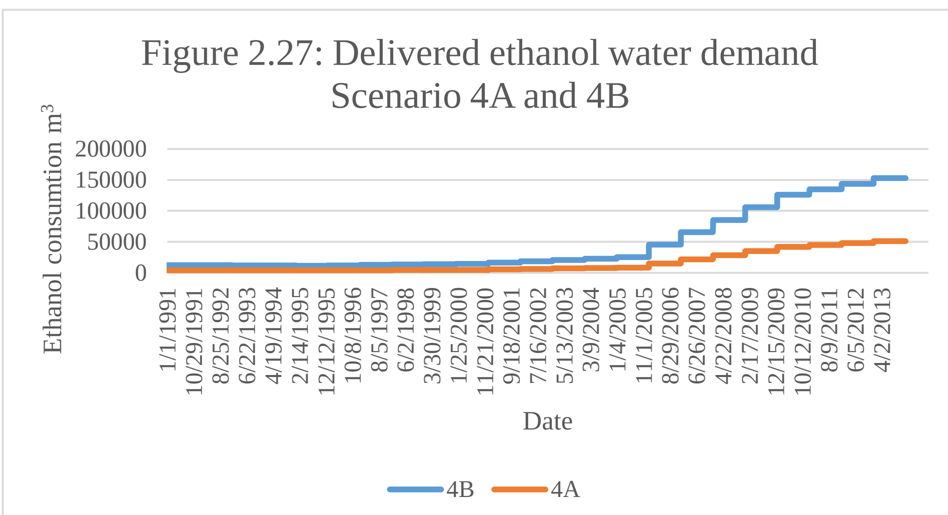


Figure 2.27: Delivered ethanol water demand for each ethanol scenario. Scenario 4A represents production demand of 1 $m^3$/t sugarcane, while Scenario 4B represents production demand of 3 $m^3$/t sugarcane.

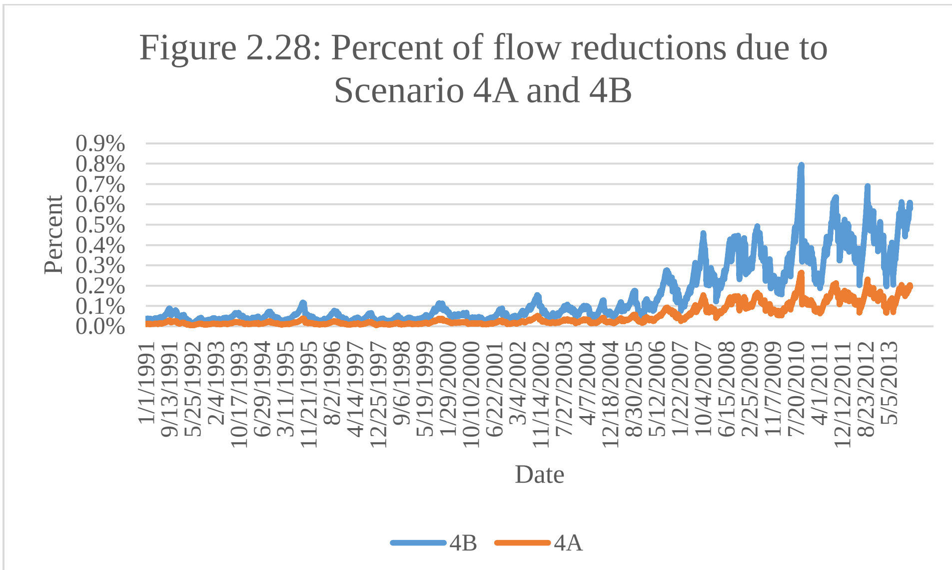



Figure 2.28: Percent flow difference at Guirai inflow point between each ethanol scenario and no ethanol demand. These values were calculated as the baseline flows (flows from Scenario 1A) minus the ethanol scenario flows, divided by the baseline flows. These values were negative indicating reductions. The figure shows positive values because this study speaks of the difference in terms of 'reduction'. Scenario 4A represents production demand of 1 $m^3$/t sugarcane, while Scenario 4B represents production demand of 3 $m^3$/t sugarcane.

## CONCLUSION

The scenarios whose design variables resulted in the most accurate modeled flows are in bold in the table below. The calibration scenario that gave the best results in terms of Nash-Sutcliffe coefficients are Scenarios 1A, 2A, 3A, 4A, and 4B, all of which use inputs of EI Grid precipitation data, IBGE crop composition data, and staggered crop scheduling (4A and 4B are practically indistinguishable from each other and 1A due to modeling a small change in water consumption). These scenarios are in bold in Table 2.16.

Ethanol demand had little effect. Because the Scenario 1A input combination produced the most accurate results, it will be used in the following chapter as the baseline to analyze the impact of irrigation on crop yield and stream flows. In Chapter 3, this scenario will be referred to and Scenario 1A, and will be the baseline to which all flow reductions are compared.

| **Scenario** | **Precipitation data** | | | **Crop Composition** | | | **Crop Scheduling** | | **Ethanol demand** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | EI Grid | ANA Average | 1 ANA Station | IBGE | 100 % Sugarcane | 100 % Grass | Staggered | All at once | 1 $m^3$/ton demand | 3 $m^3$/ton demand |
| **1A** | **x** | | | **x** | | | **x** | | | |
| 1B | | x | | x | | | x | | | |
| 1C | | | x | x | | | x | | | |
| **2A** | **x** | | | **x** | | | **x** | | | |
| 2B | x | | | | x | | | | | |
| 2C | x | | | | | x | x | | | |
| **3A** | **x** | | | **x** | | | **x** | | | |
| 3B | x | | | x | | | | x | | |
| **4A** | **x** | | | **x** | | | **x** | | **x** | |
| **4B** | **x** | | | **x** | | | **x** | | | **x** |

Table 2.16: Design variables used in each calibration scenario, with bolded scenarios representing those with the best Nash-Sutcliffe values.

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# Chapter 3: Irrigation Requirements

The Ivinhema basin experiences enough rainfall to cultivate without irrigation; however, the timing of this rainfall is sporadic and not sufficient to result in optimal crop growth. This chapter uses WEAP to investigate the effects of irrigation on crop yields from 1990 – 2013. Additionally, it investigates the flow impacts of a modeled increase in sugarcane production on water demand for ethanol production. For the purposes of this chapter, scenario 1A as discussed in the previous chapter is used as a baseline for flow comparisons. 5A has all the same design variables but includes irrigation for all crops, while 5B is only applies irrigation to sugarcane. The final scenario, 5C, is identical to 5B except that it includes the increased ethanol water demand due to higher sugarcane yields resulting from irrigation (Table 3.1).

| Scenario | Design inputs | Irrigation | Ethanol demand |
|---|---|---|---|
| **5A** | A1 inputs | All crops | -- |
| **5B** | A1 inputs | Sugarcane | -- |
| **5C** | A1 inputs | Sugarcane | 3 m3/t sugarcane (Incorporating production increase from irrigation) |

Table 3.1: Irrigation scenarios analyzed in Chapter 3.

### IRRIGATION IMPACTS ON YIELD

WEAP's soil moisture method allows modelers to specify the percent of readily available water necessary for optimal crop growth, triggering irrigation whenever soil moisture falls beneath a certain level. This level, called the *wilting point*, varies from catchment to catchment depending on soil conditions. The wilting points along with the maximum soil water capacities, termed the *field capacity*, are show for each catchment in Table 3.2. Both measurements are measured in $m^3$ of water/$m^3$ of soil. When soil water exceeds the field capacity, the soil moisture method algorithm (Appendix 1) determines the destination of that water depending on model parameters, such as preferred flow direction, soil conductivity, and deep conductivity.

| Catchment | Wilting Point | Field Capacity |
|---|---|---|
| 1 | 0.3 | 0.4 |
| 2 | 0.31 | 0.42 |
| 3 | 0.29 | 0.39 |
| 4 | 0.26 | 0.35 |
| 5 | 0.38 | 0.49 |
| 6 | 0.22 | 0.31 |
| 7 | 0.15 | 0.23 |
| 8 | 0.17 | 0.24 |
| 9 | 0.16 | 0.24 |

Table 3.2: The wilting point and field capacity of Ivinhema catchments. Irrigation was set up to start when soil moisture reaches the wilting point and stop when it reaches the field capacity.[41]

These values were entered into WEAP as percentages and the model was run for the study period, 1990 – 2013. For the purpose of this study all irrigation and ethanol demand was assumed to be met with surface water, and all demand sites had equal priority.

**Yield Calculations**

The Soil Moisture Method does not calculate crop yields based on irrigation, but the FAO provides us with a simple equation that allows difference between maximum theoretical crop yield ($Y_m$) and actual yield ($Y_a$) to be estimated (Equation 3.1).[42] This chapter will compare the ratio of actual yield to theoretical yield before and after implementing irrigation for each crop.

$$\frac{Y_a}{Y_m} = (1 - K_y\left(1 - \frac{ET_a}{ET_c}\right)) \quad \text{Equation 3.1}$$

$Y_a$ = actual yield

$Y_m$ = maximum theoretical yield

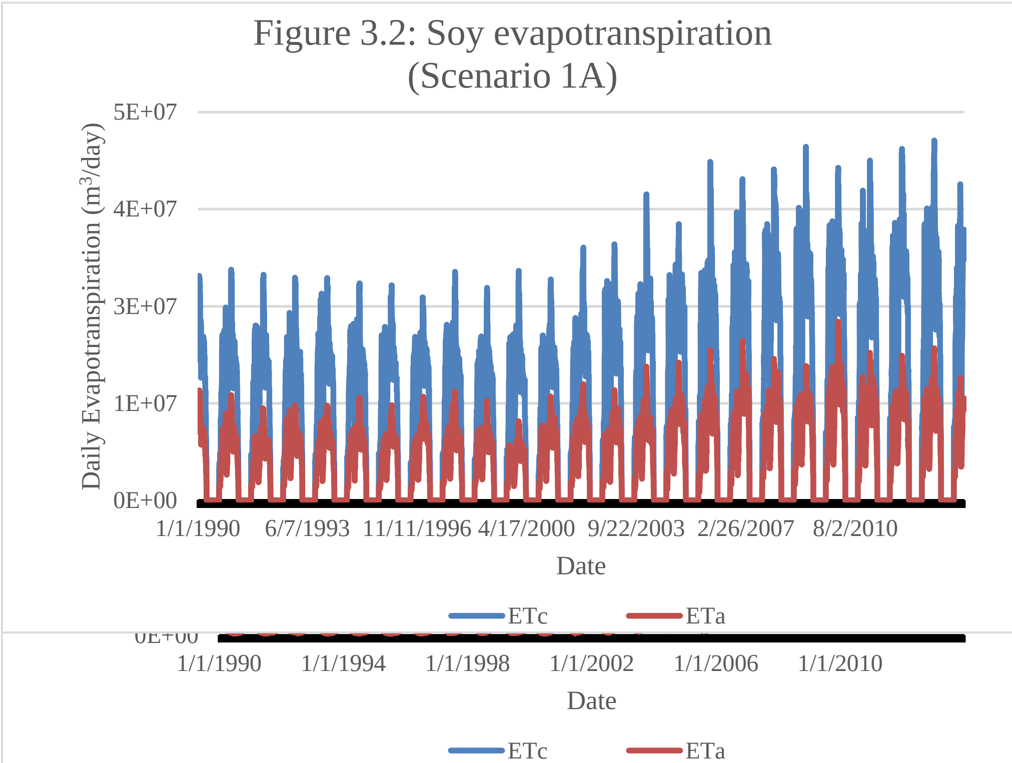
$ET_a$ = actual crop evapotranspiration

$ET_c$ = potential crop evapotranspiration

$K_y$ = yield response factor to water stress

**$ET_a$ and $ET_c$: Actual and Potential Evapotranspiration**

When water supply does not meet crop water requirements, actual evapotranspiration will be less than maximum evapotranspiration.[43] The WEAP Soil Moisture Method uses the Penmen-Monteith Equation to estimate $ET_o$, and multiplies this estimated value by the land cover fraction of a given crop and $K_c$ to estimate its total potential contribution to evapotranspiration ($ET_c$). This value is then augmented by the




amount of soil moisture available on a given day to produce to actual evapotranspiration value ($ET_a$).

Figure 3.1: Sugarcane evapotranspiration, both actual ($ET_a$) and potential ($ET_c$), with no irrigation (Scenario 1A).

Figure 3.2: Soy evaporation, both actual ($ET_a$) and potential ($ET_c$), with no irrigation (Scenario 1A).

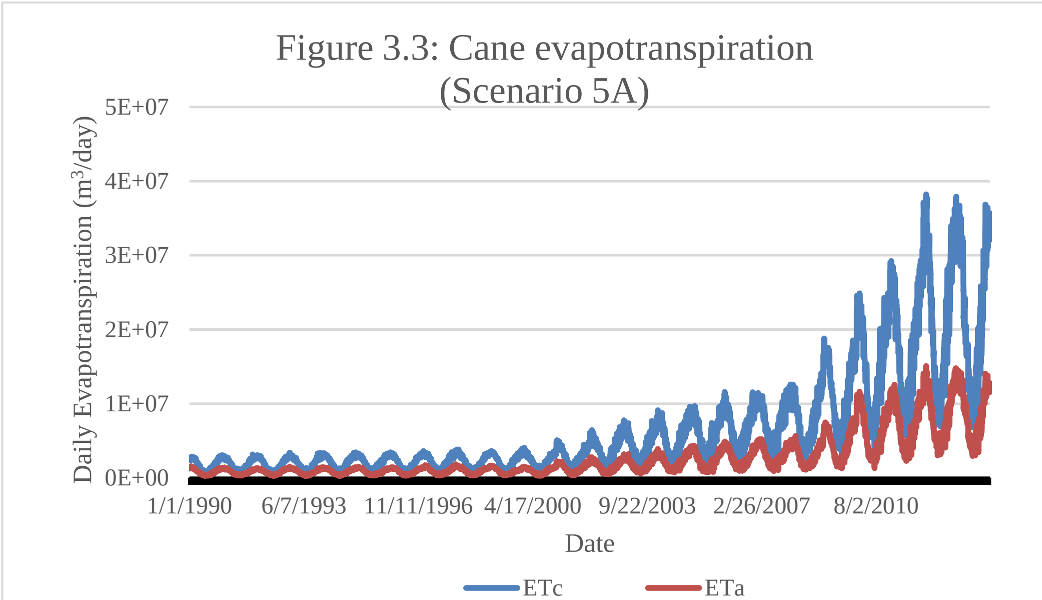



Figure 3.3: Sugarcane evapotranspiration, both actual (ETa) and potential (ETc), with irrigation (Scenario 5A).

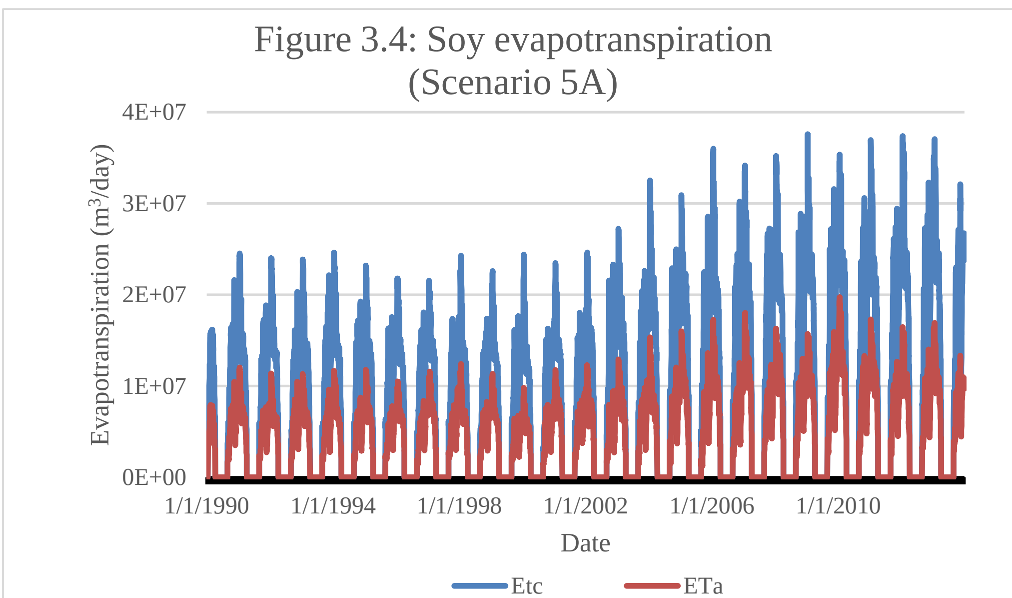



Figure 3.4: Soy evaporation, both actual ($ET_a$) and potential ($ET_c$), with irrigation (Scenario 5A).

From these outputs, $ET_a/ET_c$ ratios were calculated for each crop for both the irrigated scenario (5A) and the scenario using no irrigation (1A). A comparison of these ratios between scenarios shows that irrigating to increase soil moisture improved evapotranspiration efficiency for all crops, raising the corn and soy $ET_a/ET_c$ ratio by about 8 percent, while the $ET_a/ET_c$ ratio for cane increases by 29 percent. Average $ET_a/ET_c$ values are shown in Table 3.3. $ET_a/ET_c$ ratio is not close to one, partly due to the fact that irrigation starts that wilting point, at which $ET_a$ is significantly reduced, but partly because surface water supply is not sufficient to provide the irrigation demand in many of the upper catchments of the basin. Reliability of irrigation demand, which is the percentage of days that supply was sufficient to meet demand, is particularly low for Catchments 1, 3, and 5 (Figure 3.5).

| | 1A No Irrigation (Average) | 5A Irrigation (Average) | Difference (Average) | Percent Change |
|---|---|---|---|---|
| Cane | 0.321 | 0.415 | 0.093 | +29% |
| Corn | 0.424 | 0.459 | 0.035 | +8% |
| Soy | 0.433 | 0.462 | 0.030 | +7% |

Table 3.3: Average $ET_a/ET_c$ values over the study period (1990-2013). The difference (irrigated – non-irrigated) and percent change are also shown.

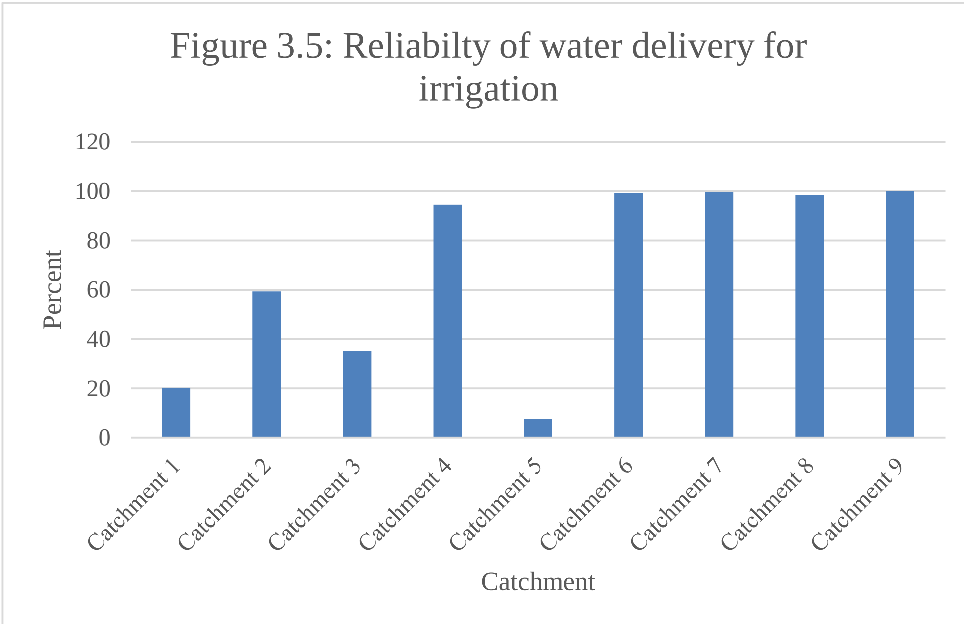



Figure 3.5: Reliability of water delivery for irrigation under Scenario 5A, irrigation of all crops

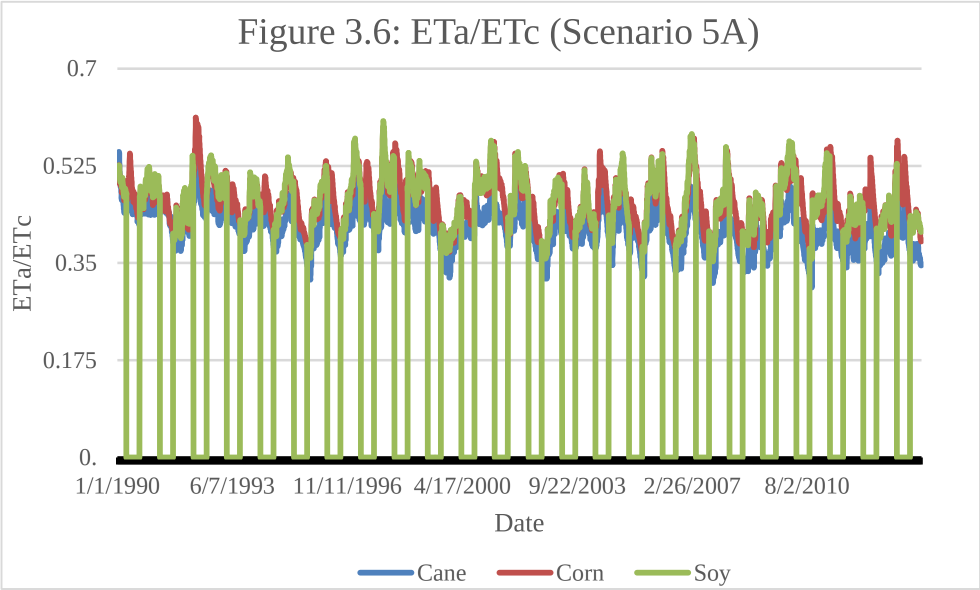



Figure 3.6: Daily $ET_a/ET_c$ ratio over the study period for all crops assuming all cultivated land is irrigation when soil moisture reaches the wilting point and stops irrigating when soil moisture reaches the field capacity.

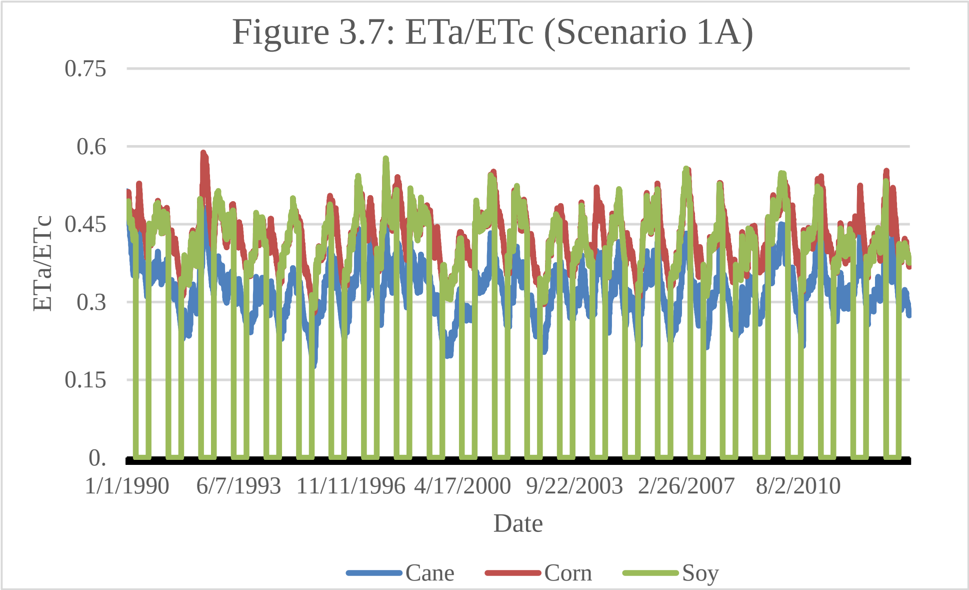



Figure 3.7: Daily $ET_a/ET_c$ ratio over the study period for all crops assuming no irrigation.

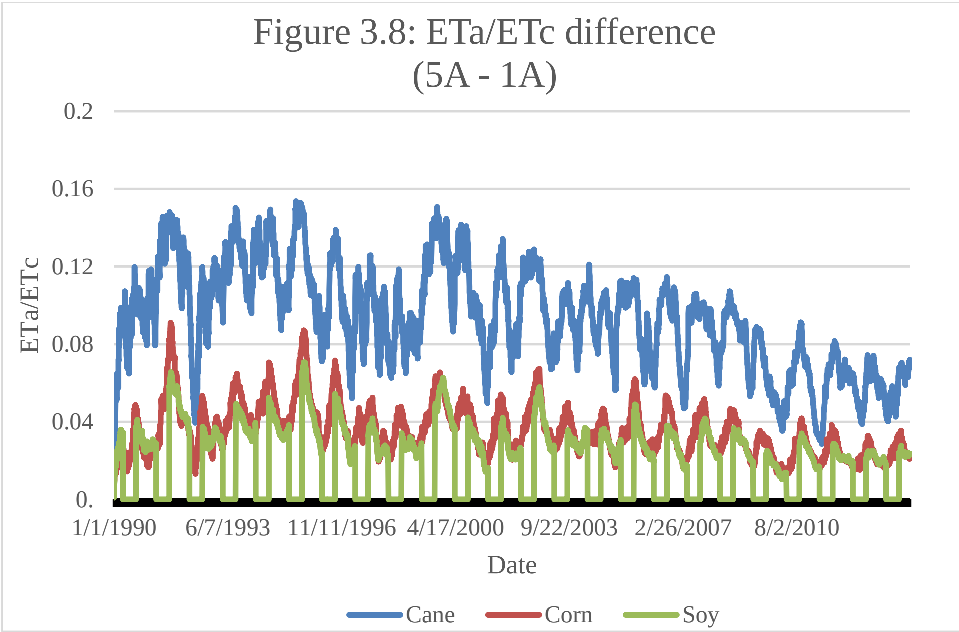



Figure 3.8: The above graph shows the daily difference in $ET_a/ET_c$ ratio between the irrigated scenario and the non-irrigated scenario over the study period for all crops.

**$K_y$: The Yield Response Factor**

Crops respond differently to water stress; some adjust to use water more efficiently while others become less efficient. $K_y$, the yield response factor, is a measurement how much water stress affects crop growth, with larger $K_y$ values representing higher sensitivity to water stress, and a $K_y$ of 1 meaning that yield reduction is directly proportional to reduced water availability. The $K_y$ is dependent on crop and the crop growth stage; for example, sugarcane has the highest $K_y$ during its initial growth stage (establishment), meaning that water deficits during this initial period have a large effect on yields, while water deficits during the final ripening stage have little impact.[44]

Due to the use of staggered crop scheduling, the $K_y$ values for each crop were calculated using the same method as the $K_c$ values described in Chapter 2. The following table shows the $K_y$ values for various crops at different stages, while Figure 3.9 shows the $K_y$ values for each crop over the course of a year.

| Crop | Source | $K_y$ establishment | $K_y$ yield formation | $K_y$ ripening |
|---|---|---|---|---|
| Maize | CONAB | 0.4 | 1.3 | 0.5 |
| Soybean | CONAB | 0.4 | 1 | 0.4 |
| Sugarcane | FAO | 0.75 | 0.5 | 0.1 |

Table 3.4: The above table shows $K_y$ values for various crop growth periods for the crops included in this study.

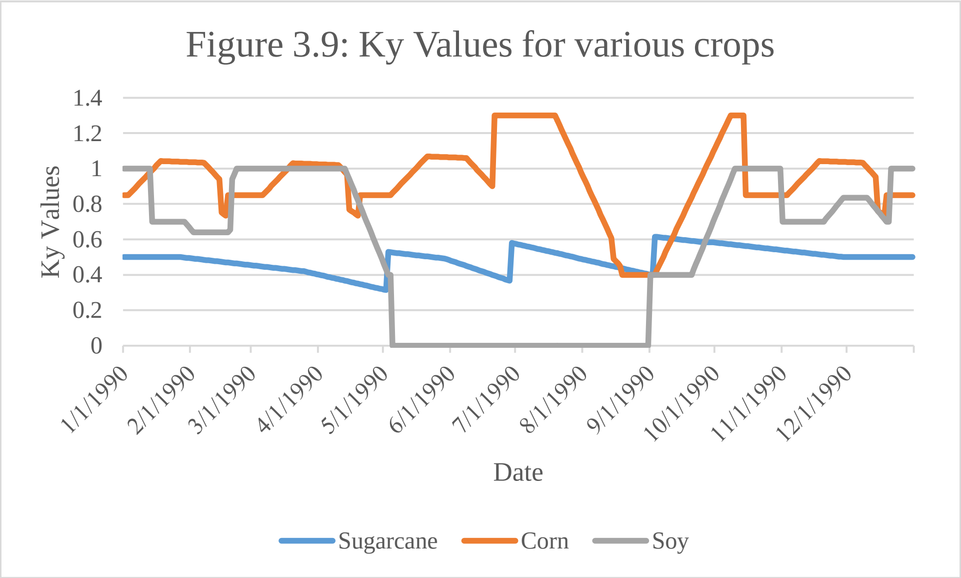



Figure 3.9: The above graph shows the $K_y$ values for the crops included in this study of the course of one year. This pattern represents an average $K_y$ for each crop, assuming a staggered planting schedule as described in Chapter 2.

**$Y_a/Y_m$: Yield Response Ratio**

The maximum yield of a crop ($Y_m$) represents yield resulting from an optimal growth environment, i.e. environments where growth is not inhibited by disease, soil deficiency, water stress, or climatic conditions.[45] When water supply does not meet crop water requirements, actual evapotranspiration will be less than maximum evapotranspiration, resulting in lower yield ($Y_a$). The ratio of $Y_a$ to $Y_m$ represents the percentage of total yield being obtained, while $1 - Y_a/Y_m$ is known as the yield reduction. $Y_a/Y_m$ was calculated using Equation 3.1.

Comparing the $Y_a/Y_m$ of the irrigated scenario to the non-irrigated scenario produces the expected results: the ratio of actual yields to theoretical yields is higher when crops are irrigated than when they are not, i.e. irrigation improves yields. The yield increases, however, are relatively small, with soybean yield increasing by 4.32 percent, corn increasing by 7.12 percent and sugarcane increasing by 6.85 percent. Table 3.5 shows the average $Y_a/Y_m$ for each crop over the study period for both scenarios.

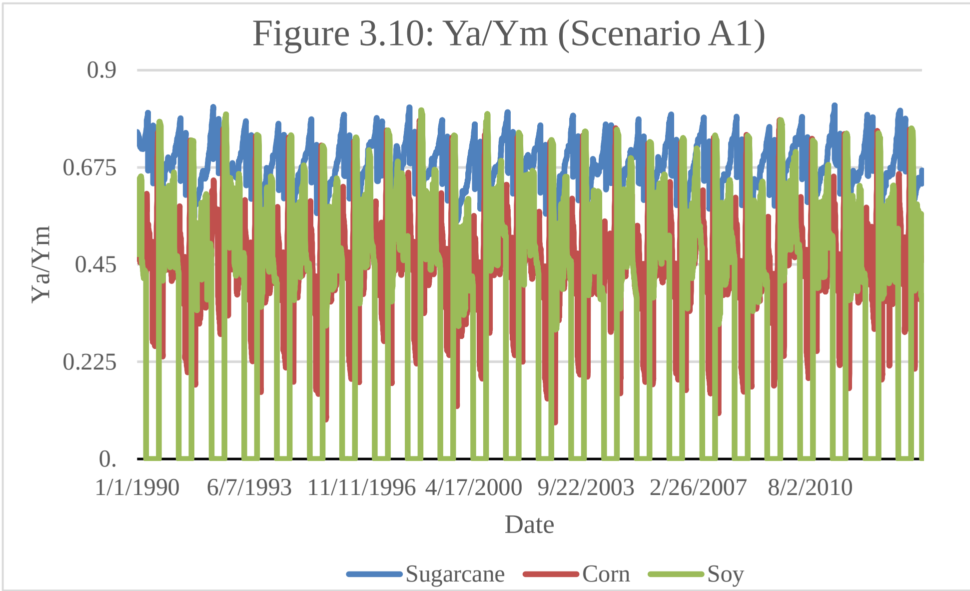



Figure 3.10: Daily $Y_a/Y_m$ for the scenario with no irrigation (1A) over the study period (1990-2013).

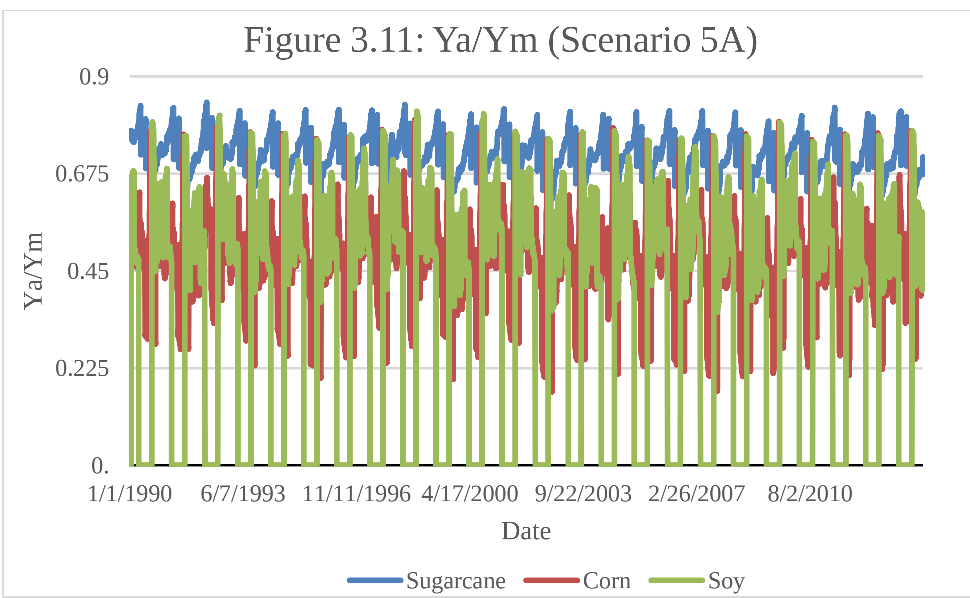



Figure 3.11: Daily $Y_a/Y_m$ for the scenario with irrigation (5A) over the study period (1990-2013).

| | 5A Irrigated (average) | 1A Non-Irrigated (average) | Average Percent Yield Increase with Irrigation |
|---|---|---|---|
| Sugarcane | 0.713 | 0.668 | 6.85% |
| Corn | 0.492 | 0.459 | 7.12% |
| Soy | 0.569 | 0.546 | 4.32% |

Table 3.5: The average Ya/Ym by crop over the study period (1990 – 2013).

If irrigation was optimized, $Y_a/Y_m$ should be equal to one. Crops take up water at their maximum rate immediately after rain or irrigation ($ET_a = ET_c$); after irrigation or precipitation stops, $ET_a$ will decrease until soil moisture reaches the wilting point, the point at which the crop is unable to draw up any more water.[46] For this study, irrigation was triggered when soil moisture levels reached the wilting point, so irrigation did not optimize yields. Additionally, because soybeans, corn, and sugarcane are irrigated in this scenario, irrigation demand was not able to be met with surface flows 100 percent of the time, especially in the upper catchments. Irrigation, as scheduled in this study, only increases crop yields in the Ivinhema basin by 4 – 7 percent on average, depending on the crop. The next section investigates the effects of irrigation under scenario 5A on flows.

It is important to note, that because irrigation was not applied to maximize yields, but instead to minimize losses, the effects of irrigation on flow volumes is less than it would be should irrigation be scheduled to maximize yields.

### EFFECT OF IRRIGATION ON FLOWS (SCENARIO 5A)

Table 3.6 shows average difference in flow volumes throughout the basin and these volumes as percentage of baseline flows for summer and winter, with summer being December through April and winter being June through September. These numbers should be approximately equivalent to the average daily volume of water used for irrigation above the inflow points mapped in Figure 3.13. As you would expect, there is less need for irrigation in the summer when precipitation levels are high, while winter requires much higher irrigation volumes. In winter, flow difference due to irrigation averages between 25 and 30 percent, in part due to the higher need for irrigation and in part due to lower baseline flows during these periods. These values are averages, and in some winters flow differences climb higher than 85 percent; in fact, flow depletion at the Guirai inflow point was greater than 85 percent for 1.86 percent of the study period, or 163 days. Flow depletion greater than 60 percent occurred at the Guirai inflow point approximately 6.75 percent of the study period, or 592 days. Less than 0.03 percent of the water used for irrigation returned to surface water in the basin.

While yield increases are desirable, flow reductions of more than 85 percent may not be an appriopriate trade-off for average-yield increases of less than 10 percent.

| | Summer | | Winter | |
|---|---|---|---|---|
| | **Flow difference (average m³/day)** | **Percent** | **Flow difference (average m³/day)** | **Percent** |
| **Santa Maria Inflows** | -535,000 | -9.5% | -1,080,000 | -25% |
| **Dourados Inflow** | -4,340,000 | -18% | -3,870,000 | -22% |
| **Vacaria Inflow** | -5,120,000 | -17% | -6,580,000 | -30% |
| **Guirai Inflows** | -5,240,000 | -15% | -7,030,000 | -28% |

Table 3.6: Average daily stream flow difference at the Guirai inflow point resulting from irrigation in both winter and summer. Winter averages are comprised of June 1 – September 30 of each year, while summer averages are comprised of data from December 1 – April 31 of each year. Flow differences were calculated by subtracting the daily flows from Scenario 5A from the daily flows from Scenario 1A. This difference was then averaged over the study period. The percent of non-irrigated flows were calculated by dividing the daily flow difference by the daily flows for Scenario 1A, then were averaged over the study period.

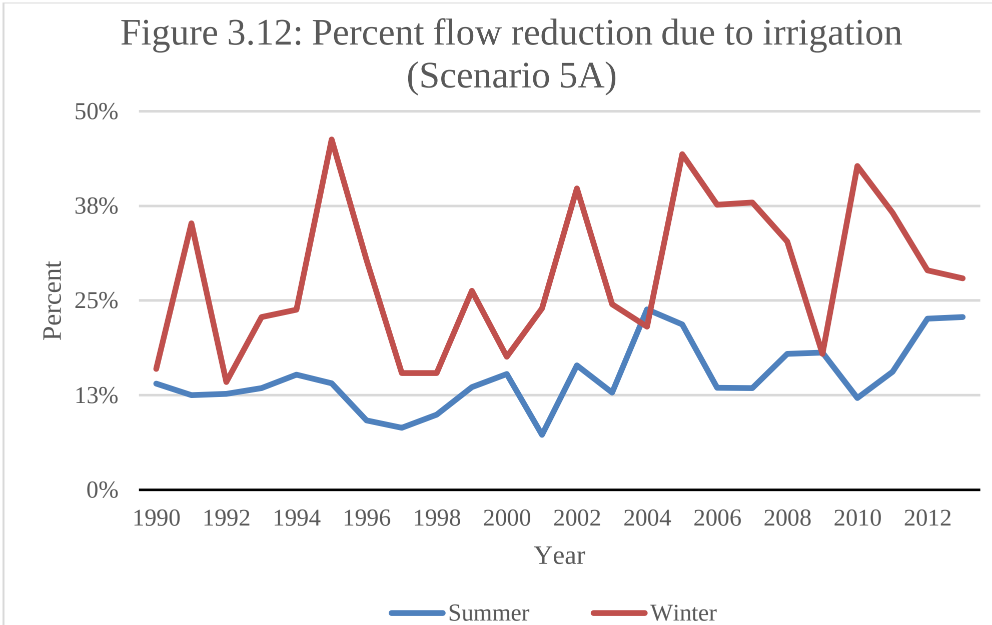



Figure 3.12: The percent daily average flow reduction (opposite of flow difference) at the Guirai inflow point due to irrigation in both winter and summer of each year of the study period. Points represent seasonal averages, with winter being June 1-September 30 of each year, and summer being December 1 – April 31.

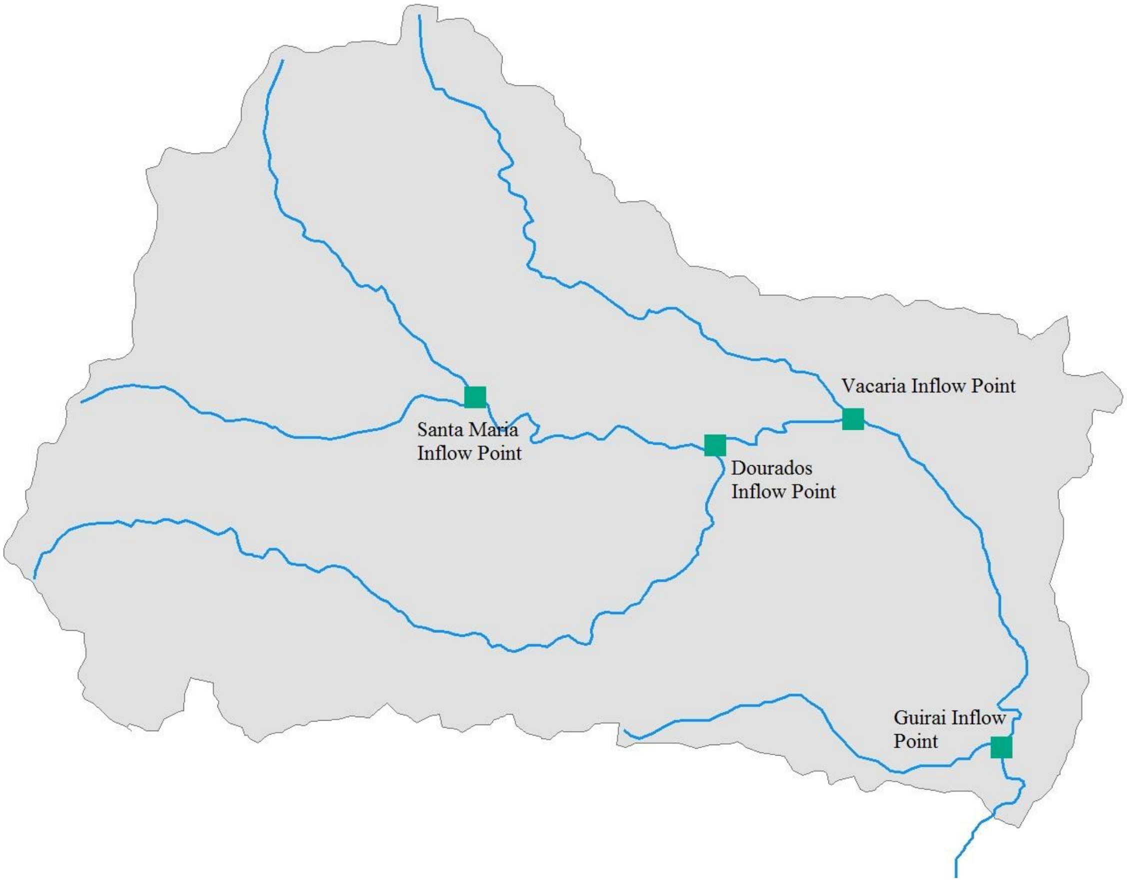



Figure 3.13: Map of confluences within the Ivinhema basin. The flows at these points are the flows used to analyze flow reduction due to irrigation.

### EFFECT OF SUGARCANE IRRIGATION ON FLOWS (SCENARIO 5B)

If only the sugarcane crop is irrigated, the impact of irrigation on stream flows drops significantly. Flows at the four confluences are only reduced by an average of 5.8 – 6.8 percent of original flows in summer and an average of 8.7 – 11.7 percent in winter. The difference in flows between Scenario 5B and the baseline at the Guirai inflow point was greater than 85 percent for 0.8 percent of the study period, or 76 days. Flow difference greater than 60 percent occurred at the Guirai inflow point approximately 1.8 percent of the study period, or 166 days, while less than 0.02 percent of the water diverted for irrigation returns to surface water in the basin.

Although this scenario has a much smaller effect on flow volumes, flow volumes are still significantly affected. Figure 3.15 shows the sugarcane yield response and the flow response to irrigation in the basin. The yield increase resulting from irrigation decreases fairly consistently over time, likely due to more consistent rainfall during more recent years. It is important to note that this yield increase (explained in the next section) is higher than the yield increase calculated for scenario 5A, resulting primarily fruom increased reliability of water supply for irrigation. While yield increases appear to decrease over time, the flow reduction increases significantly and is correlated with increased sugarcane cultivation. In more recent years, streamflow reduction has reached an average of 25 percent. Since 2008, flows at the Guirai inflow point have reached over 85 percent depletion approximately 2.5 percent of the time; while this number is relatively small, it indicates an increase in depletion in recent years. If sugarcane continues to expand throughout the basin, irrigation could have a significant environmental impact, especially during the dry winter season.

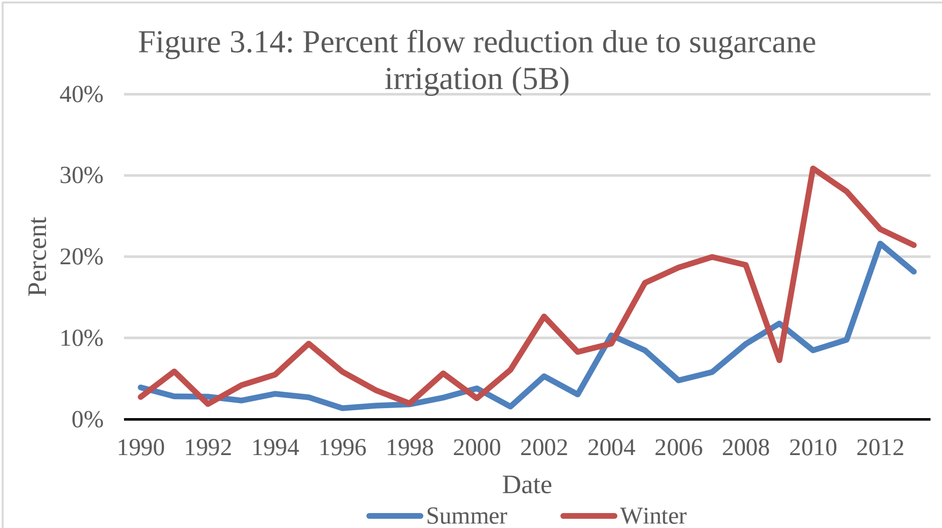



Figure 3.14: Percent flow reduction at the Guirai inflow point due to sugarcane irrigation in both summer and winter in the Ivinhema basin, calculated using the same method as the values in Figure 3.11.

| | **Summer** | | **Winter** | |
|---|---|---|---|---|
| | **Flow difference (average m³/day)** | **Percent** | **Flow difference (average m³/day)** | **Percent** |
| **Santa Maria Inflows** | -344,000 | -5.8% | -492,000 | -11.4% |
| **Dourados Inflow** | -1,330,000 | -5.9% | -1,470,000 | -8.7% |
| **Vacaria Inflow** | -1,960,000 | -6.8% | -2,500,000 | -11.7% |
| **Guirai Inflows** | -2,060,000 | -6.1% | -2,798,000 | -11.3% |

Table 3.7: Average flow difference at the Guirai inflow point due to sugarcane irrigation in the Ivinhema basin in summer and winter, calculated using the same method as the values in Figure 3.10 (daily difference, Scenario 1A minus Scenario 5B, averaged over the study period).

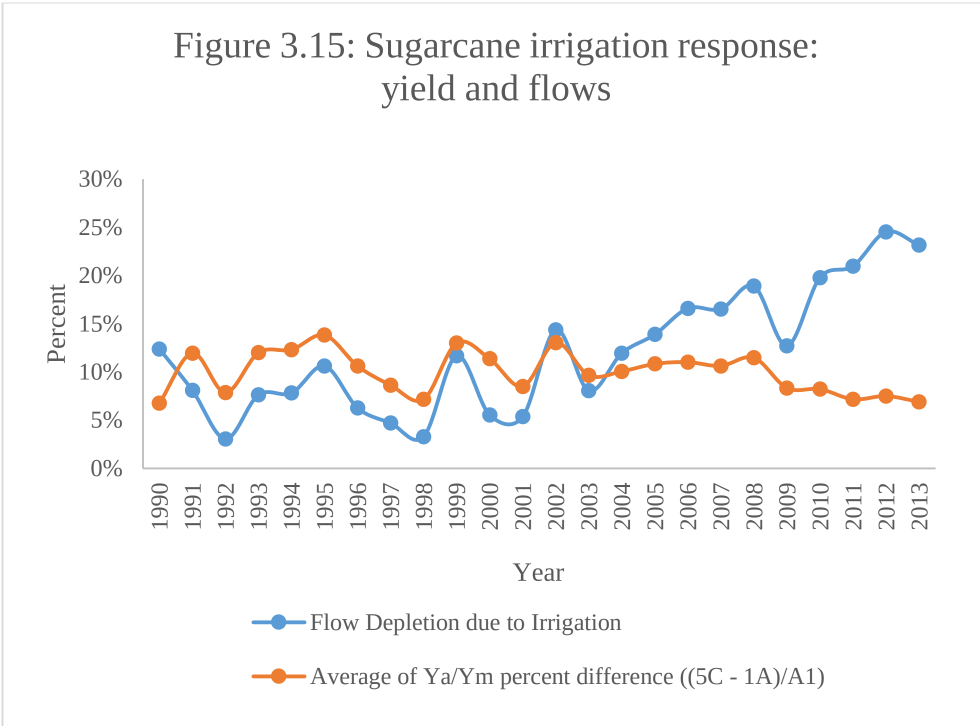



Figure 3.15: Response of both sugarcane yields and flow depletions under sugarcane irrigation (scenario 5B).

**EFFECT OF IRRIGATION AND INCREASED ETHANOL PRODUCTION (SCENARIO 5C):**

As seen earlier in this chapter, sugarcane yields increase when sugarcane is irrigated, which likely translates into an increase in ethanol production throughout the basin. This section will investigate the theoretical flow implications of sugarcane irrigation and increased water demand for ethanol production.

Before delving into this question however, it is useful to examine the scenario's water balance. This is important for two reasons: 1) it allows us to check that the model is still preforming accurately and 2) it allows us to see proportionally where the water under this scenario is going. I looked at the basin's monthly and yearly water balance over the study period. Equation 3.2 shows a typical water balance equation. To check the accuracy of the model, precipitation is graphed against the right side of Equation 3.2, both for monthly values of these variables and for yearly (Figure 3.16 and Figure 3.17). These both show close to a 1:1 ratio, indicating that the model is preforming correctly. The yearly numbers produce a ratio closer to 1, likely because they account for the lag within the system better than using monthly values.

$$P = -Q - ET - C - \Delta S \qquad \text{Equation 3.2}$$

P = Precipitation
Q = Runoff, all surface water flows
ET = Evapotranspiration
C = Consumption (ethanol)
S = Storage, either in soil or in groundwater.

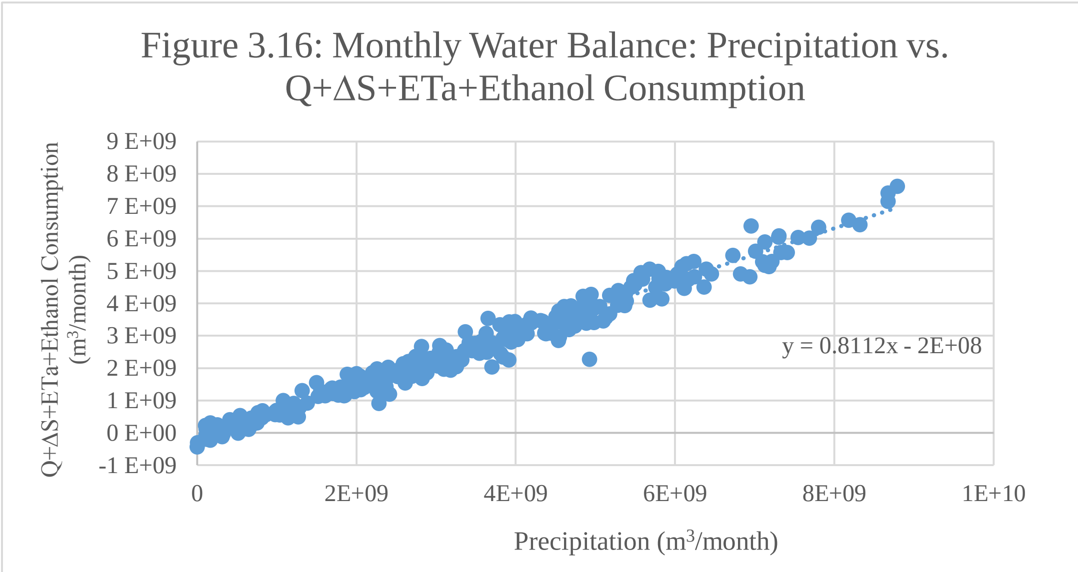



Figure 3.16: The monthly water balance for scenario 5C: precipitation versus the sum of flows, change in groundwater and soil storage, evapotranspiration and ethanol water consumption.

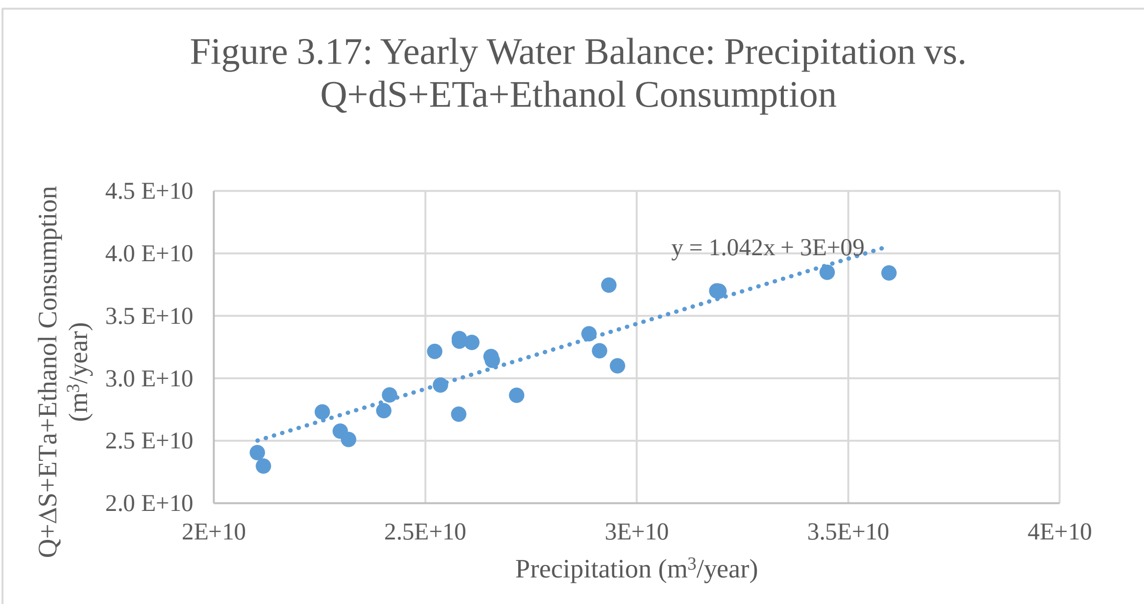


Figure 3.17: The yearly water balance for scenario 5C: precipitation versus the sum of flows, change in groundwater and soil storage, evapotranspiration and ethanol water consumption.

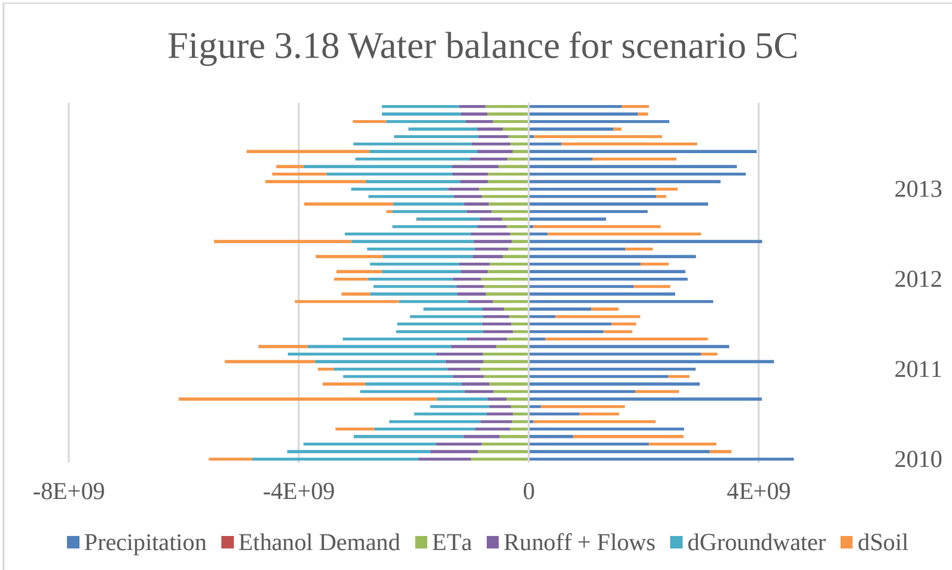



Figure 3.18: The monthly water balance for scenario 5C broken down by Equation 3.2, with negative water balance components (right side of the equation) on the left and positive water balance components on the right (ΔSoil and ΔGroundwater make up the ΔS term).

Figure 3.18 shows clearly that the vast majority of water that enters the basin becomes stored in the underlying aquifers. Evapotranspiration is the second most popular destination for water molecules, while runoff and surface water flows are the third. Soil moisture increases after intense rainfall events (negative ΔSoil) while soil moisture decreases during prolonged dry periods (positive ΔSoil). This can be seen in Figure 3.18, where negative soil moisture values balance high precipitation events and positive values fill in the troughs between said events. Ethanol demand, which is comparatively very small, will be investigated further later in this section.

### Yield Increase

Scenario 5C only involves sugarcane irrigation as opposed to irrigation of sugarcane, corn, and soybeans, increasing the reliability of irrigation water delivery when compared to Scenario 5A (Figure 3.19). This is especially true for Catchments 1, 3, and 5, which had reliabilities of less than 40 percent in Scenario 5A (Figure 3.5). Increased reliability of supply translates directly into increased $ET_a/ET_c$ values and $Y_a/Y_m$ values (Figure 3.21). The average $Y_a/Y_m$, for Scenario 5C is 0.73, compared to 0.71 (5A) and 0.67 (1A), with average yearly $Y_a/Y_m$ values ranging from 7 – 14 percent.

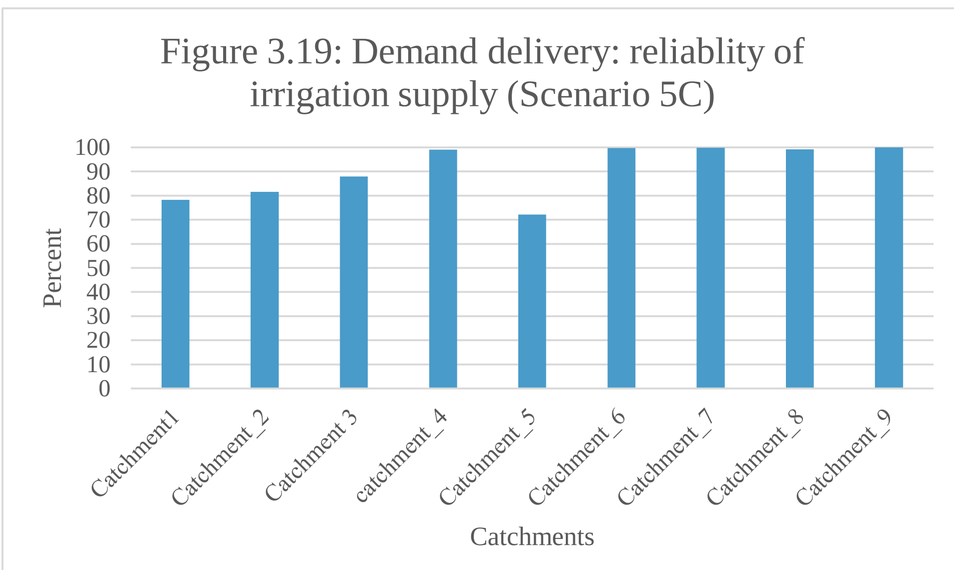



Figure 3.19: Irrigation demand delivery reliability for irrigated scenario 5C. Reliability is less than 100 for the catchments at the top of the basin, as well as in Catchment 5 which is the catchment immediately below Catchment 1.

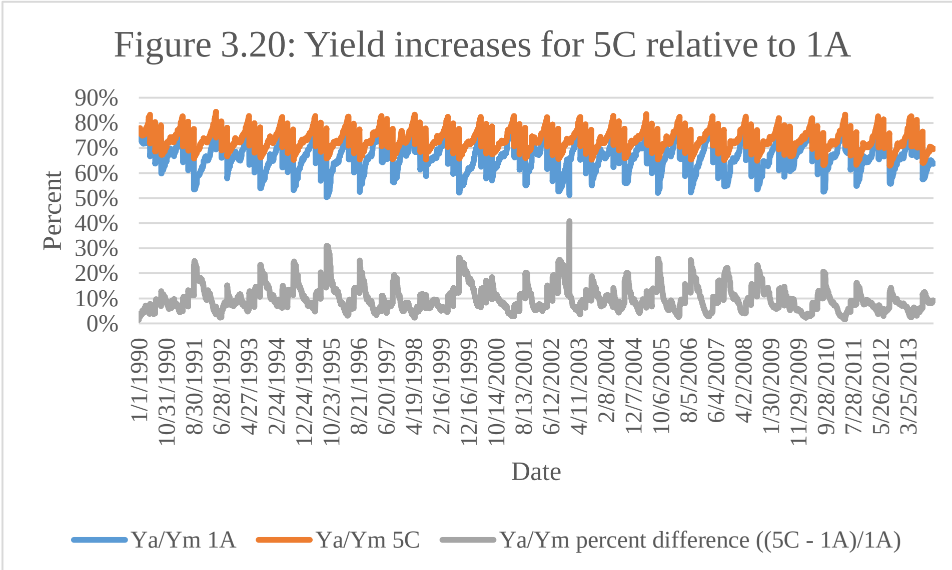



Figure 3.20: $Y_a/Y_m$ values for Scenario 1A, Scenario 5C, and the percent difference between the two. This difference is higher than between 5A and 1A, due primarily to increased reliability of supply.

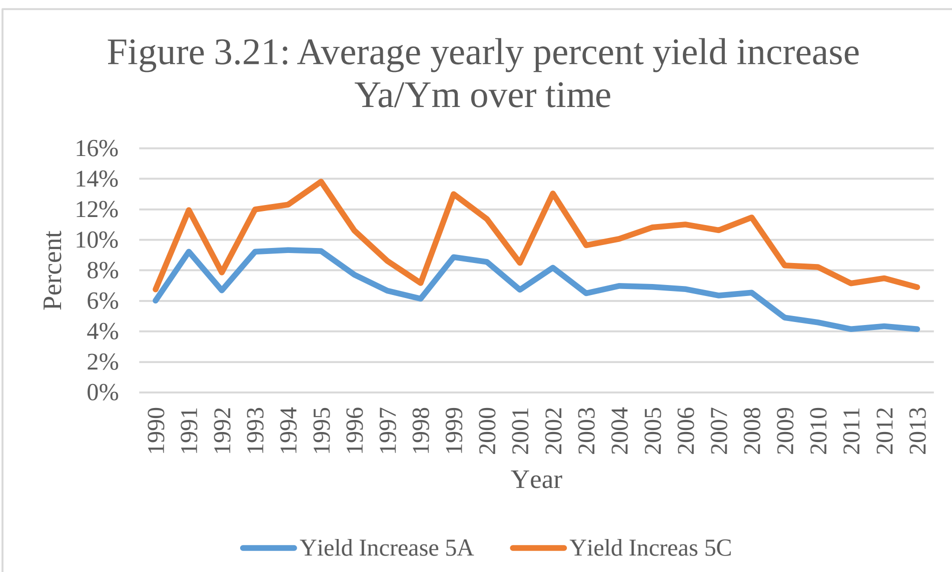



Figure 3.21: Average percent difference in Ya/Ym between 5C and 1A is consistently higher than the difference between 5A and 1A, and ranges from 7 to 14 percent, with recent years hovering around 7 – 8 percent.

**Ethanol Demand Increase**

To evaluate the theoretical effects of increased ethanol production on ethanol water demand and flows, a couple of assumptions were made. First, it was assumed that the proportion of sugarcane stock that goes to ethanol production remained at 65 percent. Because the portion of production dedicated to ethanol feedstock depends on the ethanol and sugar market, this number fluctuates more than this assumption would imply.

To calculate the amount of sugarcane produced under an irrigated scenario, the percent increase in the $Y_a/Y_m$ ratio was calculated for each catchment, which is equivalent to the increase in sugarcane production under irrigated scenarios.

| | **Average Ya/Ym Scenario 1A** | **Average Ya/Ym Scenario 5C** | **Percent increase** |
|---|---|---|---|
| Catchment 1 | 0.674 | 0.735 | 9.0% |
| Catchment 2 | 0.675 | 0.740 | 6.5% |
| Catchment 3 | 0.690 | 0.740 | 5.0% |
| Catchment 4 | 0.691 | 0.729 | 3.9% |
| Catchment 5 | 0.662 | 0.779 | 11.7% |
| Catchment 6 | 0.671 | 0.708 | 3.6% |
| Catchment 7 | 0.631 | 0.650 | 1.9% |
| Catchment 8 | 0.640 | 0.666 | 2.6% |
| Catchment 9 | 0.513 | 0.669 | 15.6% |

Table 3.8: This table shows the percent increase in sugarcane yield by catchment due to sugarcane irrigation.

The percent increase from each catchment and the historic production calculated for each catchment (Table 3.8) were used to obtain sugarcane production rates under an irrigated scenario. Assuming 65 percent of sugarcane production continued to go to ethanol production, feedstock quantities were obtained (Table 3.9).

| | 1990 | 1995 | 2000 | 2005 | 2010 | 2013 |
|---|---|---|---|---|---|---|
| **4B** | 1,516,971 | 1,391,284 | 1,738,344 | 3,046,357 | 15,331,250 | 18,607,966 |
| **5C** | 1,628,410 | 1,490,077 | 1,864,766 | 3,265,393 | 16,266,989 | 19,618,170 |

Table 3.9: The above table shows the amount of sugarcane in the Ivinhema basin going to ethanol production (t) with various irrigation scenarios.

In terms of stream flow reproduction, there was no discernable difference in ethanol scenarios between water consumption rates of 1 $m^3$/t of cane and 3 $m^3$/t of cane in the previous chapter, so the conservative value of 3 $m^3$/t sugarcane was used.

The results in the below table closely resemble the results from Scenario 5B, but are slightly larger, as one would expect. Flow depletion as a percentage of native flows ranged from 7.4 – 8.5 in the summer to 9.4 – 12 in the winter (Figure 3.22). Flow depletion at the Guirai inflow point was greater than 85 percent for 1 percent of the study period, or 83 days. Flow depletion greater than 60 percent occurred at the Guirai inflow point approximately 1.9 percent of the study period, or 170 days. This increase is due to the addition of water consumption requirements at the ethanol mills. Flow depletion over time resembles that of other scenarios: average flow depletion increases, likely due to increased sugarcane cultivation and agricultural intensification throughout the basin. As with the other scenarios, flow difference between the scenario and the baseline increases as you progress down the basin, however, the percent depletion is similar regardless of geographic location (Figure 3.23).

| | Summer | | Winter | |
|---|---|---|---|---|
| | **Flow difference (average m³/day)** | **Percent** | **Flow difference (average m³/day)** | **Percent** |
| **Santa Maria Inflows** | -469,000 | -7.4% | -530,000 | -12% |
| **Dourados Inflow** | -1,750,000 | -7.5% | -1,610,000 | -9.4% |
| **Vacaria Inflow** | -2,470,000 | -8.3% | -2,680,000 | -12% |
| **Guirai Inflows** | -2,580,000 | -7.5% | -2,990,000 | -12% |

Table 3.10: The flow difference and the percent flow difference at various inflow points in both winter and summer between Scenario 5C and Scenario 1A.

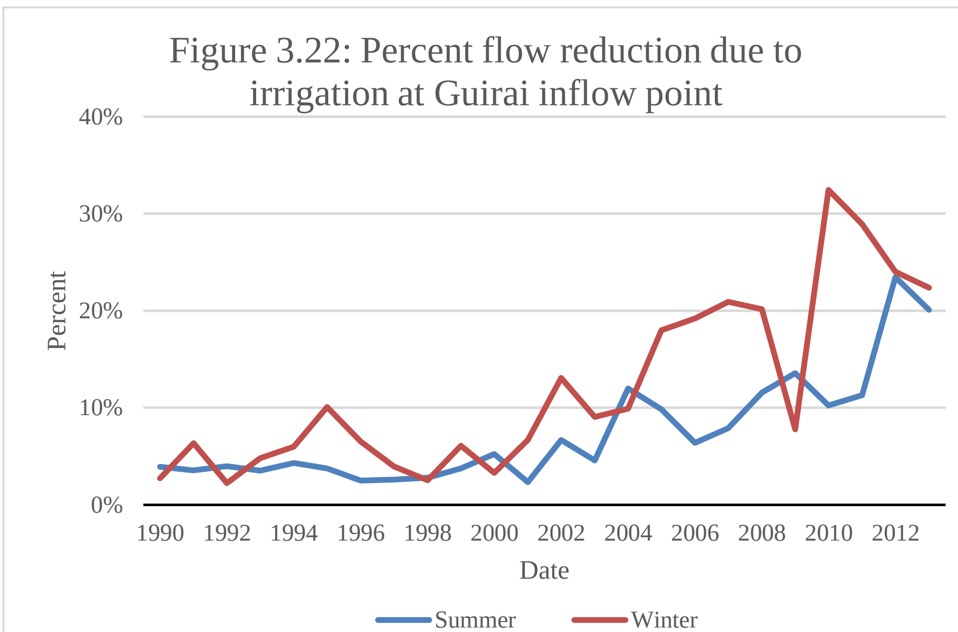



Figure 3.22: The above graph shows flow reduction at the Guirai inflow point due to both sugarcane irrigation and ethanol production (Scenario 5C) in the Ivinhema basin.

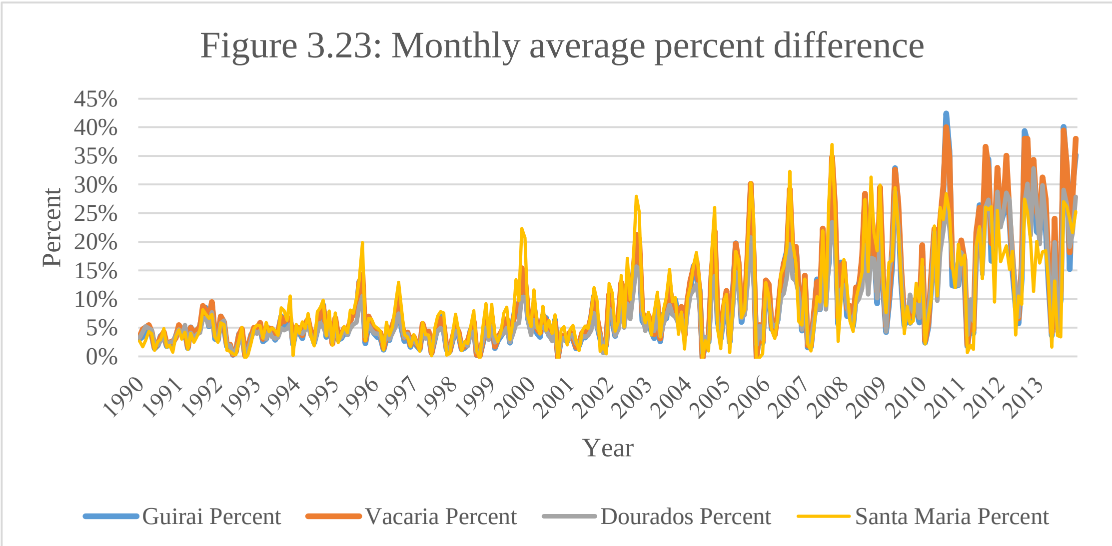
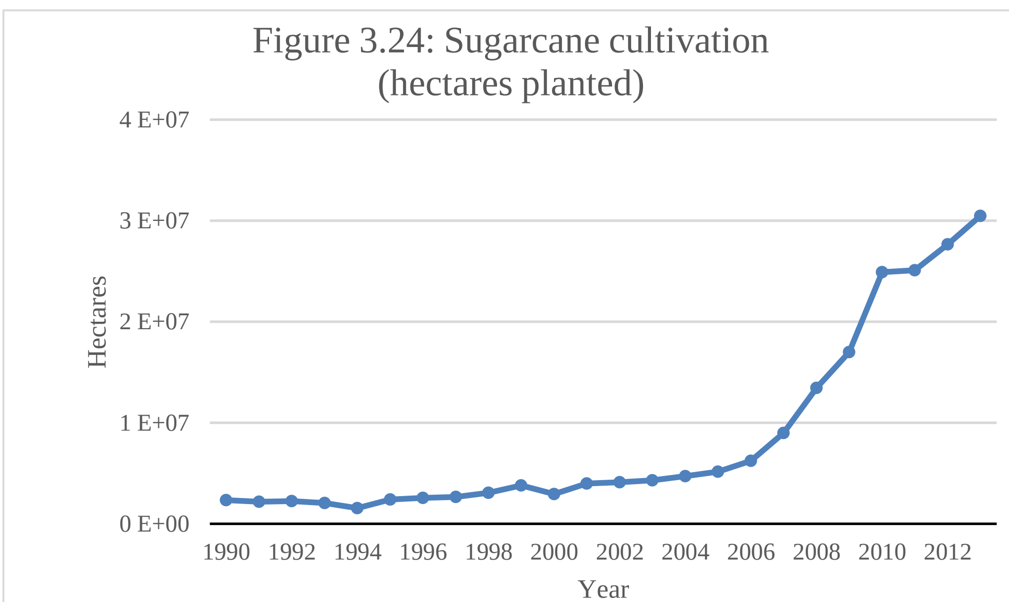



Figure 3.23: Monthly average flow reductions as a percentage of native flows at the Guirai inflow point (Scenario 5C versus 1A).

Figure 3.24: Hectares of sugarcane cultivation in counties within the Ivinhema basin over




the study period.

| | Santa Maria Inflow Point | Dourados Inflow Point | Vacaria Inflow Point | Guirai Inflow Point |
|---|---|---|---|---|
| Max | -100.0% | -74.7% | -98.6% | -100.0% |
| Min | 8.5% | 6.5% | 7.5% | 6.8% |
| Average | -9.3% | -8.3% | -10.0% | -9.2% |

Table 3.11: Maximum, minimum, and average daily flow difference percentages at various points in the basin.

**Flow Depletion and Ethanol Consumption under Scenario 5C**

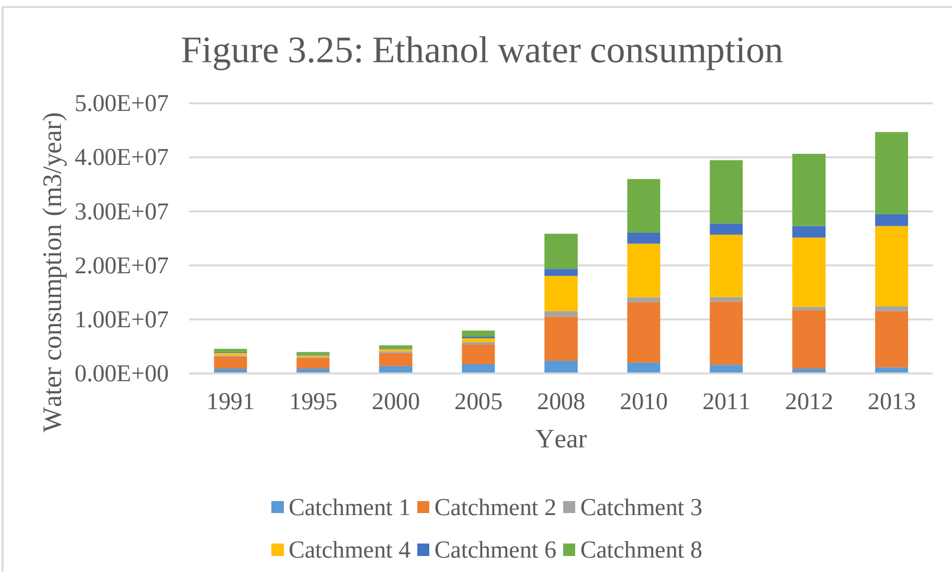



Figure 3.25: Water demand at ethanol processing sites for selected years over the study period for Scenario 5C.

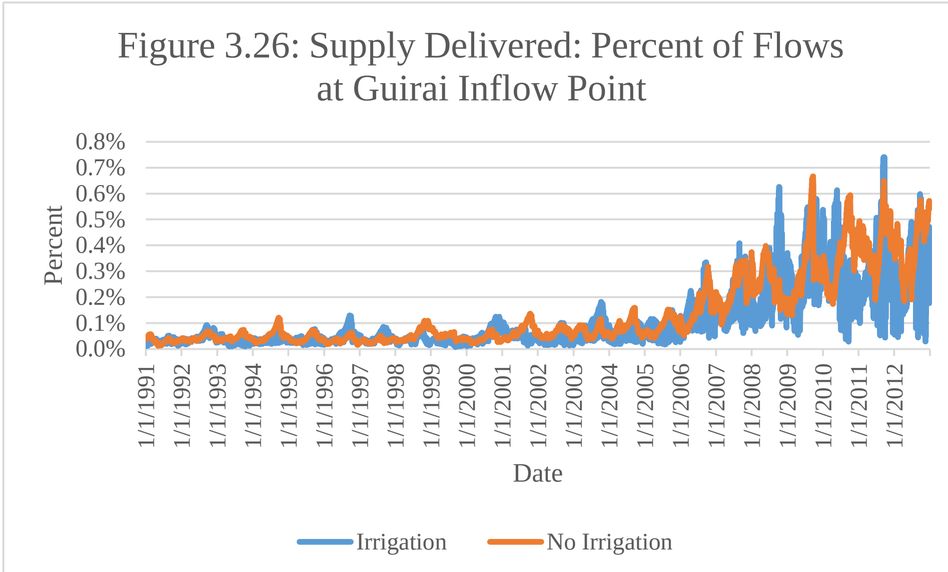



Figure 3.26: Ethanol consumption as a percent of baseline flows in at the Guirai inflow point for both irrigated (5C) and non-irrigated scenarios (4B) over the study period (1990 – 2013).

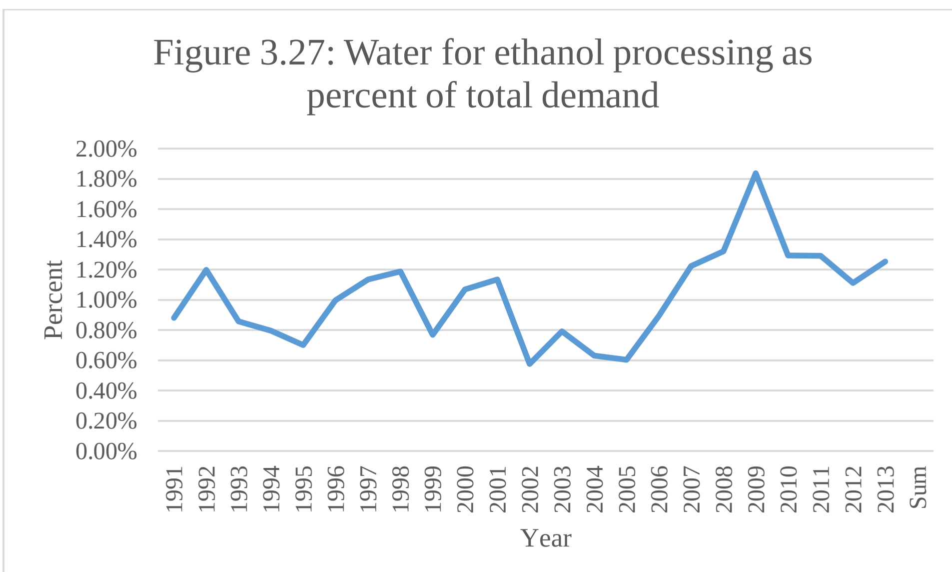



Figure 3.27: Yearly water demand delivery for ethanol as a percent of total delivered demand (ethanol processing plus irrigation).

Conversion of sugarcane to ethanol consumes a small volume of water relative to native stream flow volumes in the lower basin; on low-flow days this consumption represents 0.20 to 0.7 percent of baseline flows. At a maximum, water for ethanol processing makes up only 1.84 percent of total demand in the basin. Contrary to what was expected, more water was delivered for ethanol production in the non-irrigated scenario (Table 3.12).

| | Scenario 5C | Scenario 4B |
|---|---|---|
| Total water demand ($Mm^3$) met | 291 | 342 |

Table 3.12: Total water delivered over the study period for ethanol production for the irrigated scenario and non-irrigated scenario.

The supply going to ethanol production in the irrigated scenario is less because irrigation drastically impacts ethanol water supply reliability. Figure 3.28 shows the reliability of supply to ethanol production in the irrigated scenario as compared with the non-irrigated scenario from Chapter 2 (Scenario 4B). The reliability for ethanol processing is much lower for the irrigated scenario in the catchments with the highest sugarcane production. These catchments also happen to be at the top of the basin, so streamflow in the area is naturally much less than streamflow in the lower half of the basin. Catchment 1, 2, and 3 have low reliability, while Catchments 4, 6 and 8 have consistently high reliability, likely because these sites have higher flows. All demand sites in the WEAP model were assumed to have the same priority level, so in times of scarcity demand was cut back equally among all demand sites.

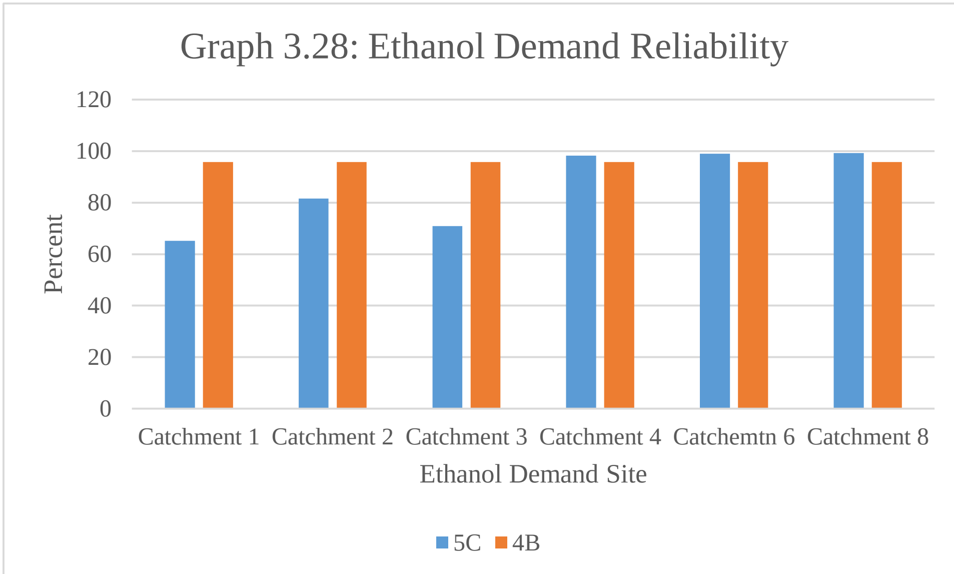



Figure 3.28: Ethanol demand reliability over the study period for both irrigated (5C) and non-irrigated ethanol scenario (4B).

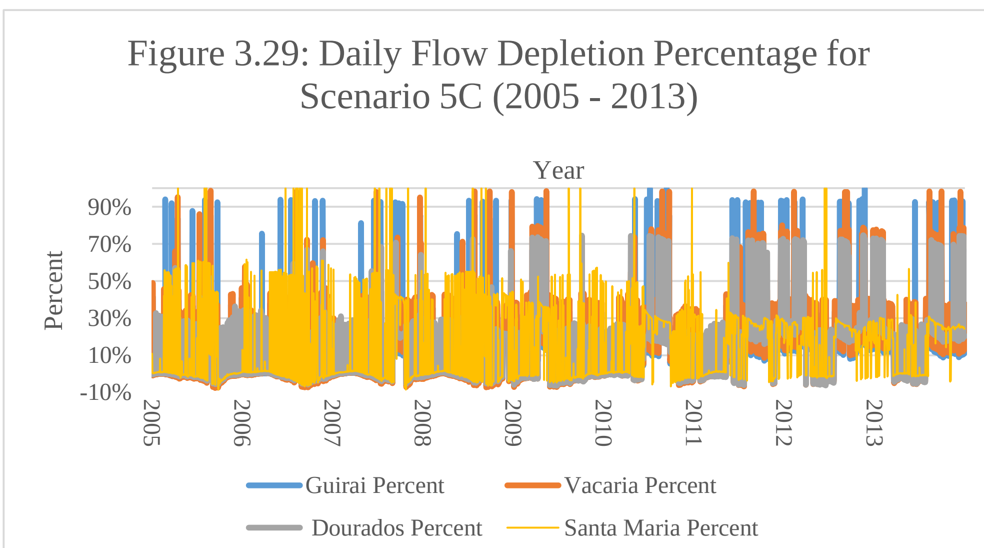



Figure 3.29: Daily percent flow reduction for scenario 5C. Negative values indicate an increase in flows.

## CONCLUSION

Sugarcane irrigation has a large impact on stream flows in the Ivinhema basin, especially as sugarcane cultivation increases. Sugarcane cultivation intensified dramatically throughout the Ivinhema from 2008 – 2013, significantly increasing the impact of irrigation and ethanol production on average monthly flows, which can be seen clearly in Figure 3.25. Flow reduction volumes compound as you move down the basin, but reduction in terms of percent of native flows is similar throughout (Graph 3.19 and 3.20). Over the study period, average monthly flow reduction percentage moves from less than five percent to over 30 percent during the dry season. While irrigation seems to have a large impact on flows for Scenario 5C, flow reduction from ethanol production is relatively small, with the maximum delivered volume over the study period only amounting to 0.7 percent.

The impact of irrigation on flow varies substantially throughout the year. Reduction is amplified during the dry winter season, when flows are low and irrigation volumes are large. The largest decreases occur in recent years during the winter season, during which the model predicts average seasonal flow depletions of greater than 30 percent (Figure 3.18) with some individual days reaching 100 percent (Graph 3.25).

Yield increases over the study period range from 7 – 14 percent, but hover around 7 percent during the last four years of the study period. These increases are higher than the yields found in Scenario 5A due to the increased reliability of irrigaton supply; however, they are still not ideal. While an economic analysis is needed to determine if flow reductions due to irrigation are justified by increased yields, the environmental and social impacts of such flow reductions are likely to outweigh the relatively small yield benefits found in this study.

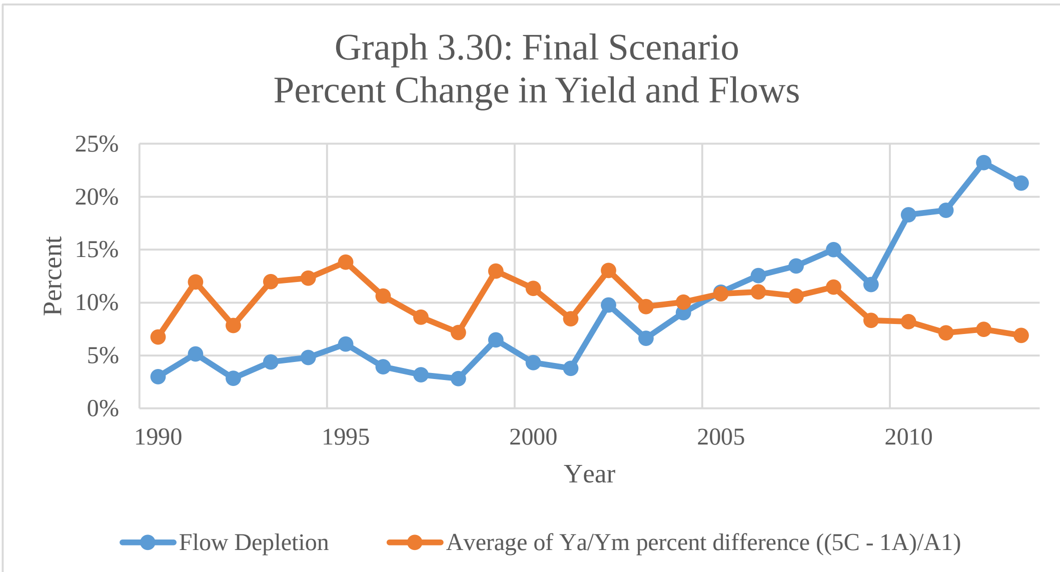



Figure 3.30: Yearly average yield increase and flow reduction percentages at Guirai inflow point for irrigated scenario with increased ethanol production.

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[41] Xavier et al., data.
[42] FAO (1979), 1.
[43] FAO (1979), 35.
[44] Steduto, Pasquale; Hsiao, Theodore C.; Fereres, Elias; Raes, Dirk. (2012) Yield response to water: FAO Irrigation and Drainage Paper No. 66. Food and Agriculture Organization of the United Nations. Rome, Italy. 7.
[45] Steduto et al (2012), 11.
[46] Steduto et al. (2012), 6.

# Appendix I

This appendix describes WEAP's Soil Moisture Method and the inputs used in the WEAP model. The Soil Moisture Method uses a one dimensional, 2-layer soil moisture accounting scheme for calculating runoff, evapotranspiration, interflow, and percolation within each catchment. The method calculates water balance using the following equation:

$$P = ET + Q + IF + P_d + SM \quad \text{Equation (Y)}$$

P = Effective Precipitation

ET = Evapotranspiration

Q = Runoff

IF = Interflow

$P_d$ = Percolation

SM = Soil Moisture

This section describes the calculation algorithms used by WEAP to calculate each of the above variables. Figure one is a schematic of these calculations sourced from the WEAP user guide. For all the below equations, j indicates the variable's value specific to a given land cover fraction for each catchment, while t represents time. $K_c$, as discussed in chapter 1 is entered into the model using daily values, and so are not included in this appendix. The parameters used in the Soil Moisture Method algorithm are defined in Table A, and their values for each catchments are displayed in Table B.

| | |
|---|---|
| Soil Water Capacity | Effective water holding capacity of the upper soil layer (unit: mm) |
| Deep Water Capacity | Effective water holding capacity of the lower, deep soil layer (unit: mm) |
| Runoff Resistance Factor | Used to control runoff response. Related to factors such as leaf area index and land slope. Runoff will decrease with higher values of RRF (range 0.1 - 10). |
| Root Zone Conductivity | Root zone conductivity rate at full saturation (Z1 = 1), partitioned according to preferred flow direction, between interflow and flow to the lower soil layer. |
| Deep Conductivity | Conductivity rate (length/time) of the deep layer at full saturation (Z2 = 1). Controls transmission of baseflow, which increases as this parameter increases. |
| Preferred Flow Direction | Preferred flow direction in the upper soil layer. 1.0 = 100 percent horizontal flow, 0 = 100 percent vertical flow. |
| Initial Z1 | Initial relative storage of the upper soil layer given as a percentage of the total effective storage of the root zone water capacity. |
| Initial Z2 | Initial relative storage of the lower soil layer given as a percentage of the total effective storage of the lower soil bucket. |

Table A: Definitions of the parameters used in WEAP's Soil Moisture Method.

| | Soil Water Capacity | Deep Water Capacity | Runoff Resistance Factor | Root Zone Conductivity | Deep Conductivity | Preferred Flow Direction | Initial Z1 | Initial Z2 |
|---|---|---|---|---|---|---|---|---|
| Catchment 1 | 1800 | 10000 | 3.5 | 76.8 | 1000 | 0.3 | 50 | 100 |
| Catchment 2 | 2000 | 10000 | 5 | 36 | 1000 | 0.36 | 30 | 100 |
| Catchment 3 | 1800 | 10000 | 6 | 36 | 400 | 0.3 | 30 | 100 |
| Catchment 4 | 1800 | 10000 | 4 | 31.2 | 1500 | 0.4 | 30 | 100 |
| Catchment 5 | 2500 | 10000 | 6 | 50.4 | 400 | 0.4 | 30 | 100 |
| Catchment 6 | 2000 | 10000 | 6 | 40.8 | 400 | 0.27 | 30 | 100 |
| Catchment 7 | 5000 | 10000 | 8 | 93.6 | 200 | 0.3 | 10 | 100 |
| Catchment 8 | 2000 | 10000 | 6 | 79.2 | 400 | 0.15 | 50 | 100 |
| Catchment 9 | 590 | 10000 | 6 | 84 | 400 | 0.25 | 50 | 100 |

Table B: Values for each of the Catchments inputs used in WEAP's Soil Moisture Method.

## SOIL MOISTURE METHOD CALCULATION ALGORITHMS

**Evapotranspiration**

$$ET(t) = ET_o(t)\ K_{c,j}(t) * (5z_{1,j} - 2z_{1,j}^2)/3$$

ET = Evapotranspiration

PET = $ET_o$

$z_1$ = relative storage given as a percentage of the total effective storage of the root zone water capacity.

**Runoff**

$$Q(t) = P(t)\ z_{1,j}^{RRFj}$$

Q = Runoff

P = Precipitation

I = Irrigation (if specified)

$z_1$ = relative storage given as a percentage of the total effective storage of the root zone water capacity.RRF = Runoff resistance factor

**Interflow**

$$IF = (C_{rz,j})(d_{,j})(z_{1,j}^2)$$

$C_{rz}$ = Root zone conductivity

d = Preferred flow direction (horizontal vs. vertical flow).

$z_1$ = relative storage given as a percentage of the total effective storage of the root zone water capacity.

**Percolation**

$$P_d = (C_{rz,j})(1 - d_j)(z_{1,j}^2)$$

$C_{rz}$ = Root zone conductivity

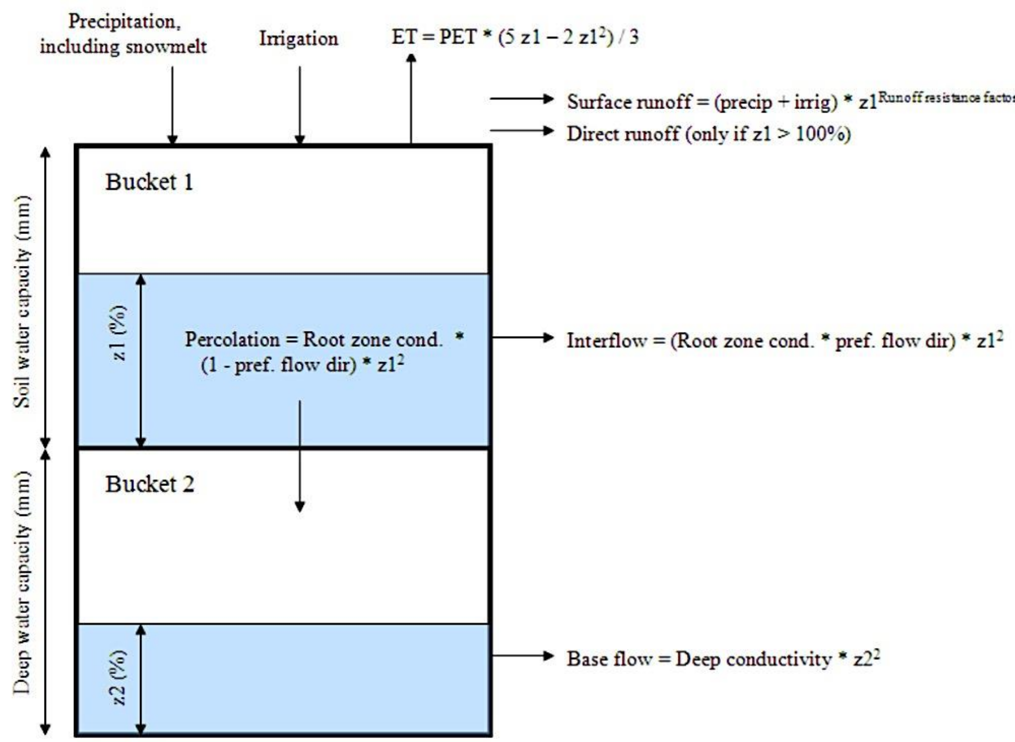
d = Preferred flow direction (horizontal vs. vertical flow).

$z_1$ = relative storage given as a percentage of the total effective storage of the root zone water capacity.

**Soil Moisture**

$$SM(t) = P(t) - ET(t) - Q(t) - IF - P_d$$

For a more detailed description of the algorithms used in this study see page 179 of WEAP's User Guide.



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