UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade de Engenharia Mecânica

THAYSE APARECIDA DOURADO HERNANDES

Assessment of the recent land use change associated with the sugarcane expansion dynamics and its consequences on water resources availability

Avaliação da mudança do uso da terra recente associada a dinâmica de expansão da cana-de-açúcar e seus efeitos sobre a disponibilidade dos recursos hídricos

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Orientador: Prof. Dr. Joaquim E. A. Seabra
Coorientador: Dr Fabio Vale Scarpare

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A Ata da defesa com as respectivas assinaturas dos membros encontra-se no processo de vida acadêmica do aluno.

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"We forget that the water cycle and the life cycle are one."

Jacques Cousteau

Resumo

Nos últimos anos, houve uma significativa expansão das áreas cultivadas com cana-de-açúcar, que ocorreu sob diferentes dinâmicas e escalas, substituindo as mais diversas classes de uso da terra. Visto que as mudanças do uso da terra (MUT) podem alterar os processos hidrológicos, esse crescimento tem levantado questionamentos sobre os efeitos da expansão da cana-de-açúcar na disponibilidade dos recursos hídricos. Uma revisão da literatura sobre o assunto, no Brasil, mostrou que, embora os resultados tenham apontando as altas taxas de evapotranspiração da cana-de-açúcar como um risco, os estudos foram, em sua maioria, qualitativos, mostrando mais direções e indícios do que evidências quantitativas. Sendo assim, o objetivo principal desta tese foi abordar as implicações da MUT associada à expansão da cana-de-açúcar na disponibilidade dos recursos hídricos, propondo um esquema de avaliação que auxiliasse na obtenção de resultados mais conclusivos. Foram escolhidas duas bacias brasileiras: uma em São Paulo (MM) e outra em Goiás (FMA) e as análises foram feitas através do modelo *Soil and Water Assessment Tool* (SWAT), que foi submetido a um extenso processo de calibração e, assim, validado para as duas bacias, para as quais também os componentes do balanço hídrico (CBH) foram avaliados de forma integrada. O uso de um modelo hidrológico semi-distribuído e a avaliação conjunta de seus CBH possibilitaram a obtenção de respostas mais conclusivas, ainda que qualitativas, sobre os impactos das MUT sobre os recursos hídricos nas bacias avaliadas. A estimativa da pegada hídrica permitiu, a nível de bacia, a avaliação dos impactos das MUT na eficiência do uso da água por culturas agrícolas. A cana-de-açúcar apresentou os menores valores de pegada hídrica entre as culturas analisadas, indicando um aumento na eficiência do uso de água por Mg produzido em áreas de expansão. Apesar de possíveis distorções regionais nos custos e preços, a abordagem econômica apresentou diferentes resultados com relação à eficiência do uso da água. Neste caso, a expansão da cana-de-açúcar em relação a outras culturas aumentou a eficiência do uso da água apenas em substituição a culturas de laranja e pastagem. Os impactos exclusivos da expansão da cana-de-açúcar foram avaliados através de cenários no SWAT. Considerando-se a expansão prevista para 2030, as análises indicam que nenhum efeito é esperado na vazão da bacia MM. Cenários com expansão mais intensa apresentaram aumentos na vazão para esta bacia, porém sem mudanças na vazão de referência. Na bacia FMA, a substituição das áreas com cultura anual e pastagem por cana-de-açúcar aumentou a regularidade da vazão, já que foram observados aumentos na estação seca e diminuições na estação chuvosa e, portanto, a vazão de referência

também foi positivamente impactada. Considerando que áreas de vegetação nativa e matas ciliares não sejam afetadas, a expansão da cana-de-açúcar favoreceu a disponibilidade de água nas duas bacias. Por fim, embora a disponibilidade de água e o balanço hídrico estejam intrinsecamente ligados às características locais de cada bacia, as simulações indicam que a substituição de culturas anuais e pastagens por cana-de-açúcar parece favorecer a regularidade do regime de escoamento.

Abstract

Sugarcane areas have expanded in Brazil, with different dynamics, scales and replacing different land uses. Given that land use changes can alter the partitioning of water and affect the hydrological processes, this expansion has raised questions about its effects on water availability. Many studies regard the high evapotranspiration rates in sugarcane areas as a risk to the water resources availability, but the works addressing sugarcane expansion effects on water resources were mostly qualitative and provided rather directions and indications than conclusive answers. Thus, the main objective of this thesis was to address the implications of land use change associated with sugarcane expansion to water resources availability, proposing an analytical framework that could provide reliable results on this subject. The work focused on two Brazilian basins, one in São Paulo (MM) and another in Goiás (FMA) state. The analyses were performed using the Soil and Water Assessment Tool (SWAT), which was subjected to an extensive calibration and validation process for these two basins, allowing the assessment of the main water balance components. The use of a semi-distributed hydrological model and the integrated assessment of its water balance components enabled attaining more conclusive (qualitative) answers about the impacts of the past land use changes in basins stream flows. Through the water footprint (WF) approach, the land use changes impacts on the crops water use efficiency were assessed in a basin level, even though impacts on basin water availability should consider water balance components beyond the evapotranspiration. Sugarcane presented smaller WF values among the assessed crops indicating that its expansion will increase water use efficiency per Mg produced without significant changes in evapotranspiration. Besides regional issues about costs and prices, the economic approach presented different results in terms of water use efficiency. In this case, sugarcane expansion over other crops only increased water use efficiency when displacing orange and pasture lands. Exclusive sugarcane expansion impacts were evaluated through dedicated expansion scenarios in SWAT. Considering the projected sugarcane expansion for 2030, the simulations indicate that no effects on the MM basin stream flow are expected. Scenarios with more significant sugarcane expansion would lead to increases in stream flow, but without changes in the reference flow in MM basin. In FMA basin, the displacement of annual crops and pasture by sugarcane regulated the stream flow as it increases flows in the dry season and decreases them in rainy season. Furthermore, the reference flow was also positively impacted. For both basins, results suggest that sugarcane expansion would favour the water availability, provided that riparian and native vegetation

areas are not affected. In general, although water availability and water balance are intrinsically linked to the local characteristics of each basin, it can be inferred that the replacement of annual crops and pasture lands with sugarcane tends to regulate the stream flow regime.

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1 INTRODUCTION

1.1 Context

Bioenergy production from different biomass sources has increased worldwide, making agricultural feedstocks for biofuels the main contributor for the general growth in agricultural demand in decades (USDA, 2015; Watkins Jr. et al., 2015). On the other hand, it is clear that large-scale production of biofuels will only be justified if their environmental and socioeconomic impacts are favourable, compared to other energy sources.

In terms of production, the most important biofuel in Brazil is sugarcane ethanol, which, according to the Brazilian Company of Supplying (CONAB, 2016), reached a production volume of 30.5 Million m^3 in the 2015/2016 season. Brazil is also the main sugarcane producer in the world, with 666 Million Mg and 8.7 Million ha of harvested area in the 2015/2016 season (CONAB, 2016). This vocation dates back to the last century, when the impact of the oil shock in the 1970's, and, more recently, the introduction of flex-fuel vehicles in early 2000's motivated the production of ethanol to enlarge its share in the energy matrix with the purpose of improving energy security (Scarpare, 2013; Walter et al., 2013).

In consequence of the increased demand for ethanol, sugarcane areas have expanded in Brazil, showing different dynamics, scales and replacing different land uses (Nassar et al., 2008; Adami et al., 2012; Hernandes et al., 2014; Scarpare et al., 2016a). In 2013, according to Canasat data (Rudorff et al., 2010), Paraná hydrographic region comprised 95% of the sugarcane areas and was also responsible for 95% of the Brazilian Centre-South sugarcane expansion from 2006 to 2013. As land use changes can alter the partitioning of water at the land surface by affecting hydrological processes such as evapotranspiration (ET), infiltration, groundwater recharge, base flow, and runoff, this recent expansion of sugarcane has raised concerns about its effects on water availability (Scanlon et al., 2005; Lin et al., 2007; Scarpare et al., 2016b).

Nevertheless, less attention has been given to the possible impacts of biofuel production on water resources, with a more significant number of works on issues concerning food security and greenhouse gas (GHG) emissions due to land use changes (LUC), including those derived from the indirect land use changes (ILUC) (Lobstein & Friel, 2008; Searchinger et al., 2008; Hochman et al., 2010; Zhang et al., 2010; Graham-Rowe, 2011; Chen & Khanna, 2012; Haberl et al., 2013; HLPE, 2013; Fargione et al., 2008; Popp et al., 2014).

Globally, Brazilian rivers hold 12% of the available fresh water in the planet (FAO, 2016). Despite the comfortable number, the resources are unevenly distributed with the major availability concentrated in Amazonia, Tocantins and Paraná basins (ANA, 2013). Furthermore, the Paraná basin, which holds the majority of sugarcane areas and is the most urbanized region in Brazil, has featured both water quality and quantity issues in the last years (ANA, 2013). Therefore, water resources will require increasingly attention regarding its use and management, especially in regions that present availability concerns and high water withdrawals.

Recent studies in Brazil concerning sugarcane expansion and water resources availability were focused mainly on the assessment of evapotranspiration, water deficit and irrigation needs and water footprint for sugarcane production and other crops (Hernandes et al., 2014; Vianna & Sentelhas, 2014; Chico et al., 2015; Fachinelli & Pereira, 2015; Silva et al., 2015; Watkins Jr. et al., 2015; Flach et al., 2016; Guarenghi & Walter, 2016; Scarpare et al., 2016a; Scarpare et al., 2016b). Many of these studies remarked the importance of the regionalized assessment when evaluating water resources, highlighting the significant impact of the scales and local conditions on this kind of evaluation. In some cases, the regional water availability was also assessed in attempt to link the changes in stream flow and/or quality parameters to the expansion of sugarcane, but with non-conclusive results.

Generally, the studies concluded that the sugarcane expansion that occurred in the last years might cause negative effects on water availability. On the other hand, due to its massive biomass production per unit of area, sugarcane crop shows the smallest water footprint values among cultivated crops in Brazil (Hernandes et al., 2014). The analyses usually connect the possible decrease in stream flow values to higher ET rates in sugarcane areas (Hernandes et al., 2014; Watkins Jr. et al., 2015; Guarenghi & Walter, 2016) in comparison to annual crops and pasture lands, which are the main land use/land cover types that have been replaced by sugarcane in the last years (Rudorff et al., 2010; Adami et al., 2012). But there were no quantitative evidences so far directly associating the sugarcane expansion and impacts on water resources availability, possibly because the evapotranspired water eventually returns somewhere through rainfall and will contribute to the stream flow, either in the same basin or elsewhere (Jackson et al., 2001; Lee et al., 2012; Spera et al., 2016). Furthermore, there are many factors in the water balance and hydrological processes that must also be considered, such as urbanization, precipitation regime, other land use changes, local conditions, etc. (Jackson et al., 2005; Scanlon et al., 2005; Folei et al., 2007; Stonestrom et al., 2009).

Despite the indications and directions drawn in the recent studies, there is still a lot of unanswered questions regarding the effects of sugarcane expansion on water resources. Therefore, a consistent impact assessment of land use change driven by the recent sugarcane expansion on water resources availability is essential to better understand the sugarcane expansion consequences. Moreover, the establishment of an analytical framework on this matter is mandatory to support the decision-making process about future policies and actions concerning a sustainable ethanol production in Brazil. An approach that combines the evaluation of hydrological processes and water balance components for different land use changes in sugarcane expansion process should lead to more conclusive answers to this question.

1.2 Objectives

The main objective of this work was to assess the implications of land use change associated with sugarcane expansion to water resources availability, proposing an analytical framework that could provide reliable results on this subject. The effects of sugarcane expansion were estimated for two Brazilian basins, considering the recent land use changes as well as possible scenarios for future ethanol production. One basin is in São Paulo state (Monte Mor-MM) on a traditional sugarcane area, and the other is in Goiás State (Fazenda Monte Alegre-FMA), which represents sugarcane expansion towards new areas in the Cerrado biome.

The specific objectives of the research were:

- Evaluate the performance of SWAT model in representing stream flow values for Brazilian basins.
- Study the past land use changes and sugarcane expansion dynamics, especially in MM and FMA basins.
- Perform a thorough SWAT calibration and validation process for the selected basins.

- Assess the impacts of sugarcane expansion on the water balance components in the selected basins.
- Evaluate the effects of land use changes on crop water use efficiency in the selected basins employing the Water Footprint approach.
- Assess the impacts of scenarios of sugarcane expansion over different land use classes on water resources availability.

Through these goals, this work sought to provide insights and appropriate tools to help in the general assessment of the consequences of sugarcane expansion on the water resources availability at the basin level in Brazil.

1.3 Thesis structure

The thesis is structured in six chapters. Chapter 1 is a general introduction, with the context, objectives and the description of the thesis structure. Chapter 2, entitled "**Brazilian Sugarcane Expansion and the Impacts on Water Resources: An Overview**", brings an overview of the impacts on water resources driven by sugarcane expansion in Brazil. Emphasis was given to the Center-South region where around 90% of sugarcane production occurs, including São Paulo State and its expansion dynamics towards new areas in the Cerrado biome. Studies concerning sugarcane expansion impacts on water resources availability, especially in Brazil, were also reviewed aiming to meet possible conclusions on this subject. The use of the Soil and Water Assessment Tool (SWAT) to assess the impacts due to land use change, at basin level, was also appraised in order to understand its potential and advantages for the assessment of sugarcane expansion impacts on the availability of water resources in Brazil.

Chapter 3, **"Assessment of the recent land use change dynamics related to sugarcane expansion and the associated effects on water resources availability for two Brazilian basins"**, assessed the Brazilian sugarcane expansion dynamics in two basins (FMA and MM) within different regions and its implications to the local water availability. The analysis was based on the recent land use change dynamics of the two basins over a ten-year period. In face of the features described in Chapter 2, SWAT was selected as the main modelling tool for the development of the study. However, a specific goal of this chapter was to mitigate the issues concerning SWAT crop growth and water balance through a comprehensive model calibration and validation process applied for both basins. Besides the assessment of SWAT model performance in representing the stream flow for the two basins by calibration and validation processes, this chapter also brings an evaluation of evapotranspiration and crop yield values given by the model through a comparison with soft data. The main components of the validated SWAT water balance (precipitation, evapotranspiration, water yield and stream flow) were quantified. Finally, conclusions about the model performance and its effectiveness in evaluating the impacts of sugarcane expansion in water availability, as well as the advantages and constraints from this are presented.

In Chapter 4, **"Assessment of the land use change effects on crop water use efficiency for two Brazilian basins",** the water footprint technique was used in the assessment of land use change effects on water use efficiency of crops, in two basins, MM and FMA. The input data to estimate the water footprint were from the previously calibrated and validated SWAT. Besides the usual water footprint indicator (WF), it was proposed an economic water footprint (EWF) based on the operating profit obtained by farmers with each agricultural product. There are conclusions about WF and EWF, evincing the link between water use efficiency results and the approach (economic or production) applied in the estimations. Both WF and EWF were useful in the evaluation of crop water use efficiency associated to land use changes in a basin level. Water availability, however, depends on other water balance components beyond evapotranspiration.

In Chapter 5, **"Assessment of impacts on basin stream flow associated with the land use change driven by medium-term sugarcane expansion scenarios in Brazil"**, the focus is on the possible impacts in the future, with the assessment of the effects of projected land use changes driven by sugarcane expansion on the stream flows for MM and FMA basins. The study considered the estimated increase of ethanol production towards 2030, as well as exploratory scenarios with more intense sugarcane expansion. The SWAT model was employed in the quantitative assessment of sugarcane expansion impacts on MM and FMA water yields, evapotranspiration, stream flow and reference flow. Even though the estimated quantitative impacts were intrinsically linked to the basins, more general conclusions about the impacts of sugarcane expansion were also drawn founded on the evidences of the modelling exercise of this study.

Lastly, Chapter 6 presents the final remarks of this thesis work, discussing the attained objectives, results, the answers to the main questions raised and the major difficulties found in the course of the study, as well as the suggestions for future work.

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2 BRAZILIAN SUGARCANE EXPANSION AND THE IMPACTS ON WATER RESOURCES: AN OVERVIEW[1]

Abstract: Brazil is the primary producer of sugarcane and the second largest producer of ethanol worldwide. The recent land use change driven by sugarcane expansion has raised concerns about its effects on water availability, since it can alter the partitioning of water at the land surface by affecting hydrological processes. This study aimed to bring an overview of the impacts on water resources driven by sugarcane expansion in Brazil. Brazilian context on water resources and sugarcane expansion are initially presented and, then, studies concerning sugarcane expansion impacts on water resources in Brazil are reviewed. The use of the Soil and Water Assessment Tool (SWAT) to assess impacts due to land use change at the basin level were also appraised to understand its potential in the assessment of sugarcane expansion impacts on the availability of water resources in Brazil. Expansion has occurred mostly over pasture lands and annual crops, towards São Paulo state and Cerrado areas and in Paraná hydrographic region, which presents significant quality and quantity issues. New research and public policies concerning water resources management, especially regarding irrigation, are mandatory in these regions to assure water supply. Sugarcane expansion and its impacts on water resources in Brazil were generally addressed in a qualitative way, indicating more directions than effective and conclusive responses. Reliable and more conclusive answers are possibly linked to assessments at basin level, considering specific classes of land uses in sugarcane expansion and addressing all hydrological processes in basin's water balance. SWAT appears to generate reliable results in the assessment of land use change impacts on water resources. Besides the available documentation and the open source code, another advantage of this model lies on the capacity of integrating different water balance components at the same time and space, enabling a combined assessment of the effects of land use changes on the evapotranspiration, crop yield, stream flow, precipitation, runoff, water yield, among others.

Keywords: land use change, sugarcane ethanol, water balance, water availability, hydrological modelling

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2.1 General context

Water resources and energy systems are intrinsically linked, especially in the case of energy from biomass, with possible implications on water availability as well as on water quality (USDA, 2015). Thus, integration of bioenergy crops production and water resources management is essential for the effective sustainability of biofuels since large-scale production of biofuels will only be justified if their environmental and socioeconomic impacts are favourable, compared to other energy sources (OECD, 2004; Sims et al., 2007; Diop et al., 2013).

Sugarcane ethanol is the major liquid biofuel produced and used in Brazil (Walter et al., 2013). Currently, Brazil is the main producer of sugarcane worldwide, with 666 Million Mg produced in the 2015/2016 season (50% used in ethanol production), and the second largest producer of ethanol, with 30.5 Million m^3 (CONAB, 2016), i.e., 29% of global production in 2015 (REN21, 2016). Local conditions for ethanol production are comparatively favourable taking into account factors such as land availability and climate conditions, long-term experience, existing commercial technology, and size of the domestic market (Walter et al., 2011; Scarpare, 2013; Walter et al., 2013).

In Brazil, public policies and the regulatory framework to support ethanol use as a fuel were mostly driven by two main forces: (1) necessity to reduce oil imports and the associated expenditure of strong currencies, and (2) the desire to improve the competitiveness of the sugarcane sector by supporting the production of an alternative product to sugar.

There were basically two significant periods of increases in ethanol production and use, the first in 1975 with the launching of the National Alcohol Program (Proalcool) where the production and use of ethanol fuel was regulated and strengthened (Walter et al., 2011; Walter et al., 2013). After the second oil shock in 1979, the Government pressured automakers to produce cars running on neat hydrous ethanol, and ethanol production increased steadily to 11.7 billion liters in 1985 (MAPA, 2009). The second period started in 2003 with the introduction of the Flex Fuel Vehicles (FFVs) into the market, which rapidly dominated buyers' preferences. Currently, more than 90% of the vehicles produced in Brazil are FFVs (Figure 2.1) (ANFAVEA, 2015).

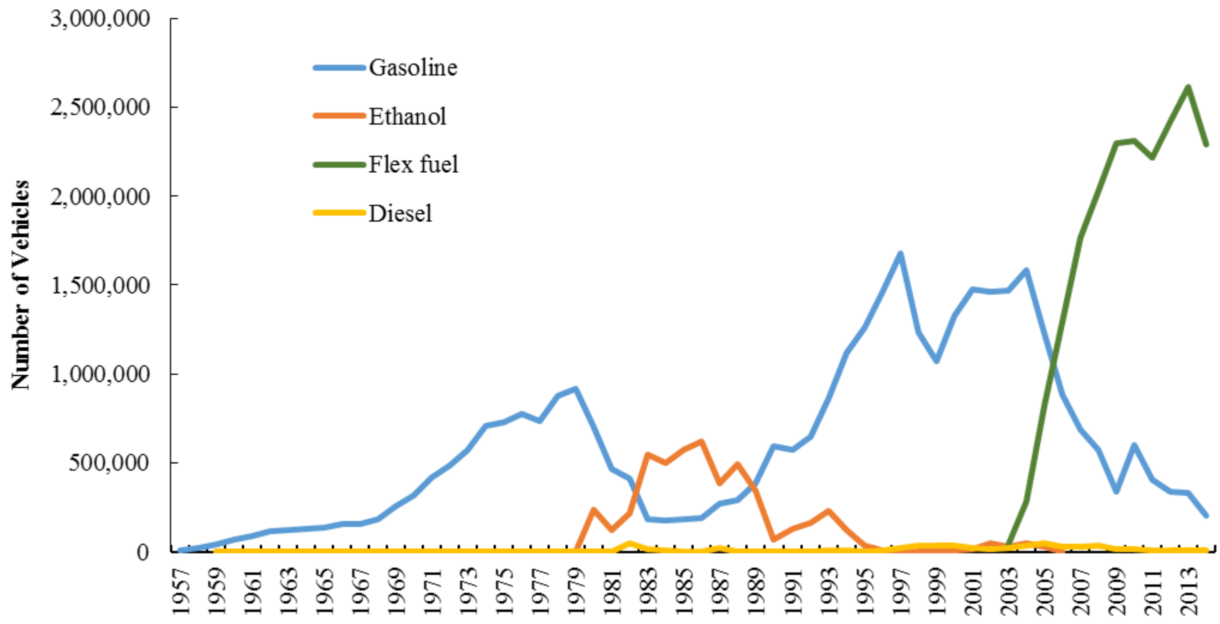

Figure 2.1 Number of Brazilian vehicles produced over time by fuel type (Source: ANFAVEA, 2015)

In general, the increase in ethanol demand caused an expansion of sugarcane production, which occurred based on productivity increase and, specially, expansion of the production areas, which arose over different dynamics, scales and land uses (Nassar et al., 2008; Adami et al., 2012; Hernandes et al., 2014; Scarpare et al., 2016a). Thus, the land use change driven by sugarcane expansion has raised concerns about its effects on water availability, since it can alter the partitioning of water at the land surface by affecting hydrological processes such as evapotranspiration (ET), infiltration, groundwater recharge, base flow, and runoff (Scanlon et al., 2005; Lin et al., 2007; Scarpare et al., 2016b).

Biofuel policies aimed at reducing GHG emissions are a step in the right direction, but many policy makers should also consider the water resources issues in the rule-making process to ensure that these policies do not drive changes that will put under stress the water supply (Fingerman et al., 2010). Since biomass energy are more water-intensive, about 70 to 400 times than other energy carriers such as fossil fuels, wind, and solar compared in energy-basis (Gerben-Leenes et al. 2008), this issue could be the ‘Achilles heel’ of biofuel production. In this sense, calculated or reported water demand for biofuel production should be incorporated into regulatory frameworks with incentives for implementing best management practices.

As more than 90% of the water needed for biofuel production (Fraiture and Berndes, 2009; Fingerman et al. 2010; Hernandes et al., 2014) is used during agricultural phase for feedstock cultivation, this study analysed peer-reviewed publications and grey literature that report the context of water resources availability and use in Brazil and the growth of Brazilian arable land use devoted to sugarcane. Emphasis was given to the Center-South region, where around 90% of sugarcane production occurs. In this sense, special attention was given to describe the sugarcane land occupation in those traditional areas, located mainly in São Paulo State, and its expansion dynamics towards new areas in the Cerrado biome. Studies concerning sugarcane expansion impacts on water resources availability, especially in Brazil, were also reviewed. The use of the Soil and Water Assessment Tool (SWAT) in the assessment of impacts due to land use change, in a basin level, were also appraised in order to understand its potential and advantages in the assessment of sugarcane expansion impacts on the availability of water resources in Brazil.

2.2 Water resources in Brazil

Brazil holds a comfortable position in terms of global fresh water availability; nevertheless, water resources are unevenly distributed across regions and users (OECD, 2015). According to the “2013 Brazilian Water Resources Situation Report” (ANA, 2013), the Brazilian territory can be divided into twelve hydrographic regions (HRs) (Figure 2.2).

Figure 2.2 Brazilian hydrographic regions. (Adapted from ANA, 2015).

The Amazônica (3), São Francisco (8) and Atlântico Leste (9) HRs together account for 93% of Brazilian surface water availability, while they represent only 20% of total water demand. In contrast, Atlântico Sul (11), Atlântico Sudeste (6) and Paraná (7) HRs account for 3.4% of total surface water availability while representing about 53% of Brazilian water demand (Table 2.1). Therefore, there is a spatial disconnection between water supply and water demand.

In the Brazilian territory, annual precipitation ranges from 500 to 3000 mm year^{-1}, with an average of 1760 mm year^{-1} (ANA, 2013). Lower mean annual precipitation usually occurs in São Francisco (8), Atlântico Leste (9), Atlântico Nordeste Oriental (5) and Parnaíba (2) HRs, in the Northeast portion of the country, while in the remaining HRs at least 1600 mm is normally expected (ANA, 2013).

Table 2.1 Brazilian hydrographic regions (HR): characterization and water use distribution

HR	Area (10^3 ha)	Water Availability ($m^3 s^{-1}$)	Population (Million)	Water Withdrawal ($m^3 s^{-1}$)	--------------------Water Use (%) --------------------					Irrigated Area (ha)
					Urban	Rural	Animal	Irrigation	Industrial	
1	27,430	782	2.2	30	17	1	41	32	9	72,281
2	28,680	379	4.2	51	16	3	5	73	3	69,587
3	386,995	73,748	9.7	79	33	3	32	20	12	149,309
4	92,192	565	3.9	155	6	1	5	82	6	455,601
5	21,463	91	24.1	262	23	2	2	62	11	553,351
6	33,306	647	13.4	295	12	1	2	66	19	720,875
7	63,858	5,956	61.3	736	24	1	5	42	28	2,106,232
8	18,755	1,886	14.3	279	11	1	4	77	7	626,941
9	36,345	305	15.1	112	31	4	8	47	10	355,488
10	27,430	320	6.2	24	48	12	18	15	7	41,468
11	87,987	1,145	28.2	214	49	1	3	27	20	377,503
12	38,816	5,447	8.6	136	13	1	16	62	8	268,493

Paraguai; 2 - Parnaíba; 3 – Amazônica; 4 - Uruguai; 5 – Atlântico Nordeste Oriental; 6 – Atlântico Sudeste; 7 – Paraná; 8 - São Franscisco; 9 - Atlântico Leste; 10 - Atlântico Nordeste Ocidental; 11 - Atlântico Sul; 12 - Tocantins-Araguaia. Source: ANA, 2013; Data available until December, 2012.

In general, water withdrawals have increased 25% in all Brazilian HRs from 2006 to 2010. The major increases occurred in Tocantins-Araguaia (12) (73%) and São Francisco (8) (54%) HRs, mainly associated to increases in irrigated lands. In the Atlântico Nordeste Oriental (5) and Atlântico Leste (9) HRs, water quality issues are generally related to the low water availability (droughts) and the limited assimilative capacity of rivers for water pollutants.

Paraná (7) HR, the most industrialized and urbanized region of the country, had the third relative growth (49%). Furthermore, this region presented the absolute largest water withdrawal among the twelve HRs, with water demand raising from 493 to 736 $m^3 s^{-1}$ (ANA, 2013). In this case, besides demand for irrigation, the main concerns regarding water quantity and quality are also related to densely populated urban areas, mainly due to the release of sewage and untreated effluents into water bodies. However, areas with a history of poor water quality, such as the Tietê basin (in Paraná HR) have shown a significant improvement in water quality indicators along the recent years, due to implementation of sanitation projects in these regions (ANA, 2013).

Because of relatively high precipitation rates, irrigation is not extensively used in Brazilian croplands. Only 10% of Brazilian irrigation potential in terms of cropland area, with an estimated 29 million ha (Christofidis, 2002; Cristofidis, 2003; Cristofidis, 2013), is effectively explored (IBGE, 2006). Yet, in seven out of the twelve HRs the water withdrawal for irrigation purposes is above 50% of the current total water demand (ANA, 2013). Moreover, the total area equipped for irrigation increased from 2.3% in 1970 to 8.3% in 2012 (Werneck et al., 1999; ANA, 2003; Cristofidis, 2003; Cristofidis, 2013), with growth expectations for the coming years. The great demand associated to an expected increase in irrigated croplands raise concerns about water availability, especially in regions with water scarcity. Therefore, irrigation practices and management emerge as an important issue to be explored in the coming years.

Thus, despite the apparent abundance of water resources in Brazil, the uneven distribution, problems related to sewage and untreated effluents and the increasing irrigation areas highlight the need for effective public policies and responsible management of the water resources, in order to preserve water quality and ensure water supply.

2.3 Sugarcane expansion and its effects on water resources

Land use for sugarcane and its expansion is part of Brazilian history and can be summarized in three main phases: i) sugarcane introduction and expansion in the Northeast dating back to the period shortly after Portuguese colonization during the 17th century; ii) implementation of the Brazilian National Alcohol Program (1975) and iii) expansion towards the Central region motivated primarily by increasing domestic demand for ethanol as a result of substantial increases in the flex-fuel vehicle fleet in the 2000´s. The focus of this work was on the third phase, which resulted in an expansion of sugarcane harvested area from 4.8 to 9.6 Mha (1990 – 2015; Figure 2.3). Expansion occurred mostly in São Paulo State; however, significant expansion also occurred in the Cerrado[2] biome in Minas Gerais, Goiás, Mato Grasso and Mato Grosso do Sul States (Figure 2.4).

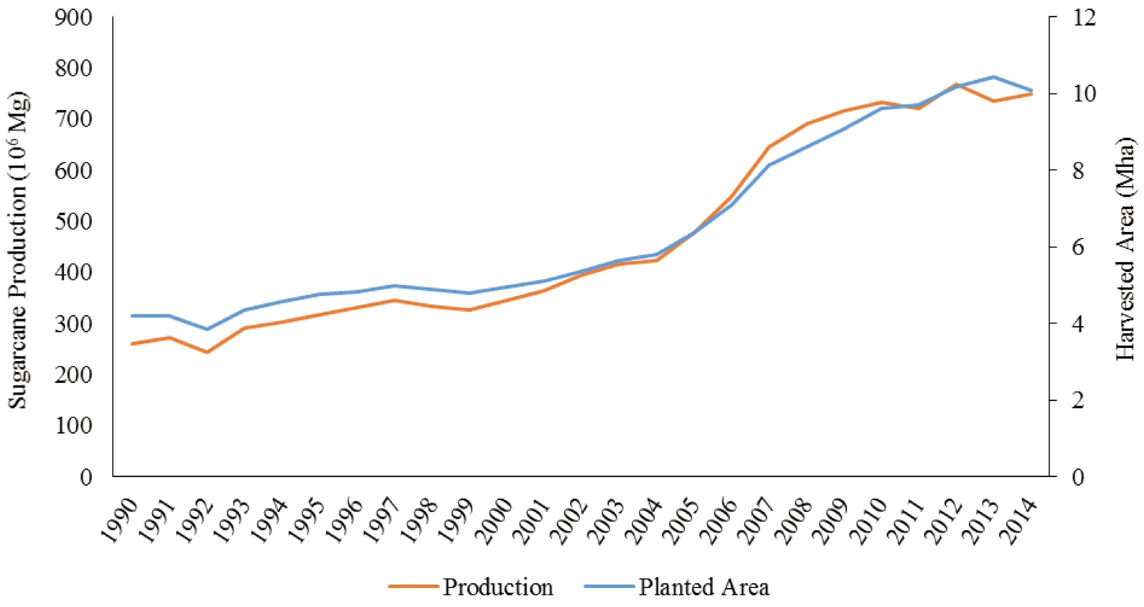

Figure 2.3 Evolution of sugarcane production and harvested area from 1990 to 2015. (Source: IBGE, 2016)

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2 *Cerrado* is the second largest Biome in South America, occupying about 22% of the Brazilian territory. Due to its biodiversity, Cerrado is recognized as the richest savannah in the world presenting innumerous species of plants and animals.

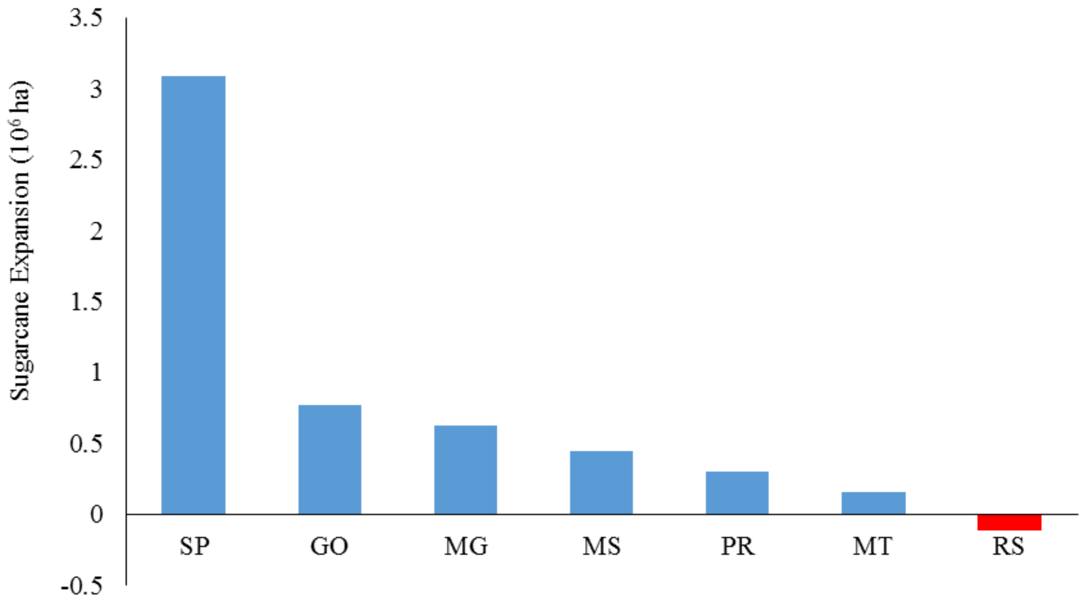

Figure 2.4 Absolute expansion of sugarcane area from 2000 to 2015. SP – São Paulo, GO – Goiás, MG – Minas Gerais, PR – Paraná and MS – Mato Grosso do Sul – RS – Remaining States from Brazil. (Source: IBGE, 2016)

Besides sugarcane harvested area (increase of 136% from 1990 to 2015), sugarcane production also increased by 185% from 263 to 749 million Mg due to improved agricultural techniques and important genetic breeding programs promoted by both Brazilian Government and private sector.

In the Centre-South region, which accounts for about 90% of Brazilian sugarcane production, around 70% of sugarcane expansion displaced pasture, and 25% displaced annual crops, while expansion over native vegetation corresponded to less than 1% of the expanded area. These results are based on analysis of MODIS satellite data from 2000 – 2010 (Adami et al., 2012). Similar results were found from the analysis of sugarcane expansion in São Paulo State, based on Landsat satellite data from 2007 – 2008, with about 57% of expansion over pasture, and 40% over annual crops. Other classes of land use (citrus, forest or natural vegetation, and reforestation) converted into sugarcane fields represented 3.2% (Rudorff et al., 2010).

In general, changes in land use can alter the partitioning of water at the land surface by affecting canopy interception, evapotranspiration (ET), infiltration, groundwater recharge, base flow, and runoff (Scanlon et al., 2005; Lin et al., 2007). As the majority of sugarcane plantations in Brazil are rainfed, the parameter most frequently related to possible impacts on water resources availability due to sugarcane land use and expansion is the magnitude of the sugarcane ET rate (Pereira et al., 2013; Hernandes et al., 2014; Filoso et al., 2015; Watkins Jr. et al., 2015; Guarenghi & Walter, 2016).

In fact, the estimations for sugarcane ET during the development cycle in Brazilian states is about 30% higher than that for pasture, the primary crop that sugarcane has replaced (Hernandes et al., 2014). Similarly, sugarcane ET for the whole development cycle is about 70% higher than that for annual crops (Hernandes et al., 2014), which has been pointed out as a possible reason to harm the water budget when expansion occurs over annual crops (Pereira et al., 2013; Hernandes et al., 2014; Filoso et al., 2015; Watkins Jr. et al., 2015; Guarenghi & Walter, 2016).

On the other hand, the duration of the development cycles in annual crops is about 3 to 4 months, while in sugarcane it takes about 12 to 18 months to complete the cycle. Considering that in Brazil 2 to 3 annual crop seasons were produced in the same area (IBGE, 2016), the actual annual ET differences between sugarcane and annual crops are certainly lower. Moreover, another study in an important agricultural frontier in Cerrado area (Spera et al., 2016) showed that displacing natural vegetation with annual crops may harm the precipitation regime, since the lower volume of water evapotranspired diminishes the amount of water recycled to the atmosphere, affecting the water regime. In this case, the double cropping practice was indicated in order to mitigate problems with low ET volumes.

Borglin et al. (2013) evaluated the effects of sugarcane expansion on surface runoff and evapotranspiration in the Rio Grande basin in Brazil using a large scale hydrological model (MGB-IPH – Collischonn et al., 2007), and the results from simulations showed a reduction of 20% on surface runoff and an increase of 9.0% in evapotranspiration rate. The author concluded that the model’s results for sugarcane expansion were very dependent on the previous land use, although the expansion scenarios were not clear since sugarcane expanded over different percentages of native vegetation, crops and pasture at the same time. Therefore, impacts of sugarcane expansion on surface runoff and evapotranspiration were not conclusive as there were no link to land uses separately.

Based on modeling results, other authors suggest that temperature and ET in sugarcane areas were closer to those of natural vegetation than to alternative crop/pasture mosaics (Loarie et al., 2011; Georgescu et al., 2013). Consequently, provided that the native vegetation is maintained, water availability in regions with sugarcane croplands instead of annual crops or pasture lands may lead to a more regulated hydrologic cycle as sugarcane water balance components apparently are similar to those from forest.

The water footprint is also a much discussed topic in recent works involving sugarcane crop and water resources. Sugarcane is a highly productive crop, presenting the highest above ground yield among the main crops produced in Brazil. It has therefore the lowest water footprint when compared to other crops, highlighting the high water use efficiency in terms of biomass production (Hernandes et al., 2014; Scarpare et al., 2016a).

Comparing global pasture lands for beef production to sugar from sugarcane, the latter have also a water footprint, in cubic meters per kilogram of product, ten times smaller than the values for the former (Hoekstra, 2016). Calculated water footprints of crops and biofuels in the Brazilian Center-South showed that values for soybean is about ten times larger than the water footprint for sugarcane, being 140 m^3 Mg^{-1} for sugarcane and 1400 m^3 Mg^{-1} for soybean (Hernandes et al., 2014).

On the other hand, comparing biofuels, biodiesel from soybean uses 40 liters of water per mega Joule (MJ) produced, while for sugarcane ethanol the water footprint is 78 L MJ^{-1} (Hernandes et al., 2014). Lower values for soybean biodiesel were due to the mass based allocation, which attributed only 18% (percentage of oil in the mass composition of the grains) of the total water use in soybean crop to biodiesel in the water footprint estimation.

Irrigation is the main agricultural practice responsible for land use intensification; hence, it has a great potential to reduce pressure on land use. With full irrigation, it is possible to significantly increase sugarcane yield, and also decrease water footprint (Hernandes et al., 2014; Fachinelli & Pereira, 2015; Scarpare et al, 2016a; Scarpare et al., 2016b). Results based on crop growth models in a traditional sugarcane producing area in São Paulo state (Tietê/Jacaré watershed) showed a potential increase of 47% in the sugarcane yield using drip subsurface irrigation (Scarpare et al., 2016a). In another study, considering an expansion region (Paranaíba basin) and using different irrigation methods according to the water deficit, the estimated potential for increasing sugarcane yield was 108% (Scarpare et al., 2016b).

Therefore, the use of efficient irrigation systems (with lower water losses) associated with appropriate irrigation management should improve the water use efficiency for sugarcane. Meanwhile, the use of efficient irrigation system, such as drip irrigation, correspond to only 0.7% of the area equipped for sugarcane irrigation (IBGE, 2006) (Figure 2.5). However, water availability must be considered, i.e. irrigation of sugarcane for energy purposes must be considered as a management practice only in basins without water supply problems.

Another possible impact linked to sugarcane expansion and water resources is soil erosion. In sugarcane fields, soil erosion is generally lower than that for areas of conventional agricultural crops, such as corn and soybeans. This occurs because sugarcane canopy rapidly closes – thus providing soil cover – and soil disturbance is limited to the replanting period (once every five or six years) (Pereira et al., 2013).

However, and due to environmental, agronomic and economic reasons, pre-harvest burning has been replaced by mechanical green harvesting in most of the sugarcane cropping areas. This practice increased the machinery traffic in the field, promoting soil compaction and, consequently, reducing water infiltration, thereby resulting in increased runoff and erosion problems (Roque et al., 2010; Roque et al., 2011). On the other hand, the trash (cane tops and leaves) left on the field, also a result from the mechanical green harvesting, helps to maintain soil moisture and greatly reduce soil erosion (Leal et al., 2013; Carvalho et al., 2016). So, there is no consensus about the effects of new practices in sugarcane harvest on soil erosion. Quantitative assessments of the effects of soil compaction and soil cover by sugarcane trash on soil erosion are therefore mandatory to elucidate this question.

In general, studies involving sugarcane expansion and water resources in Brazil addressed the impacts in a qualitative way, giving rather directions than effective and conclusive answers. Results about evapotranspiration are controversial, since the high values of sugarcane ET were considered harmful to the water balance in some studies (Pereira et al., 2013; Hernandes et al., 2014; Filoso et al., 2015; Watkins Jr. et al., 2015; Guarenghi & Walter, 2016) and beneficial in others (Loarie et al., 2011; Georgescu et al., 2013; Spera et al., 2016). Possible impacts related to irrigation, runoff and soil erosion were also inconclusive. Inconsistencies may be related to the fact that the impact evaluations were made considering water balance components individually.

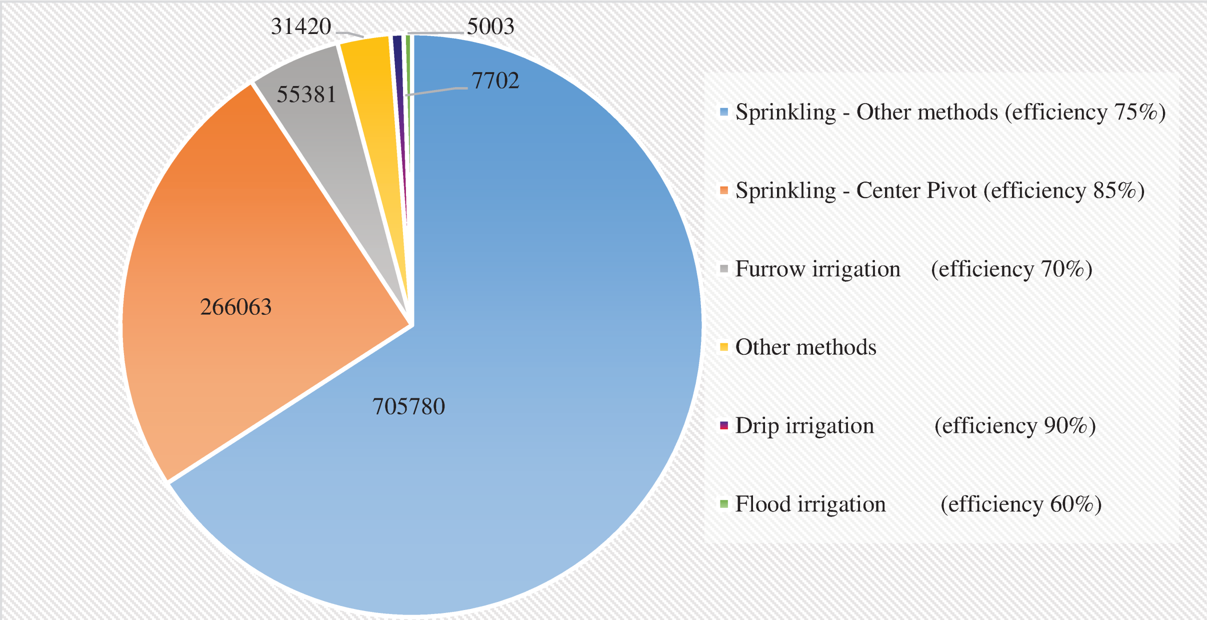

Figure 2.5. Brazilian sugarcane area equipped with different irrigation systems and their efficiencies. Area is in ha. (Source: IBGE, 2006)

There are some studies at the watershed level in the literature (Hernandes et al., 2014; Fachinelli & Pereira, 2015; Guarenghi & Walter, 2016; Scarpare et al, 2016a, Scarpare et al., 2016b), but they have not considered basin's hydrological processes and their effects on the water balance. One of them evaluated hydrological processes (Borglin et al., 2013), though without specifying the effects associated to different land use changes and considering only surface runoff and evapotranspiration, which do not give the overall picture of the effects on basins water availability.

In sum, reliable and conclusive answers concerning sugarcane expansion and water resources availability appear to be a function of watershed assessments, considering separated classes of land use in sugarcane expansion and addressing all hydrological processes in basin's water balance components, such as surface and subsurface runoff, evapotranspiration, stream flow and the management effects on it as well.

2.4 Land use change impacts assessment at basin scale using Soil and Water Assessment Tool (SWAT)

Hydrological models are widely used in water resources planning and management. These models can provide a robust scientific framework for analyzing the dynamics of these resources in watersheds and provide reliable information on system behavior (Jha, 2011). Different types of models are used to explore land use changes, such as stochastic models, optimization models, dynamic process-based simulation models and empirical models (Scanlon et al., 2005).

Multivariate statistical tools are also commonly employed for the comparison of different land uses and their impacts on water resources. However, one problem with the application of conventional statistical methods in the relationship between land use and hydrological consequences is the multicollinearity, causing undesirable effects on the regression coefficients estimations and on the general applicability of the model (Yan et al., 2013).

In recent years, many hydrological models at watershed scale have been developed. The technical integration of land use information in these models is based on maps or images through remote sensing tools. Geographic Information Systems (GIS) are often used, not only as an interface to spatial data, but also as a general user interface, while contemplating time series and static parameters (Hörmann et al., 2005).

The Environmental Policy Integrated Climate (EPIC) (Williams et al., 1984) was one of the first field-scale ecohydrological models. The EPIC has been widely used for the integration of land use change into mesoscale models because of its well-documented set of parameters. An EPIC application can be found in the Soil & Water Assessment Tool (SWAT) (Arnold et al, 2012), with the land use scheme in this model being a simplified version of the EPIC. SWAT has a complex software system that attempts to do all the simulations in an integrated way in a single model.

In addition, the TOPMODEL (Beven et al., 1995), also a mesoscale model, works on a component-based approach and is not a single model structure but a set of conceptual tools that can be used to simulate hydrological processes in a relatively simple way (Beven, 1997). However, this model does not have detailed internal options for assessing land use change and is more suitable for basins with shallow soils and moderate topography, which do not present excessive long periods of drought (Williams et al., 1984).

Other distributed physical-based hydrological models have also been refined and calibrated to simulate the effect of land-use change on water resources, such as MIKE SHE, VIC model (Variable Infiltration Capacity model), NRM3 Streamflow, Agricultural Non-Point Source Pollution Model (AGNPS), CASC2D hydrological and sediment model, the Large Basins Model (MGB / IPH), among others. However, in all these models several sets of local input data associated with the climate, soil and plant physiology are required, which is the main limitation for the reliable use of them, especially with regard to climate and stream flow historical data and to the definition of field conditions (Mello et al., 2008; Immerzeel & Droogers, 2008; Yan et al., 2013; Bormann et al., 2007).

SWAT is a distributed model based on physical processes, designed to predict the impact of management practices on water resources in river basins over long periods of time (Neitsch et al., 2011; Arnold et al., 2012). SWAT was widely used in the study of flow and sediment production in basins in different regions of the world. The model can be used in the analysis of small or large basins, which are subdivided into hydrological response units (HRUs) (Neitsch et al., 2011; Gassman et al., 2007; Arnold et al., 2012). The SWAT, coupled with a geographic information system, can integrate various spatial environmental data, including information on soil, soil cover, climate and topography (Yan et al., 2013; Bormann et al., 2007).

SWAT is an open source model with an available and well based theoretical documentation. It is also modifiable as your source code is available at the model website[3]. Besides the basin hydrological processes, the model has also an integrated crop growth module, which allows the evaluation of crop management practices (mulching, irrigation and soil tillage), crop yield and crop water balance (Neitsch et al., 2011; Arnold et al., 2012).

Sub-basins and drainage channels can be created from the digital terrain elevation model (DEM). The runoff is calculated for each HRU, which are unique combinations of land use and cover, soil type and slope, thus promoting a better description of the water balance in the basin (Eq. 1). The total stream flow is given by Equation 2 (Neitsch et al., 2011).

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[3] http://swat.tamu.edu/

$$SW_t = SW + \sum_{i=1}^{t} (P_i - q_i - ET_i - q_{lat.i} - q_{ret.i}) \quad (1)$$

$$Q = q_i + q_{lat.i} + q_{ret.i} - Tloss_i - pa \quad (2)$$

Where *SWt* is the final amount of water in the soil (mm); *SW* is the initial amount of water in the soil (mm); *t* is the time (days); P_i is the precipitation (mm) on day *i*; *qi* is the surface runoff (mm) on day *i*; *ETi* is the evapotranspiration (mm) on day *i*; *qlat.i* is the lateral flow (mm) on day *i*; *qret.i* is the return flow (mm) on day *i*; *Q* is the total flow; *Tlossi* is the rate of water lost to the water table on day *i*; And *pa* is the water accumulated in small depressions of the terrain.

The surface runoff can be calculated by two methods: the curve number method (USDA, 1972) and the Green & Ampt infiltration method (King et al., 1999). Potential evapotranspiration can be calculated by the Penman-Monteith method, by Priestley-Taylor or by Hargreaves-Samani (Neitsch et al., 2011).

The input data required to use the SWAT model are basically divided into two groups: tabular data and spatial data. In the group of geographically referenced information are the digital terrain elevation model, the pedological map and the land use and cover map. The tabular data consisting of time series of precipitation, stream flow, minimum and maximum temperature, solar radiation, relative humidity and wind speed (Neitsch et al., 2011).

The model also requires some specific information, such as the number of layers and hydrological groups for each soil class within the basin, as well as information for each soil layer, such as available water capacity, saturated hydraulic conductivity, porosity, among other information. The model has a database with standard information about the parameters for some types of land use/land cover. However, in specific cases, these parameters must be modified by the user (Neitsch et al., 2011).

Some authors have studied the SWAT performance, individually or in comparison with other models, in assessing the impacts of land use change on the availability of water resources. Bormann et al. (2007) compared three different models, SWAT, TOPLATS, and Wasim

(Schulla, 1997; Niehoff et al., 2002), with respect to sensitivity to land use change, relating changes with soil parameters. The results showed that the models show similarities regarding absolute changes, both in simulated evapotranspiration and discharge. However, they verified different sensitivities regarding soil input data. Thus, soil parametrization in agreement to the land use changes was recommended in order to achieve reliable results.

Blainski et al (2011) evaluated the effect of the displacement of croplands by forest and bare soil in the Araranguá watershed in Brazil. Average flow was increased more in the latter than in the former scenario. However, the forest scenario presented the lowest occurrence of flow below the minimum flow value in 95% of the time (Q95), suggesting a more regulated flow all over the year.

Yan et al. (2013) used an integrated approach involving SWAT and the statistical method of partial least squares regression (PLSR) to quantify the contribution of land use changes in stream flow and sediment production in the Upper Du Watershed (China). The study showed that, after calibration, the model showed good performance in evaluating land use change effects on monthly flow. For the small Khlong Phlo basin in the eastern part of Thailand, Babel et al. (2011) concluded that, in general, the model presented a good performance in the simulation of the annual water yield and monthly stream flow, corroborating the use of the model in the study of the effects of different land use change scenarios on the components of the balance and flow rate.

Nie et al. (2011) evaluated effects of land use changes in various hydrological components in the upper San Pedro in USA using SWAT. In their study, urbanization was the major contributor to the increase of surface runoff and water yield, and scrub/grassland by mesquite wood contributed to the decrease in baseflow/percolation and to the increase in evapotranspiration.

Pereira et al. (2014) used SWAT to simulate effects of land use change in runoff for Pomba river basin, in Southeast Brazil. Scenarios considered permanent preservation areas conservation, reforestation and agriculture expansion (pasture replaced by eucalyptus and crops). Results showed mean annual reductions of 14, 4 and 7 millimeters on the basins runoff, respectively. Mwangi et al. (2016) also evaluated the effects of land use change in runoff. In this case, the Mara river basin in East Africa was evaluated with an expansion of agroforestry practices, decreasing the runoff values.

Rodrigues et al. (2015) applied the SWAT model in the assessment of land use changes and its consequences on Pará river basin, in Southeast Brazil. Results showed conclusive answers concerning effects of changes in soil cover on the basin stream flow, showing a significant reduction when the basin suffers an intense expansion of reforestation over previous native vegetation. In another study at the same basin, Rodrigues et al. (2015) simulates an expansion of pasture lands over Cerrado areas, achieving an increase of 10% in the annual basin stream flow.

Bressiani et al. (2015) performed a substantial review of the SWAT application in Brazilian basins, concerning the 1999-2015 period. The review accounted for more than a hundred publications from Brazilian and international journals, conference proceedings, thesis and dissertations. On the other hand, only 15% of these publications were in English. The works explored stream flows and sediment loss results for small and large basins in diverse Brazilian regions. Difficulties in SWAT input data gathering were pointed out in many of the assessed works, which is common as Brazil is a country with continental dimensions. On the other hand, the authors presented diverse data bases concerning SWAT main inputs, such as climate and hydrological data sources, digital elevation and soil maps and sources of land use information and maps.

Therefore, the results from all those studies show that the use of SWAT in the assessment of impacts on water resources due to land use change is capable to generate satisfactory results with regard to changes in watershed stream flows. As well as other hydrological models, SWAT is capable to integrate different water balance components at the same time and space, enabling the assessment of the land use changes effects on evapotranspiration, crop yield, stream flow, precipitation, runoff, water yield, and others.

2.5 Final comments

Recently, sugarcane expansion has occurred mostly over pasture lands and annual crops, towards São Paulo state and Cerrado areas. Those areas are mainly within the Paraná hydrographic region, which has the greatest water demand among the Brazilian HRs and already presents quality and quantity issues. Therefore, it is important to promote new research and public policies concerning water resources management in those regions, especially regarding irrigation practices and water withdrawal grants, so that oriented expansion and responsible water use and management may assure the water supply.

Sugarcane expansion and its impacts on water resources in Brazil have been usually addressed in a qualitative way, which has provided rather directions than effective and conclusive answers. Results about evapotranspiration are controversial and it may be related to evaluations considering water balance components in an individual way, and not integrated in a basin. There are some studies at watershed level in the literature, but only one of them considered the basin's hydrological processes, although without conclusive results in terms of the effects of sugarcane expansion over specific land uses.

Therefore, reliable and conclusive answers concerning sugarcane expansion and water resources availability appear to be a function of watershed assessments, considering separated classes of land use in sugarcane expansion and addressing all hydrological processes in basin's water balance components, such as surface and subsurface runoff, evapotranspiration, stream flow and the management effects on it as well. Among the available hydrological models, SWAT has proved to be able to generate reliable results in the assessment of land use change impacts on water resources. Besides the available documentation and the open source code, another advantage of this model lies on the capacity of integrating different water balance components at the same time and space, enabling a combined assessment of the effects of land use changes on the evapotranspiration, crop yield, stream flow, precipitation, runoff, water yield, among others.

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3. ASSESSMENT OF THE RECENT LAND USE CHANGE DYNAMICS RELATED TO SUGARCANE EXPANSION AND THE ASSOCIATED EFFECTS ON WATER RESOURCES AVAILABILITY FOR TWO BRAZILIAN BASINS[4]

Abstract: Recent sugarcane expansion has been raising concerns about its impacts on water availability. So far, there has been no consensus regarding those impacts as hydrological processes have been almost always evaluated individually. An integrated evaluation of watershed hydrological processes should lead to more reliable answers to this question. This work assessed the effects of land use change on water availability for two Brazilian basins, Monte Mor (MM) and Fazenda Monte Alegre (FMA), which have featured different land use change and sugarcane expansion dynamics in the recent past (1997 to 2007 for MM and 2003 to 2011 to FMA). In FMA, annual crops and sugarcane expanded in expense of forest and pasture lands. In MM basin, forest and urban areas increased and the other land uses remained stagnated or reduced. The water impact assessment was made by comparison between the land use changes and the main components of the SWAT model water balance. An extensive SWAT calibration and validation work was performed for both basins, allowing the use of its water balance components in the assessment. Besides the assessment of SWAT model performance in representing the stream flow for the two basins by calibration and validation processes, it was made an evaluation of evapotranspiration and crop yield values given by the model through a comparison with soft data. The analysis of the water yields in FMA basin indicates that sugarcane expansion over annual crops tends to increase stream flow in dry periods and decrease peak flows. MM basin water yield results suggest that urban areas expansion increases the stream flow in wet months harming the flood vulnerability. Despite the reliable qualitative responses given by the calibrated model, the evaluation of a basin with more intense sugarcane expansion might enable a more consistent quantification of sugarcane impacts on water resources availability. Calibrated and validated SWAT could also be employed in future scenarios evaluation regarding land use or even climate changes.

Keywords: SWAT, calibration, validation, water yield, stream flow

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[4] A modified version was presented in the *2015 International SWAT Conference (Oral presentation).*

3.1 Introduction

Recent sugarcane expansion in Brazil has presented different dynamics, occurring in traditional and new cultivation areas, in diverse scales and replacing different land uses (Nassar et al., 2008; Adami et al., 2012; Hernandes et al., 2014; Scarpare et al., 2016). In 2013, according to Canasat data (Rudorff et al., 2010), Paraná hydrographic region comprised 95% of the sugarcane areas and was also responsible for 95% of the Brazilian Centre-South sugarcane expansion from 2006 to 2013. As land use changes can alter the partitioning of water at the land surface by affecting hydrological processes such as evapotranspiration (ET), infiltration, groundwater recharge, base flow, and runoff, the recent expansion of sugarcane has raised concerns about water availability (Scanlon et al., 2005; Lin et al., 2007; Scarpare et al., 2016).

It is generally widespread the association of the high ET from sugarcane areas with possible negative effects of sugarcane expansion in water availability (Watkins Jr. et al., 2015; Guarenghi & Walter, 2016). On the other hand, due to its massive biomass production per unit of area, sugarcane crop shows the smallest water footprint values among cultivated crops in Brazil (Hernandes et al., 2014). So far, there has been no consensus regarding the real impacts of sugarcane in water availability as hydrological processes have been normally evaluated in a separated way. Thus, the evaluation of combined hydrological processes should lead to more reliable answers to this question, especially when integrated into a watershed.

Hydrological models have been used to this purpose worldwide. One of the most employed models in watershed assessment is the Soil and Water Assessment Tool (SWAT), which is a time-continuous physically based model with spatially distributed parameters used to estimate stream flow, nutrient losses and sediment production in river basins (Arnold et al., 2012). The model has been applied in different scales and basins to predict impacts of management on water resources quality and availability (Gassman et al., 2007; Neitsch et al., 2011; Arnold et al., 2012), and its application is recommended by the United States Environmental Protection Agency (EPA) (Abbaspour et al., 2015).

Despite its widely use in the assessment of the impacts of land use and land cover changes on water resources, SWAT default management operations and default values for essential crop related parameters may lead to inappropriate results, mainly concerning the leaf area index

(LAI) and, consequently, affecting the annual evapotranspiration behavior considering wet and dry periods. In perennial crops, the major inconsistency is related to the dormancy period in temperate regions, which should not be triggered in the Brazilian central-southeast regions because of the moderate winter (Wagner et al., 2011; Strauch & Volk, 2013; Da Silva, 2013; Bressiani et al., 2015).

This work evaluated the Brazilian sugarcane expansion dynamics in two basins within different regions and its implications to the local water availability. The recent land use change was mapped for a watershed in a traditional sugarcane area, where the expansion is expected to be minor, and another in Southwest Goiás, where more intense sugarcane expansion has occurred. A specific goal of the research was to mitigate the issues concerning SWAT crop growth and water balance through a comprehensive model calibration and validation process applied for both basins. The land use change dynamics were then evaluated in association with the main components of the validated SWAT water balance (precipitation, evapotranspiration, water yield and stream flow). Comparisons were made in order to evidence relationships between land use water yields preconized by the validated model and land use changes.

3.2 Methods and data

3.2.1 Study areas

This work evaluated two basins, both located within the Paraná hydrographic region (Figure 3.1). One basin hosts traditional sugarcane areas of the state of São Paulo, and the other is in new sugarcane areas towards the Cerrado[5] biome in the state of Goiás. The selection of the study areas was guided by the data availability (stream flow and climate data), the variability of edaphoclimatic conditions, the sugarcane crop occurrence and the similarity between the basin drainage areas.

Monte Mor basin (MM) is located in the state of São Paulo. It presents a Subtropical climate, with high temperatures and wet period in the summer, and a moderate and dry winter. The drainage area hosts a traditional sugarcane zone belonging to Campinas and Jundiaí micro

[5] *Cerrado* is the second largest Biome in South America, occupying about 22% of the Brazilian territory. Due to its biodiversity, Cerrado is recognized as the richest savannah in the world presenting innumerous species of plants and animals.

regions and with urban features, partially covering twelve municipalities. The sugarcane areas in this basin present a stagnation trend due to, among other socioeconomic aspects, legal issues in pre-harvest burning and due to topography constraints for mechanical harvesting. Unpublished results derived from local interviews indicate a replacement of sugarcane areas with slopes above 15% by private residential areas. Supervised classification for Monte Mor basin's satellite images from the recent past years corroborated both the sugarcane areas stagnation and the urban areas expansion.

On the other hand, the Fazenda Monte Alegre basin (FMA) in southwest Goiás presents a strong sugarcane expansion tendency (Scarpare et al., 2016). This basin has no urban areas, being totally covered by Cerrado (ANA, 2015), pasture and annual croplands. It is located in a Tropical climate with dry winter and rainy and hot summer seasons, and all its drainage area remains within the rural area of Rio Verde municipality.

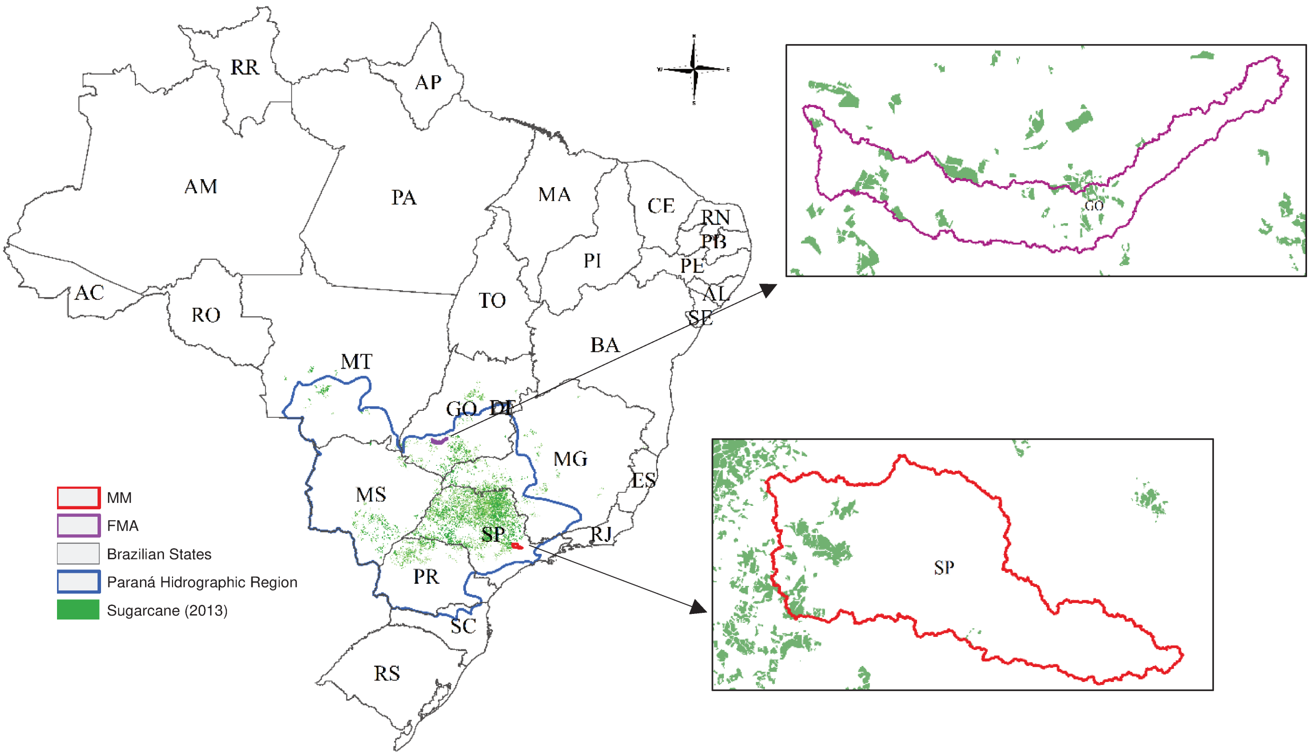


Figure 3.1 Fazenda Monte Alegre and Monte Mor basins geographical position.

3.2.2 SWAT inputs

SWAT computes water, sediment and nutrient balance combining homogeneous land use, topography, management and soil characteristics into hydrologic response units (HRU). The HRU results for the hydrological processes involved in simulations (canopy interception of precipitation, partitioning of precipitation, irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers) are integrated in subbasins and then combined to generate a weighted basin response. The basin water balance in SWAT is composed mainly by the precipitation (PREC) that falls in the basin drainage area, the actual evapotranspiration (ET) for the basin and the water yield (WY), which comprises the surface, subsurface and lateral runoff (Gassman et al., 2007; Bormann et al. 2009; Ullrich & Volk, 2009; Neitsch et al., 2011; Yan et al., 2013).

In this work, potential evapotranspiration was estimated by Penman-Monteith approach, and evaporation from plant and soil are calculated independently (Ritchie, 1972). Surface runoff is estimated with a modification of the Soil Conservation Service (SCS) curve number method from the United States Department of Agriculture (USDA SCS, 1972). The crop growth and the management practices are based on the Environmental Policy Integrated Climate (EPIC) crop growth model (Arnold and Allen, 1996; Neitsch et al., 2011).

More details in model equations and processes can be found in the SWAT Theoretical Documentation in Neitsch et al. (2011).

3.2.3 Watershed Delineation

Digital Elevation Maps (DEM) were used to define the basins drainage areas, outlets, subbasins and drainage channels (Figure 3.2). Maps were obtained from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) onboard the NASA satellite "Terra".

Drainage areas of the selected watersheds were defined through the SWAT automatic watershed delineation module, using the geographic coordinates of the outlets from the Brazilian Water Agency (ANA) flow monitoring points 60.778.000 (FMA) and 62.420.000 (MM) (ANA, 2014). In both basins, the real drainage areas given by ANA and the drainage areas done by SWAT watershed delineation module were very similar (Table 3.1).

Table 3.1 Fazenda Monte Alegre and Monte Mor watershed characterization.

Parameters	Fazenda Monte Alegre	Monte Mor
Drainage Area ANA (km^2)*	808	697
Drainage Area SWAT (km^2)*	805	698
Basin Outlet Latitude	-17.33	-22.96
Basin Outlet Longitude	-50.77	-47.30
Climate (Köeppen)	Aw	Cwa
Annual Rainfall (mm)	1550	1300
Mean Annual Temperature (˚C)	23	22

*Less than 0.5% of difference between basins drainage areas given by ANA and delineated using SWAT.

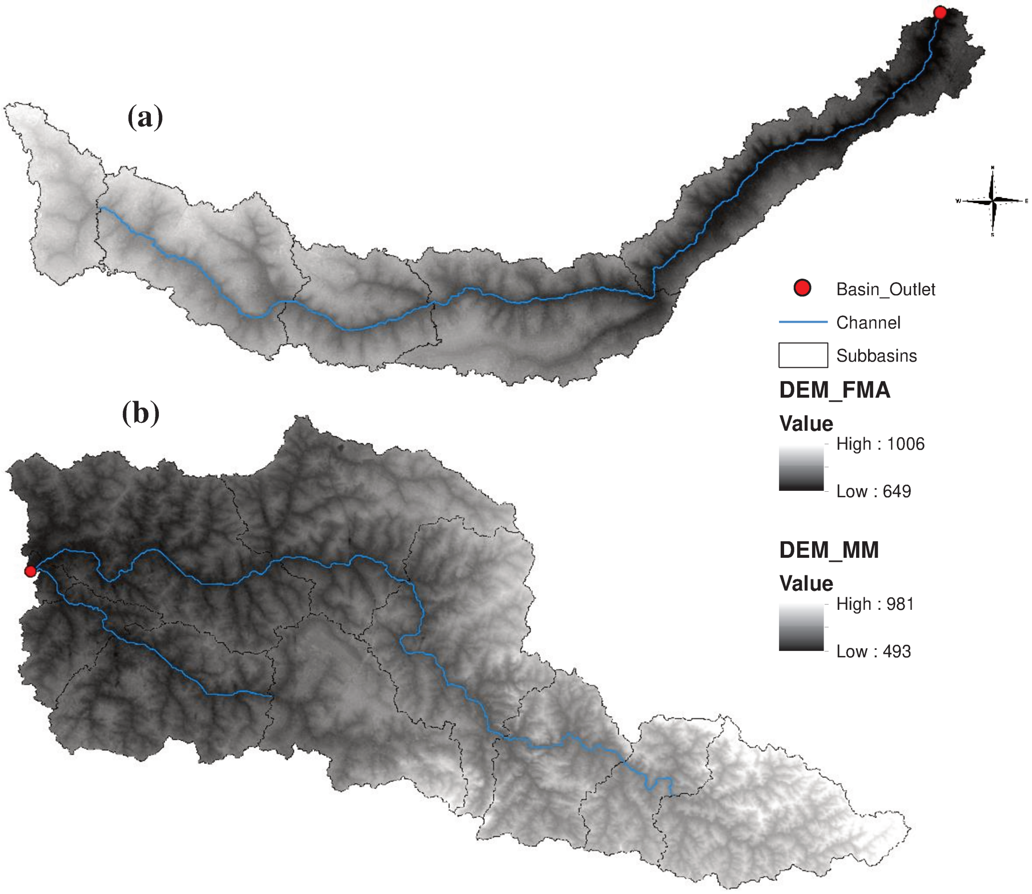


Figure 3.2 Digital elevation maps, subbasins, outlets and drainage channels for Fazenda Monte Alegre (a) and Monte Mor (b) basins. Digital elevation legend in meters.

3.2.4 Land Use Maps and Land Use Update

The SWAT module "Land Use Update" (LUP) enables the land use change control throughout the simulation years using only land use change in percentages (Pai & Saraswat, 2011). Thus, according to the available stream flow data period, it was defined a base map for FMA and MM basins and other four support maps were made in order to update land use changes in the basins. Support maps were intersected with the base map creating the percentages of changes.

Base maps (Figure 3.3) and the other required land use maps were prepared using ArcGIS 10.1 supervised classification on LandSat images (Table 3.2). For MM basin, base map corresponds to the land use in 1996, while for FMA, basin base map refers to the land use in 2004.

Table 3.2 LandSat image dates for the construction of base maps and support land use update maps.

Basin	Year	Month	Day
Monte Mor	1996	March	26
	1999	March	19
	2001	April	25
	2004	February	29
	2007	March	25
Fazenda Monte Alegre	2004	June	16
	2005	April	16
	2008	April	24
	2010	April	14
	2011	April	17

The automated classification was confirmed by comparison to the Google Earth images, when it was available at the correspondent site and date, and also by association to the MODIS sensor 1 time-series (Freitas et al., 2011). As sugarcane was the crop of interest, classification was made manually, with the support of CANASAT project maps (Rudorff et al., 2010). Urban areas were also manually classified.

Land uses were defined using SWAT crop database as described in Table 3.3, based on satellite images classification and in agricultural information from the Brazilian Geography and Statistics Institute (IBGE, 2016).

Table 3.3 Land use and land cover maps for SWAT correspondence in FMA and MM basins

Land Use	FMA (SWAT Code)	MM (SWAT Code)
Sugarcane	Sugarcane (SUGC)	
Water	Water (WATR)	
Pasture	Pasture (PAST)	
Annual Crops	Soybean/Corn Rotation (SOYB-CORN)	
Cerrado/Forest	Range Brush (RNGB)	Forest Evergreen (FRSE)
Perennial Crops	----------	Orchard (ORCD)
Urban Areas	----------	Residential-Medium Density (URMD)

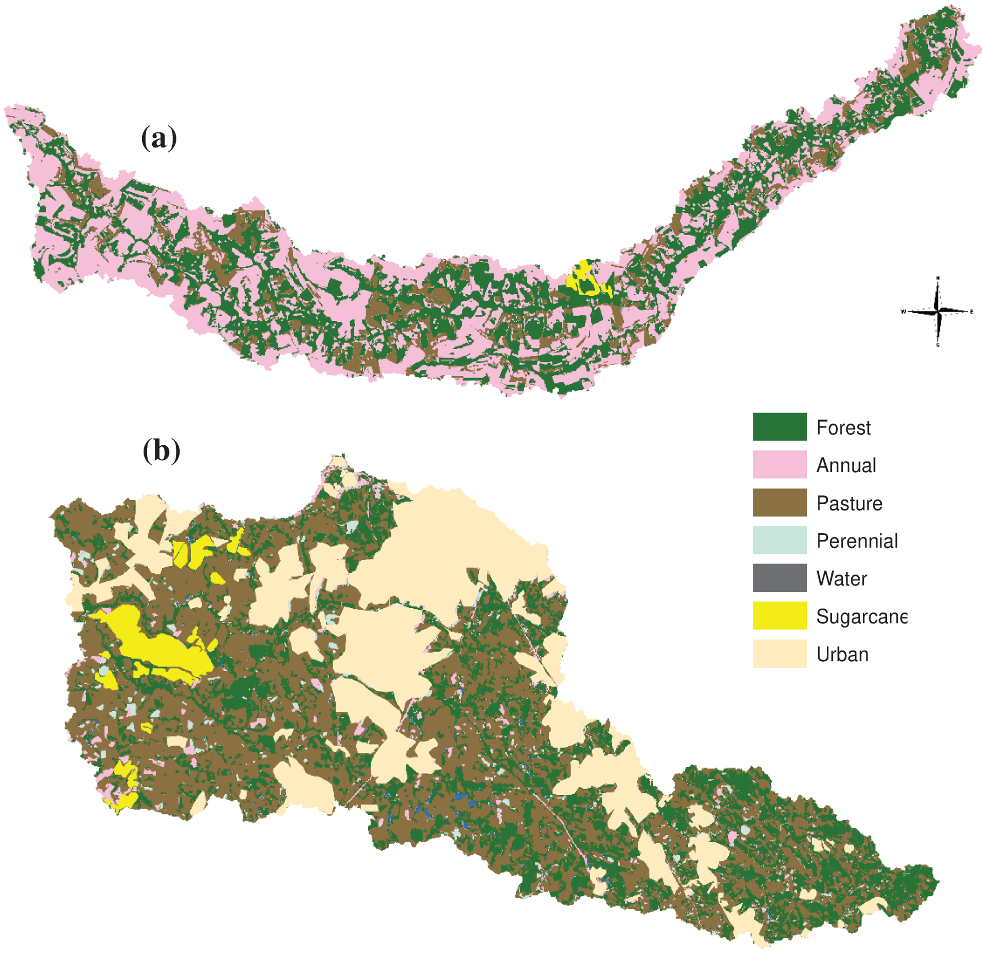


Figure 3.3. Land use base maps classified as sugarcane, forest, annual crops, pasture, perennial crops, water and urban areas for FMA (a) and MM (b) basins.

3.2.5 Climate and Soil Data

Required climatic inputs were precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed, all in daily time-step. Except for precipitation, climatic data were obtained from the National Centers for Environmental Prediction - Climate Forecast System Reanalysis (Saha et al., 2010; Saha et al., 2014), which provides more than 30 years of weather data for the whole world in a 38-kilometer grid.

Precipitation data was collected from all the available ANA rain gauge stations in FMA and MM basin areas. The rain gauge stations that have influence in precipitation occurrence in both basins were determined by the Thiessen polygons method and then added to the model database (Table 3.4, APPENDIX I). In FMA basin, data gaps represented in average 7% of the total precipitation records, while 6% of the records were missing in MM basin rain gauge stations. In both basins, all gaps in precipitation data were filled by the SWAT weather generator WGEN (Neitsch et al., 2011; Arnold et al., 2012).

Table 3.4 ANA rain gauge stations used in SWAT simulation for FMA and MM basins.

	Rain Gauge	Code	Latitude	Longitude	Altitude (m)
FMA	Ponte Rio Doce	1751001	-17.86	-51.4	755
	Fazenda Paraíso	1750008	-17.47	-50.77	680
	Montividiu	1751004	-17.33	-51.26	797
	Ponte Rodagem	1750004	-17.33	-50.68	709
MM	Itatiba	2246038	-22.94	-46.83	690
	Monte Mor	2247058	-22.96	-47.3	560
	Indaiatuba	2347007	-23.08	-47.22	630

Soil maps (APPENDIX I) for MM basin was provided by the Agronomic Institute of Campinas (IAC), in 1:500,000 scale (Oliveira et al., 1999). For the FMA basin, the soil map was found in Goiás State Geosystem Information (SIEG), in 1:250,000 scale (SIEG, 2014).

Considering the Brazilian Soil Classification System (SiBCS) (EMBRAPA, 2013), MM basin soil map shows a large area of ’Argissolos’ with spots of ’Latossolos Vermelhos’ and ’Latossolos Vermelho-Amarelos’. FMA basin is surrounded by ‘Cambissolos’, with ‘Latossolos’ in the middle. In World Reference Base (IUSS Working Group WRB, 2014), “Argissolos” correspond to Lixisols, “Latossolos” are classified as Ferralsols and “Cambissolos” are Cambisols (Rizzo et al., 2016).

The physicochemical soil parameters for MM soils were from a public database from the Brazilian Agricultural Research Corporation (EMBRAPA) (EMBRAPA, 2014), allowing to fill parameters such as the number of layers, hydrological groups, maximum rooting depth, moist bulk density, organic carbon content and soil texture. For FMA basin, the same soil parameters were inserted in the soil database, with specific data for the Brazilian Cerrado area, from Lima et al. (2014). The available water capacity and the saturated hydraulic conductivity for both basins were calculated through pedotransfer functions adapted to tropical soils (Barros et al., 2013).

3.2.6 SWAT Setup, Calibration and Validation

The assurance of reliable LAI values and behavior were essential for this work as they directly influence crop evapotranspiration and water balance (Neitsch et al., 2011; Strauch & Volk, 2013; Da Silva, 2013). Thus, in order to minimize inconsistencies, management and crop files were modified to better represent FMA and MM conditions. The modifications were made to all crop and management parameters that were available in the literature (Table 3.5 and 3.6).

For orchard areas, it was considered the orange parameters since the citrus production is very common in the municipalities covered by the MM basin (IBGE, 2016). In management operations, annual crop areas were set as a soybean-corn rotation. Concerning sugarcane, a six-year cycle was considered, with a plant cane (one year and a half of development) followed by four sugarcane ratoons. For the remaining perennial cultures (Forest, Cerrado, Orchard and Pasture), the problem with the dormancy period was mitigated through the “Harvest only” and the “Begin of growing season” operations scheduled to happen in the winter season.

Before calibration, tests were made in order to define the more appropriate method for the Curve Number (CN) estimation regarding stream flow results. For MM basin, best outcomes were obtained by the Evapotranspiration Method. For FMA basin, on the other hand, the USDA Method fitted better. For model calibration, validation, sensitivity and uncertainty analysis it was used the SUFI2 algorithm in SWAT-CUP, which is a program interface for SWAT used to perform a combined calibration-uncertainty analysis (Abbaspour et al., 2004; Abbaspour et al., 2007; Abbaspour et al., 2015). Calibration and validation were performed in monthly time step, with two years of model warm up. Simulation periods were defined based on the stream flow data availability in FMA and MM basins outlets. For FMA basin, simulation started in 2001 and finished in 2012. For MM basin the simulation period was from 1995 to 2007.

Table 3.5 Management operations for all considered land uses in FMA and MM basins

Land Use	Year	Date	Operation	Quantity (kg ha^{-1})
Soybean and corn rotation[b]	1	5-Feb	Soybean Harvest and kill	
	1	6-Feb	Corn Nitrogen application	40
	1	6-Feb	Corn Phosphorus application	20
	1	10-Feb	Corn Plant	
	1	1-Jul	Corn Harvest and kill	
	1	25-Sep	Soybean Nitrogen application	7
	1	25-Sep	Soybean Phosphorus application	33
	1	1-Oct	Soybean Plant	
Sugarcane	1	28-Feb	Sugarcane Plant	
	1, 2, 3, 4, 5	28-Feb[c]; 01-Aug[d]	Nitrogen application[a]	100
	1, 2, 3, 4, 5	28-Feb[c]; 01-Aug[d]	Phosphorus application[a]	30
	2, 3, 4, 5	01-Aug	Begin of growing season	
	2, 3, 4, 5, 6	31-Jul	Harvest only	
	6	01-Sep	Kill Sugarcane	
Forest and Pasture	1	30-Jun	Harvest only	
	1	15-Jul	Begin of growing season	
Orchard	1	1-Jun	Harvest only	
	1	1-Jul	Begin of growing season	
Cerrado	1	31-Aug	Harvest only	
	1	1-Sep	Begin of growing season	

[a]Rosseto & Dias, 2005; [b]Strauch et al., 2013; [c] Plant Cane; [d] Sugarcane Ratoon

All the SWAT parameters directly involved in stream flow process were considered in the calibration on SWAT-CUP (Table 3.8) (Arnold et al, 2012; Salles, 2012; Barbarotto Jr, 2014). Parameter changes in calibration were made using the relative method for CN2, SOL_AWC, SOL_K, SOL_ALB, SLSUBBSN and CANMX, within the parameter ranges, in order to preserve the differences related to the land use, the slope and the soil characteristics. For the remaining parameters, values included in the ranges were replaced during the calibration process.

Table 3.6 Adjusted crop related parameters for all considered land uses in FMA and MM basins

Parameter	SWAT folder	Description	SUGC	RNGB	PAST	SOYB	CORN	FRSE
ALAI_MIN	crop.dat	Minimum leaf area index for plant (m^2 m^{-2})	---	1.35[b]	0.75[g]	---	---	4.5[a]
BIO_E	crop.dat	Radiation Use Efficiency ((kg ha^{-1})/(MJ m^2))	36[c]	20[b]	---	---	---	20[b]
BLAI	crop.dat	Maximum potential leaf area index (m^2 m^{-2})	6[d,e]	3.5[b]	3[a,g]	5[i,j]	6[m]	6[a,p]
DLAI	crop.dat	Fraction of PHU when LAI begins to decline	---	0.53[b]	---	---	---	---
FRGRW1	crop.dat	Fraction of PHU corresponding to the 1st point on the optimal leaf area development curve	---	0.07[b]	---	---	---	---
FRGRW2	crop.dat	Fraction of PHU corresponding to the 2nd point on the optimal leaf area development curve	---	0.5[b]	---	---	---	---
GSI	crop.dat	Maximum stomatal conductance at high solar radiation and low vapor pressure deficit (m s^{-1})	0.0025[a]	0.003[b]	0.003[a]	---	---	0.005[a]
LAIMX1	crop.dat	Fraction of BLAI corresponding to the 1st point on the optimal leaf area development curve	---	0.15[b]	---	---	---	---
LAIMX2	crop.dat	Fraction of BLAI corresponding to the 1st point on the optimal leaf area development curve	---	0.95[b]	---	---	---	---
TBASE	crop.dat	Minimum temperature for plant growth (◦C)	16[f]	10[b]	---	10[i,j]	10[m,n]	---
VPDFR	crop.dat	Vapor pressure deficit (kPa) corresponding to the second point on the stomatal conductance curve	---	1.6[b]	---	---	---	---
CHTMX	crop.dat	Max canopy height (m)	4[a]	10[a]	---	---	---	30[a]
RDMX	crop.dat	Max root depth (m)	2[a]	6[a]	1.5[a]	---	---	6[a]
CANMX	.hru	Maximum canopy storage (mm)	1[a]	1.6[a]	0.7[a]	0.7[l]	1[o]	1.8[a]
ESCO[6]	.hru	Evaporation compensation factor	0.95	0.93	0.90	0.90	0.90	0.93
PHU_PLT	.mgt	Total number of heat units or growing degree days needed to bring plant to maturity	5700[f,q] /4500[f,r]	4500[b]	4500[h]	1800[j]	---	4500[h]
T_OPT	crop.dat	Optimum temperature for plant growth (◦C)	25[f]	---	---	30[i]	30[m]	---

[a] Da Silva, 2013; [b] Strauch & Volk, 2013; [c] Ferreira Junior, 2013; [d] Cabral et al., 2012; [e] Scarpari & Beauclair, 2008; [f] Scarpare, 2011; [g] Zanchi et al., 2009; [h] considering the PHU accumulated in one year, as for sugarcane ratoon; [i] Oliveira et al., 2011; [j] Martorano, 2007; [l] considering the same value as in pasture; [m] Gaiewski., 2009; [n] Assis et al., 2006; [o] considering the same values as in sugarcane; [p] Carreire, 2010; [q] Plant Cane; [r] Sugarcane Ratoon.

Model performance was statistically evaluated using the Correlation Coefficient (R2), the Percent Bias (PBIAS), the RMSE-observations standard deviation ratio (RSR), the bR2 coefficient (bR2) and the Nash-Sutcliffe Efficiency (NSE) (Table 3.9) (Abbaspour, 2007; Gassman et al., 2007; Moriasi et al., 2007). Uncertainty analysis in SUFI2 was quantified through the P-factor and the R-factor indexes. The P-factor is the percent of observations that

[6] ESCO values were based on the literature values variation from Da Silva (2013) and Strauch & Volk (2013). However, after personal communication with SWAT model makers, they suggested a maximum value of 0.95. Thus, ESCO values were adapted considering the maximum of 0.95.

are within the given uncertainty bounds and R-factor is the average width of the given uncertainty bounds divided by the standard deviation of the observations. Ideally, a perfect simulation is achieved when P-factor is equal to 1 and R-factor is equal to zero. However, in real situations the aim is to obtain a P-factor around 1 and a R-factor as close as possible to zero. For stream flow, the combination of a P-Factor larger than 0.7 with a R-Factor below 1 indicates a strong calibration process (Abbaspour et al., 2007; Abbaspour et al., 2015).

3.3 Results and discussion

3.3.1 SWAT Calibration and Validation

FMA and MM basins have both a wet and warm period from September/October to March/April, and a dry and moderate temperatures period from April/May to August/September. Thus, leaf area index (LAI) is expected to achieve, at least in perennial and semi-perennial crops, greater values in wet months and lower values in dry or harvest periods. As can be seen in Figure 3.4, these trends are observed after the model adjustments, providing more reliable LAI values and behavior for FMA and MM basins. Soybean and corn rotation were also very well represented, with plant and harvest dates well marked and reasonable LAI peaks, as well as in sugarcane crop (semi-perennial crop).

In order to evaluate the crop evapotranspiration and crop yields results, it was made a comparison between SWAT results and literature/soft data (Table 3.7). Results from SWAT corresponds to the average values between the two assessed basins over the whole simulated period.

All crop evapotranspiration amounts from SWAT were within the range from literature. Except for corn, evapotranspiration values were closer to the lower limits, which is reasonable since the crops were rainfed (no irrigation was considered). Crop yields were also very similar to those found in the literature, with the orange productivity as the most discrepant value. In this case, and also for pasture, values were below the references possibly because some management considerations since the considered crops were not fertilized in the simulations (see Table 3.5).

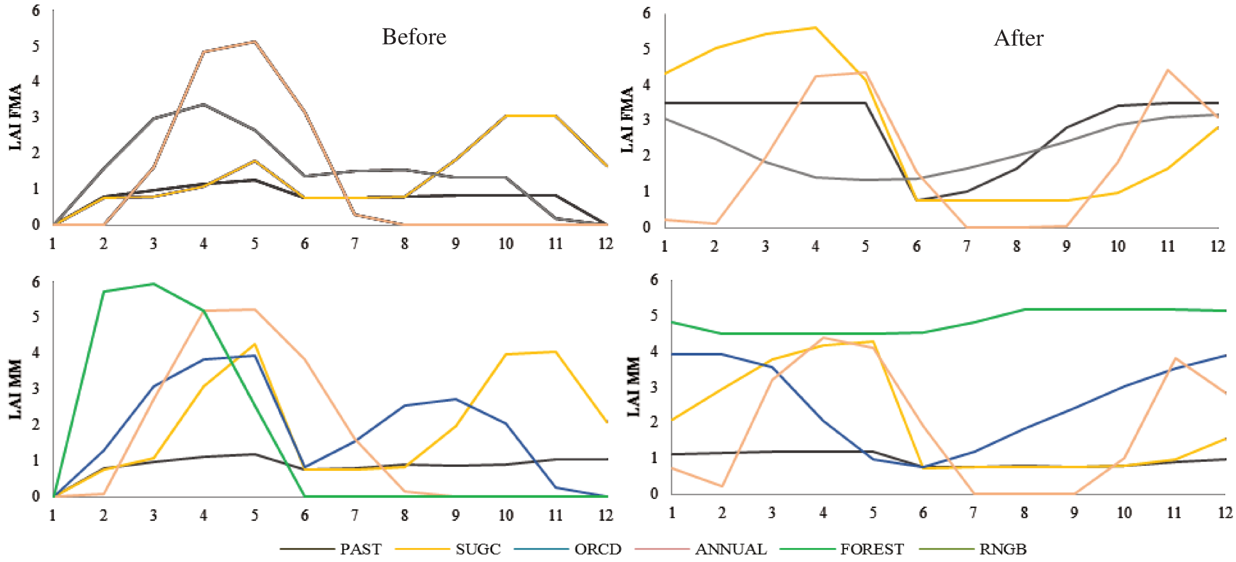


Figure 3.4 LAI behavior before and after the crop parameters and management adjustments (1 to 12 in x-axis represent the months of the year from January to December).

Table 3.7 Values of crop evapotranspiration and crop yields from SWAT and from literature.

	SWAT ET (mm)	Ref ET (mm)	SWAT Yield (Mg ha^{-1})	Ref Yield (Mg ha^{-1})
Sugarcane	895.5	800 – 2000[a]	81	78[f]
Soybean	503	450 – 800[b]	4	3[f]
Corn	424.5	350 – 500[c]	5.5	4.4[f]
Orange	1100	1000 – 1400[d]	12	20[f]
Pasture	942.5	800 – 1600[e]	9	10 to 20[g]

[a] Santos, 2005; [b] Farias et al., 2007; [c] EMBRAPA, 2016; [d] Santos Filho, 2005; [e] Voltolini et al., 2012; [f] CONAB, 2016 (Average yield for the recent 10 years); [g] Costa, 2004.

Acceptable results for crop evapotranspiration and yield, even with no specific calibration, reinforces the importance of the model setup step in achieving reliable representation of the water balance components and crop related outputs. Regarding the significance of the evapotranspiration in water balance results, although laborious and time consuming, it is imperative to be sure of using the best crop and management related parameters always as possible in order to get consistent simulations.

A sensitivity analysis was made using the parameter ranges defined in the SWAT database, which correspond to the absolute maximum and minimum values that the parameters can reach. So, the sensitivity results associated to the parameter's character helped to define the calibration ranges. In both basins, the most sensitive parameter was the CN2. Soil parameters, ESCO, CANMX, ALPHA_BF and SLSUBBSN also presented high influence in FMA and MM basins.

Calibrated values for the parameter can be found in Table 3.8. The hydrographs with observed and calibrated/validated (simulated) stream flow values for both basins are presented in Figure 3.5. In FMA and MM basins, the model adjustment was good in the considered period. Despite some discrepancies in peak stream flow values, it was observed a better fit in the calibration period in both hydrographs. In general, stream flow simulated in SWAT model were more similar to the observed values in the dry months. This behavior favors the analysis of water availability since the reference flow for water grants concession are derived from the stream flow values in dry periods.

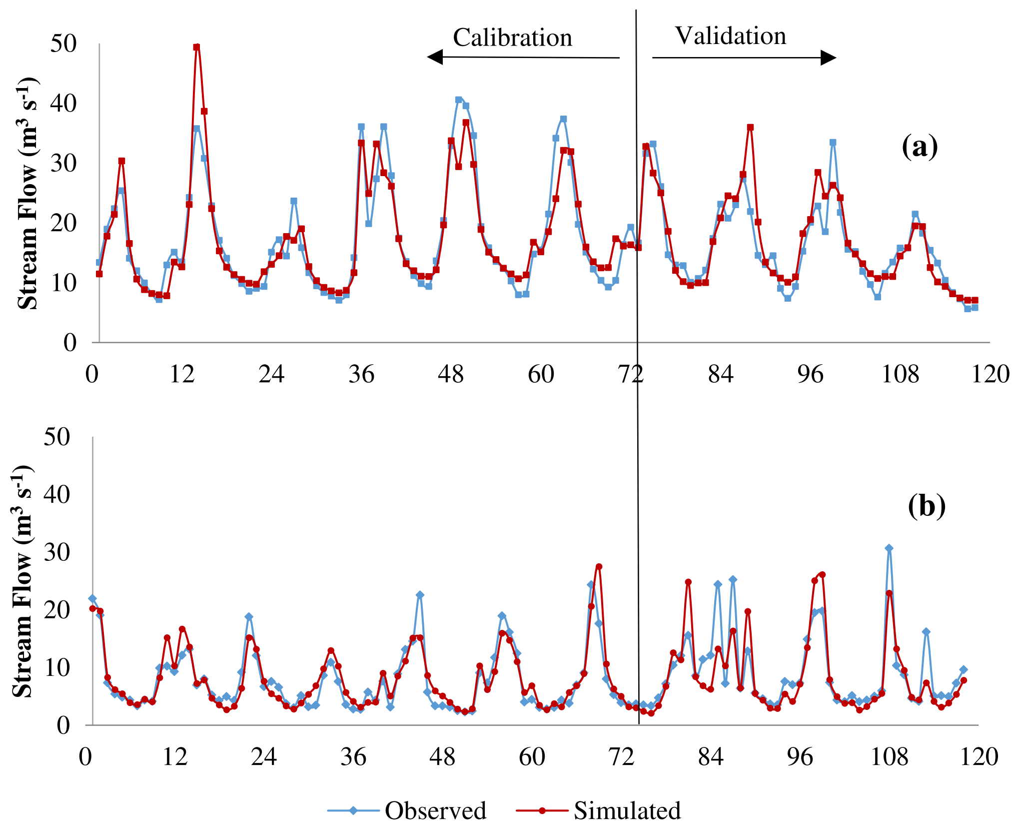


Figure 3.5 Observed and simulated stream flow values for FMA (a) and MM (b) basins. 0 to 120 represents the simulated period in months.

According to Gassman et al. (2007) and Moriasi et al. (2007) criteria, stream flow calibration and validation performance were statistically satisfactory (Table 3.9) for the two assessed locations. In accordance to Abbaspour et al. (2007) and Abbaspour et al. (2015), uncertainty analysis also gave proper values for R-factor (0.60 for FMA and 0.86 for MM) and P-factor (0.85 for FMA and 0.86 for MM). The satisfactory statistical response combined to the appropriate uncertainty results hence indicate a consistent calibration process, enabling a reliable use of SWAT water balance components.

Values in Table 3.8 showed that soil related parameters such as SOL_K, SOL_AWC and SOL_ALB presented the most significant changes in the calibration process. These results were somehow expected as the soil information and data are relatively scarce in Brazil, which made SOL_K and SOL_AWC to be obtained from pedotransfer functions. Thus, the uncertainty and error related to these parameters were high than for the others.

Table 3.8 Calibrated parameters for FMA and MM basins

Parameter	Description	Units	Range	FMA Values	MM Values
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	mm	0 - 5000	141.32	2489.84
CN2	SCS runoff curve number for moisture condition	--	-0.2 - 0.2	0.84	0.82
GW_REVAP	Groundwater "revap" coefficient	--	-0.02 - 0.2	0.02	0.08
SOL_K	Saturated hydraulic conductivity	$mm\ h^{-1}$	-0.2 - 1	1.97	1.94
SLSUBBSN	Average slope length	m	-0.2 - 1	0.96	1.01
ALPHA_BF	Baseflow alpha factor	day^{-1}	0 - 1	0.11	0.03
EPCO	Plant uptake compensation factor	--	0 - 1	0.91	0.48
SOL_AWC	Available water capacity of the soil layer	$mm\ mm^{-1}$	-0.2 - 1	0.89	1.45
GW_DELAY	Groundwater delay	day	0 - 500	452.1	206.38
SURLAG	Surface runoff lag time	day	0 - 10	4.01	4.33
ESCO	Soil evaporation compensation factor	--	-0.2 - 0	0.81	0.82
CH_K2	Effective hydraulic conductivity in main channel alluvium	$mm\ h^{-1}$	0 - 150	31.1	16.18
SOL_ALB	Moist soil albedo	--	-0.2 - 1	1.78	0.97
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur	mm	0 - 500	497.62	435.34
CANMX	Maximum canopy storage	mm	-0.5 - 0.5	0.77	0.62
CH_N2	Manning's "n" value for the main channel	--	0 - 1	0.7	0.11

Table 3.9 Model calibration and validation performance for FMA and MM basins

Statistical Parameters		Calibration		Validation		Calibration + Validation	
FMA	R^2	0.84	Satisfactory	0.8	Satisfactory	0.83	Satisfactory
	bR^2	0.74	Satisfactory	0.76	Satisfactory	0.74	Satisfactory
	NS	0.84	Very Good	0.77	Very Good	0.82	Very Good
	RSR	0.41	Very Good	0.48	Very Good	0.43	Very Good
	PBIAS	-0.13	Very Good	-3.37	Very Good	-1.32	Very Good
MM	R^2	0.85	Satisfactory	0.69	Satisfactory	0.75	Satisfactory
	bR^2	0.71	Satisfactory	0.61	Satisfactory	0.64	Satisfactory
	NS	0.85	Very Good	0.64	Satisfactory	0.74	Good
	RSR	0.39	Very Good	0.6	Good	0.51	Good
	PBIAS	-1.82	Very Good	5.26	Very Good	1.62	Very Good

3.3.2 Land Use Change and Water Resources

Land use changes for the considered period were obtained by the comparison between the most recent land use map and the base map (Figure 3.3). In MM basin, from 1997 to 2007, forests (native and/or planted) and urban areas showed an increase of 2,500 hectares, each class. Sugarcane areas were stable, with a slight increase of 300 hectares. Pasture lands were reduced in 3,400 hectares, followed by the decreases in annual (1,500 ha) and perennial crops (1,000 ha).

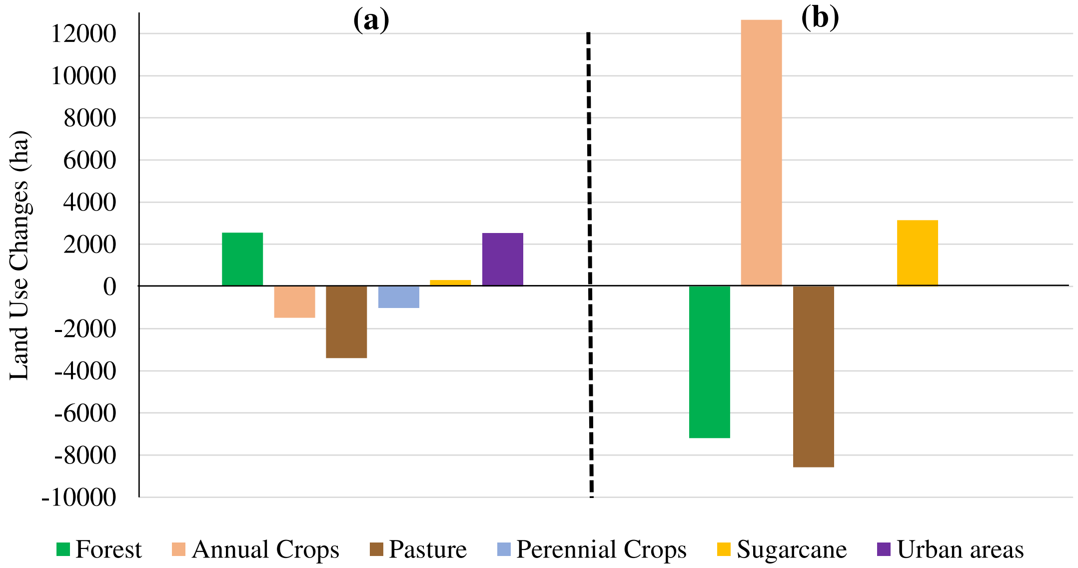


Figure 3.6 Total land use changes in MM (a) and FMA (a) basins.

In contrast, in FMA basin annual crops had a large expansion from 2003 to 2011, reaching an increase of almost 13,000 hectares. Sugarcane also increased more than 3,000 hectares. Forest and pasture lands presented a reduction of 7,000 and 8,600 hectares, respectively. In general, land use changes in FMA basin were more intense than changes in MM basin, considering absolute numbers.

Besides the total land use changes, it was possible to point over which land use classes expansions and reductions have occurred (Figures 3.7 and 3.8).

Figure 3.7 showed that annual crops in FMA basin have expanded mainly on previous forest and pasture lands. Based on processed satellite images it was possible to confirm that the former forest areas were mainly occupied by annual crops (more than 90% of the replacement). Similarly, about 90% of the decrease in pasture lands was replaced by annual crops. It was also possible to see a slight forest expansion over previous pasture lands (almost 1,000 ha). Although the increase over previous forest and pasture lands, sugarcane expansion has occurred mainly over annual crops (almost 60%). Besides, in absolute figures, the advance of annual crops over forest areas (7,000 ha) was definitely more significant than for sugarcane (1,000 ha).

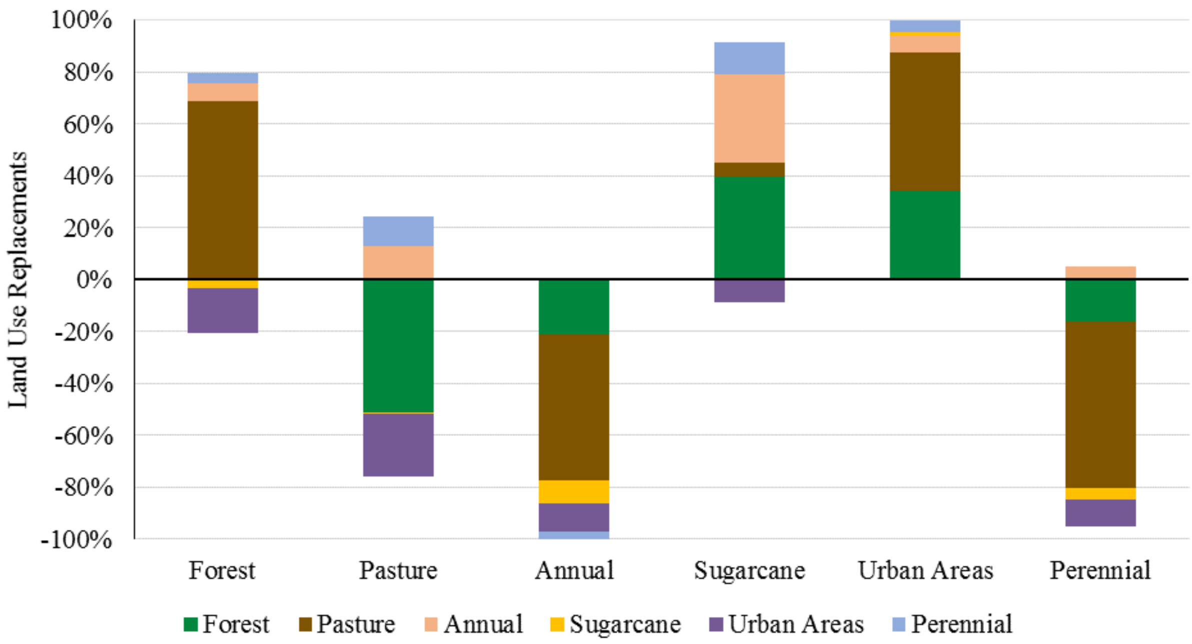


Figure 3.7 Estimated land use changes in the 2003-2011 period in FMA basin – classes replacement.

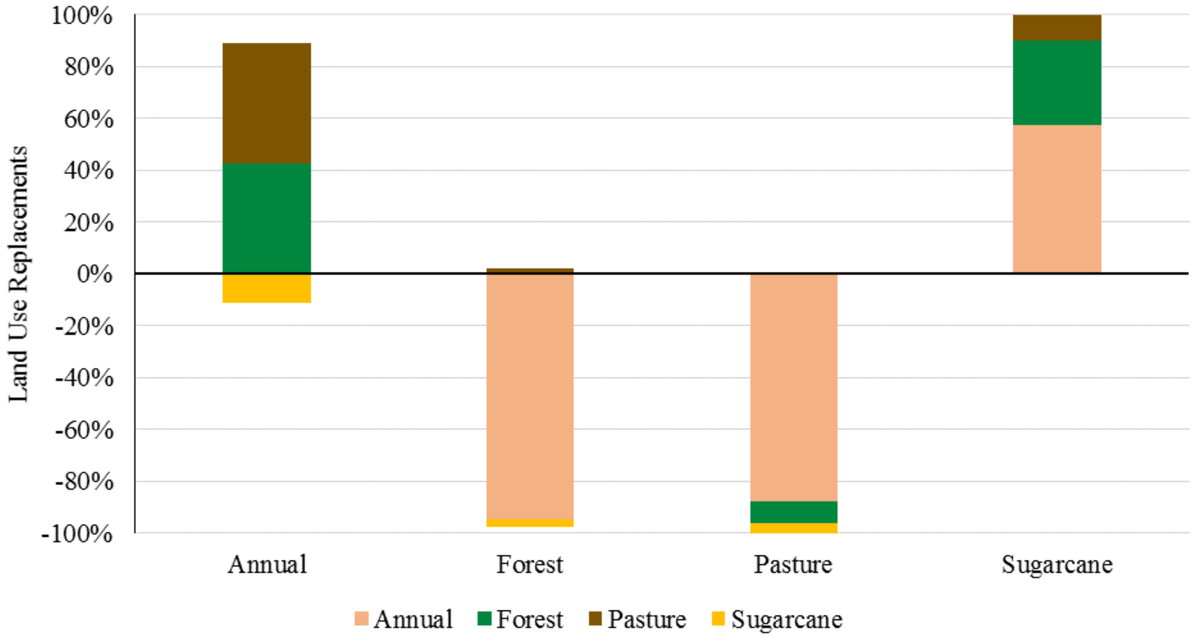


Figure 3.8 Estimated land use changes in the 1997-2007 period in MM basin – classes replacement.

In MM basin, urban areas expansion covered all the land use classes, advancing over forest (800 ha), pasture (1,500 ha), annual and perennial crops (300 ha) and sugarcane (100 ha). Forest grew specially over pasture lands (3,000 ha), which in turn expanded over annual and perennial crops (1,500 ha). Sugarcane replaced particularly forest and annual crops, even though the expansion was only 300 hectares.

In order to establish a connection between the past land use changes and water resources availability, it was taken from the validated SWAT model, for each land use class, the monthly values of water yield (average for the simulated period), which represents the amount of water that contributes to the basin stream flow (Figure 3.9). Furthermore, as an attempt to confirm the assumptions involving land use changes and water yields, and to associate the stream flow response to that, it was plotted, for two years (base map year and the most recent map year), the stream flow behavior versus the accumulated precipitation (Figure 3.10).

In terms of water yield for the different land use classes, values in FMA basin appear to be more diverse than those ones in MM basin. In MM case (Figure 3.9b), the water yield is driven mainly by the urban areas, with higher values during all the year, especially in wet months. Based on these SWAT results, it is expected in this basin that the more urban areas expand over other land uses, the greater will be the stream flow, particularly in wet months, increasing the flood vulnerability in areas at risk.

In FMA basin (Figure 3.9a), water yields for land uses are diverse, either among each other or among the months of the year. Forest water yields were significant and almost continuous during the months, which indicates a more regular stream flow regime in areas covered by this land use class. In wet months, annual crops and sugarcane are the most important contributors to the basin water yield. However, in dry months, annual crops show the smallest water yield values while sugarcane continues to be important in stream flow contributions. Thus, it is possible to affirm that sugarcane water yield in FMA basin performs similarly to forest in dry months. In any case, sugarcane expansion over annual crops tends to increase stream flow in dry periods and decrease peak flows in the basin, making the stream flow regime more regular during the year.

Considering that in FMA basin the major expansion was from annual crops over forest and pasture lands, according to the water yield results, stream flow would be expected to rise in wet months and to decline in dry months. On the other hand, a significant sugarcane increase might mitigate these effects, making the changes in stream flow less significant. In MM basin, changes were less important in terms of absolute values. There was an increase in urban areas, which according to the water yield should cause an increase in stream flow values, mostly in wet months. However, an observed growth of forest at the same magnitude in the evaluated period is expected to attenuate the changes in stream flow.

The stream flow for the FMA basin (Figure 3.10a), comparing 2011 to 2003, indicates an increase in monthly average stream flow values, particularly in dry months, even with the smaller accumulated precipitation in 2011 compared to 2003. These results partially confirm the basin land use change assumptions from water yields assessment. On the other hand, a higher stream flow value in January 2011 versus January 2003 may have been somehow responsible for the results in the subsequent dry months. Values in January 2011 was certainly influenced by the high accumulated precipitation from the previous months (November and December of 2010), which achieved 554 mm. The accumulated precipitation for November and December of 2002 was only 283 mm.

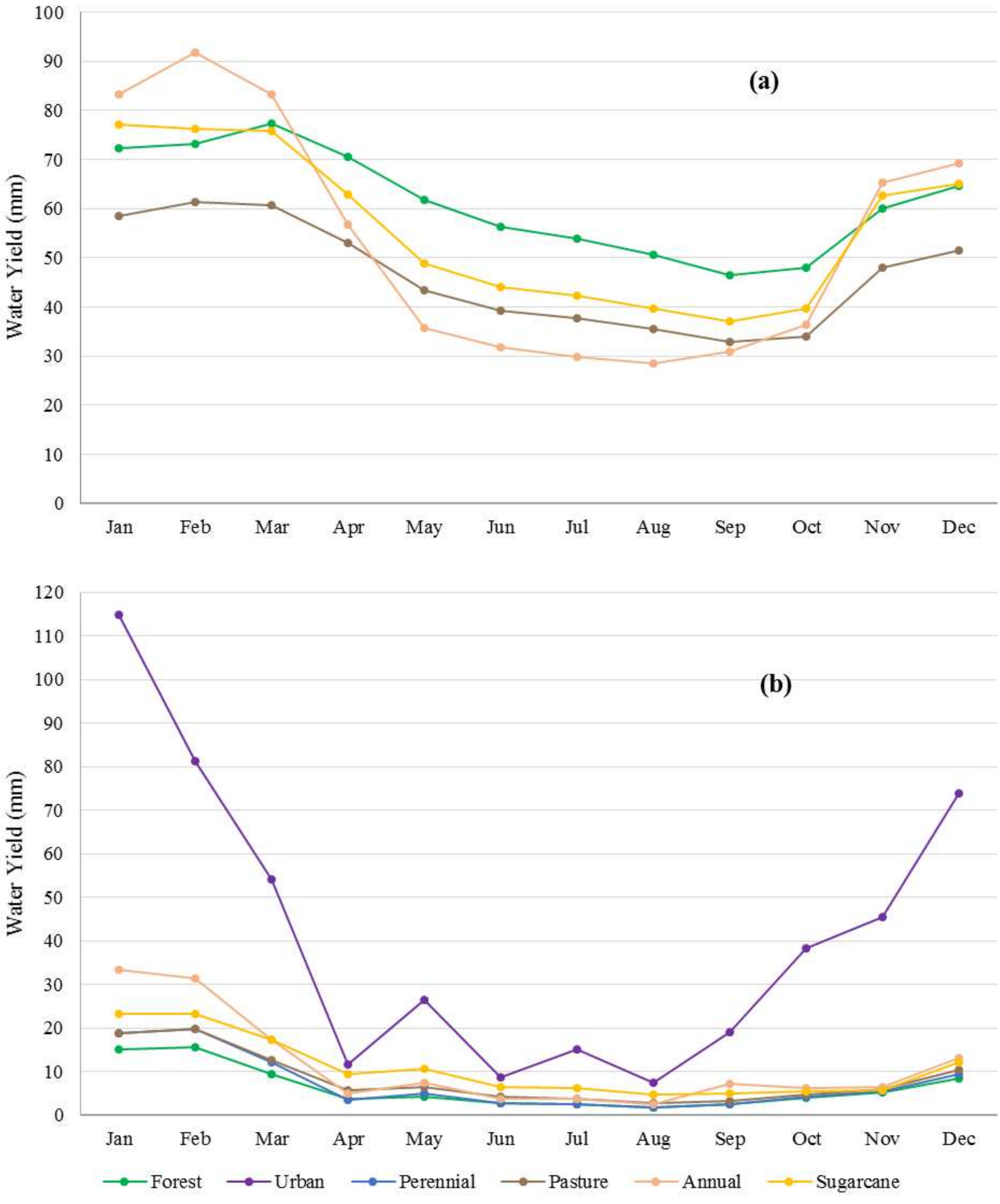
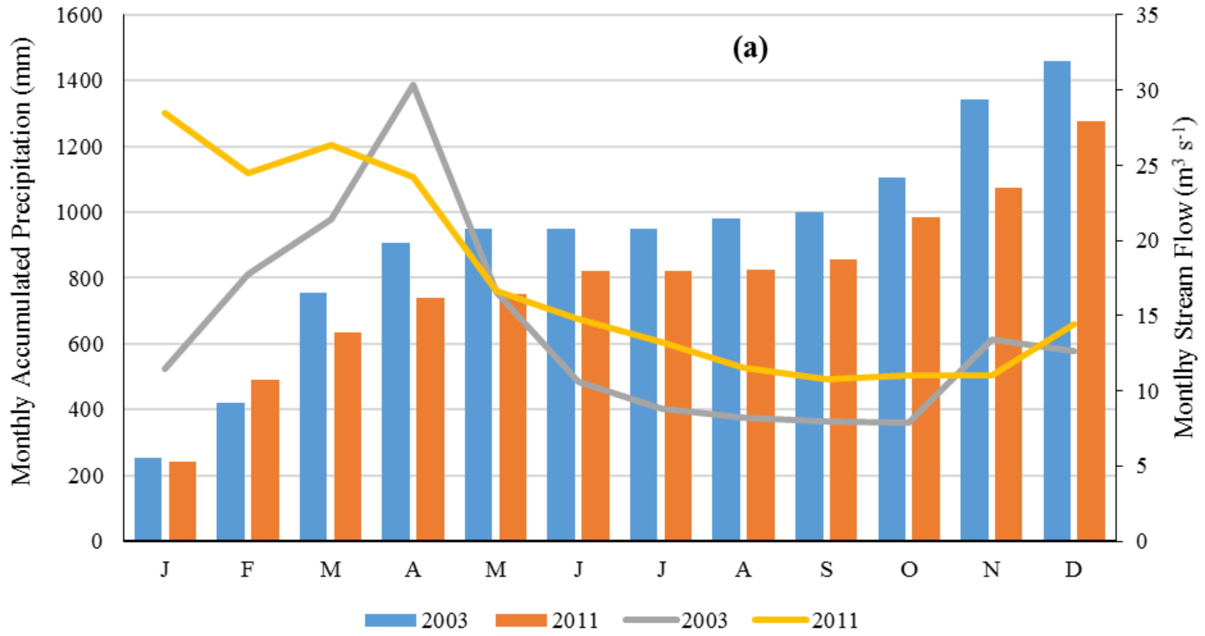


Figure 3.9 Validated SWAT average water yields for all land uses in FMA (a) and MM (b) basins.



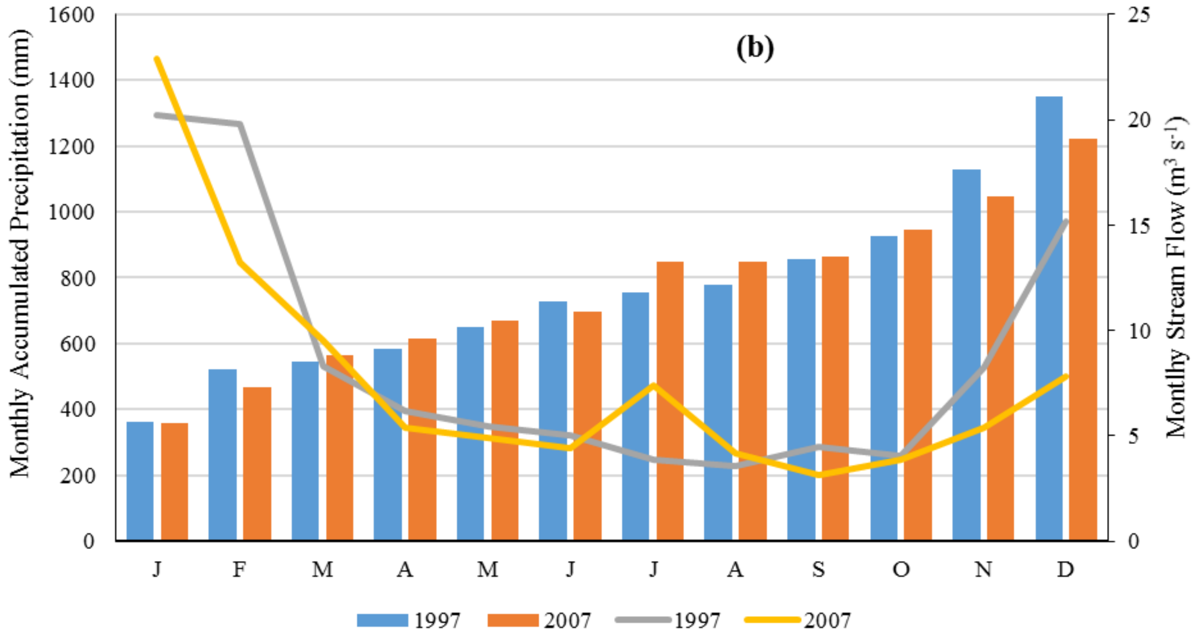


Figure 3.10 Accumulated precipitation (bars) versus average stream flow values (lines) in FMA (a) and MM (b) basins.

In the MM basin (Figure 3.10b), stream flow values in relation to the precipitation were almost the same, which was also in accordance to the expected effects from land use change and water yields. In this case, there were no inconsistencies involving precipitation amounts and stream flow responses as in FMA basin. Nevertheless, a peak in accumulated precipitation from June 1997 to July 1997 (22% of increase in precipitation) caused a high stream flow value in this last month (108%), which evidences the high response of the basin to precipitation events, as previously supposed due to the high level of urbanization. Similar behavior can be observed from October 2007 to December 2007, during which an increase of 46% in precipitation induced a stream flow growth of 400%.

Even though the main assumptions of land use change impacts on stream flow have been confirmed, the high dependence of the precipitation amounts (Guarenghi & Walter, 2016) and also the influence of other parameters as the precipitation amounts from the previous months, make it very difficult to quantify the land use change effects on stream flow from the other possible interferences. Nevertheless, the integrated assessment of the SWAT water balance components (precipitation, water yields and stream flow) enabled a more comprehensive analysis of the land use change effects on water availability.

3.4 Conclusions

During the considered period of evaluation, the assessed basins presented diverse land use change dynamics. In FMA basin, annual crops and sugarcane expanded, while forest and pasture lands reduced. In MM basin, forest and urban areas increased and the remaining land uses stagnated or were reduced.

Successful SWAT calibration and validation were achieved for the assessed basins, highlighting the great potential use of the model in the planning and management of the water resources. On the other hand, as SWAT is an input intensive model, difficulties are expected in input data collection in Brazil, especially regarding soil information. In addition to ensuring a more reliable calibration and validation process, the careful model setup concerning the local crop and management related parameters, as well as the previous evaluation of the stream flow performance for the different runoff methods and the land use changes update over the simulation period, enabled the achievement of consistent results regarding crop evapotranspiration and crop yields in the assessed basins.

In general, water yield results indicate that sugarcane expansion over annual crops tends to increase stream flow in dry periods and decrease peak flows, making the water regime more regular during the year. They also indicate that urban areas expansion increases the stream flow in wet months, hence contributing to flood vulnerability in areas at risk. Despite the difficulties to separate the land use change effects from other stream flow impacting parameters, such as the previous accumulated precipitation, the integrated assessment of stream flow, water yields and precipitation from SWAT model give reasonable qualitative responses in the assessment of the land use change impacts on water resources availability.

For past evaluations, the use of SWAT in a basin with more intense sugarcane expansion should allow more consistent quantification of sugarcane impacts on water resources availability. However, the model has a promising application in the basins planning and management, after successful calibration and validation; possible future land use scenarios or even climate changes could be assessed. Therefore, the quantification of the exclusive sugarcane impacts can be made with the simulation of scenarios considering larger increases in sugarcane areas replacing specific land use classes and stationary conditions for the remaining land uses and water balance components.

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4. ASSESSMENT OF THE LAND USE CCANGE EFFECTS ON CROP WATER USE EFFCIENCY FOR TWO BRAZILLIAN BASINS

Abstract: Even though water availability is a mandatory issue in the sustainability assessment of land use changes, the efficiency in which this resource is used by crops is essential. Provided that water footprint (WF) is one of the most applied indicators to estimate water use efficiency, this study used the WF approach for the assessment of land use change effects on water use efficiency from crops, on a basin level. Two basins were considered in the analysis, one in the state of São Paulo (MM) and another in Goiás (FMA). The input data for the WF estimations derived from a calibrated and validated SWAT model for both basins. Besides the established WF indicator, it was proposed an economic water footprint (EWF) indicator based on the operating profit obtained by farmers with agricultural products. Sugarcane presented smaller WFs indicating that its expansion over all the considered crops is advantageous in both basins, increasing the water use efficiency. Lower WF values for FMA compared to MM basin denoted high water use efficiencies by the crops in the former. Although possible regional constraints about costs and prices, the economic approach presented interesting results in terms of water use efficiency. Sugarcane expansion over other crops only increased EWF when displacing orange and pasture lands. Considering the land use changes in the evaluated period, basin average WFs of crops presented significant changes in neither basins. The basins' EWF, on the other hand, increased in MM and significantly decreased in FMA, both intrinsically related to their land use changes. In general, WF and EWF were very useful in the assessment of land use changes effects on the water use efficiency of a basin. However, issues regarding water availability must consider other water balance components beyond the evapotranspiration.

Keywords: water footprint; evapotranspiration, water yield, SWAT, basin impact assessment.

4.1 Introduction

Sugarcane crop in Brazil surpassed 9 million harvested hectares in the 2015/2016 season, with an expansion of 3.5 million hectares in the last decade (CONAB, 2016). About 50% of the produced sugarcane was used for ethanol production (CONAB, 2016), the main liquid biofuel produced and used in Brazil (Walter et al, 2013). The land use changes driven by the sugarcane expansion has raised concerns about its effects in the water resources availability, as it can affect the water balance through changes in hydrological processes such as evapotranspiration (ET), infiltration, groundwater recharge, base flow, and runoff (Scanlon et al., 2005; Lin et al., 2007).

Even though water availability is a mandatory issue in the sustainability assessment of land use changes, the efficiency in which this resource is used by crops is essential. Water use efficiency can shed some light on the decision-making process regarding the substitution of crops, even across different river basins. The water footprint is one of the most applied indicators to estimate efficiency of water use, comprising crops, energy carriers, among others in Brazil (Hernandes et al., 2014; Scarpare et al., 2016a; Scarpare et al., 2016b) and worldwide (Gerbens-Leenes et al., 2009; Mekonnen & Hoekstra, 2010; Hoekstra et al., 2011; Hoekstra, 2014; Mekonnen & Hoekstra, 2014; Hoekstra, 2016). The WF for crops depends on regional characteristics as climate, soil properties and management. The weighted global average WF of sugarcane is 196 m^3 Mg^{-1} (Mekonnen & Hoekstra, 2010), while in a regionalized study in Brazil the WF for sugarcane ranges from 124 to 170 m^3 Mg^{-1} (Hernandes et al, 2014). Soybeans, on the other hand, feature a much higher global weighted WF, achieving 2107 m^3 Mg^{-1} (Mekonnen & Hoekstra, 2010), whereas in Brazil values were between 1360 and 1781 m^3 Mg^{-1} (Hernandes et al., 2014).

However, the use of the WF approach to assess the effects of land use changes in a river basin requires spatiotemporal variable data on water requirements and yield within the area. Furthermore, spatiotemporal land use changes must also be considered. GIS tools and hydrological models can therefore be extremely useful in the assessment of land use changes effects in the water use efficiency of a basin. SWAT is a process-based semi-distributed ecohydrological model largely employed in the assessment of water balance and hydrological processes in river basins worldwide. It is an open source model which, besides the hydrological processes, has also an integrated crop growth module, which allows the evaluation of crop management practices (mulching, irrigation and soil tillage), crop yield and crop water balance (Gassman et al., 2007; Neitsch et al., 2011; Arnold et al., 2012). Once well calibrated and validated, SWAT can give reasonable results in terms of stream flow, nutrient losses and sediment production in river basins (Douglas-Mankin et al., 2010; Arnold et al., 2012)

This study used the water footprint approach to assess the impacts of sugarcane expansion and derived land use changes on water use efficiency of crops, at a basin level. The input data to estimate the water footprints derived from calibrated and validated SWAT model for two basins, one in São Paulo state (Monte Mor) and another in Goiás state (Fazenda Monte Alegre), which featured different land use change dynamics and diverse edaphoclimatic conditions. Evaluations were made considering the land use changes occurred in a ten-year period. One of the issues when comparing the WF of different crops is the varied composition, purposes and uses among the agricultural products. To cope with this aspect, an economic water footprint is also proposed in this work with the aim to produce a fairer comparison among crops, as economic performance is more linked to crops' purposes than the biomass yield per se.

4.2 Methodology

4.2.1 Study Areas

The water footprint was estimated for crops in two similar basins in terms of drainage areas, one located at São Paulo state (Monte Mor – MM; 698 km^2), and another in Goiás state (Fazenda Monte Alegre basin – FMA; 805 km^2) (Figure 4.1). The latter has an agricultural vocation, being covered by annual crops, forests (Cerrado[7]) and pasture lands, while the former is an urban basin featured by medium-large urban areas, covered mainly by pasture lands and with few areas of sugarcane, perennial (mostly orange) and annual crops. The model was

[7] *Cerrado* is the second largest Biome in South America, occupying about 22% of the Brazilian territory. Due to its biodiversity, Cerrado is recognized as the richest savannah in the world presenting innumerous species of plants and animals.

successfully calibrated and validated for stream flow results in the two basins, considering a period of at least 10 years of simulation (see Chapter 3).

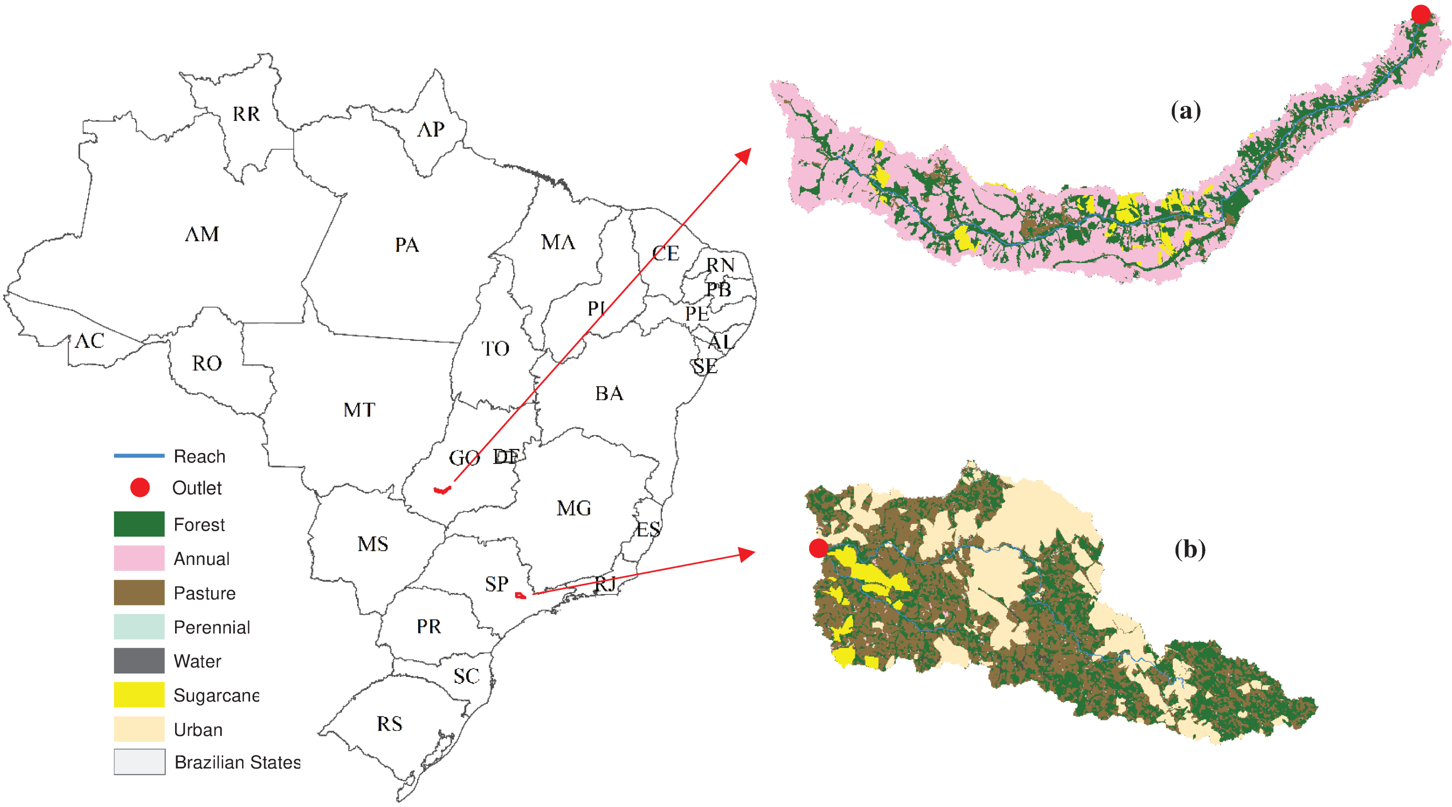

Figure 4.1 FMA (a) and MM (b) basins on Brazilian States map.

4.2.2 Water Footprint Estimation

The methodology to obtain the water footprint for the crops (Pasture, Sugarcane, Annual (Soybean + Corn) and Perennial (Orange)) was based in Hoekstra et al. (2011). Since SWAT simulations were based on rainfed (no irrigation) conditions, only the green water footprint was considered in this case, calculated according to Eq. 1

$$WF(m^3 Mg^{-1}) = \frac{ETa * 10}{Ya} \qquad (1)$$

Where *ETa* is the crop evapotranspiration (mm) and *Ya* is the crop productivity (Mg ha^{-1}). Evapotranspiration and productivity for the crops were provided by the validated SWAT model and were considered as the average values for all the simulated period (about ten years).

In addition to WF, the economic water footprint (EWF) was also evaluated so that crops with different purposes could be compared on a fairer basis. Instead of yields, EWF indicator is based on the economic performance of crops, given by the Operating Profit (OP) obtained by farmers from agricultural products (sugarcane, soybean, corn, cattle and orange) (Eq. 2).

$$EWF\ (m^3 US\$^{-1}) = \frac{ETa * 10}{Ya * OP} \quad (2)$$

Where *EWF* is Economic Water Footprint, *ETa* is the evapotranspiration (mm), *Ya* is the productivity (Mg ha^{-1}) and OP is the operating profit, all for the specific product. Crop evapotranspiration and productivity were also from SWAT model, while the OPs were calculated as the difference between the average selling price and the average total operating costs (TOC) of the agricultural products. These economic parameters were estimated based on a seven-year time series (2008 to 2013 and 2015) of available data. The resulting average values considered in the analysis are reported in Table 4.1.

Table 4.1 Average prices, total operational costs (TOC) and operating profit (OP) for agricultural products.

Parameter	**Units**	**Price (US$)**	**TOC (US$)**	**OP (US$)**
Sugarcane	Mg of stalks	29.03[b]	25.51[d]	3.52
Soybean	60 kg	27.51[c]	12.10[e]	15.41
Corn	60 kg	13.03[c]	8.28[e]	4.75
Orange	40.8 kg	6.52[c]	5.98[c]	0.55
Cattle[a]	15 kg	48.50[c]	38.86[f]	2.99

[a] Considering 0.91 heads per hectare (IBGE, 2006) and 16 arrobas per head (IBGE, 2016b). [b] Prices paid to the farmers (UNICADATA, 2016). [c] (CEPEA, 2016). [d] (PECEGE, 2016). [e] (CONAB, 2016). [f] (IMEA, 2016). Annual crops, orange and cattle were monthly priced in US$. Sugarcane prices and all crops costs were converted from R$ to US$ using the monthly quotations from annual crops prices.

In order to understand the effects of land use change on WF, EWF and ED, average values considering all the crops were calculated for the basin, weighted by the crop areas in the first and in the more recent year within the evaluated period, according to Eq. 3

$$WF_{Basin} \; or \; ED_{Basin} = \frac{\sum_{i=1}^{t} (WF_i or ED_i * A_i)}{\sum_{i=1}^{t} (A_i)} \quad (3)$$

Where WF_{Basin} and ED_{Basin} are the average water footprint and the average evapotranspiration demand in the basin, respectively. *WFi* refers to both the WF and EWF values for the crop or product *i, EDi*, is the evapotranspiration demand for crop *i* and *A* is the area of the crop or product *i* in the basin.

4.3 Results and Discussion

Through the validated SWAT model it was possible to estimate average yields and evapotranspiration rates for all the crops in MM and FMA basins for the simulated period (Table 4.2).

Table 4.2 SWAT average evapotranspiration and yield for crops in FMA and MM basins

Crop	Yield (Mg ha^{-1})		Evapotranspiration (mm)	
	FMA	MM	FMA	MM
Sugarcane	81	81	814	977
Soybean	4	4	436	570
Corn	5	6	362	487
Orange	---	12	---	1100
Pasture	12	6	874	1011

Water footprint for the crops (Figure 4.2) presented the same trend in MM and FMA basins. FMA basin presented, in general, lower values of water footprint especially due to the lower values of evapotranspiration. In this basin, sugarcane was the most efficient crop, with the need of 101 cubic meters of water to produce one Mg of sugarcane stalks. Pasture was in the second place (726 m^3 Mg^{-1}), followed by corn and soybean with 726 and 1101 m^3 Mg^{-1}, respectively.

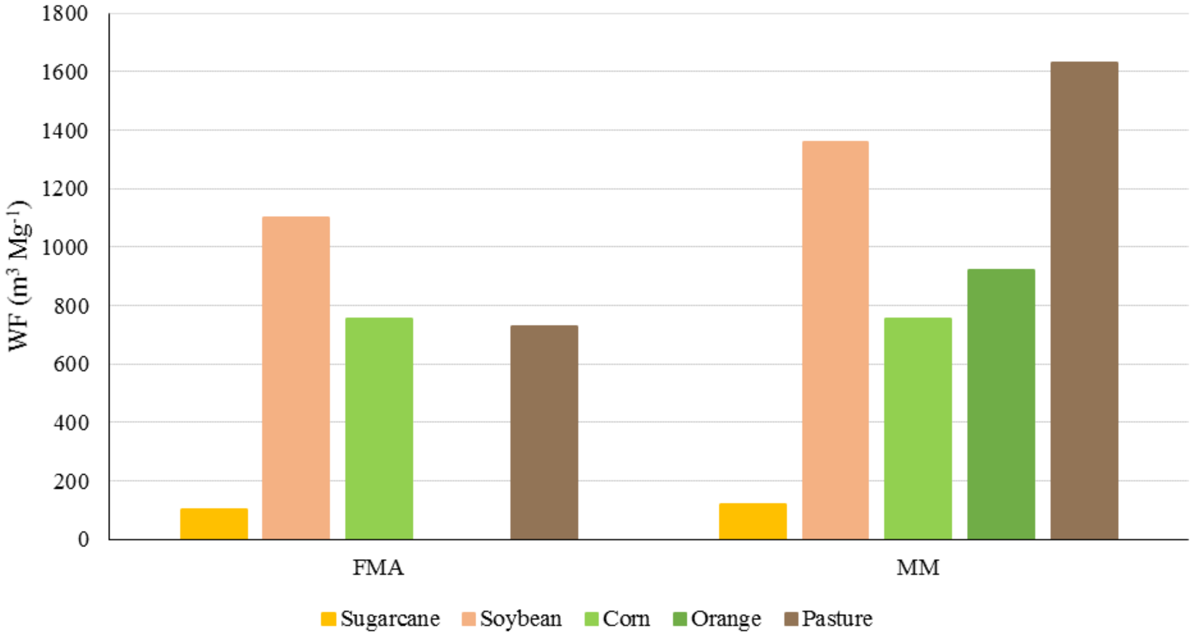

Figure 4.2 Water footprint of crops.

In MM basin, sugarcane was also the most water use efficient crop (121 m^3 Mg^{-1}), followed by corn and orange with 756 and 919 m^3 Mg^{-1}, respectively. Soybean and pasture presented again the more intense water use in terms of crop production, respectively with 1360 and 1630 m^3 Mg^{-1}.

Thus, in both basins sugarcane expansion will certainly decrease the water use intensity in terms of crop production since sugarcane water footprint was considerably smaller than the values of the remaining crops. In FMA basin, differences will be higher when sugarcane replaces soybean (sugarcane WF is more than ten-times smaller than soybean). Considering a soybean-corn rotation practice, water footprint also tends to be smaller when sugarcane replaces annual crops, with a reduction of almost nine times the annual crop WF value.

In the MM basin, the major difference was between sugarcane and pasture lands (sugarcane WF was more than ten times smaller than pasture WF). If sugarcane replaces a soybean-corn rotation, water footprint will be reduced by more than eight times. Besides, orange WF was higher than for corn, but when a corn-soybean rotation is considered (annual crops), both crops presented almost the same WF (919 for orange against 1054 m^3 Mg^{-1} for annual crops).

The difference between the water use efficiency for pasture in the two basins was mainly influenced by the pasture land yields, since the evapotranspiration was higher and the yield was lower for MM basin, which is explained by an assumption in SWAT simulations. According to the satellite images and to Google Earth, pasture lands seemed to be more vigorous in FMA basin when compared to the same land use in MM basin. To capture this difference, the pasture land yields was set to reach a minimum value in FMA simulations, which increased the correspondent yield.

Table 4.3 Average annual evapotranspiration from crops.

	Evapotranspiration (mm)			
	FMA		**MM**	
Sugarcane	814	33%	977	24%
Annual (Soybean+Corn)	798	32%	1057	26%
Perennial	---	---	1100	27%
Pasture	874	35%	1011	24%

Considering a period of one year, crops evapotranspired almost the same amount of green water (Table 4.3) among each other in both FMA and MM basins. Therefore, as sugarcane presented by far the smallest water footprint per Mg of produced stalks, it was possible to conclude that sugarcane expansion over all the considered crops is advantageous in both basins, increasing the water use efficiency per Mg produced without any significant changes to annual evapotranspiration. Comparison between the two basins for the same crop, on the other hand, indicated that the water use efficiency of crops were higher in FMA.

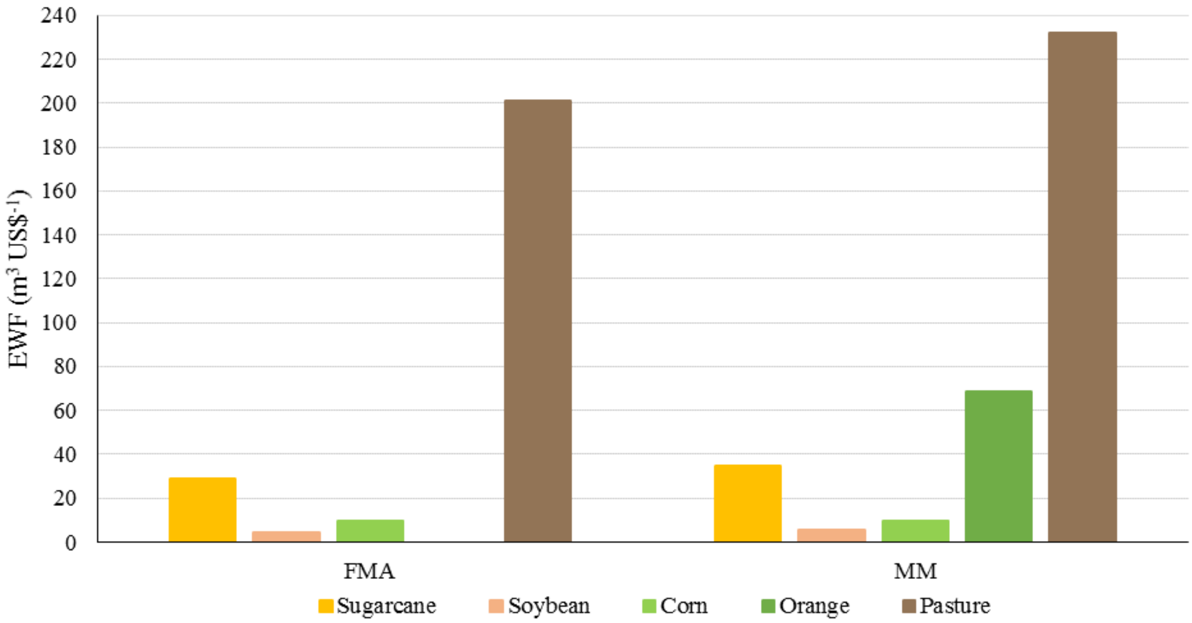

Figure 4.3 Economic water footprint of crops.

With respect to the economic water footprint, FMA and MM basins presented very similar results, with a minor advantage of FMA in water use efficiency. In this case, sugarcane did not keep the same position on the water use intensity ranking, being only the third in FMA and MM basins. Sugarcane EWF achieved 29 and 34 cubic meters of water per dollar earned in FMA and MM basins, respectively. Orange also presented high values of EWF, reaching 68 m^3 $US\$^{-1}$.

On the other hand, even with high values of water footprint for crops, soybean and corn were very efficient in terms of the economic return of the water use, with a minimum of 4 and a maximum of 10 m^3 of water used per US dollar earned, respectively. Considering the soybean-corn rotation, water footprint reached an average of 7 cubic meters of water per US dollar earned.

The highest intensities in water use were found for cattle raising on pasture lands, with EWF values of 201 and 232 m^3 $US\$^{-1}$ in FMA and MM basins, respectively. Thus, considering sugarcane expansion over other crops, the efficiency in water use in terms of economic return will only increase when it displaces orange and pasture lands. In general, in terms of economic water use efficiency, crops performed better in FMA than in MM basin. However, it is important to mention that those estimations are intrinsically associated with operating costs and selling prices, which were very difficult to find in Brazilian databases. The data gathered considered the average Brazilian selling prices and operating costs, which is an important limitation of the analysis, especially for the comparisons between the basins, as they are located in different states, possibly featuring different labor, logistics and management costs.

Lastly, the aggregated water footprint for the basins are presented in Table 5 considering the crop areas in the first and last years of simulation (Table 4.4).

Table 4.4 FMA and MM crop land use changes for the simulated period

Crop	**Area FMA**				**Area MM**			
	2003		**2011**		**1997**		**2007**	
	ha	**%**	**ha**	**%**	**ha**	**%**	**ha**	**%**
Sugarcane	443	1%	3603	6%	2126	6%	2430	8%
Annual	38842	76%	51546	88%	1842	5%	355	1%
Perennial	---		---		1429	4%	416	1%
Pasture	11803	23%	3150	5%	29459	85%	26065	89%

In the FMA basin (Table 4.5), the decrease in pasture lands and the increase in sugarcane areas would be expected to make both WF and EWF to decline. On the other hand, increases in annual crops should increase WF values. In EWF, all the considered land use changes should increase water use efficiency. These tendencies were confirmed by the basin average water footprint from crops, with a small reduction in WF (less than 1%) and a more significant decrease in EWF (almost 59%), considering the changes between 2003 and 2011.

Table 4.5 Water footprint and evapotranspiration demand considering the land use change in the simulated period.

	FMA		**MM**	
	2003	**2011**	**1996**	**2007**
WF (m^3 Mg^{-1})	898	895	1421	1469
EWF (m^3 $US\$^{-1}$)	32	13	192	208
ED (mm)	816	803	970	994

Evapotranspiration demand from crops in FMA basin was not significantly altered (about 2%) during the evaluated period. Thus, it is possible to conclude that the land use changes increased the economic water use efficiency (EWF) within the evaluated period. In terms of water use efficiency per Mg of crop, however, WF was not affected by the changes in land uses, remaining almost the same during the evaluated period.

In MM basin, even with a reduction in absolute area, pasture lands increased its relative participation in basin crop areas (85% to 89%), as almost all crops shrunk within the evaluated period. Even though sugarcane presented an expansion in the considered period, the growth was smaller than the other crops reductions. Thus, because of the larger participation of pasture lands, crop WF for the basin showed a minor increase from 1996 to 2007 (3%). The increase in EWF was slightly higher (8%) since reductions in annual crop areas have negative impacts on water use efficiency with respect to economic earnings. As ED decreased only 3%, reductions in EWF indicate a decrease in economic water use efficiency by the crop areas in MM basin, mainly driven by the higher participation of pasture lands in the crop areas in the basin within the evaluated period.

4.4 Conclusions

Sugarcane presented the smallest WFs indicating that its expansion over all the considered crops would be advantageous in both basins, increasing the water use efficiency per Mg of agricultural product without bringing any significant changes to evapotranspiration. Lower WF values for FMA compared to MM basin denoted high water use efficiencies by the crops in the former.

Although possible regional constraints about costs and prices, the economic approach presented interesting results in terms of water use efficiency. In this case, sugarcane expansion over other crops only increased water use efficiency when it displaces orange and pasture lands. In general, crops also performed better in FMA than in MM basin.

Regarding the effects of land use changes, the basin average water footprint from crops (WF) presented significant changes neither in FMA nor in MM basin in the evaluated period. The EWF, on the other hand, increased in MM basin and decreased in FMA. Reductions in the latter were mainly due to decreases in pasture and increases in sugarcane and annual crops participation in the total crop area in the basin. In MM, economic water use efficiency dropped because of both, the increase of pasture and the reduction of other crops participation in the basin.

In general, WF and EWF were very useful in the assessment of land use changes effects in the water use efficiency of a basin. However, issues regarding water availability must consider other water balance components beyond the evapotranspiration.

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5. ASSESSMENT OF IMPACTS ON BASIN STREAM FLOW ASSOCIATED WITH THE LAND USE CHANGE DRIVEN BY MEDIUM-TERM SUGARCANE EXPANSION SCENARIOS IN BRAZIL[8]

Abstract: The benefits of using bioethanol instead of fossil fuels on the mitigation of greenhouse gases emissions are widely known. However, there is no scientific consensus on the effects of bioethanol feedstock production on the availability of water resources, especially in new areas towards the Cerrado[9] biome. This study assessed the effects of land use change driven by sugarcane expansion on the stream flow in two selected basins, one located in traditional sugarcane areas (Monte Mor – MM), where a stagnation in sugarcane area is expected, and the other in full expansion areas towards the Cerrado biome (Fazenda Monte Alegre – FMA). The evaluation was made through calibration and validation of the Soil and Water Assessment Tool (SWAT) model. Scenarios represented the sugarcane expansion expected for 2030 and, in order to observe trends and magnitudes of the effects, exploratory scenarios with more intense sugarcane expansion were also evaluated. Calibration, validation and uncertainty analysis results were very satisfactory. In MM basin, the predicted sugarcane expansion for 2030 showed no substantial impacts on stream flow, nor on the reference flow (Q90) in flow duration curves. Major expansion seems to increase stream flow values, especially in dry months and with less intensity in wet months, on the other hand, without effects on reference flow. Significant impacts were observed in the urbanisation scenario, which appears to worsen basin management as it increases the flooding risks. In the FMA basin, sugarcane expansion would increase stream flow during the dry season and decrease during the rainy season. The same behaviour was observed in the reference flow, with a rise of 10% when sugarcane holds 45% of the basin's land use. Considering that the riparian and native vegetation areas are not affected by the scenarios, despite the high values of sugarcane evapotranspiration, replacing annual crops and pasture lands with sugarcane appears to regulate the stream flow regime by decreasing stream flow peaks and, consequently, the flood risk, while also increasing water availability during the dry season.

[8] A modified version was presented in the *2015 International SWAT Conference (Oral presentation).*

[9] *Cerrado* is the second largest Biome in South America, occupying about 22% of the Brazilian territory. Due to its biodiversity, Cerrado is recognized as the richest savannah in the world presenting numerous species of plants and animals.

Keywords: SWAT, water resources, sugarcane bioethanol, reference flow.

5.1 Introduction

Brazil retains the largest area of sugarcane cultivation of any country in the world, at 10 Mha of harvest area (IBGE, 2016), and is responsible for approximately one third of the global harvested area and production (Pereira et al., 2013). This vocation dates back to the last century when the impact of the oil shock in the 1970s and, more recently, the introduction of flex-fuel vehicles in the early 2000s motivated the production of ethanol to enlarge the share in the energy matrix for the purposes of improving energy security (Moraes, 2000; Walter et al., 2011; Scarpare, 2013).

In consequence of the increased demand for ethanol, sugarcane field crops expanded, mostly in the São Paulo State, towards the Centre-South region, primarily in the Cerrado (Savannas) environment. Based on the analysis of MODIS satellite images during the 2000–2010 period, it was found that sugarcane mostly replaced pasture (~70%) and annual crops (~25%), while native vegetation accounted for less than 1% of the expanded land use (Adami et al., 2012). Inherent to the monoculture model, the occupation of large areas associated with some agricultural practices raises concerns of possible impacts on local water resources. Moreover, sugarcane is a highly productive crop, thus it is expected to require large amounts of water for development and growth (Pereira et al., 2013a; Pereira et al., 2013b; Hernandes et al. 2014, Scarpare et al., 2016).

One possible consequence of increasing the amount of a particular land use type in a catchment area is the effect on the local hydrological processes (Gedney et al., 2006; Sampaio et al., 2007). Therefore, it is crucial to understand the possible impacts of expansion areas with sugarcane in an increasing water dispute scenario. In this context, stream flow information is often referred to in hydrological analysis, aiming to understand the dynamic characteristic of some rivers or watersheds (Guarenghi and Walter, 2016).

Watershed models can be used to simulate stream flows to be compared with observed data, enabling the evaluation of possible effects of land use changes. One of these tools is the Soil and Water Assessment Tool (SWAT), which is a semi-distributed process-based hydrologic model that can simulate most of the key hydrologic processes at the basin scale (Arnold et al., 1998). The model has already proven to be an effective tool for supporting water resource management for a wide range of scales and environmental conditions across the globe (Gassman et al., 2007). Previous results have shown that, once well-calibrated and validated, the model presents good performance in the simulation of annual water yields and monthly stream flows, thereby corroborating its utilisation for studying the effects of different land use change scenarios over the components of water balance and stream flow (Gassman et al., 2007; Douglas-Mankin et al., 2010).

The main objective of this study was to assess the possible effects of projected land use changes driven by sugarcane expansion on basins' stream flows, considering the estimated increase of ethanol production towards 2030. Two basins were evaluated: one located in a traditional sugarcane area and another in an expansion area in the Cerrado biome. Exploratory scenarios with more intense sugarcane expansion were also evaluated in order to understand the differences and similarities when sugarcane areas replace diverse land uses.

5.2 Methods and Materials

5.2.1 SWAT Input Data

SWAT is a time-continuous physically based model with spatially distributed parameters applied to estimate stream flow, nutrient losses and sediment production in river basins (Arnold et al., 2012). The model has been used worldwide in different scales and basins to predict impacts of management on water resource quality and availability (Gassman et al., 2007; Neitsch et al., 2011; Arnold et al., 2012). The input data consists in basin maps (Digital Elevation Maps (DEM), land use/land cover and soil maps) and specific edaphoclimatic data (soil characteristics, climate data and crop growth and management information).

Two basins with similar drainage areas in the Paraná hydrographic region were assessed (Figure. 4.1). The Monte Mor basin (MM) in the state of São Paulo has a subtropical climate. The drainage area (698 km^2) hosts a traditional sugarcane area comprising Campinas and Jundiaí micro regions. It partially covers twelve municipalities, where a stagnation in sugarcane areas is expected, specifically linked to legal issues in pre-harvest burning and to topography constraints for mechanical harvesting. Satellite images supervised classification from the recent past years showed an expansion in urban areas and also confirmed sugarcane area stagnation. The second studied basin, Fazenda Monte Alegre basin (FMA), is in the municipality of Rio Verde in southwest Goiás. It has a tropical climate located in a region with a strong sugarcane expansion trend. The FMA basin drainage area (805 km^2) is totally covered by Cerrado vegetation (ANA, 2015), pasture and annual croplands.

Digital Elevation Maps were obtained from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), and drainage areas for MM and FMA were defined using the outlets from the Brazilian Water Agency (ANA) flow monitoring points 60.778.000 (FMA) and 62.420.000 (MM) (ANA, 2014).

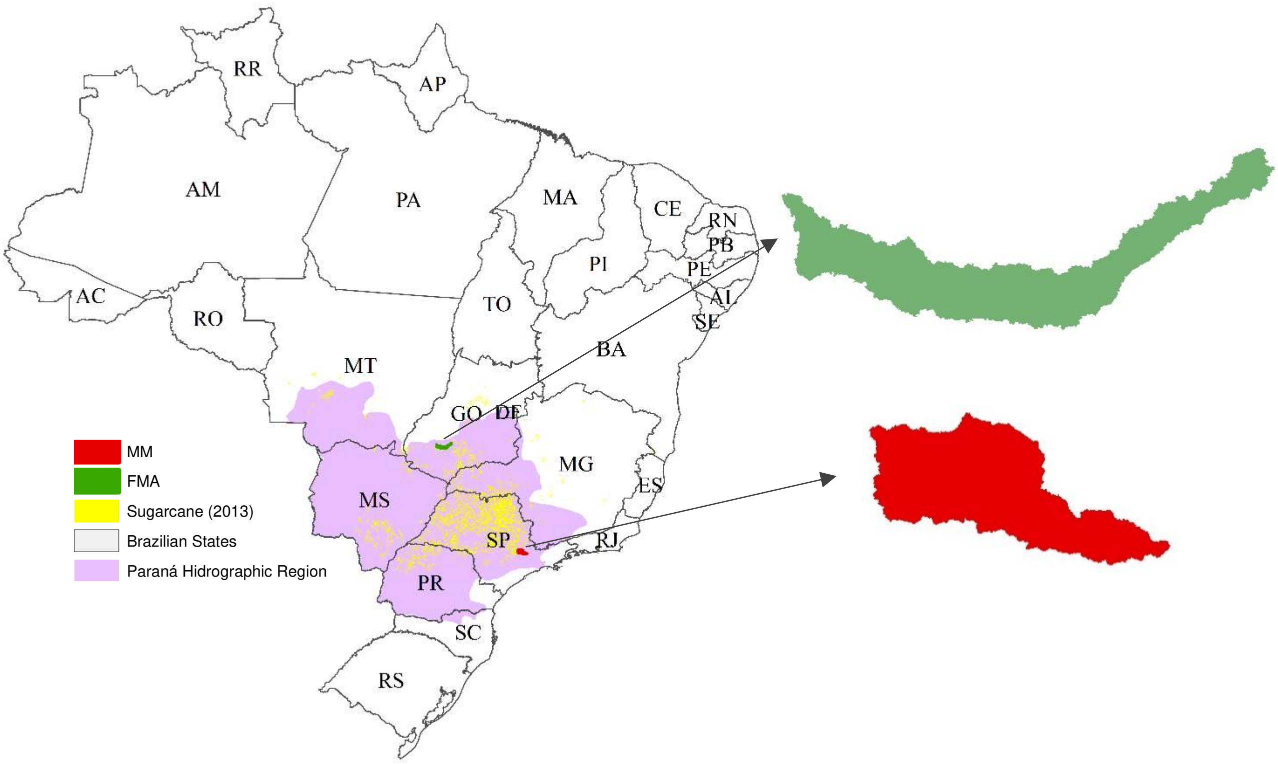


Figure 5.1 Geographic position of FMA and MM basins on Brazilian States map.

Land use maps were prepared using ArcGIS 10.1 supervised classification on LandSat images, supported by Google Earth images and MODIS sensor 1 time-series, when available at the corresponding site and date. Land use updates were made using the "Land Use Update" tool (Pai & Saraswat, 2011). For the MM basin (Figure 5.2b), the land use base map was from 1996 and updates were made in 1999, 2001, 2004 and 2007. In FMA (Figure 5.2a), the base map was from 2004, updated in 2005, 2008, 2010 and 2011. Land uses were classified as annual crops (SOYB + CORN), pasture (PAST), sugarcane (SUGC), Cerrado (RNGB), forest (FRSE), urban areas (UMRD) and perennial crops (ORCD).

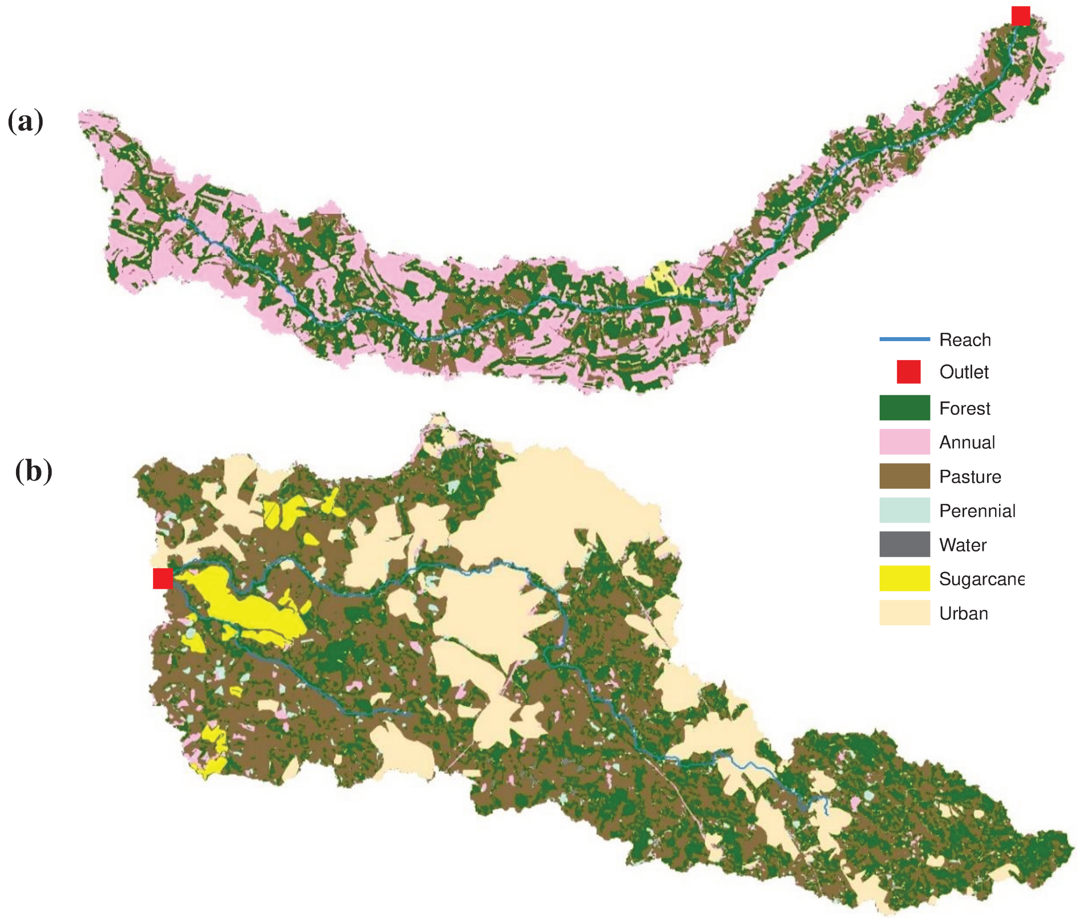


Figure 5.2 Land use base maps classified in sugarcane, forest, annual crops, pasture, perennial crops, water and urban areas for FMA (a) and MM (b) basins.

Climatic inputs (maximum and minimum air temperature, solar radiation, relative air humidity, and wind speed, all in daily time-step) were obtained from the National Centers for Environmental Prediction – Climate Forecast System Reanalysis (Saha et al., 2010; Saha et al.,

2014) in a 38 km grid. Precipitation data was collected from ANA's rain gauge stations in the FMA and MM basins and the data gaps were filled by the SWAT weather generator WGEN (Neitsch et al., 2011; Arnold et al., 2012).

Soil maps for the MM basin were provided by the Agronomic Institute of Campinas (IAC), on a 1:500,000 scale. For the FMA basin, the soil map was found in Goiás State Geosystem Information (SIEG), on a 1:250,000 scale (SIEG, 2014; Oliveira et al., 1999). The physicochemical soil parameters for MM soils were obtained from a public database compiled by the Brazilian Agricultural Research Corporation (EMBRAPA, 2014) and from Lima et al. (2014). Pedotransfer functions were applied in the estimations of the available water capacity and the saturated hydraulic conductivity. Further details on basin, climatic, land use and soil data sources and definition can be found in Chapter 3.

5.2.2 Model setup, Calibration and Validation

Inconsistencies concerning the leaf area index (LAI) and the dormancy period (Wagner et al., 2011; Da Silva, 2013; Strauch & Volk, 2013; Bressiani et al., 2015) were minimized through adjustments in management and crop files. For annual crops, a soybean/corn rotation was used. Concerning sugarcane, a six-year cycle was considered and for the remaining perennial cultures, the dormancy period constraints were diminished through the "harvest only" and the "beginning of growing season" operations scheduled during the winter season.

After the model setup for Brazilian conditions, calibration, validation and an uncertainty analysis were made using the SUFI2 algorithm in SWAT-CUP (Abbaspour et al., 2004; Abbaspour et al., 2007; Abbaspour et al., 2015), considering all the SWAT parameters directly involved in the stream flow process (Arnold et al, 2012; Salles, 2012; Barbarotto Jr, 2014). Model calibration and validation were evaluated using the correlation coefficient (R^2), the percent bias (PBIAS), the RMSE-observations standard deviation ratio (RSR), the Nash-Sutcliffe efficiency (NSE) and the coefficient of determination multiplied by the linear regression coefficient (bR^2) (Gassman et al., 2007; Moriasi et al., 2007; Bressiani, 2015). Stream flow calibration and validation performance were satisfactory for the two watersheds (Table 5.1).

Details on model setup, calibration, uncertainty and validation processes can be found in Chapter 3.

Table 5.1 Stream flow calibration and validation performance.

Statistical Parameters		Calibration + Validation	
FMA	**R^2**	0.83	Satisfactory[a]
	bR^2	0.74	Satisfactory[b]
	NS	0.82	Very Good[c]
	RSR	0.43	Very Good[c]
	PBIAS	-1.32	Very Good[c]
MM	**R^2**	0.75	Satisfactory[a]
	bR^2	0.64	Satisfactory[b]
	NS	0.74	Good[c]
	RSR	0.51	Good[c]
	PBIAS	1.62	Very Good[c]

[a] Gassman et al. (2007); [b] Bressiani (2015); [c] Moriasi et al. (2007).

5.2.3 Scenarios Definition and Assessment

Land use change scenarios were assessed considering two sugarcane expansion intensities. For the first one, the sugarcane expansion expected to occur from 2012 to 2030 (expansion scenarios) was estimated based on economic scenarios for future ethanol supply and demand. For the second one, the basins were stressed, considering a larger sugarcane expansion, replacing different land uses, in order to intensify possible hydrological impacts on the basin's stream flow (exploratory scenarios). In the MM basin, an additional exploratory scenario was considered with the aim to evaluate the expansion of urban areas, which is a land use change trend in this region. These land use change scenarios (expansion and exploratory scenarios) were reproduced in the validated model using the LUP module.

Expansion scenarios were based on the results from the Brazilian Land Use Model (BLUM), which is a partial equilibrium economic model for the Brazilian agricultural sector (Nassar et al., 2011). Scenarios from BLUM, as well as the water resources assessment in this study, were made in the context of a research project funded by Fapesp and developed by researchers from CTBE, Unicamp and Utrecht University. Sugarcane expansion estimations were based on future Brazilian ethanol demand and supply scenarios, founded on basic macroeconomic variables such as the world and the Brazilian Gross Domestic Product (GDP), oil prices, the Brazilian population, sugarcane yields, and total ethanol and gasoline production. The economic modelling, however, was not part of the present work.

It was estimated almost 4 Mha, in the 2012 to 2030 period, of sugarcane land expansion, achieving 13.6 Mha of sugarcane area in Brazil in 2030. Results were regionalised in the Piracicaba (PI) and Southwest Goiás (SW-GO) micro regions, where MM and FMA are respectively located, producing a sugarcane area increase of 19% and 85%, respectively. For 2030 scenarios, it was considered that the same expansion that occurred in the PI and SW-GO micro regions (as a percentage) would also occur in the MM and FMA basins, respectively. As in this work the expansion was estimated considering the 2012–2030 period, in the MM basin, the sugarcane expansion from 2007 (last model update) to 2012 was estimated through the CANASAT sugarcane maps (Rudorff et al., 2010). Thus, from 2007 to 2030, sugarcane is expected to expand from 2430 to 3443 hectares in the MM basin. In the FMA basin, sugarcane areas would increase from 3587 to 6536 hectares.

Land use updates in SWAT for 2030 and exploratory scenarios were made considering the sugarcane and other land use distribution from the base maps. The land use changes in the LUP module can only be updated in previously defined land uses on base map sub-basins (Pai & Saraswat, 2011). Land use changes, in hectares and in percentages, as well as the descriptions for the considered scenarios for MM and FMA areas, are given in Table 5.2. Sugarcane expansion scenarios were made considering the maintenance of the areas classified as forest (natural vegetation fragments, planted forests and riparian areas). Moreover, sugarcane new areas were preferably expanded nearby previous sugarcane areas regarding economic and logistic matters, e.g., the proximity to the mills, the land prices, the plot sizes, etc.

The impact assessment of sugarcane expansion was made by comparing the monthly values of basin evapotranspiration and basin water yield from the different scenarios. Water yield represents the amount of water that contributes to the basin stream flow (Arnold et al., 2012). The impact of sugarcane expansion in stream flow in each scenario was quantified in terms of the stream flow gap (%), defined as the monthly average (± the mean variance) difference between the scenario results and the validated stream flow values.

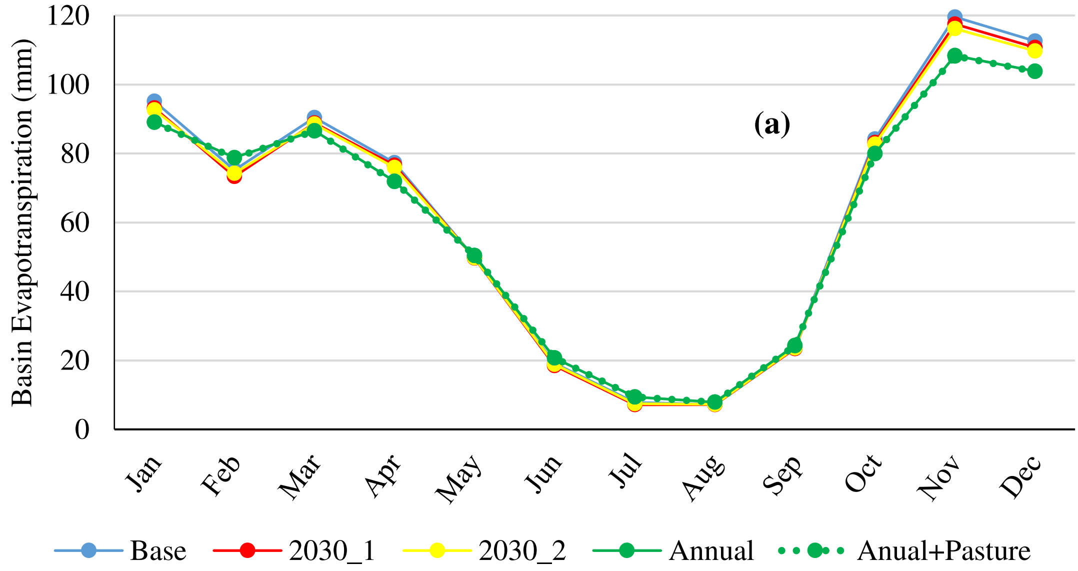
In addition, flow duration curves were constructed for the FMA and MM basins, as recommended in the manual for water use permits from ANA (National Water Agency), in order to identify possible impacts on the reference flow (RF). RF is the value employed as a limit in water use grant decision-making. In this study, RF was represented by Q90, which means that stream flow values in the basin are equal or higher than the Q90 value in 90% of the considered time (ANA, 2011; ANA, 2013).

Table 5.2 Scenarios description.

Basin	Scenarios	Descriptions	Land Use Change	
			Hectares	% of the basin
FMA	2030_1	2030 expected sugarcane expansion replacing all available pasture area (in sub-basins with sugarcane) and the remaining expansion of annual crops	6,137	8
	2030_2	2030 expected sugarcane expansion replacing annual crops	6,137	8
	Annual	All available annual crop areas (in sub-basins with sugarcane) replaced by sugarcane	32,212	40
	Annual+Pasture	All available annual crop and pasture areas (in sub-basins with sugarcane) replaced by sugarcane	35,893	45
MM	2030	2030 expected sugarcane expansion replacing pasture areas	1,330	2
	PAST	All available pasture areas (in sub-basins with sugarcane) replaced by sugarcane	12,729	18
	URB	All available sugarcane areas (in sub-basins with urban areas) replaced by urban areas	1,461	2
	SUGC	All available pasture, annual and perennial crop areas (in sub-basins with sugarcane) replaced by sugarcane	13,976	20

5.3 Results and discussion

Figures 5.3 and 5.4 show monthly evapotranspiration and water yield, respectively. Evapotranspiration and water yield were compiled for the Base scenario (without changes in land use) and for the expansion scenarios described in Table 5.2.



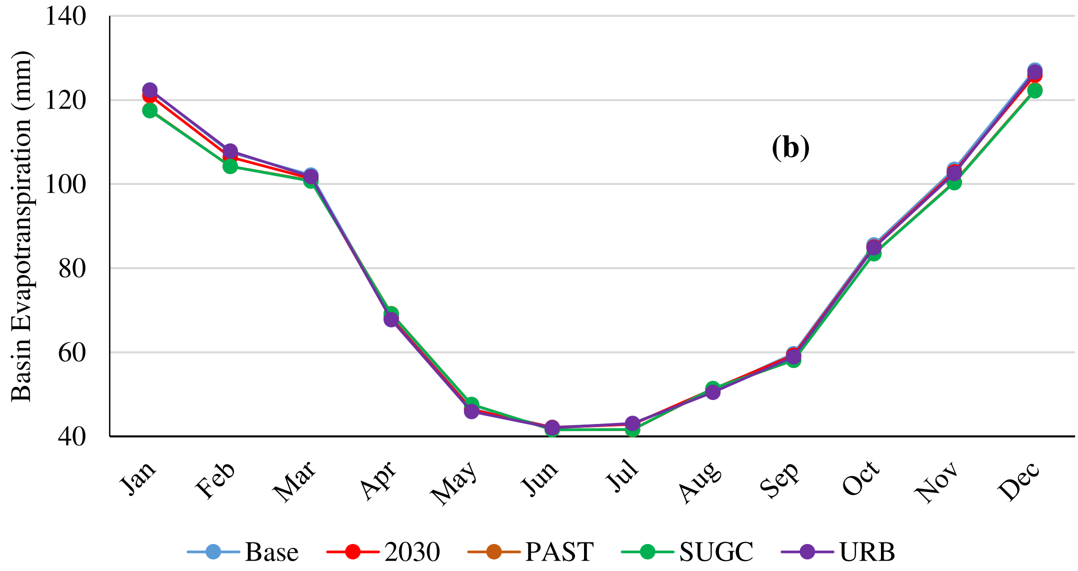


Figure 5.3 Monthly average evapotranspiration for FMA (a) and MM (b) basin scenarios.

Simulations results showed that monthly evapotranspiration amounts were very similar among the considered scenarios, either in MM or FMA basins. Slight differences were observed in Annual and Annual+Pasture scenarios, when sugarcane replaced 40% and 45% of the annual crops and pasture lands in FMA basin. In this case, evapotranspiration presented a minor reduction in wet months. The same behaviour was observed in SUGC scenario in MM basin.

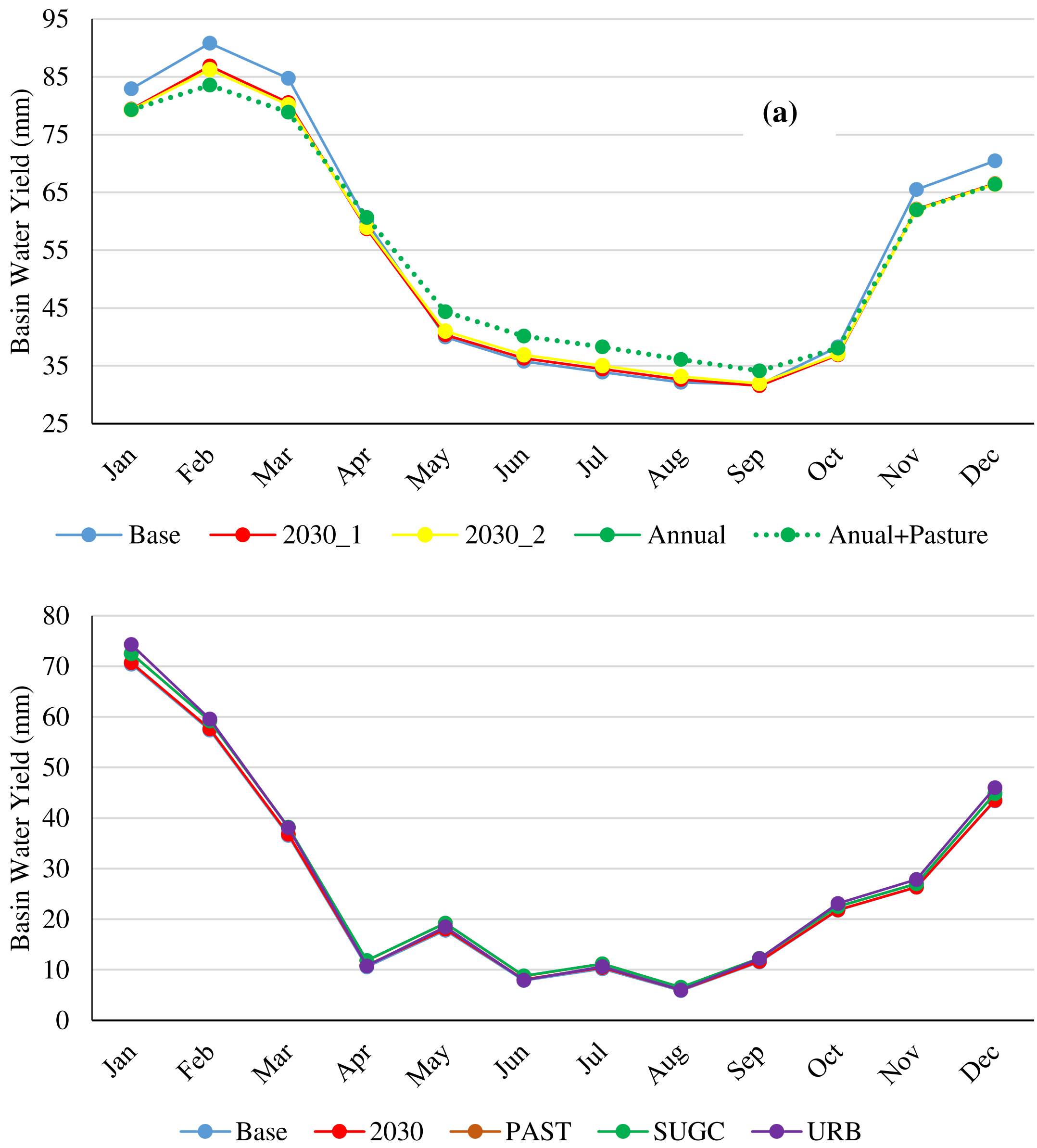


Figure 5.4 Monthly average water yields for FMA (a) and MM (b) basin scenarios.

Considering the two basins, the average sugarcane evapotranspiration in the simulations results was 900 mm, while pasture lands presented an evapotranspiration of 940 mm. According to the recent studies in Brazil, sugarcane expansion over annual crops should increase evapotranspiration (Pereira et al., 2013; Hernandes et al., 2014; Filoso et al., 2015; Watkins Jr. et al., 2015; Guarenghi & Walter, 2016). In fact, simulations for the two basins returned higher evapotranspiration for sugarcane when compared to soybean (500 mm) and corn (425 mm). On the other hand, annual crop areas in Brazil are usually double cropped, with a soybean crop season that starts in October and ends in February, followed by a winter corn that is cultivated from February to June/July (MAPA, 2015). Thus, sugarcane expansion scenarios did not increase the evapotranspiration in the basins as the average evapotranspiration from annual crop areas, considering a soybean/corn rotation, was 925 mm.

Regarding the contributions to the stream flow in FMA from October to December and from January to April (rainy season), the more the sugarcane expands, the more the water yields decreases when compared to the Base scenario values. For dry months (April/May to September/October), on the other hand, contributions to the basin stream flow grew as sugarcane expanded over previous annual crops and pasture lands. Therefore, as water yield is the main contributor to the basin stream flow, sugarcane expansion in FMA basin is expected to decrease flow values in rainy season while increases the basin stream flow in dry months.

For MM basin slight differences among the scenarios were observed for water yields. In this case, even if the variations were minor, sugarcane expansion appeared to increase the stream flow contributions in all the considered months. Urban expansion scenario (URB), on the other hand, showed an opposite trend when compared to the sugarcane expansion effects in FMA basin, i.e., the more the urban areas expand over sugarcane areas, the more the contributions to the MM basin stream flow decrease in dry months and increase in wet periods.

Figure 5.5 shows the stream flow gap results for all land use change scenarios considered. Gaps for the FMA basin are shown in Figure 5.5a, while Figure 5.5b presents the stream flow gaps for the MM basin.

In FMA scenarios, as sugarcane increased participation in the basin's land use, increased effects on stream flow would be observed. In general, during the dry period (from May to October), the more sugarcane crops replace annual crops, the more the stream flow gaps increase, reaching almost 15% (i.e., projected stream flows would be almost 15% above the validated values). From November to April (rainy season), the stream flow gaps are always negative. In MM basin scenarios, the stream flow gaps are similar to FMA results, with major effects in dry months. The more sugarcane expands over pasture and crop areas, the more the stream flow values increase. Moreover, gaps were always positive in MM basin, increasing stream flow even in wet periods. On the other hand, results were minor in MM basin, peaked at 7%, with the majority of the values between 0% and 5%.

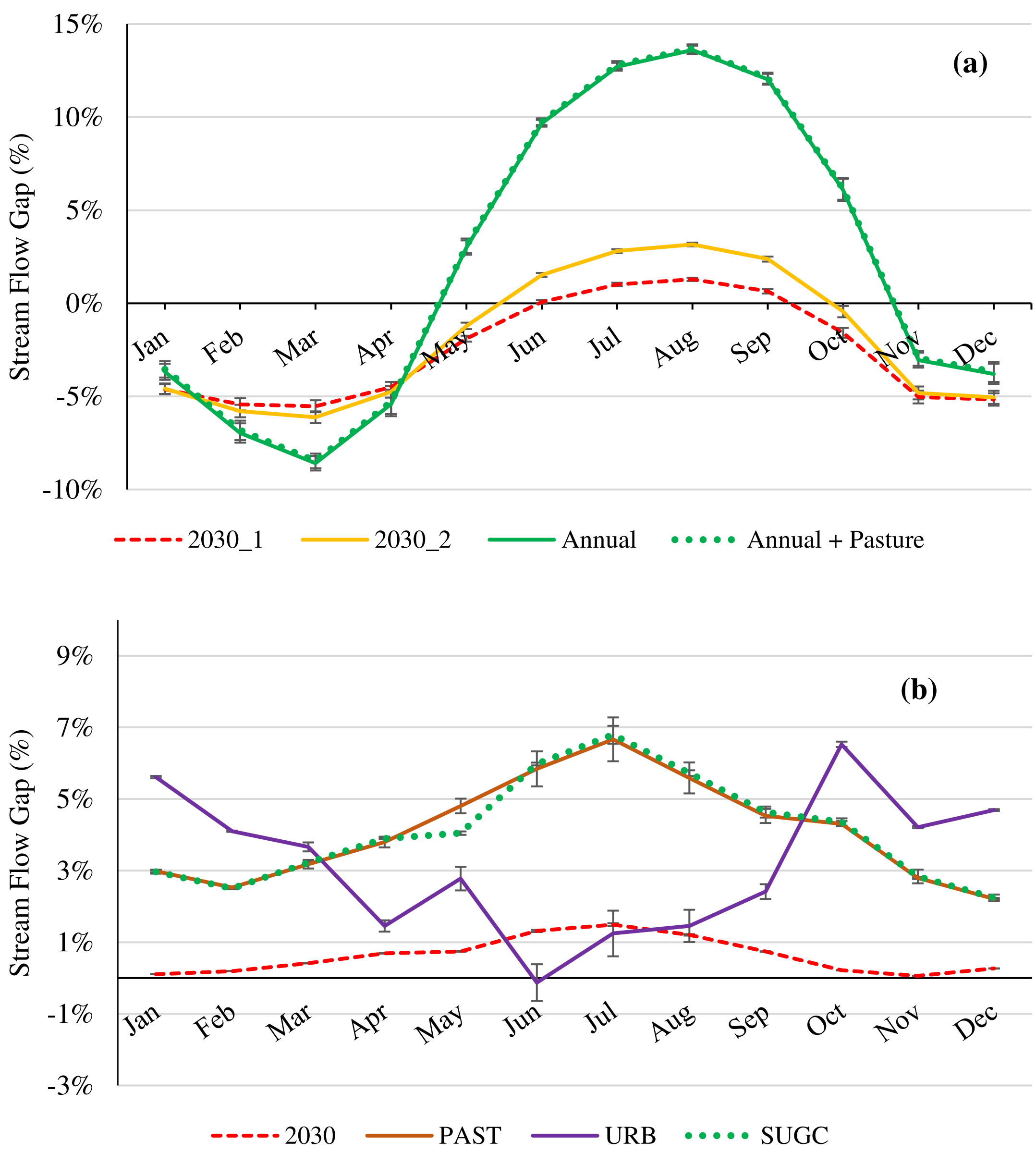


Figure 5.5 Stream flow gaps in the FMA (a) and MM (b) basin scenarios.

The two future scenarios of sugarcane expansion (2030_1 and 2030_2) for the FMA basin presented similar results, with slightly more evident impacts when sugarcane replaces annual crops. In both scenarios, the stream flow gaps for the dry periods are between -1% and 3%. From November to April, the values were negative, achieving a minimum value of -6%. According to the simulations, expected sugarcane expansion for 2030 seems to have no significant effect on the MM basin stream flow as the gaps are always below 1.5%. In some way, this result was already expected as the expansion of sugarcane attained only 2% of the

MM basin area. However, in the FMA basin, sugarcane expansion projected for 2030 would produce visible impacts on stream flow. The increase in sugarcane crop areas, representing 8% of the basin area, is projected to increase stream flow in the FMA basin outlet during the dry months and decrease stream flow during the wet months.

In general, the exploratory scenarios helped make clear, in a more systematic way, the dynamics of the sugarcane expansion effects. In the MM basin, as the 2030 sugarcane predicted growth is negligible, the exploratory scenarios allowed for a more assertive assessment of the sugarcane expansion effects on stream flow. Similarly, in the FMA case, the scenarios with strong sugarcane expansion can confirm the trend of land use change effects on the basin stream flow.

Annual and Annual + Pasture scenarios followed the results observed in the previous scenarios in the FMA basin, but with a certain intensification of the effects. In other words, when sugarcane replaces annual crops or pasturelands, the stream flow in dry months tends to increase even more than in 2030 scenarios, confirming the observed tendency. On the other hand, stream flow gaps that were negative in wet months for BLUM scenarios were even lower for exploratory scenarios, reaching almost -9% in March.

These stream flow and water yield results in the FMA basin indicate that sugarcane effects on stream flow during wet periods are more similar to those found for forests compared to those observed for annual crops or pasture lands, since it appears to regulate the surface runoff and shows a reduction in the peak stream flow values (Bonnel, 1993; Costa et al., 2003; Bruijnzeel, 2004; Balbinot et al., 2008).

Considering the PAST and SUGC scenarios in the MM basin, with almost 13,000 hectares of pasture and other cropland replaced with sugarcane (about 20% of the basin area), simulations indicate that the advance of sugarcane crops over previous pasture lands leads to an increase of the stream flow values. Stream flow gaps ranged from 3 to 7% of growth. Hence, differently from FMA results, sugarcane expansion in MM basin seems to increase both dry and wet flows, which suggests more attention on flood vulnerability. However, even with 20% of sugarcane occupation increase, stream flow gaps for rainy season achieved 3% on tops, indicating minor issues regarding peak flows.

The URB scenario also features a change of only 2% in the MM basin land use distribution, but in this case, urban land cover would replace all available sugarcane areas, as expected in some areas, especially those with slopes above 15% (non-mechanisable areas). The results show that in this scenario, even with a very small change, effects on stream flow are evident, reaching an average increase of 7% in October. The increments are possibly related to the typical rise in soil impermeability due to the urbanisation process, which favours the surface runoff occurrence, especially in intense precipitation events (Shuster et al., 2005; Yan et al., 2013).

In general, although urbanisation increases stream flow, it is expected to worsen the basin's management as it increases, in particular the peak stream flows, harming the flood control. Moreover, urbanisation usually brings water quantity and quality problems derived from high and concentrated water withdrawals and the disposal of untreated sewage in the channels (ANA, 2012; Wang et al., 2014; Guarenghi and Walter, 2016).

The behaviour of the flow duration curves for the considered scenarios followed different trends in the two considered basins. In the FMA basin, curves differed among each other in the periods where the stream flow values showed low permanence (peak values), as well as in periods of high stability (Q70 to Q95). The MM basin showed dissimilarity among the scenarios only up to Q20, with no significant differences among the curves in periods of stream flow high permanence. The trends confirm the stream flow gap results, such as in the effects of FMA land use changes during rainy and dry seasons, while in the MM basin, the impacts occur especially in the peak stream flow values, with no substantial changes in low values.

Regarding the FMA basin, Annual and Annual+Pasture scenarios show increases in stream flow trends above 50% and a decrease below 25% of permanence, with substantial effects in scenarios with more sugarcane expansion. In this case, the reference flow (Q90) changed from 12.8 to 14.1 $m^3 s^{-1}$, indicating an increase of 10% in the limit for water use grant decisions. Despite the increases in stream flow in the MM basin, expected expansion in sugarcane areas apparently would not impact the flow duration curve when compared to validated values.

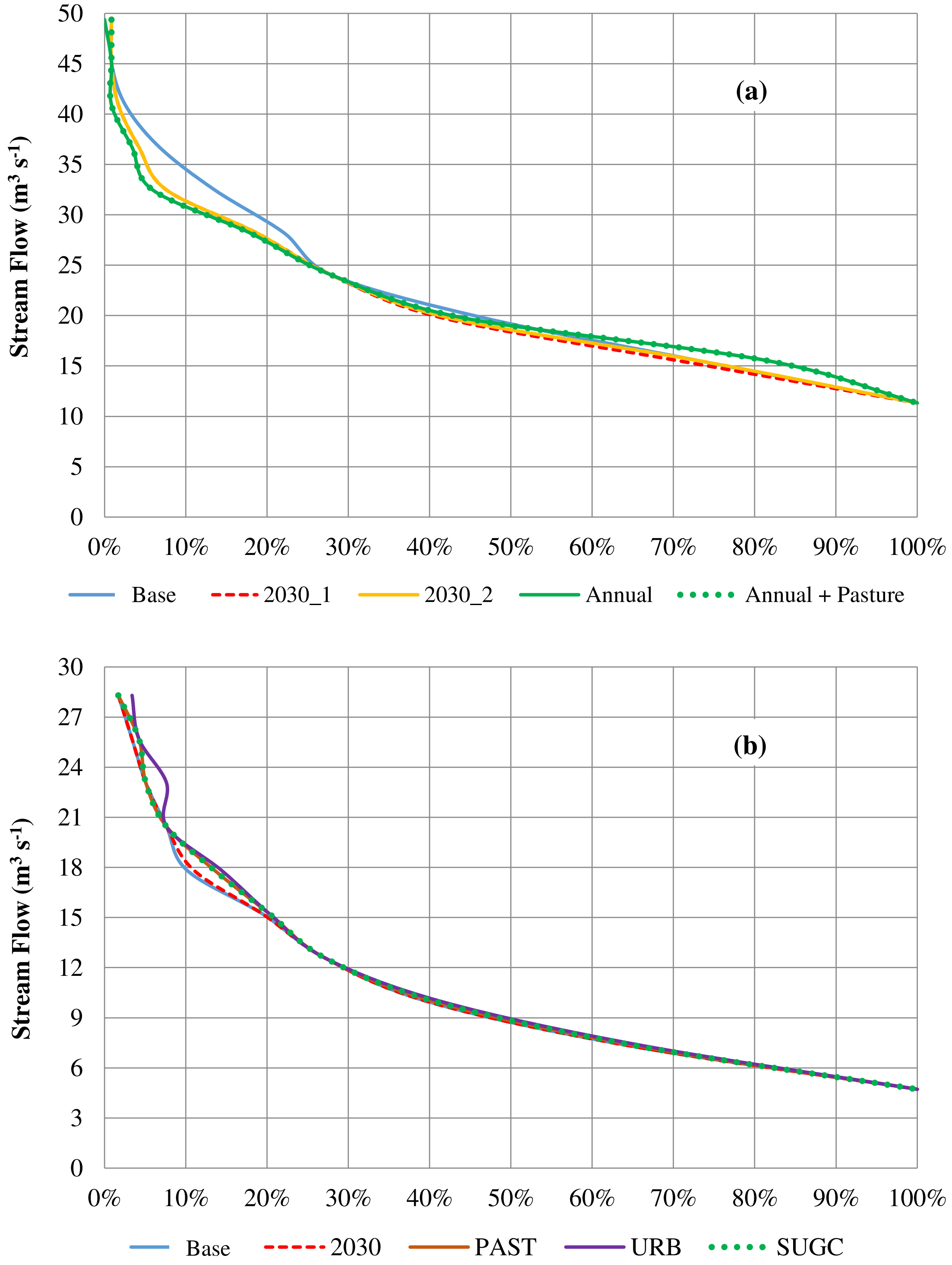


Figure 5.6 Flow duration curve for validated (Base) and for land use change scenario stream flow values in the FMA (a) and MM (b) basins.

The basin's outlet flow depends on several factors, such as land use and land cover, as well as soil characteristics, rainfall and other specificities that influence interception, evapotranspiration, infiltration and other processes (Neitsch et al., 2011). Although contribution areas are similar in both assessed basins (the FMA area is only 15% larger than is the MM), Q90 for validated stream flows are very discrepant, reaching 12.8 and 5.5 $m^3 s^{-1}$ in the FMA and MM basins (more than 130% difference), respectively. The stream flow amplitude during ten years of evaluation shows that, in the MM basin, the higher values of stream flow are almost six times higher than Q90 (30 $m^3 s^{-1}$), while the FMA peak flows are around four times higher than are the Q90 values. This suggests that the FMA basin has a more regular stream flow regime than MM, possibly due to the high level of urbanisation in the latter against a basin with no urban areas in the former.

Another important factor that affects stream flow in the basin's outlet is the excessive water withdrawals and the untreated sewage disposal in the watercourses. The MM basin is located in a region that has experienced several problems concerning water quality and quantity, particularly linked to the high level of urbanisation (ANA, 2012). In addition, although forest areas (which include riparian areas, planted forests and fragments of natural vegetation) are similar in the two basins, riparian areas are more abundant in the FMA basin than in the MM basin (Figure 5.2), which is associated with the notion that lower volumes of water withdrawals certainly contribute to larger stream flow values and to a more regular stream flow regime.

5.4 Conclusions

According to the simulations, the expected sugarcane expansion for 2030 seems to have no effect on the MM basin stream flow. As sugarcane expansion is envisaged to be negligible (2% of the basin area), no substantial impacts are expected on either stream flow or on reference flow in flow duration curves. In scenarios with more significant sugarcane expansion, increases in stream flow are noted, but without changes in the flow duration curve. Urbanisation showed substantial impacts on stream flow, especially in peak values, which intensifies the risk of flooding in the basin. In addition, urbanisation had no positive impact on reference flow, which is very important in terms of basin water availability.

Regarding the FMA basin, the replacement of other land uses by sugarcane, especially annual crop areas, is expected to increase the stream flow at the basin's outlet during the dry season and decrease during the rainy season, which points toward a more regular stream flow. Despite the fact that the results show significant reductions in peak flows, which possibly decreases the annual average stream flow at the basin, the reference flow was positively impacted by the flow increases during dry period, with a rise of 10% in Q90 when sugarcane holds 45% of the basin's area.

In all scenarios, sugarcane expansion would favour the water availability in the assessed basins, provided that riparian and native vegetation areas are not affected. In general, although water availability and water balance are intrinsically linked to the local characteristics of each basin, replacing annual crops and pasture lands with sugarcane appears to regulate the stream flow regime.

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6. FINAL REMARKS

In general, the recent sugarcane expansion occurred mainly in São Paulo state and towards the Cerrado areas, replacing annual crops and pasture lands. Expansion to new areas, with different edaphoclimatic conditions, as soil water capacity and rainfall regimes, may demand irrigation practices to maintain traditional sugarcane yield performances. About 95% of sugarcane are cultivated in Paraná hydrographic region (HR), which was also the hydrographic region where 95% of the recent expansion has occurred.

Paraná HR presents the biggest water demand in Brazil and has been showing, over the last years, several issues on water quality and quantity. Therefore, it is important to promote new research and public policies concerning water resources management in this HR. Oriented expansion and responsible water use and management will certainly aid to assure a satisfactory water supply.

There is a lack of data and information about sugarcane expansion and related impacts on water resources in Brazil as most of the results were inconclusive about the impacts of sugarcane farming and its expansion. Studies usually performed qualitative analysis and considered the water balance components in a separated way. Nevertheless, water footprint for sugarcane crop were always lower when compared to annual crops and pasture lands, leading to a larger biomass productivity in terms of committed water.

The use of SWAT model in the assessment of land use change impacts on water resources generates satisfactory and more conclusive results with regard to changes in water availability, as extensively reported in the literature. Advantages lie in the capacity to integrate different water balance components at the same time and space, thus enabling an integrated assessment of the land use changes effects on the evapotranspiration, crop yield, stream flow, precipitation, runoff, water yield, and others. Besides, it is an open source and an open code model with an available and well documented theoretical basis. On the other hand, similarly to other ecohydrological models, SWAT requires a significant volume of input data regarding soil, climate, land use and crop information.

This work had as the main objective to assess the effects of land use change associated with sugarcane expansion to water resources availability. The effects were evaluated in two Brazilian basins with different sugarcane expansion dynamics, considering the recent land use changes as well as possible scenarios for future ethanol production. The aim was to contribute to a consistent impact assessment of land use change driven by the recent sugarcane expansion and its impacts on water resources availability, indicating a practicable scheme to analyse this subject in order to support the decision-making process about future policies and actions concerning a sustainable ethanol production in Brazil.

Brazil is a large country and data is unevenly distributed and not always available over its territory, which made data gathering one of the most time intensive stages of the SWAT modelling. For this particular work, the main difficulties in data collection were found in soil data and soil maps. Land use and land use change also demanded considerable time as the only way to obtain reliable information on that was through the classification of satellite images for the assessed period.

The ArcGIS supervised classification was satisfactory, allowing an assessment of land use change dynamics in the studied basins. FMA basin presented an expansion in annual crops and sugarcane, while forest and pasture lands were reduced. In MM basin, forest and urban areas showed an increase and the remaining land uses were stagnated or reduced.

Despite of the difficulties in data gathering, SWAT was satisfactorily calibrated and validated for the assessed basins, hence highlighting the great potential of the model application for planning and management of water resources.

Regarding WF and EWF results, sugarcane presented smaller values among the assessed crops, indicating that its expansion certainly will increase the water use efficiency per Mg produced without leading to significant changes in evapotranspiration. Besides regional issues about costs and prices, the economic approach presented different results in terms of water use efficiency. In this case, sugarcane expansion over other crops only increased water use efficiency when displacing orange and pasture lands. In general, WF and EWF were very useful in the assessment of land use changes effects in the water use efficiency of a basin. However, issues regarding water availability must consider other water balance components beyond the evapotranspiration.

The integrated assessment of the SWAT water balance components provided reasonable responses in the assessment of the land use change impacts on water resources availability. It was also clear that not only sugarcane expansion but all land use changes must be considered in the impact assessment, which is an advantage of using SWAT, provided that its simulations consider all changes in land use maps. The assessment of the total changes in land use and land cover allowed to understand effects that were associated to other changes beyond increases in sugarcane areas.

On the other hand, as in previous studies, it was also difficult to separate land use change effects from other stream flow impacting parameters, such as the precipitation intensity and frequency and the previous stream flow and precipitation conditions in the basin. Thus, for a more accurate evaluation of the exclusive sugarcane impacts, expansion over a specific land use class must be isolated from the other land use changes and also from the other main water availability intervenient parameters.

To achieve more conclusive results concerning sugarcane expansion effects on water resources, it is recommended an assessment of sugarcane expansion scenarios, considering larger increases in sugarcane areas and replacing specific land use classes. Other conditions (precipitation, temperature, etc.) should be kept constant. This assumption was adopted in Chapter 5, in which SWAT simulations provided more comprehensive results about sugarcane expansion and its consequences on water resources availability.

The expected sugarcane expansion for 2030 showed no effect on the MM basin stream flow. In scenarios with more significant sugarcane expansion, increases in stream flow were noted, but without changes in the reference flow. Urbanization, however, presented substantial impacts on peak values, intensifying the flood risk without favour the basin's water availability.

In FMA basin, the replacement of annual crops and pasture lands by sugarcane indicated a stream flow regulation since it increased the flow in the dry season and decreased it in rainy season. Furthermore, the reference flow was positively impacted, with a rise of 10% in Q90 when sugarcane holds 45% of the basin's area.

Sugarcane expansion would favour the water availability in the assessed basins, provided that riparian and native vegetation areas are not affected. In general, although water availability and water balance are intrinsically linked to the local characteristics of each basin, replacing annual crops and pasture lands with sugarcane appears to regulate the stream flow regime.

Overall, the adopted methods in this work were satisfactorily applied for the assessment of sugarcane expansion and its effects on water resources availability. As the model was satisfactorily calibrated and validated, reliable results were achieved and the SWAT model can be applied in the assessment of other basins, provided that input data is carefully gathered and treated, and similar performance on calibration is achieved. As pointed out in several studies, more attention should be given to the quality and availability of data in Brazil, especially concerning soil information. Systematic collection, treatment and availability of data certainly will increase the number and the quality of the Brazilian research related with this topic.

Finally, as an intensive input data model was applied in the assessment, more specific and representative data, especially concerning soil and climate inputs, will certainly improve the calibration and validation and, consequently, the results concerning the stream flow. Besides, more accessible and systematic data sources can also enable the assessment of more representative basins, considering large areas of sugarcane. Hence, the attainable scheme proposed in this thesis applied in the Paraná basin, which accounts for the major portion of sugarcane areas in Brazil, with regard to the specific dynamics of the various subbasins comprised in its territory, will certainly be important in the sustainability assessment of sugarcane ethanol.

APPENDIX I – Soil Maps

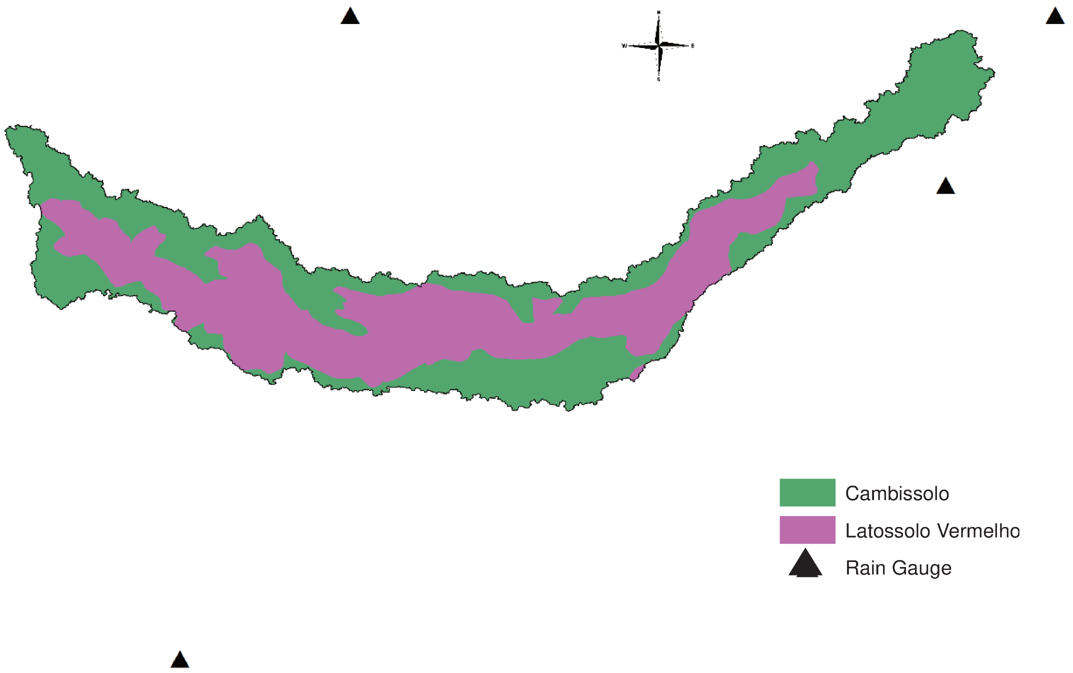

Figure 1. Soil map and rain gauge stations for Fazenda Monte Alegre basin.

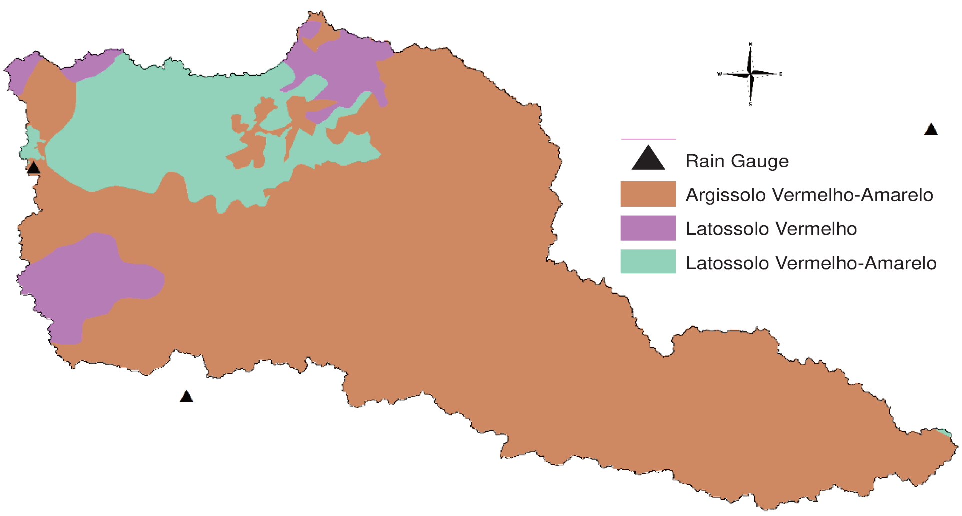

Figure 2. Soil map and rain gauge stations for Monte Mor basin.