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Marcilla Silva Pena

Influência da mudança da cobertura do solo na disponibilidade hídrica da bacia do rio Doce

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Orientador: Prof. Dr. Britaldo Silveira Soares Filho.
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PROGRAMA DE PÓS-GRADUAÇÃO EM ANÁLISE E MODELAGEM DE SISTEMAS AMBIENTAIS

FOLHA DE APROVAÇÃO

Influência da mudança da cobertura do solo na disponibilidade hídrica da bacia do rio Doce

MARCILLA SILVA PENA

Dissertação submetida à Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em ANÁLISE E MODELAGEM DE SISTEMAS AMBIENTAIS, como requisito para obtenção do grau de Mestre em ANÁLISE E MODELAGEM DE SISTEMAS AMBIENTAIS, área de concentração ANÁLISE E MODELAGEM DE SISTEMAS AMBIENTAIS.

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Belo Horizonte, 13 de março de 2018.

“ Traga-me um copo d'água, tenho sede
E essa sede pode me matar
Minha garganta pede um pouco d'água
E os meus olhos pedem o teu olhar”
(...)

Dominguinhos (1941 – 2013)

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Recebam todos os meus sinceros agradecimentos.

Abstract

The understanding of how river discharge responds to changes in land-use and land-cover (LULC) is inextricably linked to good natural resources governance and to the United Nation Sustainable Development Goals. This study aims at modeling the stream flow of the Doce river, in Brazil, to quantify the impacts of historical and future LULC changes on the discharge of this river considering the scenarios forecasted for the agricultural use of the soil until the year of 2030 by the reference scenario of *OtimizaAgro-SimMinas* model. This study used the model *THMB - Terrestrial Hydrological Model with Biogeochemistry*, which simulates the river discharge using morphology data, climate data and data from the agroecosystem model Agro-IBIS. THMB is a spatially distributed model implemented on DINAMICA EGO environmental modeling platform to calculate the river discharge at each point of the studied drainage network. The results have shown that land cover change in the Doce river basin from 2013 to 2030 has been little. It seems that the impact on the river discharge is influenced the most by the size of the basin area. The minimum difference between the 1995-2013 and the 2014-2030 simulated discharges occurred in Colatina river gauge (0.5%) and the maximum in Fazenda Cachoeira D'Antas and Naque Velho river gauges (1.2%).

Keywords: Doce river, Dinamica EGO, THMB; water availability; land cover change.

Resumo

O entendimento dos impactos sobre os recursos hídricos decorrentes das mudanças no uso e cobertura do solo é parte fundamental para uma boa governança dos recursos naturais e para o alcance dos Objetivos do Desenvolvimento Sustentável da ONU. O objetivo deste trabalho é modelar a disponibilidade hídrica na bacia do rio Doce para a quantificação dos impactos da mudança do uso e ocupação do solo, histórico e futuro, sobre os recursos hídricos superficiais em função de cenários de uso agrícola do solo no Estado até o ano de 2030 resultantes do modelo OtimizaAgro-SimMinas. O modelo a ser implementado é o THMB - *Terrestrial Hydrology Model with Biogeochemistry* que modela as vazões dos rios usando dados da morfologia das bacias, dados climatológicos e dados de saída do modelo ecossistêmico Agro-IBIS. O THMB é um modelo de propagação de vazões, espacialmente distribuído implementado na plataforma de modelagem ambiental DINAMICA EGO que calcula a vazão em qualquer ponto dos rios que compõem a rede de drenagem da bacias em estudo. Os resultados mostraram que a diferença na cobertura da terra de 2013 para 2030 foi pequena e que o impacto sobre a descarga do rio Doce depende mais significativamente do tamanho da área de contribuição da estação fluviométrica. A menor diferença entre as vazões simuladas nos períodos 1995-2013 e 2014-2030 foi em Colatina (0.5%) e as máximas em Fazenda Cachoeira D'Antas e Naque Velho (1.2%).

Palavras-chave: Rio Doce, Dinamica EGO, THMB; disponibilidade hídrica; mudança cobertura do solo.

Contents

Enquadramento, justificativa e objetivo

Entender o funcionamento regional do ciclo da água e a sua variabilidade em resposta às mudanças ambientais globais devidas à intervenção humana é fundamental para a manutenção da vida no sistema terrestre. A água sustenta a vida nas suas mais diversas formas e está presente em todas as necessidades básicas dos seres humanos, seja na produção de alimentos, no lazer e na manutenção da salubridade ambiental (COE, 2000), seja nas suas necessidades sociais de desenvolvimento e geração de emprego e renda.

Água está na agenda política dos países e da Organização das Nações Unidas como um assunto estratégico. Todos os países desenvolvidos têm em seu sistema de governo alguma agência responsável pela gestão das águas de seu território ou algum instrumento legal que regule o uso deste recurso natural, além de acordos internacionais para águas transfronteiriças. Na estrutura de governança da ONU, por sua vez, a água está presente nas ações de várias agências especializadas e programas como a UNEP, FAO, WMO, WHO, UNESCO, IMO, mas não se limitando a estes. Finalmente, disponibilidade de água potável, saneamento e conservação dos oceanos figuram nos Objetivos do Desenvolvimento Sustentável (ODS), agenda da ONU com os 17 objetivos para transformar o mundo - acabar com a pobreza, proteger o planeta e assegurar prosperidade para todos. (UN, 2017)

As mudanças ambientais globais que vêm sendo estudadas e aceitas pela comunidade científica têm grande influência sobre o ciclo hidrológico, tendo, portanto, grande impacto sobre o meio ambiente, as pessoas e as atividades econômicas. As mudanças climáticas, por sua vez, têm sido amplamente aceitas como um fenômeno que traz grandes modificações permanentes na dinâmica da atmosfera, podendo modificar significativamente o regime de chuvas em escala global e expor centenas de milhões de pessoas a estresse hídrico (IPCC, 2007).

Neste contexto, o Brasil aparece historicamente como um país de fartos recursos hídricos. Os ecossistemas terrestres que se desenvolveram no país são caracterizados pela elevada pluviosidade que predomina na maioria do território brasileiro. O relevo, por sua vez, foi moldado e dissecado pelas águas das chuvas, formando uma rede de drenagem extremamente intricada, densa e difundida. Tudo isto permitiu que o país seja extremamente dependente dos seus cursos d’água e das suas chuvas: a matriz elétrica brasileira é predominantemente hidráulica (Oferta Interna de Energia Elétrica Hidráulica: 2015 - 64,0%; 2014 - 65,2%) (BRASIL, 2016) e as suas principais atividades econômicas (agricultura, pecuária e mineração) dependem fortemente das águas do seu território.

O Estado de Minas Gerais segue essas mesmas características no que tange às águas e às chuvas. Minas é popularmente conhecido como a “caixa d’água brasileira” por ser uma região de cabeceira, não recebendo a drenagem de nenhum de seus estados vizinhos. (CSR, 2013). No território do Estado estão presentes quatro das 12 regiões hidrográficas (RH) brasileiras, a saber: RH Paraná, RH Atlântico Sudeste, RH Atlântico Leste e RH São Francisco. Minas também se destaca por gerar energia elétrica predominantemente hidráulica (95,8% em 2010; 86,4% em 2014) (CEMIG, 2011; CEMIG, 2015), pela atividade minerária, tipicamente consumidora de água, e por sua agropecuária, contribuindo com produtos tanto para o mercado interno quanto o externo.

Entender o funcionamento regional do ciclo da água no Estado de Minas é, portanto, crucial para a mitigação e eliminação dos impactos negativos sobre as águas decorrentes das mudanças globais, e para a maximização dos eventuais benefícios advindos delas; tendo em vista que os impactos sobre as águas de Minas reverberam em vários outros Estados do Brasil (CSR, 2013). Entender a variabilidade da disponibilidade hídrica de forma espacialmente explícita é, portanto, um conhecimento estratégico para a expansão sustentável das atividades econômicas, principalmente a agropecuária, e para o desenvolvimento sustentável do Estado no médio e longo prazos.

Este conhecimento é igualmente estratégico para o Estado de Minas Gerais acompanhar o cumprimento da legislação ambiental em vigor em seu território. Minas, em 2017, por meio da Portaria IGAM 49, 1 de julho de 2010, determina 30% da $Q_{7,10}$ como o limite máximo de derivação consuntiva a ser outorgada nas bacias hidrográficas (Minas Gerais, 2010). Entretanto, atualmente, vários segmentos de bacias já apresentam relação entre demanda (outorgas) e disponibilidade (vazão média) de até 40% (CSR, 2013).

O objetivo do presente trabalho é fazer a simulação da disponibilidade hídrica da bacia do rio Doce no período de 1995 até 2030, com base no cenário de mudança de uso da terra previsto no OTIMIZAGRO-SimMinas. Para tal, foi utilizada uma versão do modelo Hidrológico THMB - *Terrestrial Hydrology Model with Biogeochemistry* na plataforma de modelagem ambiental DINAMICA EGO, com dados do Agro-IBIS e dados climáticos do Estado.

Modeling the hydrological impact of land-use change on the discharge of the Doce river system, in Brazil, using Dinamica EGO

1 Introduction

Water is still one of the most important issues in the actual United Nations development agenda despite all the advances achieved in terms of water access and sanitation in the 21st century. Water plays a key role in the UN development agenda through its relation to the ambitious sustainable development agenda and through its inherent importance for all earth ecosystems. (UN, 2015) As human development continue to alter the global environment, it is essential that the water systems and the changes they are experiencing are understood in order to reach the Sustainable Development Goals.

Although the importance of water and its interfaces with sustainable development, it is still very challenging for the scientific community to tackle the water matter in all its aspects. Water is a natural resource, but it is also a substance that sustains life in all forms, it is essential for the economic development of all countries and for the health of humans; therefore, it has to be managed with justice, balancing out rather diverging interests of many stakeholders.

Overtime, in the history of the human development, the benefits of safe water access for the public health consolidated the importance of a clear understanding of the behavior of the river systems. However, the complexity of the hydrologic cycle and its interconnectedness with climate and soil sciences restricted the advances to the small scale. Advances in large-scale hydrology were only possible with the advances in large-scale rainfall and discharge monitoring and also with the development of computer hydrological models. (Tucci, 2005; Singh, 2018)

The development of hydrological models is extremely meaningful because they are important tools for understanding hydrology in the global, regional and local levels. They can predict not only the water availability over time in a river basin under specific conditions but also the transport, accumulation and degradation of nutrients and pollutants in groundwater and along the river channels, giving important information on water quality and the population experiencing water stress (Weiler et al., 2015; Tucci, 2005; Singh, 2018).

The applications of hydrological model are not limited to the government environmental authorities or scientists but they can be useful for all stakeholders in a river basin. They provide a good understanding of the river basin behavior, which can forecast extreme events that could put people under water stress, such as floods and droughts. They are also very useful for industry, agriculture and energy planning, sectors which are fundamental for the development of the countries.

In this study, we present an analysis of the Brazilian Doce river discharges for the period 1995-2030 integrating the outputs of three different models. An ecosystem model (Agro-IBIS) and a hydrologial model (THMB) were used in the simulation forced with a regional land cover model *OtimizaAgro-SimMinas* to quantify the impact of the land cover change on the Doce river discharge. The focus of the study on this river is because of its regional, social and environmental importance and its critical need of regeneration after Fundão tailing dam collapsed on November 5th 2015, when around 31 million cubic meters of tailings reached the Doce river, in the biggest environmental accident reported in Brazil so far.

1.1 Hydrological Modeling: approach and development

Hydrological models of rivers are a simplified physical representation of a real river basin and its processes. Therefore, the river models are systems composed of many parts that interact and have their main result from this interaction. Every individual part affects the functioning of the whole system and the synergies from the interactions generate a greater result than the sum of the individual action of each part. River systems are a result of the interactions of solar energy, hydrosphere, biosphere and lithosphere that generate many natural processes such as the distribution of freshwater on the earth, formation of the relief, support of biodiversity and the recharge of groundwater.

The development of hydrological models is extremely meaningful because these could be important tools for water management in the global, regional and local levels. Governments, scientists and engineers in general are keen on the explaining and predicting capabilities of hydrological models. They can predict not only the available water over time in a river basin under a specific condition but also the transport, accumulation and degradation of nutrients and pollutants in the waters along the river channels, giving important information on water quality and the population experiencing to water stress.

In the beginning of hydrology modeling, the models were limited to the description of the water cycle individual processes. For instance, Horton's (1933) model for infiltration; Darcy's model for drainage; MacCarthy's (1939) for river discharge, and Muskingun and Puls (1928) for reservoir flow. From the 1950s rainfall-runoff models were developed, such as *Streamflow Simulation Watershed Model - SSARR* (1958), the Standford Watershed Model (1966) and the Hydrologic Engineering Center – HEC 1 (1968). These models were mainly used for the designing of hydraulic structures and for the expansion the historical series for river flow regulation. The main challenge at that time was finding accurate rainfall temporal and spatial data. (Tucci, 2005)

Over time, a myriad of large-scale distributed models has been developed with the increasing computational capabilities, advances in numerical mathematics and availability of spatial and hydrological data (Weiler, 2015; Singh, 2018). From the 1970s up to nowadays, hydrology modeling has experienced increasing reliability. Models started to use less inputs parameters, included the terrain and land-use characteristics, which reduced the number of equations involved in the processes, making calibration and validation easier. (Tucci, 2005)

With these advances, several large-scale hydrological models were developed, including: TOPMODEL - *Topography Based Hydrological Model* (1970) e o SHE -

Système Hidrologique Européen (1986); VIC family of models (Wood et al., 1992); ISBA-MODCOU (Habets et al., 1999); WATFLOOD (Kouwen et al., 2002; Soulis et al., 2004); LARSIM (Ludwig and Bremicker, 2006); SWIM (Krysanova et al., 1998); *Soil and Water Assessment tool – SWAT* (Arnold et al., 1998); *Terrestrial Hydrology Model with Biogeochemestry – THMB* (Coe, 2000), and MGB-IPH (Collischonn et al., 2007).

2 Study Area: Rio Doce Basin

Doce river basin is located in the southeastern region of Brazil, in the Southeast Atlantic hydrographic region. The whole basin is 86,715 km^2, 86% of which is within Minas Gerais and the remaining 14% in the state of Espírito Santo. The doce river springs in Minas Gerais, in Espinhaço and Mantiqueira mountains, and follows a 850 km route until the Atlantic ocean, in a municipality called Regência, in Espírito Santo.

The basin occupies around 13% of the territory of Minas Gerais and has a significant importance because of its economy and its history – the region was reference for the first gold explorers who established the first settlements of the State on the river and its nearby regions.

Historically, in terms of climate and vegetation, the region is very homogeneous. Around 98% of the whole river basin was originally within the Atlantic Forest Biome (83,400 km^2) (Fernandes et al., 2016), which over the years of human settlement was largely deforested and substituted by pastures and plantations. The climate is sharply divided by two distinct seasons: wet hot summers and dry mild winters. The rainy season starts in October and finishes in March, with rainfall ranging from 800 mm to 1,300 mm; the dry season goes from April to September, with rainfall ranging around 150 mm to 250 mm. (Consórcio Ecoplan-Lume, 2010)

The basin is home for 3.3 million people, 68.7% of which live in the 228 municipalities (202 in Minas Gerais and 26 in Espírito Santo). The basin landscape is very mountainous and the soils are very prone to erosion, which conditioned the urban settlement to the floodplains and constrained the economic development of the region. The main agricultural uses of the soils are pastures and long-cycle permanent crops, such as coffee and citrus. The industry of the region is responsible for more than 15% of the GDP of Minas Gerais state due to the 'Steel Valley' (*Vale do Aço*), the largest steel mill complex of Latin America, and other economic activities such as forest plantations, coffee plantations and mining. (Consórcio Ecoplan-Lume, 2010)

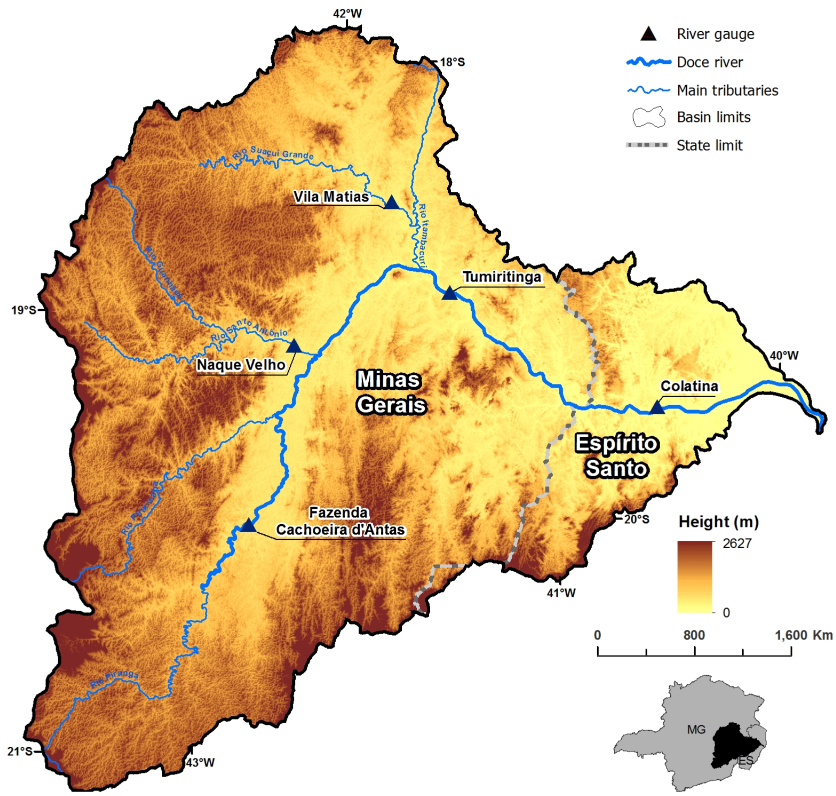


Figure 1: Doce river basin with the stream gauge stations of the study. (Author: Lilian Machado/CSR-MG)

Recently, the Doce river basin experienced a significant environmental accident. On November 5th 2015; 663 km of the 850 km Doce river course was contaminated with around 31 million m^3 of iron tailings of *Fundão* dam (Hatje et al., 2017, Morgenstern, 2016). It was one of the major tailings dam failures ever recorded in the mining sector and had a significant repercussion on the international media. The dam failure increased substantially the sediment load in the river, deposited large amounts of metal waste along the river course and washed away natural forests, plantations, crops, buildings and lives (Fernandes et al., 2016; Hatje et al., 2017; Carmo et al., 2017).

Since then, the scientific community has been trying to fully apprehend the total extent, magnitude and reversibility of the impacts of the contaminants present in the sediment in the river. The ecological, economic and cultural impacts estimated were more than 1 million people with reduced access to clean water in 41 municipalities, damage of crops, livestock production, fluvial and estuarial fisheries, destruction of historical heritage, displacement of around 600 people of Bento Rodrigues settlement and a death toll of 19 people (Fernandes et al., 2016; Hatje et al., 2017).

3 Methodology

3.1 Experiment design

Two sets of simulations were made with *IBIS* and *THMB* forced with identical climate data. First, with *OtimizaAgro-SimMinas* reference scenario land cover, which will be called '*Current Land Cover*' for the period 1995-2013, and *'Future Land Cover'* for the period 2014-2030. Second, with the land cover from the ecosystem model *Agro-IBIS*, which hereinafter will be called '*Potential Natural Vegetation'*. Both models will be explained here in the methodology section.

Five stream gauge stations were selected for the analysis: (1) *Fazenda Cachoeira D'Antas*, (2) *Naque Velho*, (3) *Vila Matias-Montante*, (4) *Tumiritinga* and (5) *Colatina* (Figure 1). The time was divided in two periods: 1995-2013, for the validation of the simulations, and 2014-2030, for the projection of the future impact of the land cover change on the river discharge.

In order to quantify only the impact of the land cover change on the river discharge, the rainfall data set used in the simulations was the same for both simulations (see: https://utexas.app.box.com/v/Xavier-etal-IJOC-DATA). This rainfall data set is result of a work for the generation of high-resolution grids basic meteorological data for the estimation of evapotranspiration for Brazil published by Xavier et al. (2016). Using the same rainfall data set reassured that the difference between the simulations are the ones due to the change in the land cover only; therefore, using identical climate made the experiment to reflect the impact of the land cover change alone.

In this study, the *Agro-IBIS* model was used to generate the surface vertical water balance for the two sets of simulations. This is the water component of the simulations and represent the surface runoff and the subsurface The analysis of the two simulations were named as follows: (a) *'Potential Natural Vegetation'* versus *'Current Land Cover'* and (b) *'Current Land Cover'* versus *'Future Land Cover'*.

3.2 Models descriptions

3.2.1 OtimizaAgro-SimMinas and Agro-IBIS

OtimizaAgro-SimMinas is a modeling platform for the simulation of the agricultural land use of Minas Gerais State territory that integrates economic and environmental variables in order to quantify the land cover change, the CO_2 emissions and the environmental impacts associated with the land cover change (Soares-Filho et al., 2018).

This is a management tool that supports the conciliation of three remarkable policies in Brazil: (1) the National Forest Code (*Lei 12.651, de 25 de maio de 2012.)* and the (2) National Plan for Climate Change (*Plano Nacional de Mudanças Climáticas – PNMC*) with the (3) Federal Agriculture and Livestock Ministry (*MAPA*) policies. In these policies, on the one hand, there is a demand for conservation and restoration of forests in order to reach the emissions reduction goals; and, on the other hand, there is a demand for more agricultural land for the food production increasing forecasts (Soares-Filho et al., 2018).

In this model, the historical reconstruction and allocation of the state land use used a combination of remote sensing data and agriculture census data, following methodologies previously used for the global and Brazilian land use reconstruction (Soares-Filho et al., 2018). Then, the projected deforestation and the allocation of cultures in the future is a result of the combination of variables, such as culture profitability, transport logistics and the agriculture suitability of the region. The spatial allocation of the cultures uses a cellular automata mechanism in the modeling platform *Dinamica EGO* (Soares-Filho et al., 2013)

Agro-IBIS is the agricultural version of the *Integrated Biosphere Simulator* (IBIS), a physically-based terrestrial model that integrates a wide range of processes including water and energy balances that happen simultaneously among soil, vegetation and the atmosphere. This model has been thoroughly described in previous studies for estimating the land surface water balance in global and regional scales, in temperate and tropical climate (Foley at al., 1996; Coe, 2000; Kucharick et al., 2000; Cuadra et al., 2011; Webler et al., 2012).

Agro-IBIS is able to model canopy physiology, vegetation phenology, and long-term ecosystem dynamics (vegetation dynamics and carbon cycling), including natural and crops plant types. Its water module is able to hourly simulate the variation of the soil volumetric water content based on Richard's flow equation. The soil water content varies in time and space as a function of soil hydraulic conductivity, soil water retention curve, plant water uptake and upper and lower boundary conditions. The result is a explicit simulation of the the surface runoff and subsurface drainage as a function of soil, vegetation and climate conditions (Foley et al., 1996; Coe et al., 2009; Cuadra et al. 2011).

Here, Agro-IBIS was run over the entire state of Minas Gerais and generated monthly means of surface runoff and base flow for the period from 1995 to 2030, using two land cover scenarios: (1) *'Potential Natural Vegetation'* of *Agro-IBIS* model (Ramankutty and Foley, 1999) and the (2) reference scenario of *OtimizaAgro-SimMinas* (Soares-Filho et al. 2018).

3.2.2 THMB terrestrial hydrology model

Terrestrial Hydrology Model with Biogeochemestry – THMB (Coe, 2000; Coe et al., 2002, 2007, 2009; Costa et al., 2002), is a physically-based hydrological model, spatially distributed for large river basins. The full version of THMB simulates the progression of the river flows using morphology, climate and land use input variables. The outputs of the full version of THMB are the river discharge, the stage of the lakes and floodplains and the extension of the floodplains.

The conceptual model of THMB represents the space in a linear reservoirs approach, where the processes take place (Coe, 2000). In the full version of THMB, there are surface, subsurface, the river and the floodplains linear reservoirs. The discharge is part of a connected river network, which includes the transport of the flow in the rivers, lakes, wetlands and reservoirs.

In this study, a simplified version of THMB was used. In this version the model is able to simulate the flows in the drainage network, calculating the discharge at each point of the river but the floodplains and the river stage modules are not included. We considered this version more suitable for Doce river case study because it does not have extensive floodplains that would justify the use of the full version of THMB.

3.2.2.1 Modeling the river discharge with THMB

The model is based in the physics principle of mass conservation, where the rainfall over the river basin is transformed in discharge, water table storage and evapotranspiration of the vegetation. The water available in the soil reservoirs (surface and subsurface) is calculated by Agro-IBIS (S_{in} and D_{in}). THMB is then responsible for the horizontal transport, in the soil matrix and in the drainage network (S_{out} and D_{out}) (Figure 2).

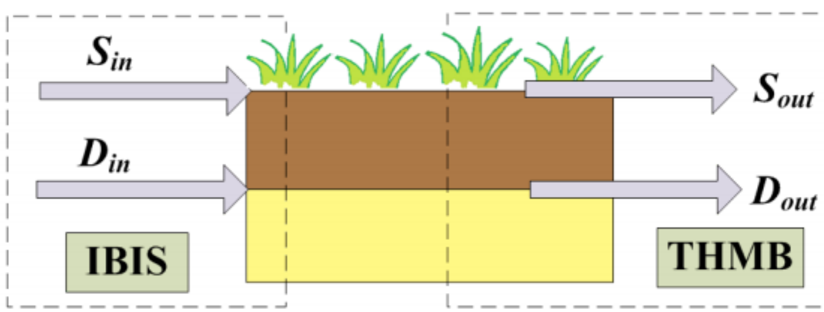


Figure 2: Soil reservoirs: S=surface and D=subsurface. (Lima, 2011)

In THMB each process occurs in each linear reservoir and the flow between the reservoirs is based on the hydraulic continuity equation according to equation (1). The volume variation (*dW/dt*) of the accumulated volume in each time step is the inflow (Q_{in}) minus the outflow (Q_{out}).

$$Q_{in}\text{-}Q_{out} = \frac{dW}{dt} \quad (1)$$

The total water volume that enters in each cell of the river network *(dW_R/dt)* is the sum of the surface runoff *(W_S/T_S)*, the base flow (W_D/T_D) and the upstream flow from the river drainage network ($FLUX_{in}$). The total water volume that leaves the river reservoir (W_R/T_R) is the river volume divided by the residence time in the river reservoir (Equation 2). The linear reservoir simulates the water transport on a flow direction map derived from the Digital Elevation Model (DEM), using the flow velocities and the residence times inside each cell.

$$\frac{d(W_R)}{dt} = \left(\frac{W_S}{T_S} + \frac{W_D}{T_D}\right) - \left(\frac{W_R}{T_R}\right) + \sum FLUX_{in} \quad (2)$$

In the first stage, THMB calculates the horizontal water balance in the surface and subsurface reservoirs, pixel by pixel, from the Agro-IBIS vertical water balance. IBIS simulates the monthly means for surface and subsurface runoff, which are inputs for THMB. The residence times, T_S and T_D, in the surface and subsurface reservoirs are prescribed by Agro-IBIS (Equation 3).

$$\frac{d(W_S)}{dt} = S_{in} - \frac{W_S}{T_S}$$
$$\frac{d(W_D)}{dt} = D_{in} - \frac{W_D}{T_D} \quad (3)$$

In the next stage the flow in the river reservoir is calculated using the incoming flow from upstream the river ($FLUX_{in}$), the surface runoff and base flow contributions (W_S/T_S and

W_D/T_D) and the outgoing flow from the river (W_R/T_R). The residence time in the river is not prescribed, it is calculated in the model based on the distance that the flow travels and the effective velocity of the flow inside the drainage network (Equation 2).

4 Results

4.1 Doce river basin land cover change analysis

Figure 3 presents the analysis of the land cover change for *'Current Land Cover',* modeled for 2013, *and 'Future Land Cover'*, modeled for 2030, in the contribution area of the Colatina (#56994510) stream gauging station, which covers 88% of the Doce river basin area and includes the 5 river gauges in the analysis.

In broad terms, the land cover change in the study area has been little from 2013 to 2030. This means that the majority of the land cover change, from the original Atlantic Rainforest to pastures and agriculture, occurred before the period of analysis here and that the process has achieved a level of stability.

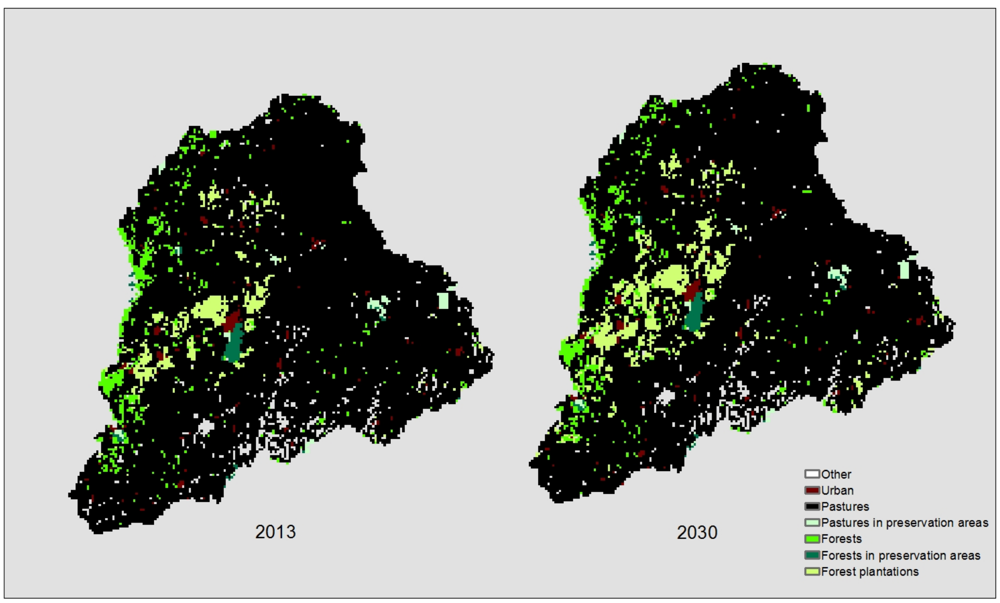


Figure 3: *'Current Land Cover'* and *'Future Land Cover'* for the contribution area of Colatina river gauge (#56994510).

It is worth noticing that the assumptions of the economic model and the parameters of the *OtimizaAgro-SimMinas* for the reference scenario have constrained the land change and forced specific conversions to restoration areas and forest plantations mainly because of law enforcement and the economic conjuncture (Table 1).

Figure 4 shows that the most of the area of study was classified as pastures, around 87% in 2013 and 85% in 2030. The second largest land cover class is forest, native and plantations, which, altogether, account for 7.8% in 2013 and 10.1% in 2030. Pastures and forest plantations were also the categories with the most change in terms of area, with 1,552 km^2 in losses and 1,864 km^2 in gains respectively (Table 1).

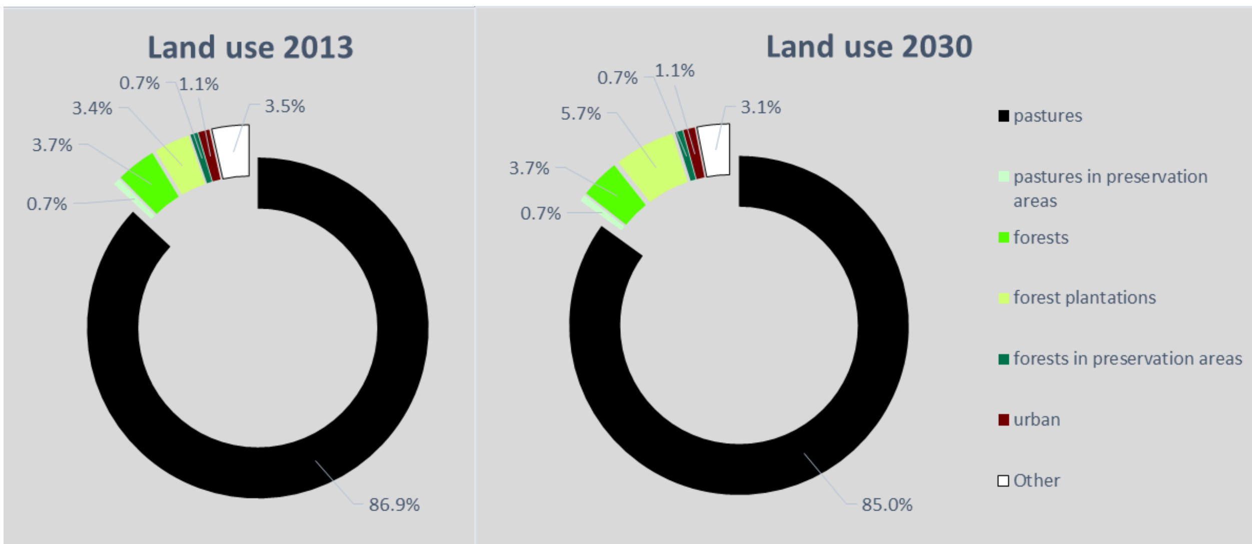


Figure 4: Percentage of land cover from *'Current Land Cover'* and *'Future Land Cover'* for the drainage area of Colatina (#56994510).

The gains in restoration areas and the losses in cultivation areas of maize, rice and beans were proportionally the largest. The basin went from 0 to 76 km^2 in restoration areas and lost 100% of its exclusive rice and beans cultivation sites. Maize also is predicted to lose proportionally a large area, which represents a 54% reduction compared to 2013. Although percentage loss is high, these land cover categories were not large in terms of absolute area (720 km^2 in 2013 and 304 km^2 in 2030) (Table 1).

Table 1: *'Current Land Cover'* and *'Future Land Cover'* change analysis.

Category	Current Land Cover – 2013 (km²)	Future Land Cover – 2030 (km²)	Land cover change 2030-2013 (km²)	Land cover change 2030-2013 (%)
water	80	84	4	5%
urban	836	860	24	3%
pastures	68,496	66,944	-1,552	-2%
pastures in preservation areas	524	520	-4	-1%
savanna	300	300	0	0%
savanna in preservation areas	56	56	0	0%
forests	2,948	2,944	-4	0%
forests in preservation areas	540	548	8	1%
restauration areas	0	76	76	-
sugar cane	332	340	8	2%
maize	**616**	**284**	**-332**	**-54%**
rice	**8**	**0**	**-8**	**-100%**
beans	**12**	**0**	**-12**	**-100%**
Arabica coffee	1,128	1,108	-20	-2%
Robusta coffee	156	160	4	3%
manioc/kasava	0	8	8	-
forest plantations	**2,664**	**4,528**	**1,864**	**70%**
maize-beans	84	20	-64	-76%
Total	78,780	78,780	-	-

4.2 Doce river basin 'Potential Natural Vegetation' analysis

The original *'Potential Natural Vegetation'* data set was created by Ramankutty and Foley (1999) to quantify the historical changes in the global land cover. They created a reasonable, high-resolution (5 minutes) characterization of the potential vegetation for the whole globe. The goal of their work was to estimate the geographically explicit changes in global croplands from 1700 to 1992. The potential vegetation was, thus, necessary to represent the baseline of comparison and assessment of the land cover change (Ramankutty and Foley, 1999).

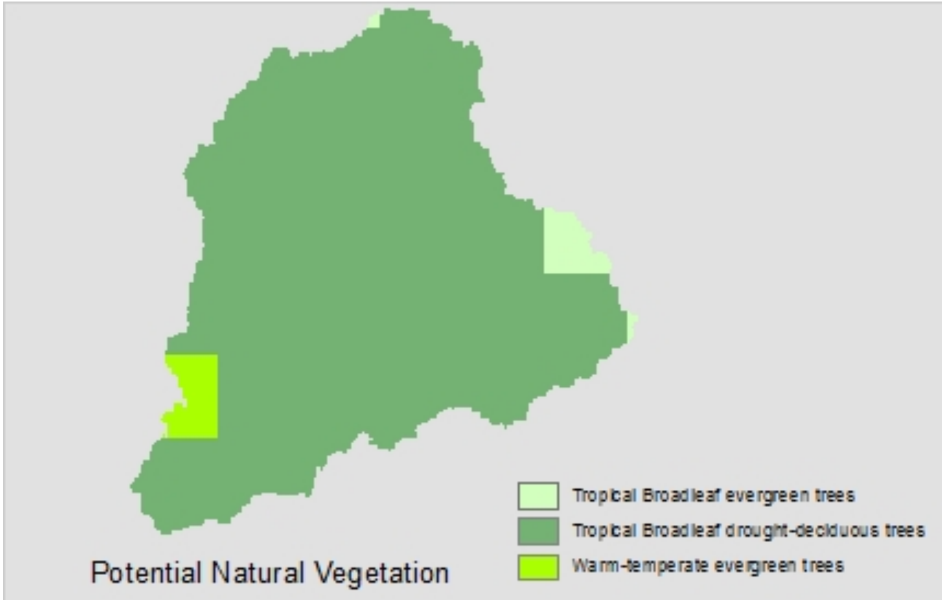


Figure 5: ‘Potential Natural Vegetation’ for the drainage area of Colatina river gauge (#56994510).

In the present study, Figures 5 and 6 present the analysis of the land cover for the *‘Potential Natural Vegetation’* in the contribution area of the Colatina (#56994510) stream gauging station. This is a representation of the vegetation that would most likely be in place if there were no human activity in the area extracted from Ramankutty and Foley (1999), which is the original land cover used within the Agro-IBIS model.

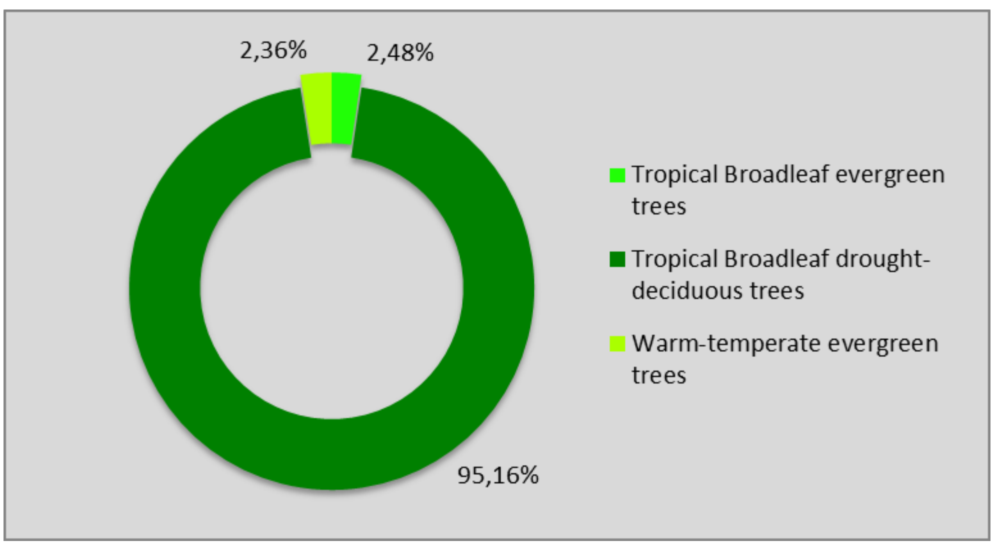


Figure 6: Percentage land cover from *‘Potential Natural Vegetation’* scenario for the drainage area of Colatina (#56994510).

Table 2 shows that the *'Potential Natural Vegetation'* is composed of three classes of forest: the Tropical Broadleaf drought-deciduous trees is the prevailing one on 95.16% (74,968 km^2) of the area; the Tropical Broadleaf evergreen trees, on 2.36% (1,856 km^2) of the area; and the Warm-temperate evergreen trees, on 2.48% (1,956 km^2) of the area.

Table 2: '*Potential Natural Vegetation'* land cover analysis.

Category	Land Cover (km^2)	Percentage Area (%)
Tropical Broadleaf evergreen trees	1,856	2.36%
Tropical Broadleaf drought-deciduous trees	74,968	95.16%
Warm-temperate evergreen trees	1,956	2.48%
Total	78,780	100%

4.3 Doce river basin evaluation of the simulated discharge

4.3.1 Annual mean 1995-2013

Figure 7 shows the specific annual mean discharges for 1995-2013. In general, comparing both simulations, *'Potential Natural Vegetation'* versus *'Current Land Cover'*, with the observed annual mean discharges; the outputs of THMB in the *'Potential Natural Vegetation'* are in good agreement (Pbias<10%) (Table 2) with the observations and the *'Current Land Cover'* has a larger percent error to the observed data.

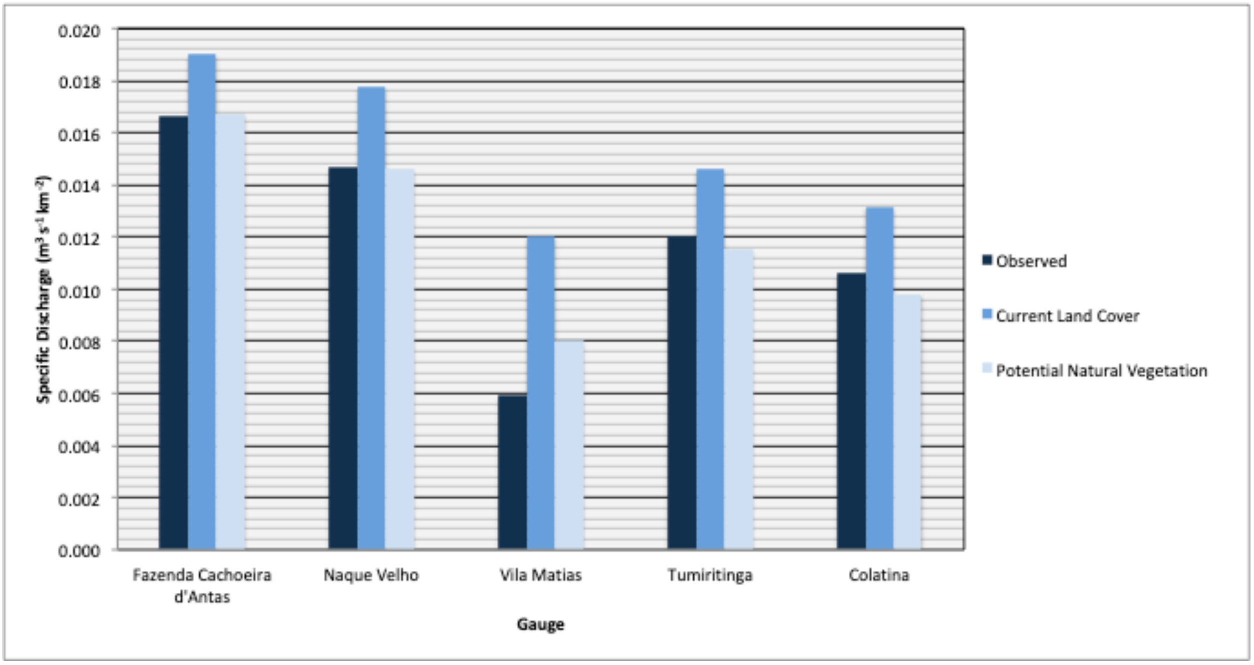


Figure 7: Specific mean annual discharges – 1995-2013.

Overall, for the long-term mean, both models presented satisfactory results with Pbias $\leq$25% in average (Table 2). In average, considering Pbias $\geq$25% unsatisfactory (Moriasi et al., 2007), *Vila Matias-Montante* stream gauge station is an outlier because its Pbias was the only ones over the acceptance threshold.

The discharge generated in *Vila Matias-Montante (#56891900)* has the largest difference in both simulations. This river gauge has presented a very distinct value when compared with the other river gauges in all simulations and this could be due to a consistent measurement error at the station due to malfunction.

Table 3: Observed and simulated annual mean discharge and percentage error for the 5 stream gauge stations for the period 1995-2013.

Stream gauge station	Annual mean discharge: Observed (m^3/s)	Annual mean discharge: 'Current Land Cover' (m^3/s)	Annual mean discharge: 'Potential Natural Vegetation' (m^3/s)	Pbias* 'Current Land Cover' and Observed (%)	Pbias* 'Potential Natural Vegetation' and Observed (%)	Number of years of simulation
Fazenda Cachoeira d'Antas	168	192	169	-14	-0.40	19
Naque Velho	149	180	149	-21	0.41	19
Vila Matias-Montante	60	123	82	-103	-36	19
Tumiritinga	664	804	635	-21	4	19
Colatina	811	1,006	749	-24	8	19

*negative values indicate overestimation.

Comparing the simulations, the results show that the annual mean discharge from *'Current Land Cover'* simulation is always above the discharge from *'Potential Natural Vegetation'* simulation for the period of 1995-2013 (Table 3).

In hydrology modeling, Nash-Sutcliffe coefficient is a broadly accepted indicator of goodness-of-fit between simulated discharges and observed data. The Nash-Modified is a variation that is less sensitive to the extreme values of discharge (Legates, 1999). The closer to 1, the better fit to the observed data; negative values indicate the observed mean is a better predictor than the simulated data and 0 indicates that the mean of the observed data is as good predictor as the simulated data (Legates, 1999; Moriasi et al., 2007; Brighenti, 2016, Rodrigues, 2017).

Table 4 shows the Nash-Sutcliffe and Nash-Modified for the annual means from 1995 to 2013. None of the stream gauging stations showed satisfactory results ($\geq$0.5) (Moriasi et al., 2007). The majority of the values are negative, which means the observed mean is a better predictor of the discharge than the simulated by the model. Only *Fazenda cachoeira D'Antas* and *Colatina* have positive values, but they do not indicate a good fit because they are less than 0.5.

Table 4: Annual mean discharge Nash-Sutcliffe and Nash-Modified – 1995-2013.

	Indicator	Fazenda Cachoeira D'Antas	Naque Velho	Vila Matias-Montante	Tumiritinga	Colatina	Number of years of the analysis
	Drainage area (km^2)	10,079	10,170	10,200	55,100	76,400	-
Current Land Cover	**Nash-Sutcliffe**	-0.51	-0.68	-10.77	-0.67	-0.60	19
	Nash-Modified	-0.15	-0.23	-2.73	-0.26	-0.39	19

4.3.2 Seasonal cycle – monthly means 1995-2013

In Figures 8 to 12, the hydrographs of monthly means for each stream gauge station show the general trend for observed and simulated monthly discharge from 1995 to 2013. Notice that in the five gauges there is a trend towards overestimation of the maximum monthly mean discharges in the rainy season (November to March) and an underestimation of the minimum monthly means (April to October) in the dry season.

Overall, the model was able to simulate the seasonal variability of the monthly means in accordance with the climate pattern, having the maxima in the rainy season (November to March) and the minima in the dry season (April to October). In all gauges in both simulations, the monthly mean discharge is in better agreement with the observations in the dry season. In the *'Potential Natural Vegetation'* simulations, Agro-IBIS consistently delayed the peak in a month average, though.

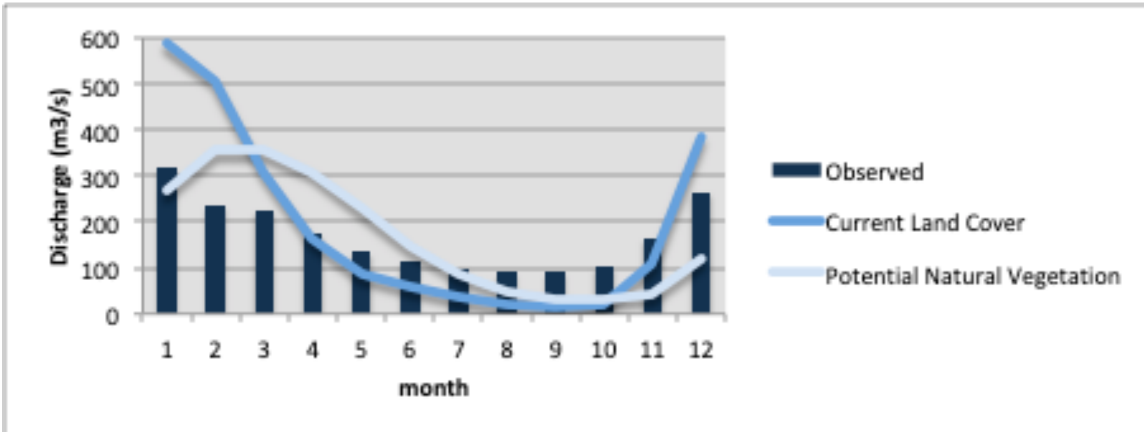


Figure 8: Monthly means of simulated and observed discharge of Doce river at Fazenda Cacheira D'Antas stream gauge station (#56425000) – 1995-2013.

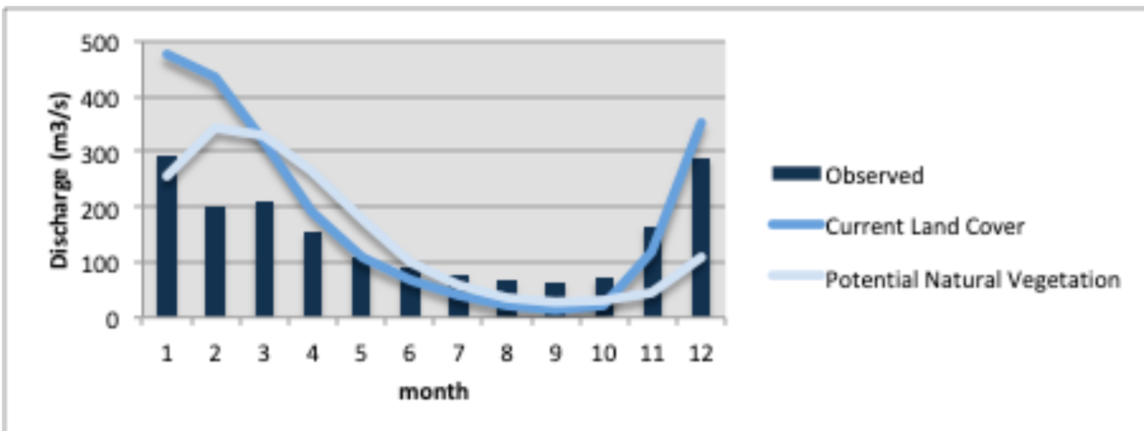


Figure 9: Monthly means of simulated and observed discharge of Doce river at Naque Velho stream gauge station (#56825000) – 1995-2013.

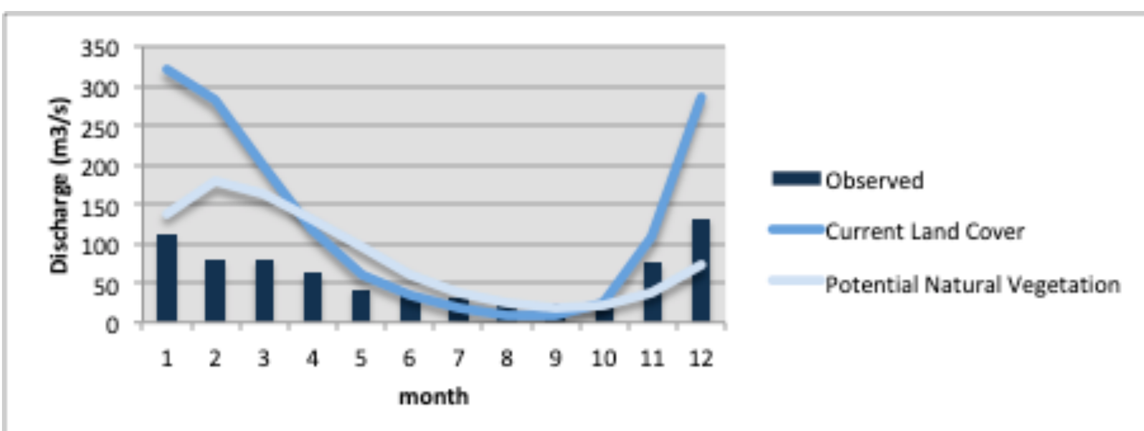


Figure 10: Monthly means of simulated and observed discharge of Doce river at Vila Matias-Montante stream gauge station (#56891900) – 1995-2013

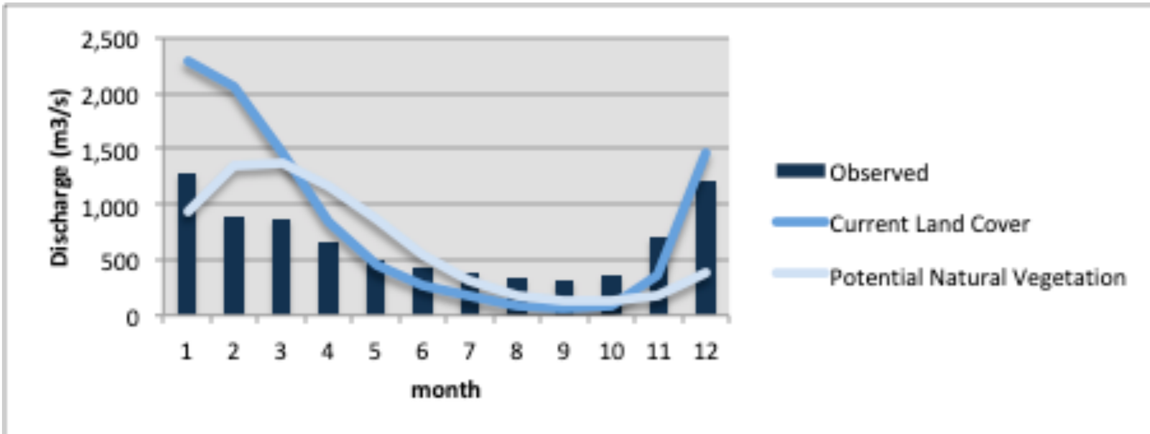


Figure 11: Monthly means of simulated and observed discharge of Doce river at Tumiritinga stream gauge station (#56920000) – 1995-2013.

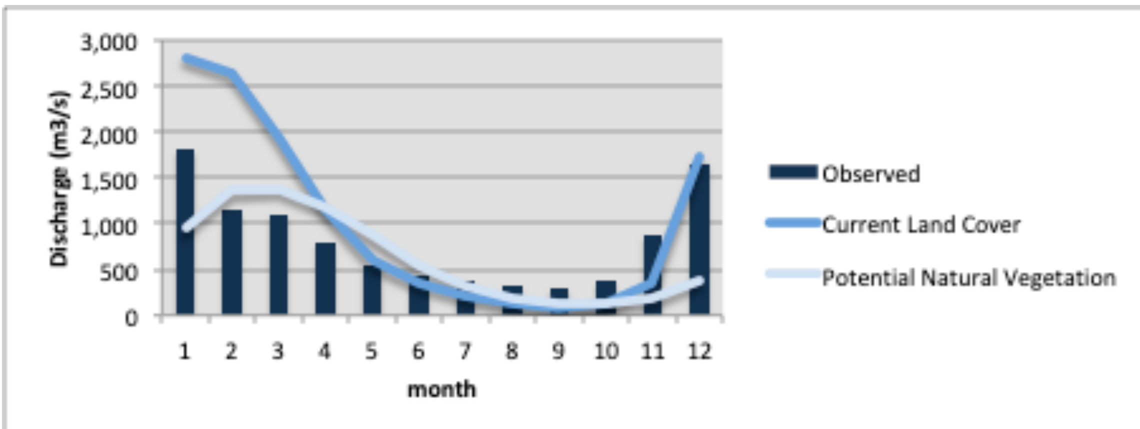


Figure 12: Monthly means of simulated and observed discharge of Doce river at Colatina stream gauge station (#56994510) – 1995-2013.

4.3.3 Seasonal cycle – monthly discharge 1995-2013

The seasonal cycle of both simulations of the river discharges for the 19 years are shown in the scatter diagrams below. Both compare the whole simulation (5 locations x 19 years of monthly data for each gauge) with the observed data. The one-to-one agreement lines are shown for comparison.

For the *'Current Land Cover'* simulation, the correlation coefficient (R^2) with the observed discharge for the 1,140 months of the observed data is 0.77. The clustering points above the 1:1 line indicates the bias toward overestimation in this simulation when compared with the observed data, as shown in the mean annual discharge analysis (Figure 13).

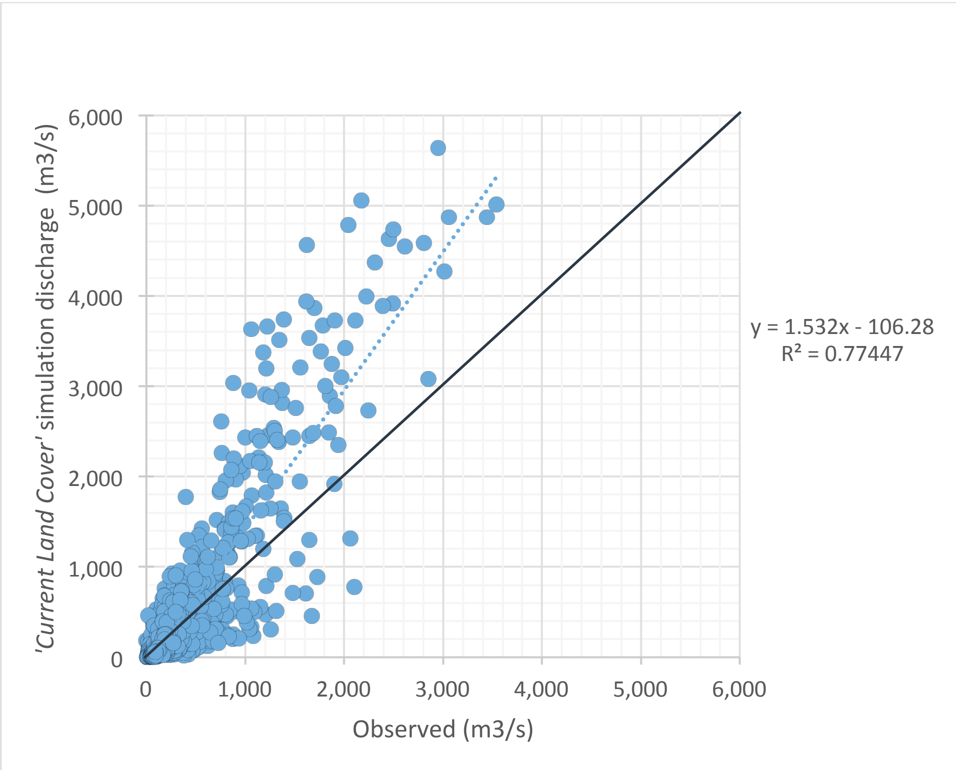


Figure 13: Scatter diagram of simulated observed versus monthly river discharge for this study. The sample size is 1,140 (5 stations with 19 years of monthly data per station) – 1995-2013.

For the *'Potential Natural Vegetation'* simulation, the opposite happens. The clustering points under the 1:1 line indicates the bias toward underestimation of the mean discharge when compared with the observed data, as shown in the mean annual discharge analysis. The correlation coefficient (R^2) with the observed discharge in this case for the 1,140 months of data is 0.41 (Figure 12).

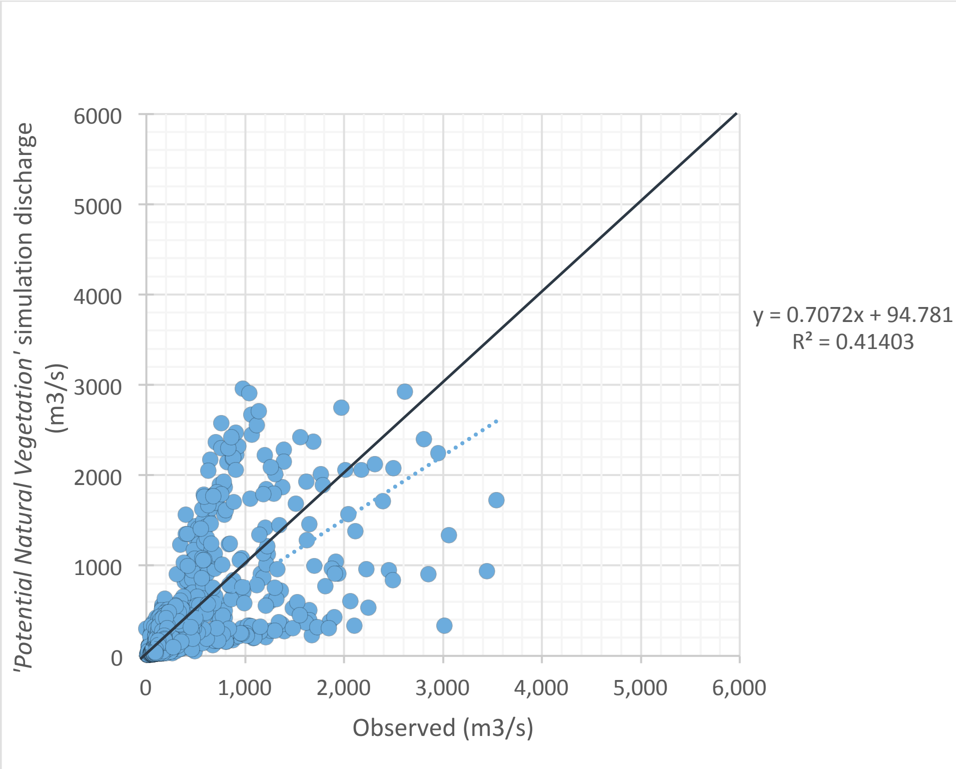


Figure 14: Scatter diagram of simulated versus observed monthly river discharge for this study. The sample size is 1,140 (5 stations with 19 years of monthly data per station) – 1995-2013.

4.3.4 Seasonal cycle between simulations – monthly discharge 1995-2013

In FIgure 15 the scatter diagram shows the relation between the *'Potential Natural Vegetation'* and *'Current Land Cover'* simulations. The clustering below the 1:1 line indicates a trend of lower discharge values in the *'Potential Natural Vegetation'* simulation when compared with the *'Current Land Cover'* simulation in the mean annual discharge. It can also be confirmed in the analysis of the annual means, where the *'Potential Natural Vegetation'* annual mean is always lower than the *'Current Land Cover'* simulation.

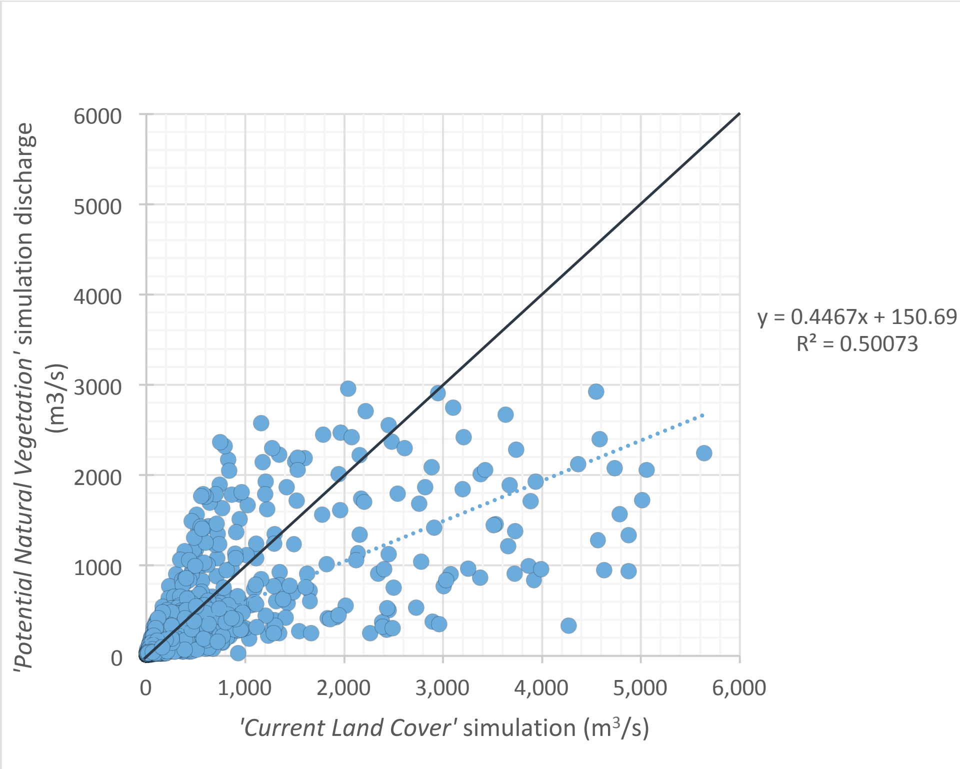


Figure 15: Scatter diagram of simulated monthly river discharge of current use simulation versus potential natural vegetation. The sample size is 1,140 (5 stations with 19 years of monthly data per station) – 1995-2013.

In Table 5, neither of the Nash coefficients indicated a good fit of the simulations for the monthly means. Here, the indicators confirm the previous trend observed in the data: the *'Current Land Cover'* tends to overestimate the discharge whereas the *'Potential Natural Vegetation'* tends towards underestimation.

Table 5: Monthly discharge Nash-Sutcliffe, Nash-Modified and Pbias analysis– 1995-2013.

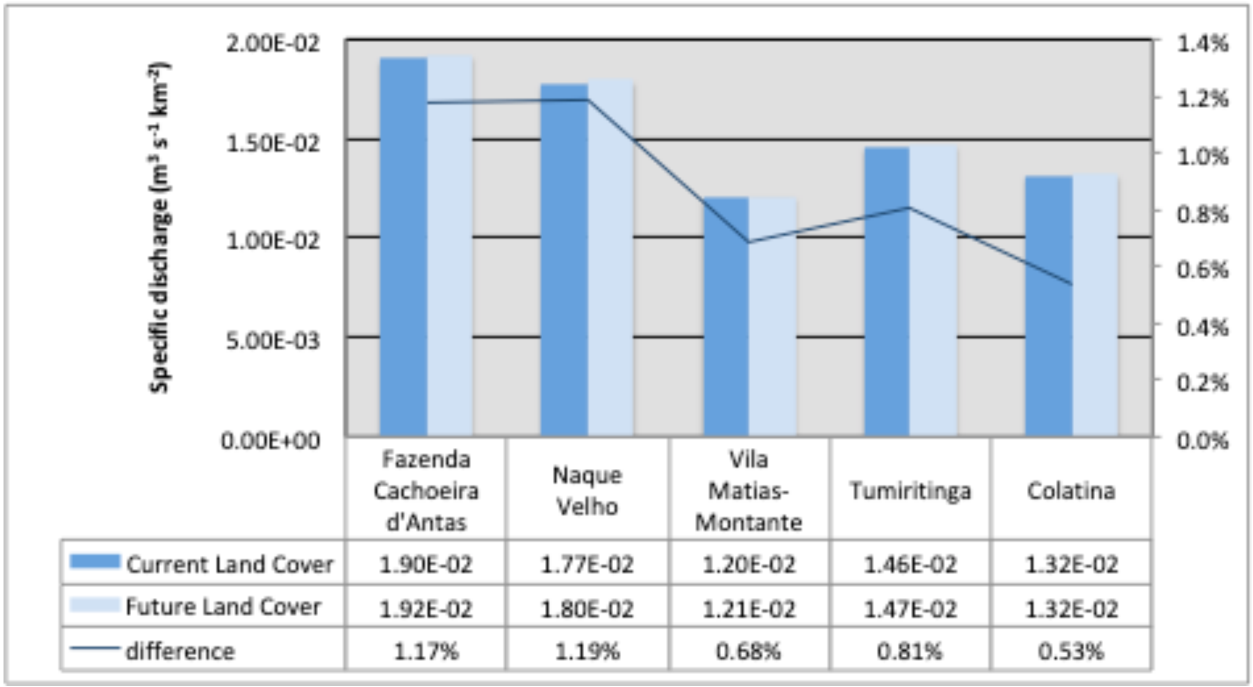
Current Land Cover				
Stream gauge station	Nash-Sutcliffe	Nash-Modified	Pbias*	Number of months in the analysis
Fazenda Cachoeira D'Antas	-1.89	-0.55	-14%	228
Naque Velho	-0.38	-0.07	-21%	228
Vila Matias-Montante	-6.08	-1.04	-103%	228
Tumiritinga	-1.35	-0.39	-21%	228
Colatina	-0.41	-0.04	-24%	228

*negative values indicate overestimation.

4.3.5 Annual Mean Discharge 2014-2030

Figure 16 shows the future land cover impact on the Doce river discharge, considering *OtimizaAgro-SimMinas* model land cover results. The analysis is between different time periods but for the land cover in 2013 and 2030 modeled by this model.

In Figure 16, the biggest difference was of 1.2%, which means the simulated long term mean discharge for the period of 2014-2030 is 1.2% larger than the one for 1995-2013. Two stream gauge stations, *Fazenda Cachoeira d'Antas* (#56425000) and *Naque Velho* (#56825000), have shown this difference and they are also the ones with the smallest drainage area. The least difference was in *Colatina* (#56994510) stream gauge station, with a 2014-2030 annual mean river discharge 0.5% bigger than the one for 1995-2013.



	Fazenda Cachoeira d'Antas	Naque Velho	Vila Matias-Montante	Tumiritinga	Colatina
Current Land Cover	1.90E-02	1.77E-02	1.20E-02	1.46E-02	1.32E-02
Future Land Cover	1.92E-02	1.80E-02	1.21E-02	1.47E-02	1.32E-02
difference	1.17%	1.19%	0.68%	0.81%	0.53%

Figure 16: Future land cover impact on the river discharge –*'Current Land Cover'* versus *'Future Land Cover'*.

5 Discussions and conclusions

The model results suggest that land cover change as per *OtimizaAgro-SimMinas* model may have an impact on the Doce river discharge, and, at the scale of this study, it is not significant because the land cover change was not significant as well (Figure 3). It is known that at the micro and meso-scales, land cover change from forests to pasturesand crops in general leads to less interception, a decrease in total evapotranspiration and an increase in the surface runoff due to the smaller leaf area index (LAI) of grasslands, crops and pastures; and the decreased root density and depth (Coe et al., 2009).

Studies have shown that changing land cover from forests to crops and pastures, which have larger albedo and demand less water from the soil, results in increased river discharge and it seems to have already impacted the Amazon river basin and its tributaries. Coe et al. (2009) have shown that, altogether, these factors alone generate larger river discharges; nonetheless they have to be analyzed in conjunction with the potential impacts on the precipitation, interception, infiltration at a regional scale for the Amazon river basin.

In our simulations for the Doce river basin there are uncertainties intrinsic to the THMB model sensitivity and *Agro-IBIS* parameters, assumptions and inputs. Here, we acknowledge the uncertainties that come from the methods of observation of the river discharges (direct measurement or rating curve); the errors from the climate input dataset used in the Agro-IBIS simulation for the Doce river basin and the sensitivity of *Agro-IBIS* to its numerous parameters and inputs.

The calibration of *Agro-IBIS*, for instance, is still an ongoing process and it is very dependent on soil and vegetation specific parameters, which is a big challenge to overcome in order to obtain better results with THMB for Minas Gerais. The state has a very diverse natural land cover and climate, which results in a wide range of phytophysiognomies with varied physiologies and responses to the climate conditions;

and representing them into the models, *Agro-IBIS* and THMB, is still a gap for Minas Gerais.

The main limitation that was observed in the results relates to the capability of THMB to properly simulate the monthly mean discharges. As opposed to the annual mean discharge, the monthly means strongly depend on the capability of *Agro-IBIS* to simulate the relation between surface runoff and total runoff, which is a direct result of the land cover properties, here, *OtimizaAgro-SimMinas* outputs and soil hydraulic conductivity.

It was observed in the outputs from *Agro-IBIS* that the relation between surface runoff and total runoff is extremely high (>90%) and not adherent to the reality of the region, mainly in the rainy season. For the study area, this results in unreal high peaks of discharge in the rainy seasons and lower discharges in the dry season, nevertheless it is due to the internal uncertainties.

In addition, it was observed that the majority of the land cover of the Doce river region dataset is pastures and that the conversion from 2013 to 2030 is very little (Figures 2 and 3). The *OtimizaAGRO-SimMinas* reference scenario considers that the land cover rate of change has a trend according to a specific economic and political conjuncture that constrained land cover change. This had a significant impact on the land cover and, consequently, on the water balance results.

In practical terms, this means deforestation projections in the reference scenario presupposed the full compliance and effective enforcement of the Brazilian National Climate Change Plan and, most importantly, of the Atlantic Forest Law *(Lei nº 11.428, de 22 de dezembro de 2006.)***,** which establishes no deforestation unless it is a service of benefit of everyone. Here, it was observed that this could be the main reason the differences between the THMB scenarios, 1995-2013 and 2014-2030, very little.

Finally, it is worth noticing that in our simulations, the influence of the feedbacks from the land cover change to the precipitation has not been included, neither the potential future change in the precipitation due to the climate change. The results here convey the impact of the land cover change alone, with the climate forcing unchanged.

Although the changes in the river discharge at the regional scale of Doce river are a complex result of how land use and land cover changed in the past and will be changing in the future, the results here support that conservation actions can have a positive impact on the discharge of Doce river. Mainly because of the importance of the recuperation of the Atlantic Forest biome and of the waters of the river after the Fundão dam accident.

Even though recovering the land with more water-demanding forests can decrease water availability over time, the increased resilience of the whole basin to extreme weather conditions, the long term impact on the regulation of the discharge and the soils basin stabilization strongly justify tighter policies and larger institutional action toward the recovery of deforested areas in the Doce river basin.

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Appendix

A. Hydrological models development

Every hydrological model is a simplified representation of a real river system. A system itself is a whole composed of many parts that interact and have its main intrinsic purpose from this interaction. A system is, therefore, indivisible; every individual part affects the functioning of the whole and the synergies from the parts' interactions generate a greater result than the sum of the individual action of each part.

River systems are the result of the interactions of the solar energy, hydrosphere, biosphere and lithosphere. They are responsible for the distribution of freshwater on the earth, and for many other processes, such as formation of the relief, support of biodiversity, recharge of water tables, and so on.

The development of hydrological models is extremely meaningful because these are important tools for water management in the global, regional and local levels. Scientists and engineers in general are keen on the explaining and predicting capabilities of hydrological models. They can predict not only the available water over time in a river basin under a specific condition but also the transport, accumulation and degradation of nutrients and pollutants in the waters along the river channels, giving important information on water quality and the population experiencing water stress.

The application of hydrological model are not limited to the government or scientists. These models can be useful for all stakeholders in a river basin, mainly for the prevention of extreme events that could put people under water stress, like floods and droughts. It is also very useful for food security and agriculture planning and engineering projects like dams and hydropower plants; hydroways and ports and for the energy prices market, specially in Brazil, which is well known for its hydropower dependency and strong agriculture sector.

In the beginning of hydrology modeling, it was limited to the description of the water cycle individual processes. For instance, Horton's (1933) model for infiltration; Darcy's model for drainage; MacCarthy's (1939) for river discharge, and Muskingun and Puls

(1928) for reservoir flow. From the 1950s rainfall-runoff models were developed, such as *Streamflow Simulation Watershed Model - SSARR* (1958), the Standford Watershed Model (1966) and the Hydrologic Engineering Center – HEC 1 (1968). These models were mainly used for the designing of hydraulic structures and for the expansion the historical series for regulating riverflows. The main challenge of this time was rainfall temporal and spatial representation. (Tucci, 2005)

From the 1970s modeling experienced an increasing computation capability and reliability. Hydrology modeling started to use less inputs parameters and to include the relief and land-use caracteristics, which eased the calibration and reduced the number of equations involved in the processes. TOPMODEL - *Topography Based Hydrological Model* (1970) e o SHE - *Système Hidrologique Européen* (1986) are examples of this new approach. (Tucci, 2005)

B. Hydrology modeling approach and classification

According to Tucci (2005), the first hydrology modeling systems, in the 1950s, were basically graphical and empirical methods restricted to the probability of the observations and the statistical indicators of the processes. There was no description of the physics underlying the processes (interception, infiltration, evaporation, runoff and drainage). This was only possible with the enhancement of the computer methods and the increase in the reliability of the results from the 1970s.

Since then, hydrological modeling has evolved and brought about many classifications for the models. In terms of spatial scale, hydrological models can represent large river basins or medium to small catchments. On the one hand, the first are suitable for representing phenomena that occur in large geographical scales, such as land use land cover change or climate change. They can also be used to evaluate and validate the results of General Circulation Models – GCM, as it was done in this research for Agro-

IBIS. On the other hand, the latter are more sensitive to the variability of the spatial phenomena and are applicable in less generalized cases.

In terms of the system modeled, hydrology models can be propagation models, which simulate the flow of the water in the river channels; rainfall-runoff models, which simulates the response of the flow to the rainfall events and rainfall-propagation models, which integrates both, the rainfall and the river flow overtime. (Tucci, 2005)

Hydrological models can also be classified according to three intrinsic characteristics; (a) the nature of the algorithm (empirical or conceptual); (b) the nature of the inputs (stochastic, deterministic or process based) and (c) the spatial representation (lumped or distributed). (Grayson et al., 2000)

The nature of the algorithm differs the mathematical approach of the phenomena in each model. On the one hand, empirical models, known also as ‘black-boxes’, use regression to adjust the results calculated in the models to the ones observed, not considering the physics underlying the processes. On the other hand, conceptual models progressed in the representation of the physics of the hydrology, taking advantage of the development of computer capabilities. The challenge in this case is how to represent the processes inherent variability and how to represent the parameters effectively. (Grayson et al., 2000, Tucci, 2005)

In terms of the nature of the input, stochastic models use probability distribution functions instead of specific values. In this case, the results are a range of values associated to a probability. In contrast, deterministic models have a single set of specific inputs and always generate the same single set of outputs, regardless of the parameters. (Grayson and Bloschl, 2000)

Finally, the spatial representation of the area can be lumped, where the whole basin is represented in one point (outlet) and by an average result; or distributed, where the whole basin is divided in finite elements of area. In the last approach, for each point in the space the model calculates the processes in the continuum of the river basin. (Tucci, 2005)

C. The Brazilian Water System

The modern framework of the Brazilian Waters Management System is rather recent. The latest Federal law that regulates planning and management of the water resources of the country dates from 1997, which establishes the objectives, the tools and the responsibilities at the national level. The main principles on which the law is based is the decentralization of the decision making process, the multiple and shared uses of the waters and the river basin as the main management boundaries.

It is worth noticing that the Brazilian National Water Resources Policy, the *“Lei 9.433, de 8 de janeiro de 1997”*, establishes as a general directive for action the conjunction of the land use with the water resources management, which is also one of the goals of the model presented here. (Art. 3º, V) This research and the model we propose has the capability of integrating land use and water resources management in an effective and accessible way.

Brazil divided its territory in 12 ‘planning units’, comprising the Watersheds National Division (*Divisão Hidrográfica Nacional*), established in the regulation called *‘Resolução nº32, do Conselho Nacional de Recursos Hídricos (CNRH), de 15 de outubro de 2003’*. (Figure A1) Each planning unit comprises a main national river basin and is the jurisdiction for the water resources planning and management. (Brasil, 2003) Also, the River Basins Committees were established based on this division, which are the agencies responsible for the shared management of the water resources.

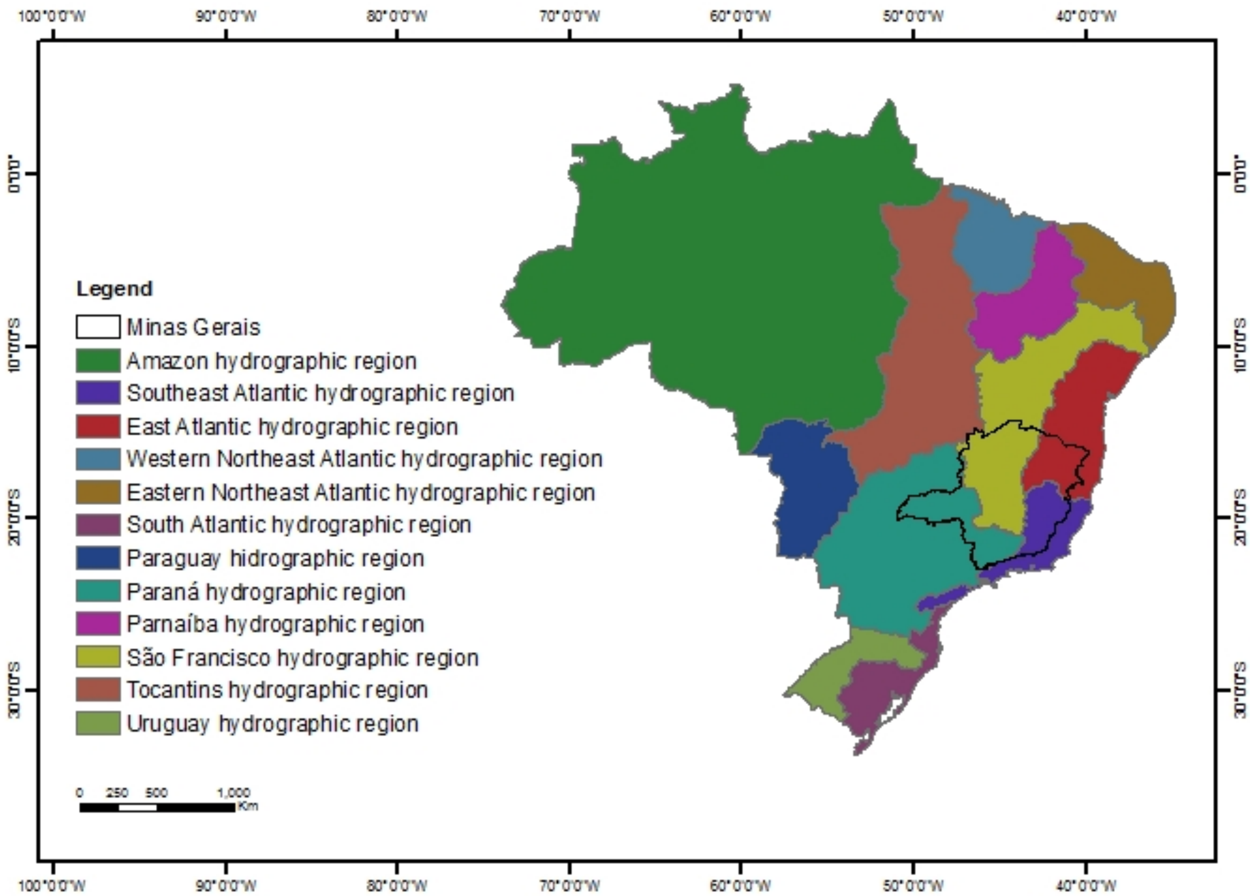

Figure A1: Brazilian Watersheds National Division.

Minas Gerais plays a key role in the Brazilian hydrology. The State holds the springs of two of the countries' main rivers, São Francisco river and Paraná river; and all its neighboring States are downstream of Minas Gerais, which creates a certain dependency between the policies and the uses of the waters. There are 9 main river basins with its heads in this territory, which are São Francisco, Pardo, Jequitinhonha, Mucuri, São Mateus, Doce, Paraíba do Sul, Grande, Piracicaba/Jaguari and Paranaíba rivers. The basins are then divided in 36 Water Resources Planning and Management Units (UPGRH), which are the boundaries for the water laws and policies enforcement within the State. (Minas Gerais, 2002)

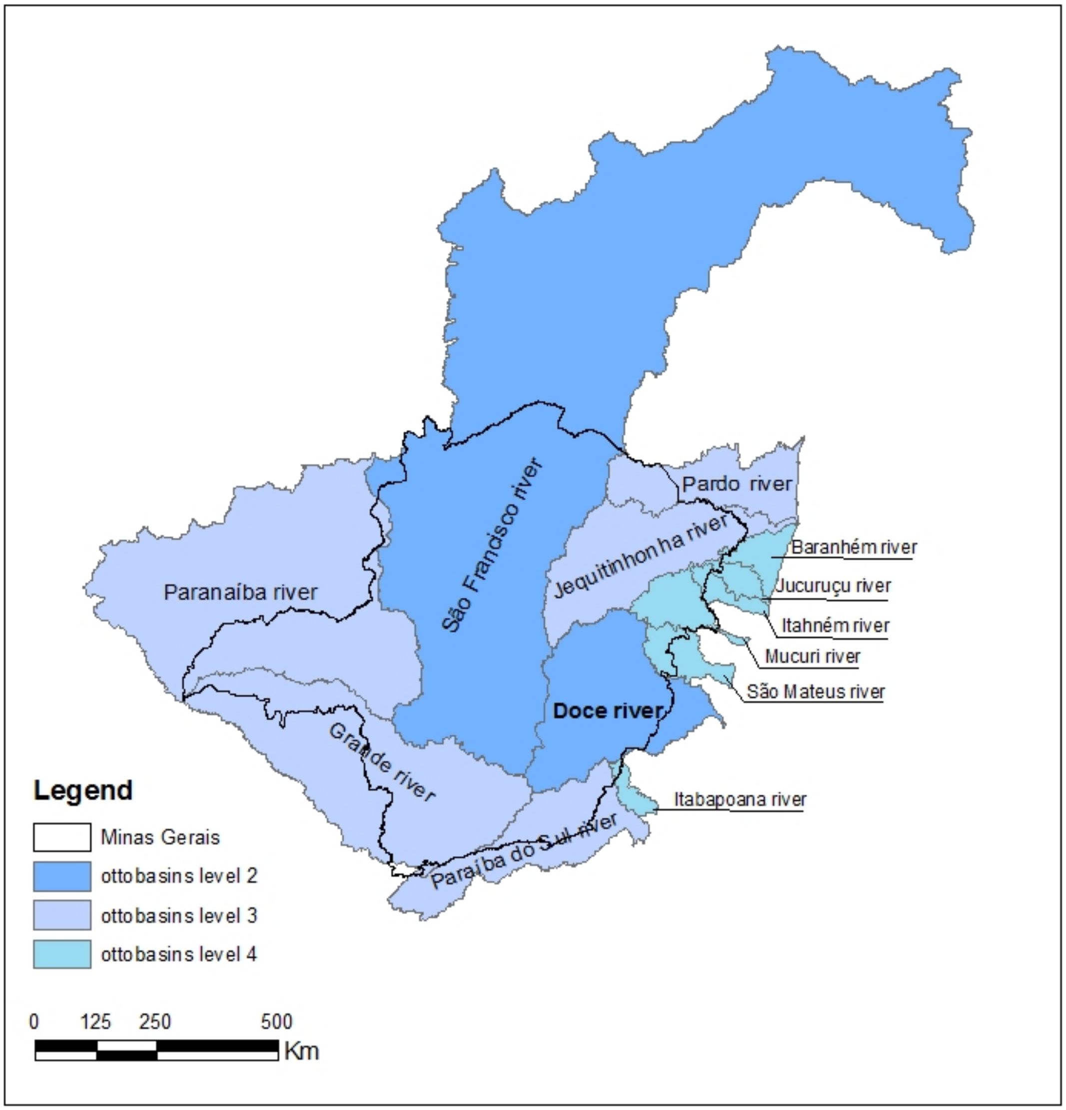

Figure A2: Minas Gerais river basins.

Overall, there are 12 river basins in Minas Gerais (Figure A2), which contribute for the 6.495 m^3/s total mean discharge of the state. In general, the water availability is associated with many environmental factors, such as land use, rainfall, evapotranspiration, and so on. Table 2 summarizes the water availability data of state river basins. It is worth noticing that the rainfall increases from north to south and from northeast to southwest, which reflects in the river discharge.

Tabela A1: Minas Gerais river basins áreas and annual mean discharges.

River Basin	Total Area (km^2)	Annual mean discharge (m^3/s)
São Francisco	235,442	2,057
Grande	86,347	1,524
Paranaíba	70,833	938
Doce	71,468	928
Jequitinhonha	65,852	419
Paraíba do Sul	20,776	310
Mucuri	14,859	161
Pardo	12,763	46
São Mateus	5,683	36
Piracicaba/Jaguari	1,161	24
Itanhém	1,519	19
Itabapoana	671	13
Jucuruçu	712	12

Source: CSR, 2013.

D. THHMB Model Inputs

Table A2: THMB Model Inputs.

Type	Data	Description
Morphological	DEM	Digital Elevation Model
	River flow accumulation	Represents the contribution area at each point of the river route
	River flow direction	Represents the river route
	Sinuosity	Establishes a sinuosity coeficient
	Cell area	Represents the resolution the each cell area individually
	Basin mask	Indexes and establishes the areas of each basin
Climate	Surface runoff	IBIS monthly runoff output
	Drainage	IBIS monthly drainage output
Constant	Initial Year of Simulation	-
	Initial Month of Simulation	-
	Meriadiano Cell Length (m)	-
	Reference Slope Value	-
	Residence Time of Drainage Reservoir (seconds)	-
	Timestep (seconds)	-
	Residence Time Surface Runoff Reservoir (seconds)	-
	Reference Velocity of Rivers	-
	Number of years to run the model	-

E. Models integration flowchart

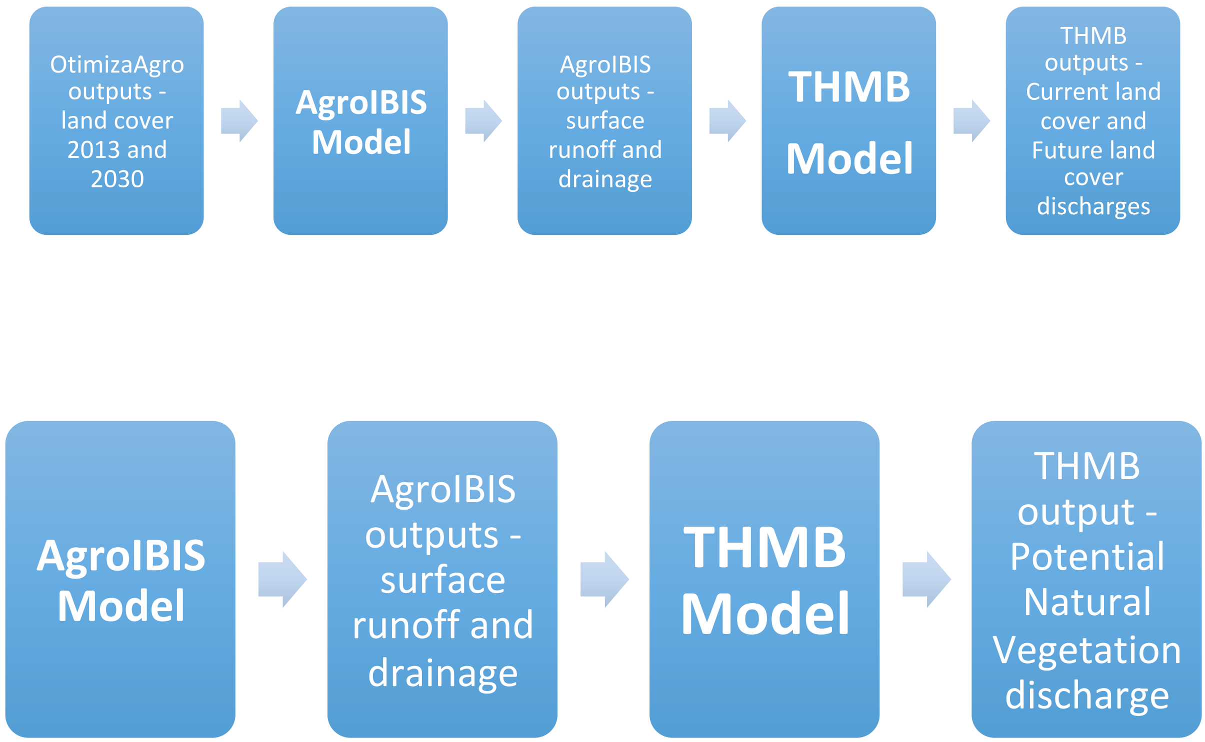

Figure A3: Models integration flowchart.