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Deforestation impact on discharge regime in the Doce River Basin

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ABSTRACT

The construction of scenarios using hydrological models can evaluate the hydrological response in watersheds, due to changes in the soil use. In this context, this study analyzed the consequences of deforestation in the hydrological behavior of the Doce River Basin, which has a drainage area of approximately 86.715 km². The basin presents problems regarding water availability, floods, indiscriminate deforestation and inadequate soil management. The Model of Large Basins (MGB-IPH) was selected, using daily data from 1990 to 2014, 11 fluviometric, 81 rainfall and 12 meteorological stations, numerical model of the land, soil maps, and use and land cover. Hydrological modeling was performed in the following steps: calibration of parameters (1990 and 2005), validation (2006 to 2014) and simulation of deforestation scenarios (2000 to 2014). It was observed that the replacement of forests by pasture caused reductions in the average annual flows, indicating a decrease in average flows in deforestation scenarios. As for the behavior of floods, deforestation caused them to increase, while the annual minimum flows reduced with deforestation. The results demonstrate the worsening that the simulated scenarios can cause in the problems already found in the basin, such as floods and water shortages, to supply the uses for which the basin is intended.

Keywords: deforestation, Doce river basin, hydrological simulation.

Impacto do desmatamento no regime de vazões da bacia hidrográfica do rio Doce

RESUMO

A resposta hidrológica em bacias hidrográficas devido às mudanças do uso do solo pode ser avaliada por meio da construção de cenários, usando modelos hidrológicos. Nesse contexto, o objetivo desse trabalho foi analisar as consequências do desmatamento no comportamento hidrológico da bacia hidrográfica do rio Doce, que possui uma área de drenagem de 86.715 km². Alguns dos problemas enfrentados pela bacia estão relacionados à disponibilidade hídrica, inundações, desmatamento indiscriminado e manejo inadequado do solo. Sendo assim, foi selecionado o Modelo de Grandes Bacias (MGB-IPH), onde foram usados dados diários de 11 postos fluviométricos, 81 pluviométricos e 12 meteorológicos, modelo numérico do terreno, mapas de solos e uso e cobertura do solo (2000). A modelagem hidrológica foi realizada nas seguintes etapas: calibração dos parâmetros (1990 a 2005), validação (2006 a 2014) e simulação dos cenários de desmatamento (2000 a 2014). Foi constatado que a substituição de florestas por pastagens provocou reduções nas vazões médias anuais, indicando uma diminuição das vazões médias em cenários de desmatamento. Quanto ao comportamento das cheias, o desmatamento provocou o aumento das mesmas, enquanto que às vazões mínimas anuais reduziram com o desmatamento. Os resultados demonstram os agravamentos que os cenários simulados podem acarretar nos problemas já encontrados na bacia como inundações e escassez de água para suprimento dos usos para os quais a bacia se destina.

Palavras-chave: bacia do rio Doce, desmatamento, simulação hidrológica.

1. INTRODUCTION

Anthropogenic activities, such as high standards of living, demographic changes and intense land and water consumptions are pressuring natural resources, undermining sustainability and thereby environmental issues. Pressure on water resources at local, regional and national scales for human consumption, irrigation, energy production, and industrial uses, among others, are steadily increasing. All these pressures imposed on the soil-vegetation-water system impact the hydrological cycle, generating uncertainties in the sustainable maintenance of water resources in watersheds.

Due to difficulties in monitoring and data scarcity, water discharge in a river basin can not be constantly monitored. Thus, the impact of anthropic activity on hydrological variables in watersheds can be evaluated in qualitative and quantitative terms through the construction of scenarios by means of mathematical and physical models associated with geographic information systems (Prado, 2005). As a part of mathematical models, hydrological modeling emerges as a worldwide tool used for several applications, such as the analysis of hydrological response due to changes in land use and occupation (Abbaspour *et al.*, 2015).

The Large Basin Model (MGB-IPH) is a hydrological model that has been applied to determine the impacts of changes in land use on the hydrological regime in different types of climate and vegetation. Caram (2010), Bayer (2014) and Beserra (2016) conducted studies on the impacts of changes in land use in watersheds using MGB-IPH.

Land-use change processes encompass natural vegetation removal or degradation, both associated with significant ecological impacts on practically all scales. Globally, they contribute to greenhouse gas emissions that are associated with global climate change, while regionally and locally, they affect hydrological responses in the watershed (Ibarra-Montoya *et al.*, 2011).

The Doce River Watershed is an example of a basin that has issues related to indiscriminate natural vegetal removal and inadequate soil management. Consequently, the area constantly experiences extreme events (floods and droughts) and water availability and quality issues. This paper therefore estimated flow variations in the Doce River Basin over different deforestation scenarios, using the MGB-IPH.

2. METHODOLOGY

2.1. Study Area

The Doce River Watershed is located in the Southeast region of Brazil, covering part of states of Minas Gerais and Espírito Santo. The basin has a drainage area of approximately 86.715 km², of which 86% belongs to the State of Minas Gerais and the remaining 14% to the State of Espírito Santo (CBH-DOCE *et al.*, 2006). The main headwaters are located in the state of Minas Gerais, in the Mantiqueira and Espinhaço hills, and its water runs about 850 km until reaching the Atlantic Ocean, in the state of Espírito Santo (PIRH- DOCE, 2010).

Cupolillo *et al.* (2008) state that the predominant climate in the basin is classified as humid tropical. The rainy season starts in November and lasts until May with annual precipitation exceeding 700 mm. Most of the entire basin has high average annual temperatures (above 18°C) during most of the year, even during winter. In general, the river water level follows the rainfall, characterized as perennial. The higher flows occur in the months of December, January, and March, while the lowers occur in August and September (PIRH-DOCE, 2010).

According to PIRH-DOCE (2010), in the Doce River Watershed, the higher specific flows, which mean the water flow per extension of an area, are not directly associated with the larger drainage areas, but with soil type and rainfall periodicity. The basins that are located closer to the headwaters present a higher water production than those in the state of Espírito Santo, indicating a diversity of water availability, which may require different actions for each specific sub-basin.

Floods, which are a major problem in the Doce River Basin, are mainly recorded in the months between December and February. In addition to the intense rainfall that causes flooding, since the begging of the 19th century, the Doce River Basin had its natural vegetation cover (Atlantic forest) removed due to the planting of coffee and sugarcane crops, logging and pasture formation. These actions modify soil infiltration and storage capacity, aggravating the effects of floods, especially in small basins. Along with to this, the disordered occupation of the floodplain areas, especially in urban areas, has aggravated the damages caused by floods (PIRH-DOCE, 2010).

2.2. MGB-IPH Model

The Large Basin Model (MGB-IPH), developed by Collischonn (2001), is a large-scale distributed hydrologic model that performs flow propagation using the Muskingum-Cunge method. The model uses conceptual and physical equations to simulate the terrestrial hydrological cycle: soil water balance; energy balance; evapotranspiration, interception, flow generation (surface, subsurface, and base flow); and flow propagation. In the present study, the MGB-IPH, Version 3.0, was used, which considers a discretization of the basin in irregular units (mini-basins) and Hydrologic Response Units (HRU's), both using the Digital Elevation Model (MDE), land-use map and according to similarity in hydrological behavior (Fan and Collischonn, 2014). The vertical water and energy balances are computed independently for each HRU in each mini basin. The balance is performed considering only one layer of soil, according to Equation 1:

$$\frac{dW}{dt} = P - ET - D_{sup} - D_{int} - D_{bas} + D_{cap} \quad (1)$$

Where: W (mm) is the water storage in the soil layer, P (mm dt^{-1}) is rain that reaches the ground, ET (mm dt^{-1}) is the evapotranspiration, $Dsup$ (mm dt^{-1}) is the surface runoff, $Dint$ (mm dt^{-1}) is the subsurface runoff, $Dbas$ (mm dt^{-1}) is the percolation to the water table, and $Dcap$ (mm dt^{-1}) is flow due capillary forces (Collischonn, 2001). The energy and evapotranspiration balance of soil and vegetation are estimated by the Penman-Monteith equation (Equation 2):

$$ET = \left(\frac{\Delta.A + \rho_A c_p \frac{D}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \right) \frac{1}{lam.\rho_w} \quad (2)$$

Where: λ (MJ kg $^{-1}$) is the latent heat of vaporization, Δ (kPa °C^{-1}) is the function of saturation vapor pressure gradients, A (MJ m^{-2} s^{-1}) is the available energy, ρ_a (kg m^{-3}) is the air density, ρ_w (kg m^{-3}) is the specific weight of water, c_p (MJ kg^{-1} °C^{-1}) is the specific heat of humid air, D (kPa) is the vapor pressure deficit, γ (kPa °C^{-1}) is the psychrometric constant, rs (s m^{-1}) is the surface resistance of the soil cover and ra (s m^{-1}) is the aerodynamic resistance (Collischonn, 2001). The model parameters that are important to discriminate soil land use and coverings are: albedo (α), leaf area index (IAF), aerodynamic resistance (ra), surface resistance (rs) and the interception coefficient (α), in addition to the parameter Wm, which determines the maximum storage in the soil and must be altered according to the land use and cover typologies (Collischonn, 2001).

The value of the albedo parameter defines the energy that is available for the evapotranspiration process. Deforestation tends to reduce evapotranspiration and increase runoff; thus, deforestation causes an increase in albedo (Collischonn, 2001). The albedo value was assigned from 0.12 to 0.16 for the forest and the albedo value from 0.18 to 0.24 for the pasture, which constitutes deforestation.

Regarding the IAF parameter, the higher the IAF, the greater the maximum interception blade, decreasing the flow. For the forest, the value was assigned from 4.0 to 9.0 and for the pasture, the value from 1.0 to 4.0.

The surface resistance represents the process of the flow of the water from the soil, through the interior of the plant, to the outside of the leaves, besides controlling the sweating process. The higher the surface resistance, the less sweating. In forests, the surface resistance is approximately 100 s / m in pasture, approximately 70 s / m (Shuttleworth, 1993).

As for the parameter of soil storage capacity, this is different for different vegetative cover, because the forests draw water from depths greater than the field vegetation, since the roots of the forest trees reach greater depths. This difference is fundamental in analyzing the hydrological consequences of land use change, especially during periods of drought, because while the volume of water available to the field vegetation is already depleted, the forest vegetation continues to perspire at a normal rate (Collischonn, 2001).

It is likely that parameter b has a strong relation with infiltration capacity; however, it is not possible to directly estimate the values of b based on the characteristics of the vegetative cover. Sensitivity analysis revealed that the higher the value of b, the larger the peaks of small and medium floods; however, b does not profoundly alter the peaks of the highest floods. Basins with deforestation should be represented by the model with higher values of b (Collischonn, 2001).

Both the maximum storage parameter (Wm) and parameter b are used as calibration parameters of the MGB model.

2.3. Input database

The first database required for modeling in MGB-IPH is composed of slope, pedology and land use/cover. The slope data used comes from an SRTM (Shuttle Radar Topography Mission), produced by NASA (National Aeronautics and Space Administration), with a spatial resolution of 90 meters (CGIAR, 2017). For pedology, data was extracted from the Brazilian soil map (EMBRAPA, 2001) in the scale of 1:5,000,000. Finally, for land use and occupation data, a map available from the Brazilian Institute of Geography and Statistics (IBGE, 2000) was used, in a 1: 1,000,000 scale, corresponding to the calibration and validation periods. The agricultural class predominates in the basin, occupying 67.60%, followed by the Atlantic forest class, covering 18.54%.

The other data required for modeling refer to pluviometric, fluviometric and climatological variables. Data from 81 rainfall stations was used for these, and even though there were 60 fluviometric stations inside the basin, only 11 of them were used due to reliability. The historical series of these stations were taken from January 1, 1990, to December 31, 2014, and the data were publically available through the National Water Agency (ANA, 2017). The climatological data (temperature, relative air humidity, wind speed, atmospheric pressure and insolation) were made available by the National Institute of Meteorology (INMET, 2017), totaling 12 meteorological stations. Figure 1 shows the location of the river basin and the stations used.

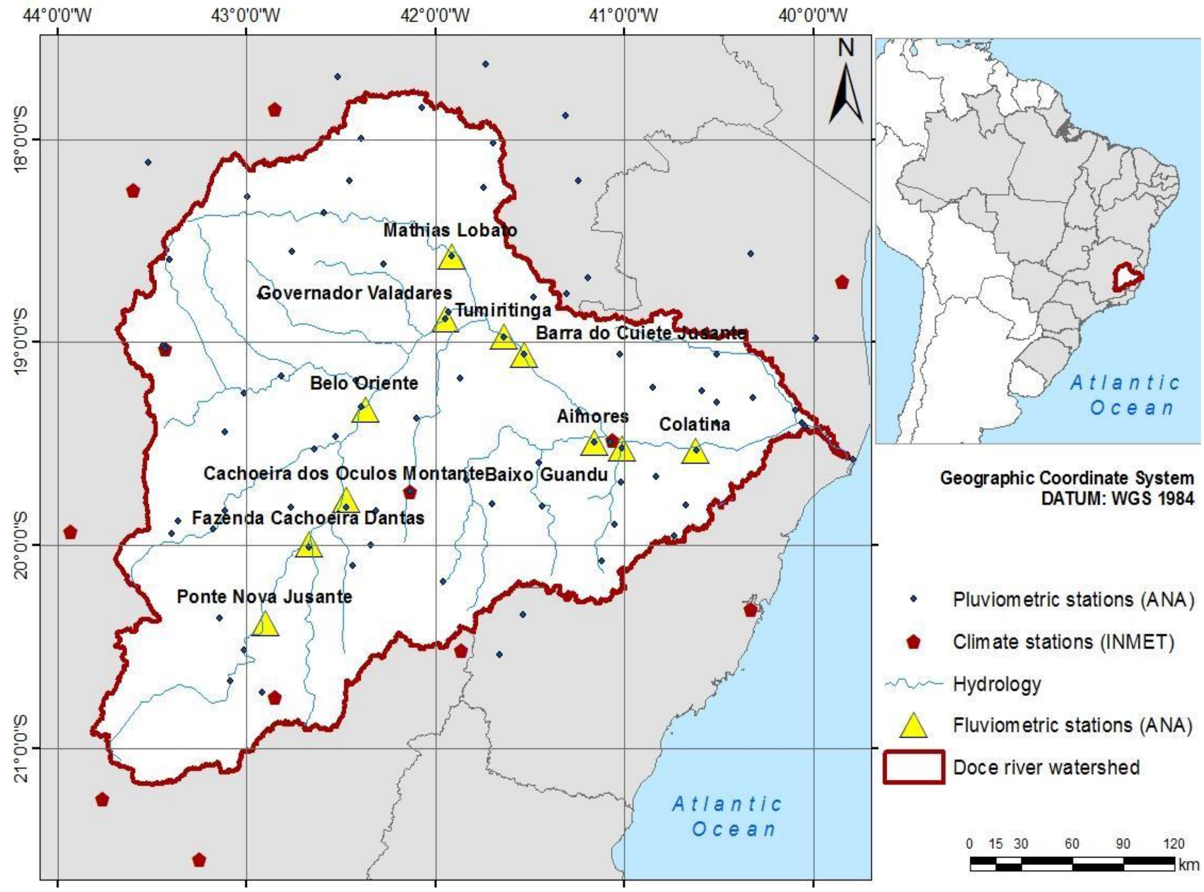

Figure 1. Location of the fluviometric, pluviometric and meteorological stations used in the simulation.

2.4. Hydrological Modeling

Hydrological simulation began with the spatial data discretization in ArcGIS. The drainage network was defined, and then divided into parts, which allowed the delimitation of the contributed areas for each part (mini-basins). The sub-basins were delimited according to the locations of the fluviometric stations and the basin outlet. As a result, 581 mini-basins and 12 sub-basins were identified.

Soil typologies were grouped in terms of two subjective classes of potential generation of runoff: 1) low potential or deep soils; 2) high potential or shallow soils. The first class comprises soils with low- and medium potential generation for runoff and high potential for water storage (latossoil and argissoil). The second class includes soils with high runoff generation capacity and low capacity for water storage (neosoil, gleysol, and cambisols). The final combination of reclassified soil types was used to generate HRU classes.

The land-use and cover map was also simplified by grouping some of its classes by hydrological similarity in order to facilitate analyses of the influence of vegetative change influence. For reclassification, the "Forest" class was considered to include natural vegetation (Atlantic forest), farm forestry and agroforestry. Similarly, natural and planted pastures were grouped into the "Pasture" class. With the simplified data, the 10 URHs were generated. Figure 2 shows the sub-basins and URHs created.

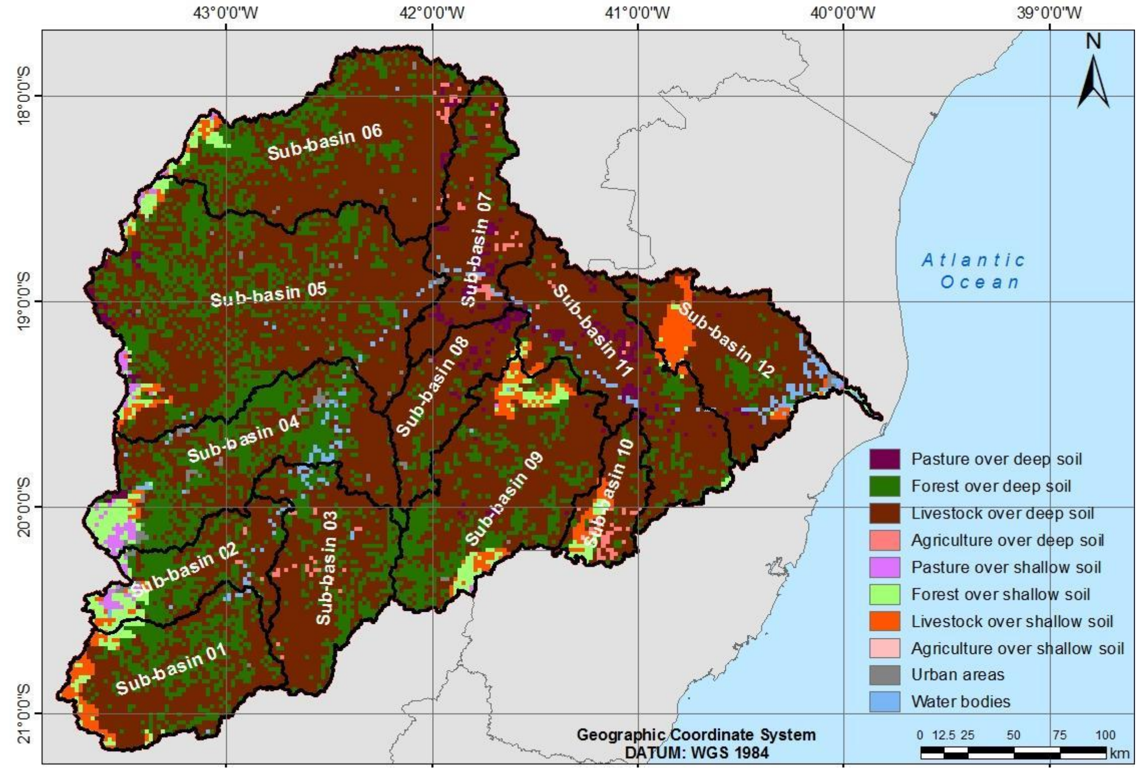

Figure 2. Sub-basins and HRUs created for the simulation in the MGB-IPH model.

Before the modeling, precipitation and flow data needed to be discretized according to the location of their pluviometric and fluviometric station location in the mini basin. Soon after, the climate data were prepared, in which the climatological averages and the daily climate files were generated. Vegetation data were also prepared, characterizing each HRU by the magnitude of albedo (a), leaf area index (LAI), canopy height (h) and surface resistance (Rs) parameters. The values adopted for each HRU were according to those cited by Collischonn (2001). It is important to mention that, for HRUs that had agricultural land uses, the vegetation parameters values were attributed by means of an arithmetic mean of the values of the parameters of the HRUs that contemplate the uses pasture and agriculture, as was done in the work of Collischonn (2001).

The model was manually calibrated with subsequent automatic calibration. The automatic calibration process occurred only for the sub-basins Number 01, 06 and 08, which obtained inferior performance after manual calibration. The results were compared visually from the hydrograms and flow permanence curves and from three performance metrics: the Nash and Sutcliffe efficiency coefficient (ENS), the R^2 adjusted for the flow logarithm (ENSlog) and the relative error of the total volume of the hydrograms (ΔV). The calibration period used was from 1990 to 2005, while the validation step was the period from 2006 to 2014.

2.5. Deforesting scenarios

A major problem regarding land-use and occupation changes in the Doce River Basin lies in the replacement of the Atlantic Forest biome (natural landscape) into other uses. In order to evaluate the impact that land use and occupation has on the hydrological process, we estimate the discharge in 2000 using the MGB-IPH and compare with other five scenarios based on hypothetical levels of deforestation. The hydrological model considered scenarios where, initially, 100% of the basin was covered by forests. Simulations were then carried out using progressive stages of deforestation (25%, 50%, 75%, and 100%), with pasture in substitution for the existing forest.

In order to analyze the effects of deforestation on the discharge, the simulation was repeated for each scenario considering the same historical period from 2000 to 2014, and climatological and precipitation data. Thus, the effects of the impacts of land-use changes on climate and precipitation were not considered in the paper. The values of the vegetation parameters adopted for the forest and pasture were the same as for calibration, while the soil parameters values were the ones found at the end of the automatic calibration.

3. RESULTS AND DISCUSSION

The calibration process considered 11 sub-basins, since there was no fluviometric station downstream from the sub-basin (11). Thus, the modeling results of sub-basin (11) were analyzed and not those of sub-basin (12). When comparing the results from the validation period with the calibration period, the results were slightly different for most of the stations, and the values estimated by the model showed good agreement with those monitored in the field, according to the performance metrics used. The flow estimations for all the scenarios proposed are presented numerically in Table 1 and graphically in Figure 3.

Table 1. Maximum, minimum and mean annual discharges per year and annual runoff difference compared to the actual situation in 2000, obtained for the period between 2000 and 2014 for sub-basin 11.

SCENARIOS	Q_{Mean} (m³/s)	ΔQ_{Mean} (%)	Q_{Max} (m³/s)	ΔQ_{Max} (%)	Q_{Min} (m³/s)	ΔQ_{Min} (%)	Q_{Med} (mm/ano)	ΔQ (%)
Actual simulation (year 2000)	847,09	-	4495,97	-	316,41	-	3656,76	-
0% Past. and 100% Flor.	985,12	16,29	4055,55	-9,80	483,28	52,74	4275,82	16,93
25% Past. and 75% Flor.	937,92	10,72	4124,24	-8,27	430,43	36,04	4070,43	-4,80
50% Past. and 50% Flor.	890,72	5,15	4198,59	-6,61	377,57	19,33	3865,02	-5,05
75% Past. and 25% Flor.	843,53	-0,42	4274,67	-4,92	324,67	2,61	3659,61	-5,31
100% Past. and 0% Flor.	796,33	-5,99	4353,98	-3,16	271,74	-14,12	3454,22	-5,61

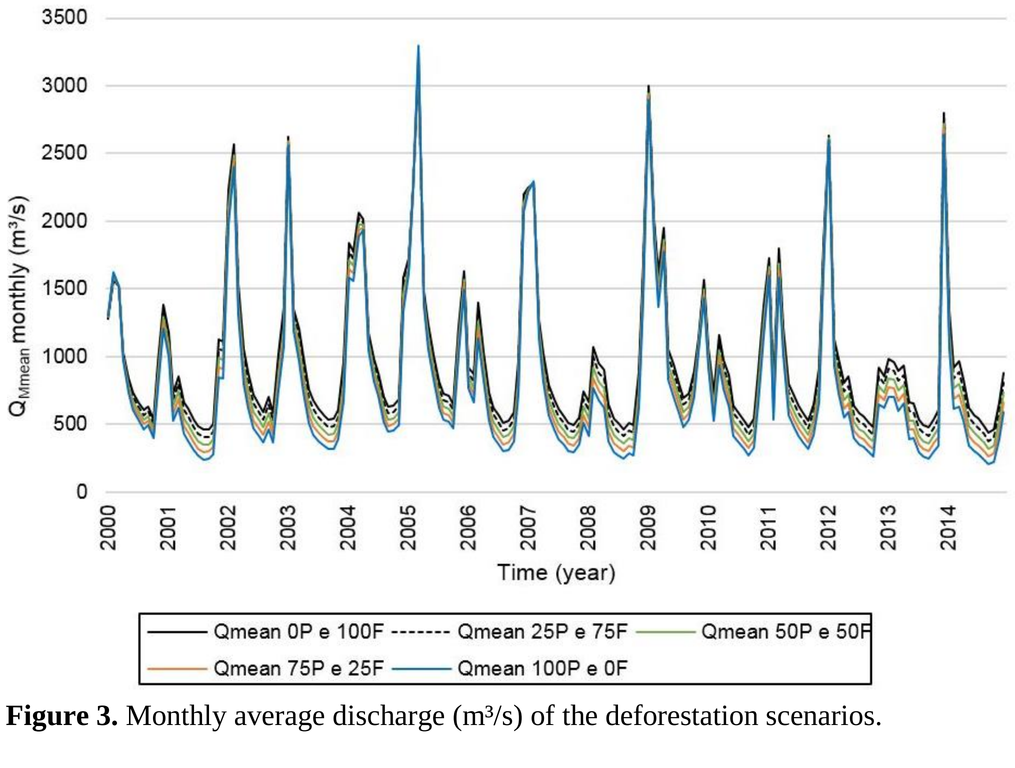

Figure 3. Monthly average discharge (m³/s) of the deforestation scenarios.

According to the results, in the first three scenarios, there was not an increment in the annual average discharge, while there was in situations with 75% and 100% natural vegetation removal. This result was expected, since the land-use/cover map used (year 2000) has 70.29% pasture and agricultural uses, and thus, only the scenarios with the highest percentages of pastures (75% and 100%) would imply in reductions in the annual average discharge. Considering all the scenarios, the one that considers 100% cover of natural forest has the largest increase (16.29% - 142.5 m^3/s) in an annual average flow, corresponding to 619 mm increase in annual flow. The average annual outflow for the 100% forest maintenance scenario was 985.12 m^3/s. Regarding the maximum annual discharge, in all the scenarios there was a decrease compared to the scenario of 2000. On another hand, the minimum annual flows increased in all scenarios, except in the one with 100% pasture cover.

A 25% deforestation caused a rise in the annual maximum discharge of 68.69 m^3/s and a reduction in the annual minimum flow of 52.85 m^3/s, and an annual average of 47.2 m^3/s, corresponding to a decrease in the outflow average of 205.4 mm/year when compared to the complete forest cover. This result is not consistent with the data found by Bosch and Hewlett (1982) and Collischonn (2001), who estimated, respectively, average increases of 10 to 25 mm and of 9 mm for every 10% reduction of deciduous forest. However, these results were measured in small basins (Bosch and Hewlett, 1982) or in a 26,900 km^2 basin with high slope and soil type that favors the rapid generation of large floods (Collischonn, 2001). Similarly, when the 50, 75 and 100% pasture scenarios were simulated, there were reductions in the average and minimum annual discharges and a rise in the maximum annual flow.

It was observed that the 100% substitution into pasture caused a 5.99% (50.76 m^3/s) reduction in the average annual discharge, while in the scenario of 100% forest caused a rise of 16.29% (138.03 m^3/s), when compared to the year 2000 simulation. This result indicates a decrease in annual mean flows in deforestation scenarios, which is in agreement with the average behavior of the results obtained in experimental basins (Bosch and Hewlett, 1982; Collischonn, 2001). However, Caram (2010) and Beserra (2016), when performing hydrological simulations using MGB-IPH in watersheds located in the Brazilian Southeast region, as well as in the Doce River Basin, also found results contrary to the average behavior observed in experimental basins. Additionally, during long drought periods, the average flow tends to suffer more influence from the base flow, which reduced the average annual discharge. The decrease in annual mean flow rates in deforestation scenarios, especially in drought periods, can be explained by the greater capacity of storing water in the soil covered by forests. While the volume of water available for grazing is already depleted, forest vegetation continues to perspire at a normal rate, demonstrating one of the negative effects of deforestation and land conversion on pasture, aggravating the problem of water shortage in the basin.

The results suggest a rise in flood possibilities due to deforestation processes, which are consistent with the results found by Bayer (2014) and Andreassian (2004). On another hand, deforestation process results in the reduction of the annual minimum flows, also are in agreement with the previous papers (Caram, 2010; Beserra, 2016). The increase in floods caused by deforestation can be attributed to the hydrological role of surface water absorption forests and the regularization of liquid flows, avoiding floods. In this way, the replacement of forests by pastures or deforestation causes an increase in the occurrence of floods.

The permanence curve of sub-basin 11 was also analyzed (Figure 4). Related to the impact of deforestation on the minimum flows, we evaluated the Q95 flows (flows associated with the 95% permanence). There was a reduction of 11% in the scenario of 25% of deforestation, 23% in the 50% of deforestation, 34% in the 75% of deforestation and 46% in the 100% of deforestation.

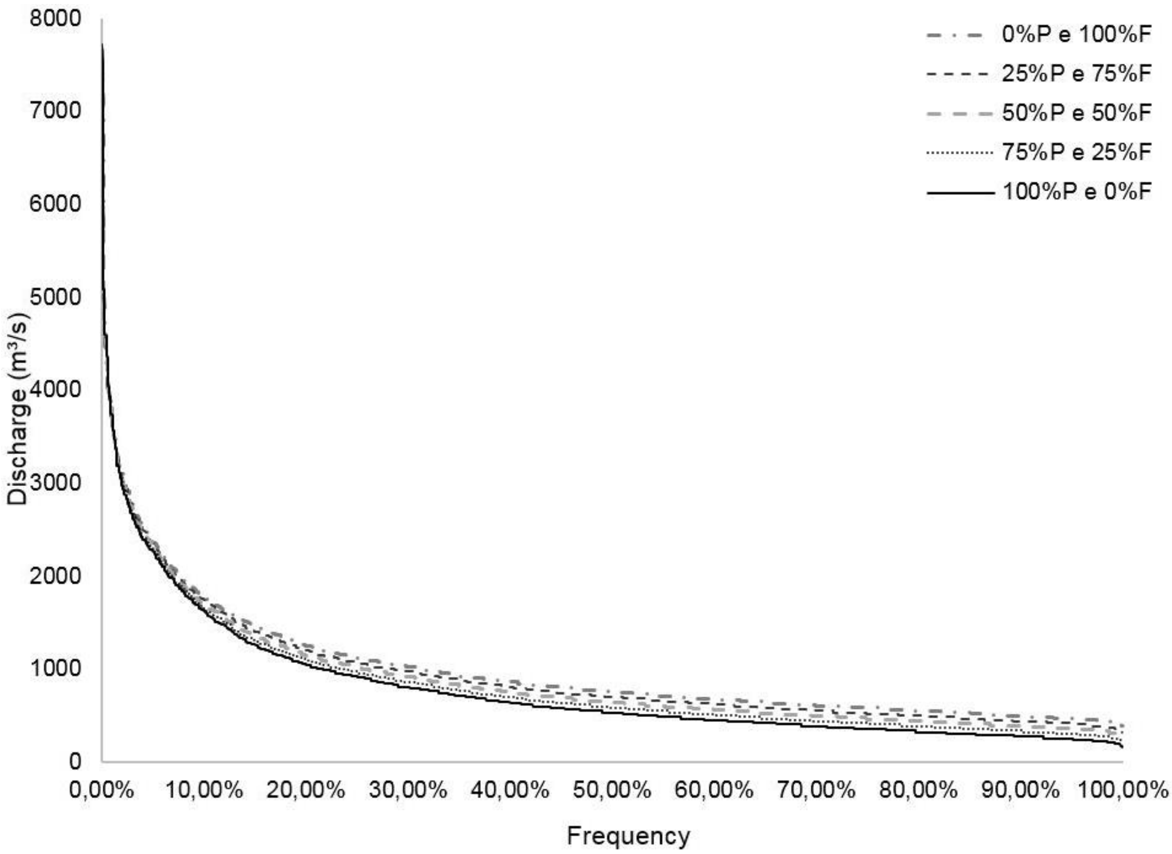

Figure 4. Permanence curve in sub-basin 11.

4. CONCLUSION

The MGB-IPH model had satisfactory adjustments for daily flow simulation in calibration (1990-2005) and validation period (2006 - 2014). It proved to be a powerful tool in hydrological simulations, suitable in the management of the water resources of this basin.

We verified that the replacement of forests by pastures caused reductions in annual average discharge, indicating a decrease in average flows in deforestation scenarios. On another hand, deforestation caused an increment in floods, unlike that of the minimum annual flows, which reduced with deforestation. Although these results are not in agreement with the average behavior of those obtained in experimental basins, they are consistent with studies carried out in other basins located in the Brazilian Southeast region.

Finally, the results from these simulated deforestation scenarios allow the anticipation of deteriorating problems that already exist in the basin, such as floods, due to the increments in maximum flows, and water scarcity with minimum flow reductions.

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