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Biomass Model and Water Balance Application for Watershed Drought Analysis

Aplicação de Modelo de Biomassa e Balanço Hídrico para Análise de Seca em Bacia Hidrográfica

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Abstract

The hydrological cycle is an important process for monitoring various functions of the landscape. However, changes from land use and natural events, such as drought, have caused several problems in watersheds, such as water scarcity episodes. Thus, the creation of tools for monitoring these events is important in environmental research. Therefore, the objective of this work is delimiting the potential biomass and elaborates the water balance of the Serra Azul stream sub-basin (MG) to analyze the influence of drought on the water storage of the hydrographic basin. The used methodology involved the calculation of the Vegetation Condition Index (VCI), application of the biomass model and evaluation of water balance. Furthermore, a regression analysis was performed between the analyzed data to verify the influence of the variation in biomass and water balance in the worsening of drought in the study region. The results indicated that variations in land use and the natural changes in the hydrological cycle contributed to the worsening of drought proving the effectiveness of biomass model associated to water balance and VCI data for monitoring drought.

Keywords: Seasonality; Geostatistics; Remote sensing

Resumo

O ciclo hidrológico é um processo de grande importância para o monitoramento de diversas funções da paisagem. Entretanto, as alterações advindas do uso do solo e de evento naturais como a seca, têm proporcionado diversos problemas em bacias hidrográficas, como episódios de escassez hídrica. Dessa forma, tem se tornado cada vez mais importante a criação de ferramentas que possibilitem o monitoramento desses eventos. Assim, o objetivo desse trabalho é aplicar uma metodologia para delimitação de biomassa potencial e elaborar o balanço hídrico da sub-bacia do Ribeirão Serra Azul (MG) para analisar a influência da seca no armazenamento hídrico da bacia hidrográfica. A metodologia utilizada envolveu o cálculo do Índice de Condição de Vegetação (ICV), aplicação do modelo de biomassa e o cálculo do balanço hídrico. Além disso, realizou-se uma análise de regressão entre os dados analisados para verificar a influência da variação da biomassa e do balanço hídrico no surgimento da seca na região de estudo. Os resultados indicaram que as variações do uso do solo em conjunto com alteração naturais do ciclo hidrológico contribuíram no agravamento da seca e comprovaram a eficácia do modelo de biomassa para o monitoramento da seca em conjunto com os dados de balanço hídrico e de ICV.

Palavras-chave: Sazonalidade; Geoestatística; Sensoriamento remoto

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1 Introduction

The hydrological cycle is the process which studies the natural behavior of water in relation to the environment and human activities. In this aspect, water is evaporated from the oceans and the continental surface combining with the atmosphere components. Subsequently, the humidity turns into precipitation and is flow on the continental surface and oceanic regions. In the process of precipitation, vegetation can intercept the water on the land surface by means of soil infiltration. This cycle involves several hydrological processes, such as evaporation, precipitation, interception, transpiration, infiltration, percolation and others (de Paula & de Oliveira 2021; Dutra 2021; Lima 2008; Naghettini & Pinto 2007; Villela & Mattos 1975).

Drought is affected by climate changes and directly interferes in the hydrological cycle, causing a water entry decrease into the system. These factors are associated with decreased rainfall, increased temperatures and low humidity. In the occurrence of serious changes in the system, caused by drought events, the regions are susceptible of water scarcity, which consists in water volume decrease of rivers, lakes and reservoirs. This process was registered in several regions of the world, mainly in the year 2015, such as in Western Europe and South America, and has been the focus of studies in academic area. These studies aim to understand how far the extreme of this event can unbalance the hydrological cycle and how the impacts can be mitigated and managed (Changnon et al. 2000; Dutra 2021; Dutra et al. 2021; Luz et al. 2021; Mishra & Singh 2010; Van Lanen et al. 2016).

Currently, the studies related to water scarcity investigate how changes in the land use from deforestation, agricultural expansion and misuse of water resources are impacting the worsening drought and its climatic effects in the loss of biodiversity. The suppression of vegetation for expansion of urban areas causes changes in precipitation, availability of water in the soil and evapotranspiration. Although the existence of several studies identifying these relationships, there are still uncertainties about the future influences of socio-environmental and land use factors on availability of ecosystem services, mainly those associated with climatic issues (Briassoulis 2019; Foley et al. 2005; Popp et al. 2017; Suekame et al. 2021).

The influence of land use changes in worsening drought is due to the fact that this event is directly impacted by climate changes and by the hydrological cycle. Thus, it is of great importance to create mitigation measures, such as disaster monitoring and management plans to avoid serious consequences of drought in a region. In this perspective, the use of effective tools, such as remote sensing technologies, have allowed the observation and production of estimates using times series data to statistical and geospatial analysis (Anderson et al. 2016; Dutra et al. 2021; West, Quinn & Horswell 2019).

In this context, the objective of this work is delimiting the potential biomass and evaluate the water balance of the Serra Azul stream sub-basin to analyze the influence of drought on the water storage of the hydrographic basin.

2 Methodology and Data

2.1 Study Area

The Serra Azul stream sub-basin is especially important for the water supply of Belo Horizonte Metropolitan Region because of the presence of a water supply reservoir managed by Companhia de Saneamento de Minas Gerais (COPASA in Portuguese). This region is located between the parallels 20º 15 ‘and 20º 00’ south latitude and the meridians 44º 15 ‘and 44º 35’ west longitude (Figure 1), encompassed in the municipalities of Mateus Leme, Igarapé, Juatuba and Itaúna (Dutra et al. 2021; Dutra, Brianezi & Coelho 2020; Dutra, Elmiro & Garcia 2020).

2.2 Calculation of Vegetation Conditional Index (VCI)

For the calculation of the VCI, it was use the methodology proposed by Kogan (1995a) and MODIS sensor data referring to normalized difference vegetation index (NDVI). All the time series (2013-2018) images were organized according to seasons of the year and then calculated the averages of NDVI values for each season, according to Equation 1, where IM relates to images of each season of the year; X is the average of a set of numerical data; and Ni are the NDVI values.

$$\bar{X} = \frac{1}{IM}\sum_{i=1}^{IM} Ni \qquad (1)$$

The VCI was obtained through Equation 2, proposed by Kogan (1995a), by calculating the average of values for each season of the year in order to obtain the drought regions over the analyzed period. In equation 2, $\overline{\mathrm{IM}}_p$ is the average, per season, of the vegetation index for each year; $\overline{\mathrm{IM}}_{min}$ is the average of minimum values of the vegetation index of each season throughout the time series; and $\overline{\mathrm{IM}}_{max}$ is the average of maximum values of the vegetation index of each season throughout the time series. After calculating the VCI, resulting images were reclassified according to Table 1.

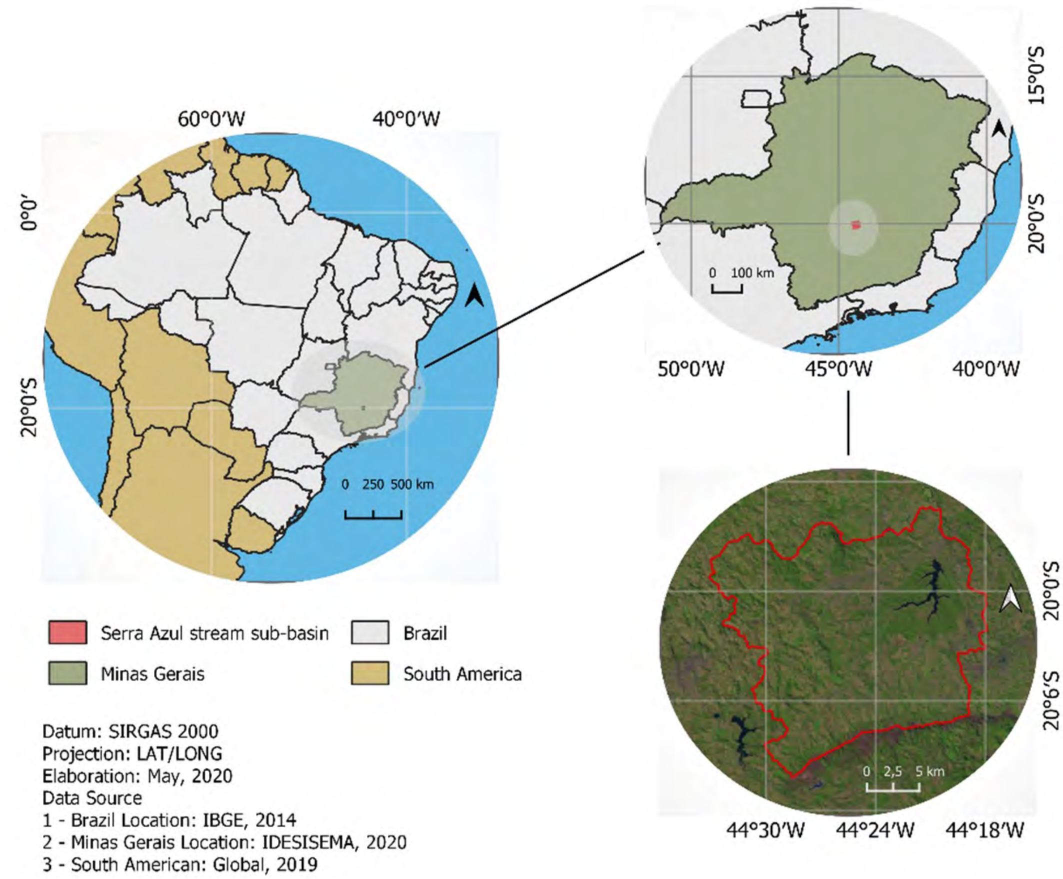

Figure 1 Location of the study area, Serra Azul stream sub-basin.

Table 1 Class range values and corresponding VCI classification: Modified from Bhuiyan and Kogan (2010) and Covele (2011).

Values (%)	**VCI classification**
X < 20	Extreme Drought
20 ≤ X < 40	Severe Drought
40 ≤ X < 60	Moderate Drought
60 ≤ X < 80	Mild Drought
X ≥ 80	No Drought Occurrence

$$VCI = \frac{\overline{IM}_p - \overline{IM}_{min}}{\overline{IM}_{max} - \overline{IM}_{min}} * 100 \quad (2)$$

The analysis of agricultural drought was carried out by comparing the data of potential biomass and the VCI. The calculation of Potential Biomass Index (PBI) used the methodology proposed by Iverson et al. (1994) and modified by Martins et al. (2009), Figure 2, to identify the biomass variation in rural properties in the study region. The DINÂMICA EGO platform (Soares Filho et al. 2004) was used to create the model.

Equation 3, proposed by Iverson et al. (1994), was used to calculate the potential biomass of the region. According to Martins et al. (2009), the calculation is performed by creating four indexes, namely: Modified Week Climate Index (MWCI); Rainfall Index (RI), Soil Index (SI), and Topography Index (TI). The weights were obtained according to the adaptations presented by Martins et al. (2009) for Iverson et al. (1994) methodology, where each index layer received a weight varying from zero to 25, so that the maximum final result obtained is equal to 100 (see Supplementary Material).

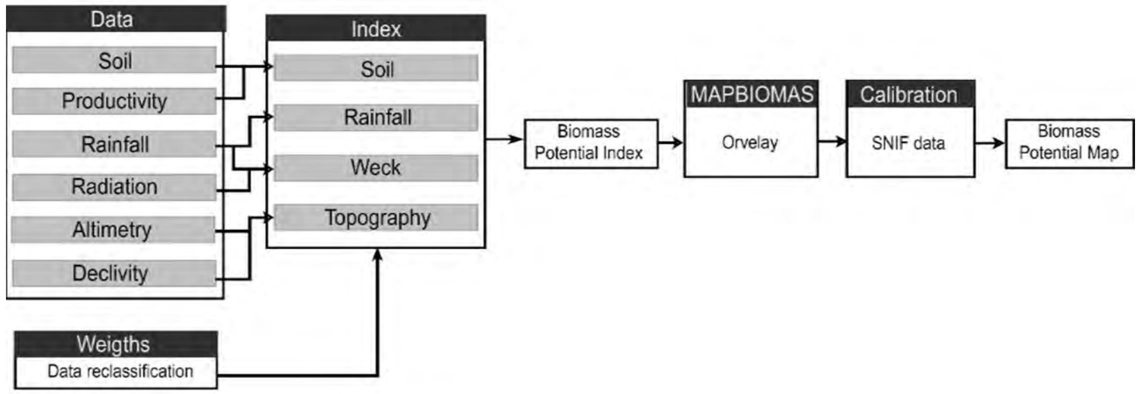

Figure 2 SIG diagram model for calculate the potential biomass map: Modified from Iverson et al. (1994) and Martins et al. (2009).

$$PBI = MWCI + RI + TI + SI \quad (3)$$

The biomass calculation (ton / ha) was performed by multiplying the PBI by the average values of biomass found in the literature, obtained by the Sistema Nacional de Informações Florestais, SNIF (2020) (see supplementary material). According to Melo and Durigan (2006) methodology, the determination of dry biomass consists of the potential stock of 50% of the value obtained in the calculation. Finally, to validate the model, the results were compared with the work of Baccini et al. (2012) and Soares Filho et al. (2016) to verify the corroboration of the results with the biomass calculations already estimated in the literature for areas within Brazilian territory.

2.3 Calculation of Water Balance

Works by Tucci (2012) and Vaz and Hipólito (2013) on drought analysis, propose the water balance analysis to study the anthropic pressure influence on water storage in hydrographic basins. The objective of this technique is analyzing the conservation of mass within the water cycle. For applications using remote sensing data, Macedo et al. (2018) and Moreira et al. (2018) propose changes in the water balance equation to perform the calculation using TRMM and MODIS16A2 images (Equation 4). For that purpose, it is used precipitation data obtained by TRMM (P); flow into the system obtained by the Soil Conservation method (Qe); outflow from the system obtained by ANA data and by IGAM grant decision (Qs); infiltration with a fixed value of 0.00283 for the study region soil as proposed by ANA (2018) (I); and evapotranspiration obtained by MODIS sensor data (ET).

$$\left(P + Qe\right) - \left(Qs + I + ET\right) = \Delta V \quad (4)$$

2.4 Comparation with VCI Data

The drought monitoring data over the time series (2013 to 2018), corresponding to the VCI, were compared with biomass and water balance data. The coefficient of determination (R^2) was used as a criterion for assessing the ability of VCI to monitor drought.

3 Results

3.1 Drought Variation Along the Study Area

The average seasonal variation of the VCI values in the study region indicated the majority of pixels, in a large part of the region, belonging to the classes of mild drought and without occurrence of drought as indicated by the variation of the VCI data between 60% and 80% (Figure 3). The presence of seasonality in the study region was identified by the lowest values of VCI in the driest periods, between the autumn and winter seasons, over the time series (2013-2018).

The most of the study area was characterized in the mild dry class, with VCI between 60% and 80%. When the values of moderate drought and mild drought decrease (Figure 4), there is an increase in areas without drought. In the summers from 2014 to 2016, the classes of severe drought and extreme drought (Figure 5) appeared to a large extent and the event coinciding with the period of water crisis in the sub-basin (officially declared by the local authorities).

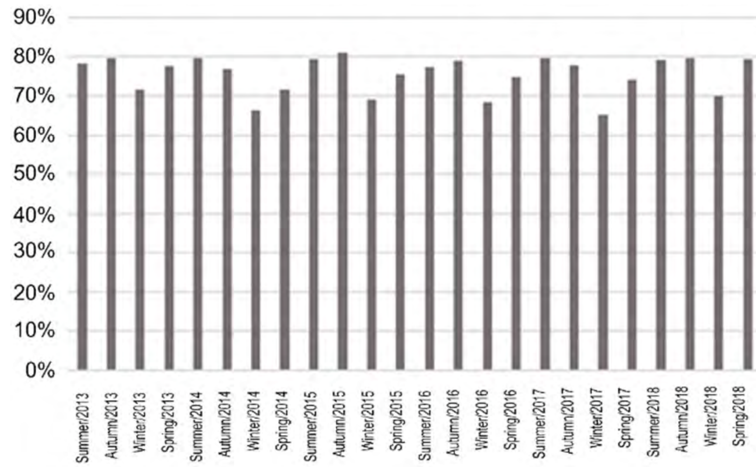

Figure 3 Average variation of VCI over the analyzed time series (2013-2018)

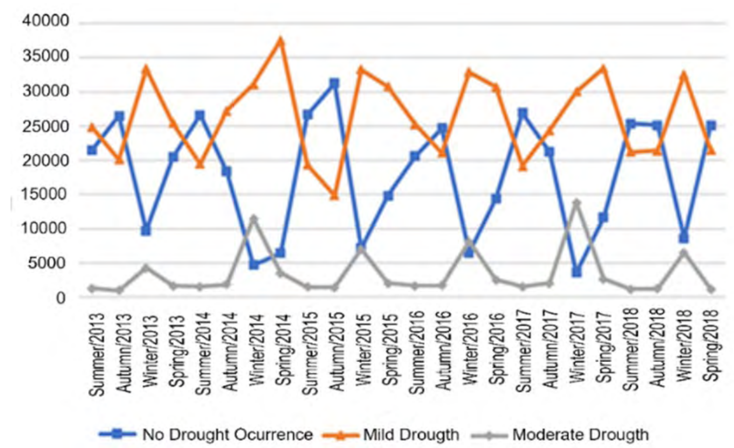

Figure 4 Area variation (ha) in the VCI classes (no occurrence, mild and moderate drought) over the time series (2013-2018)

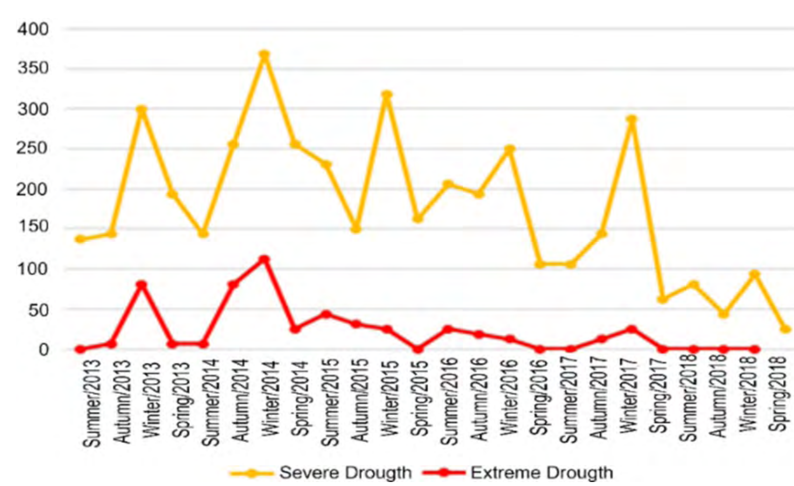

Figure 5 Area variation (ha) in the VCI classes (severe and extreme drought) over the time series (2013-2018)

3.2 Biomass Model

The results of the biomass model indicated a variation in values from zero to 288 ton / ha (Figure 6). The null values characterized the urban centers present in the sub-basin. The highest concentrations of biomass were assigned to native vegetation areas, corresponding to Atlantic Forest remnants and the special protection area of the Serra Azul reservoir.

The validation of the model (Figure 6), performed in comparison with the works of Soares Filho et al. (2016) and Baccini et al. (2012), presented similarity between the simulated and the observed map varying from 0.45 to 0.58. It is found that the model presented greater similarity with the data generated by Baccini et al. (2012), especially using 3x3 and 5x5 windows, where the similarity increases of 0.09 and 0.06 were identified, respectively, in relation to data by Soares Filho et al. (2016).

3.3 Biomass Variation in Rural Properties

The study region is located in an area of transition from rural to urban use, where the most properties are composed of pasture, forest and agricultural areas (Figure 7). Inside the rural properties, the increase of anthropized areas caused the decrease of average biomass, showing values between 0 and 72 ton/ha. In the year 2013, the forests showed the highest amount of biomass while the lowest value of the time series occurred in the next year, with a value of 214.174 ton/ha.

The results of regression analysis showed the biomass with a moderately strong relationship with the VCI data ($R^2 = 0.63$) indicating that changes in vegetative vigor due to drought alter the carbon storage of plant structures. In this respect, the increase of drought in the study region causes the decrease of carbon storage and biomass presented by the vegetation formation.

3.4 Relationship Between the Water Balance and Forest Biomass

The results identified the decrease of maximum storage (Sd) over the time series (Figure 8). Furthermore, it can be seen that the increase in the water volume has not contributed to the increase of Sd. In the year 2016 for instance, it can be observed that the water amount stored was the highest in the period, but the Sd showed a tiny increase. This mismatch suggests the influence of other factors decreasing the water storage.

The decrease of Sd is associated with factors external to the water cycle, such as anthropic pressures. As shown in Table 2, variations in land use change contributed to the increase of impermeability and difficult the increase in Sd over the years. Over the time series, forest and rock vegetation areas counted losses of 8% and 4%, respectively. These losses are generated by activities that increase soil impermeability, such as urban expansion resulting in actions that contributed to an overall increase of 24% in soil impermeability of the basin.

The strong positive relationship between forest areas and water balance (Figure 9) indicates that land use changes influence on the carbon storage. Over the time series, it was found that a reduction in the water storage volume implies a decrease in the average biomass storage in the study region (Figure 10).

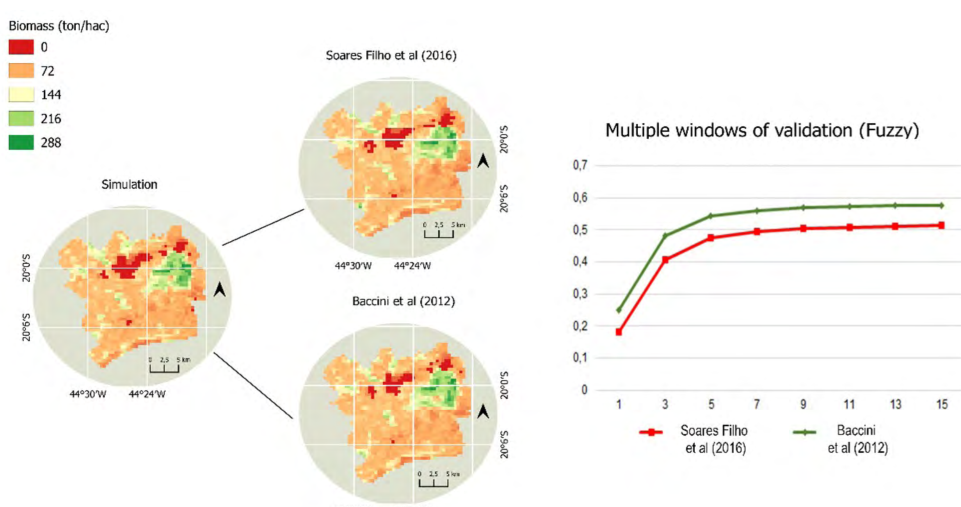

Figure 6 Average variation of biomass over the time series (2013-2018) and validation with the products estimated by Baccini et al. (2012) and Soares Filho et al. (2016) models

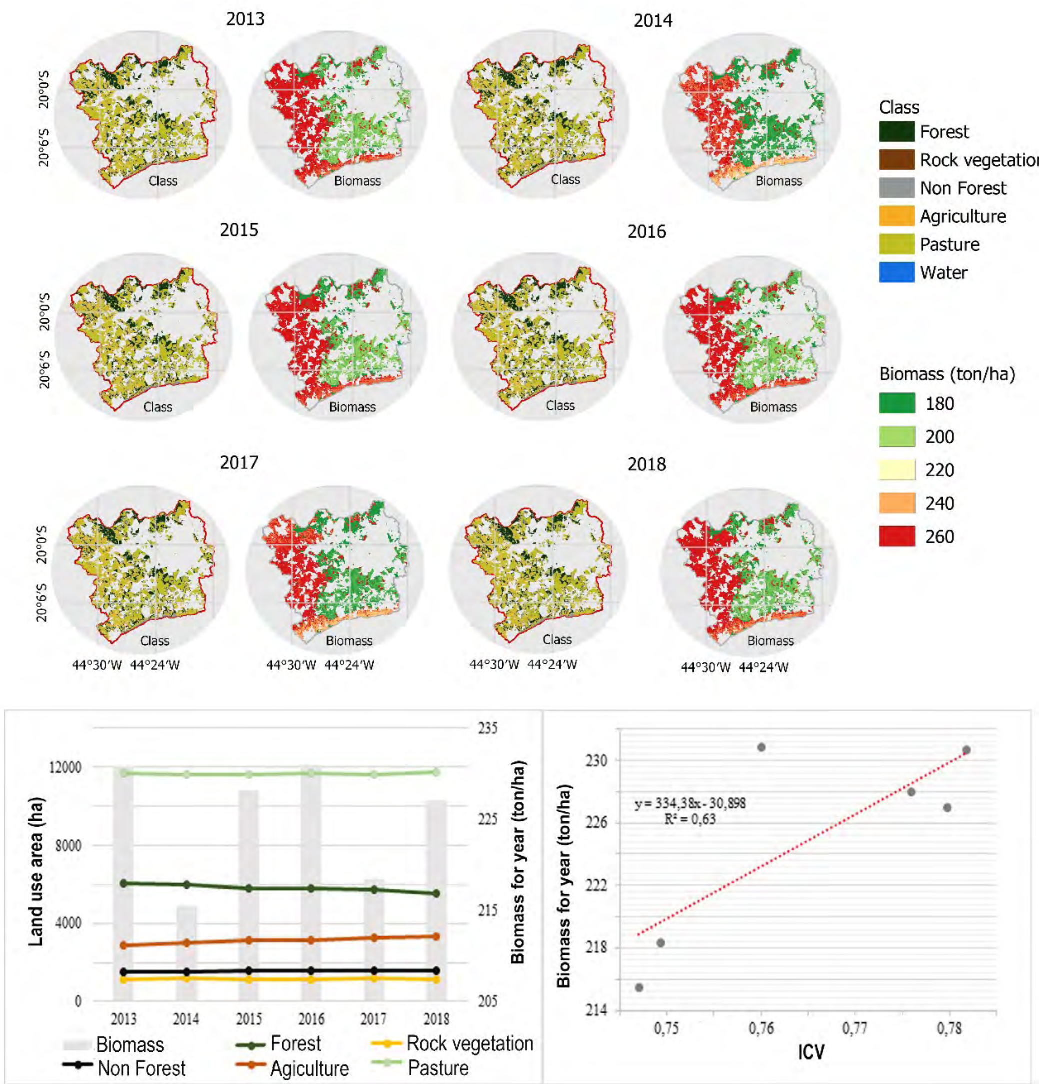

Figure 7 Biomass variation across the land use classes and the result of regression analysis between biomass and VCI data

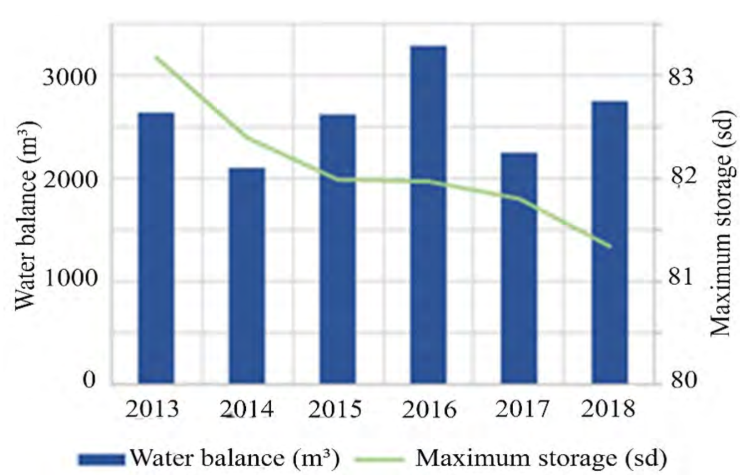

Figure 8 Variation of the water balance and the maximum storage of the basin along the time series

Table 2 Area (ha) of the six land use classes according to MAPBIOMAS (Souza et al. 2020) reclassification data used for the elaboration of land use in the region

Ano	Forest	Rock vegetation	Pasture	Agriculture	Non-forest	Water
2013	13537,82	2168,05	18891,50	5278,81	4349,53	555,470
2014	13367,12	2174,44	18765,75	5474,39	4615,51	383,966
2015	13161,06	2153,33	18697,84	5694,45	4714,14	360,368
2016	13029,47	2141,01	18843,83	5708,77	4694,30	363,807
2017	12956,28	2168,53	18726,24	5839,16	4735,41	355,568
2018	12548,87	2071,73	19020,69	5913,79	4838,77	387,325

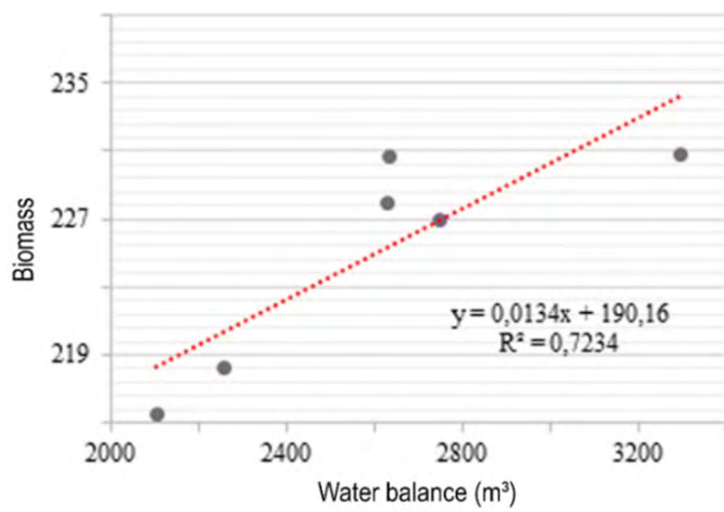

Figure 9 Relationship between the water balance and the forest biomass produced over the time series

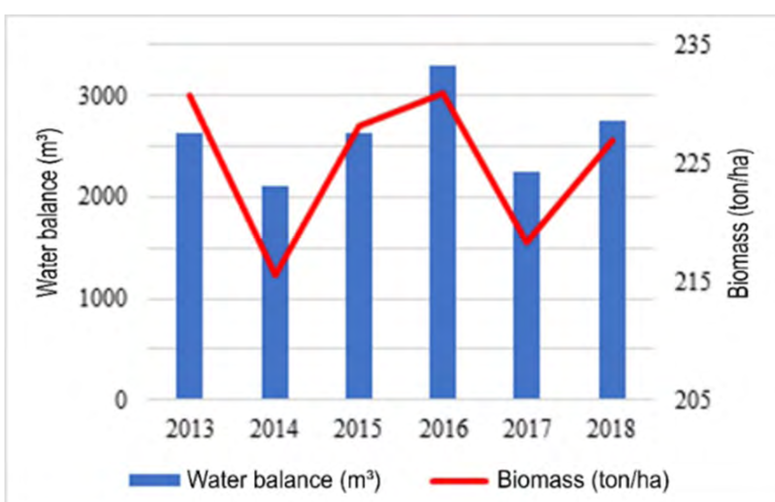

Figure 10 Variation of forest biomass and water balance over the time series

4 Discussions

4.1 The Drought Condition Index as a Drought Monitoring Tool

The results showed that the drought interferes in the volume of water entering and leaving the basin, especially when associated to variation of the vegetative vigor in forest formation. In the years 2014 to 2015, the region presented an aggravation of the drought phenomenon, so that the results are corroborated by similar estimates found in other regions of the world, mainly in agricultural areas, as demonstrated by Eyoh, Okeke and Ekpa (2019) and Kamble et al. (2019).

The influence of vegetative vigor within the hydrological cycle is associated to water storage in plant structure, because the increase in storage decreases the impact effects in vegetation caused by drought events. Thus, the VCI is an effective tool to indicate the less probability of the worsening drought. This relationship was corroborated in the studies by Baniya et al. (2019), Eyoh, Okeke and Ekpa (2019), Kamble et al. (2019), Uttaruk and Laosuwan (2017) and Yulistya, Wibowo and Kusratmoko (2019), which identified that VCI allows the mapping of the best and the worst scenarios for a region, based in precipitation and temperature variations.

Regarding the landscape management, the VCI is an easily accessible tool for monitoring drought events due to its ability to demonstrate the best and worst drought conditions over a period. Through the analysis of the time series, the VCI investigate the seasonal drought variations and identify disaster situations, such as the cases related to water supply volume for populations (Baniya et al. 2019; Yulistya, Wibowo & Kusratmoko 2019).

The use of remote sensing techniques allows the improvement of projects related to natural disasters and assists river basin committees in creating effective monitoring systems to prevent water crisis events. According to Cunha et al. (2017) and Leivas et al. (2014), the ability of the VCI to estimate various water stress conditions allows the analysis of different aspects of drought in tropical regions. However, there are still several challenges that need further studies, such as the inclusion of accurate monitoring systems in water supply companies. Thus, despite the acceptable effectiveness of VCI for monitoring drought, it is still necessary to invest in effective management tools to mitigate the drought effects.

4.2 Influence of Land Use in the Drought Aggravation

The results from biomass model were similar to that prepared by Soares Filho et al. (2016) and Baccini et al. (2012), so endorsing the model suitable for studies related to the biomass variation in the study region. However, a further validation of the model is recommended by temporal monitoring of forest areas through field analysis and application of allometric equations, such as performed in studies by Brianezi et al. (2013) on carbon estimation in anthropized areas.

The variations in land use can contribute to the worsening of drought in watersheds. In the study region, the soil impermeability caused a decrease in the maximum storage of water volume.

According to Araújo, Moreir and Neves (2020) and Tucci (2012), the loss of forest areas cause a decrease of maximum water storage in basins. The results identified this pattern through the transitions between the loss of forest areas and the expansion of urban and agricultural areas, which cause a decrease in the storage of forest biomass. This relationship was corroborated in the studies by Araújo, Moreira and Neves (2020) and Sanquetta et al. (2018) and which demonstrated the tendency of biomass decrease over anthropic areas subjected to loss of native vegetation.

The drought aggravation is associated with land use changes and also with natural changes in landscape, as corroborated in studies by Alves, Martins and Reboita (2020) and Montaño and Souza (2016), where variations in hydrological cycle, due to decrease in rainfall, caused land use changes, especially in rural regions. According to INMET (2020), the external events, such as air masses, cause a worsening of water balance changes and motivate water scarcity events in hydrographic basins. In the study region, this relationship was verified between the years 2014 and 2015. Over this period, the movement of air masses together with the decrease of precipitation caused hydrological cycle changes and increased extreme and severe drought areas, which contributed to water scarcity events in the basin, as registered by Minas Gerais (2015) and also indicated by VCI variation values.

The worsening drought from anthropic or natural changes is a challenge in monitoring natural resources, so it is important considering the issues related to the impacts of riverbanks and urban occupation in the water scarcity episodes. The identification of environment priority regions through remote sensors assists in the allocation of resources and in the elaboration of projects for maintenance of hydrographic basins. The use of sustainability tools in public management assist in the personnel training and development of hydrological monitoring technologies for drought studies through environmental models (Alvalá et al. 2019; Lima & Cupolillo 2018; Tucci & Chagas 2017).

5 Conclusion

The results showed that the VCI and the biomass model are effective tools for monitoring drought in river basins. These analyzes associated to water balance calculations identified the impact of land use variations on the maximum water storage of the Serra Azul stream sub-basin. Water balance changes associated to decrease of forest biomass caused changes to hydrological cycle, mainly in the presence of external events, such as air masses, which cause the decrease of precipitation. The importance of applying drought monitoring measures has become evident in order to identify causes associated with drought, mitigate the effects and acquire consistent knowledge for avoid alleviating the harmful consequences of new episodes of water scarcity in the region, as occurred between the years 2015 and 2016. Furthermore, the use of free software, such as QGIS, R and DINAMICA EGO, together with open public data allows the reapplication of the methodology by research institutions and public bodies, helping to develop databases and monitor and prevent aggravation of weather events.

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Débora Joana Dutra: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **Marcos Antônio Timbó Elmiro:** conceptualization, supervision, writing – review and editing; visualization.

Conflict of interest

The authors declare no potential conflict of interest.

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