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Impacts of changes in land cover and land use on the hydrological cycle of the Tapuio River sub-basin/AL

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ABSTRACT

The climate forecasts in the IPCC latest assessment report (AR6) point to rising global temperatures. The northeastern semi-arid region is characterized by extreme droughts and intense rainfall, indicating a scenario of climatic extremes. Climate change directly affects the hydrological cycle because it modifies the entire dynamics of the system, causing major environmental impacts in river basins. These impacts are intensified by changes in land cover, favoring modifications to landscapes through alternative land uses. In this sense, the study arises from the need to analyze how changes in land use and cover can affect the dynamics of the hydrological cycle in the Tapuio river sub-basin from a space-time perspective. The region was chosen based on the observation of data collected during the IV scientific expedition to the Lower São Francisco. For the study, a simulation was carried out using the SWAT tool with land use and land cover data (2000 and 2020), soil type, slope and climate data (precipitation and temperature). The simulation generated the delimitation of 24 microbasins and 553 HRUs for the year 2000 and 662 for the year 2020, as well as visualizing the main parameters of the hydrological cycle. It was found that there was a significant increase in surface runoff of 4%, sediment production of 9% and a reduction in potential evapotranspiration of 0.42%. The conclusive analyses indicate that the conversion of the savannah formation use classes for pasture and temporary crops would have been the main cause of the changes in the hydrological cycle in the Tapuio river sub-basin.

Keywords: Global warming, Deforestation, Erosion.

Impactos das Mudanças na Cobertura e Uso do Solo no Ciclo Hidrológico da Sub-bacia do Rio Tapuio/AL

RESUMO

As previsões climáticas no último relatório de avaliação do Painel Intergovernamental sobre Mudanças Climáticas (IPCC AR6) indicam um aumento nas temperaturas globais. A região semiárida nordestina é caracterizada por secas extremas e chuvas intensas, apontando para um cenário de extremos climáticos. As mudanças climáticas afetam diretamente o ciclo hidrológico, modificando toda a dinâmica do sistema e causando impactos ambientais significativos em bacias fluviais. Esses impactos são intensificados por alterações na cobertura do solo, favorecendo modificações nas paisagens por meio de usos alternativos do solo. Nesse sentido, o estudo surge da necessidade de analisar como as mudanças no uso e cobertura do solo podem afetar a dinâmica do ciclo hidrológico na sub-bacia do rio Tapuio, considerando uma perspectiva espaço-temporal.

A região foi escolhida com base na observação de dados coletados durante a IV expedição científica ao Baixo São Francisco. Para o estudo, uma simulação foi realizada utilizando a ferramenta SWAT com dados de uso e cobertura do solo (2000 e 2020), tipo de solo, declividade e dados climáticos (precipitação e temperatura). A simulação gerou a delimitação de 24 microbacias e 553 Unidades de Resposta Hidrológica (HRUs) para o ano 2000 e 662 para o ano 2020, além de visualizar os principais parâmetros do ciclo hidrológico. Verificou-se um aumento significativo no escoamento superficial de 4%, na produção de sedimentos de 9% e uma redução na evapotranspiração potencial de 0,42%. As análises conclusivas indicam que a conversão de classes de uso da formação de savana para pastagem e cultivos temporários teria sido a principal causa das mudanças no ciclo hidrológico na sub-bacia do rio Tapuio.

Palavras-chave: Aquecimento global, Desmatamento, Erosão.

1. Introduction

The effects of climate change have been widely discussed since the last century, mainly due to the environmental impacts generated by these changes (PIMENTEL, 2015). The AR6[1] report by the IPCC - Intergovernmental Panel on Climate Change (2023) estimates that global temperatures will increase by 1.5 ºC in the near future due to global warming.

The northeastern semi-arid region is characterezed by high temperatures, intense sunshine and low rainfall for most of the year. Although this region experience a lack of rainfall, the months when it does occur have high intensity, resulting in climatic extremes (ANGELOTTI; SÁ; MELO, 2009).

According to Marengo et al. (2011), the region has an average annual rainfall of less than 800 mm, making the volume of available water low.

These climate changes have a direct impact on the hydrological cycles, as the surface-atmosphere dynamics are altered by land use changes, intensified by anthropogenic activities (PIMENTEL, 2015).

Hydrology is understood as the study of the physical aspects and disposition of water in a space-time dynamic with the aim of evaluating the impacts of changes occurring in a river basin and how these changes affect hydrological processes (TUCCI, 1993).

Applied hydrology therefore aims to understand:

> "... the collection of basic data such as the amount of water precipitated or evaporated and the flow of rivers; the analyses of these data to establish their mutual relationships and understand the influence of each possible factor and, finally, the application of the knowledge gained to the solution of numerous practical problems" (PINTO et al., 1976, p. 3).

According to Machado (2017), one of the main areas under development in Brazil linked to applied hydrology is rural land use, as its intensification and establishment has brought negative aspects linked to sediment production and nutrient release in rural basins, causing increased loss of fertile soil and silting of rivers.

Global warming and land use and cover have a significant impact on the hydrological cycle is evapotranspiration. According to Ruddiman (2015), the conversion of original forests into pasture areas in the tropics increases solar radiation, wich prevents the recycling of water vapors in the atmosphere. This reduction in evapotranspiration (ET) and contribute to warming the climate.

Potential evapotranspiration is the synchronised loss of water from the soil through the processes of evaporation and transpiration of plants, according to the maximum water demand of each crop (BARROS et al., 2012).

According to UNESCO (2021), there is currently a 69% demand for water for agricultural activities, rising to 95% in wealthier countries. This fact, coupled with population, technological and industrial growth, ends up compromising the volume and quality of water bodies and causing problems such as deforestation, soil compaction, silting up of streams, pollution of rivers and aquifers (JÚNIOR, 2022).

According to Bertoni and Lombardi Neto (2010), vegetation cover is the main factor protecting soils from erosion. Depending on the type of land use, losses can vary, according to studies by the “Agronomic Institute of Campinas” (Instituto Agronômico de Campinas - IAC), which presented data for soils in the state of São Paulo for vegetation (0.004 t/ha-¹), pasture (0.04 t/ha-¹), coffee (0.9 t/ha-¹) and cotton (26.6 t/ha-¹).

Angelotti (2009) argues that the concentration of some gases on the atmospheric surface, specifically in the last century, has been increasing mainly due to anthropogenic actions such as the growing use of fossil fuels, an increase in deforested areas, the increasing generation of organic waste and the use of substances and gases from agricultural activities and industrial processes that contribute to the intensification of the greenhouse effect, which is the main factor influencing global warming.

As pointed out in the IPCC AR6 report (2023), man-made climate change has been favouring extreme weather events worldwide. These changes tend to impact mainly on the poorest populations, where the condition of vulnerability is most present.

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[1] Sixth Assessment Report (AR6) on climate change.

Aspects related to hydrological cycles can be simulated using mathematical models, including the Soil and Water Assessment Tool (SWAT). This is a semi-distributed model for small and large river basins used to diagnose the impacts of land use on sediment production and the application of chemical products to water resources, using data related to land use and cover, soils and slope and climatological data (SOIL AND WATER ASSESSMENT TOOLS, 2023).

This study aims to analyze changes in hydrological cycles in a sub-basin in the lower São Francisco region and how these changes affect the dynamics of potential evapotranspiration, surface runoff, and sediment production from a space-time perspective. The analysis is based on current trends in climate change due to the increase in global temperature linked to changes in land use and land cover in recent decades.

2. Materials and methods

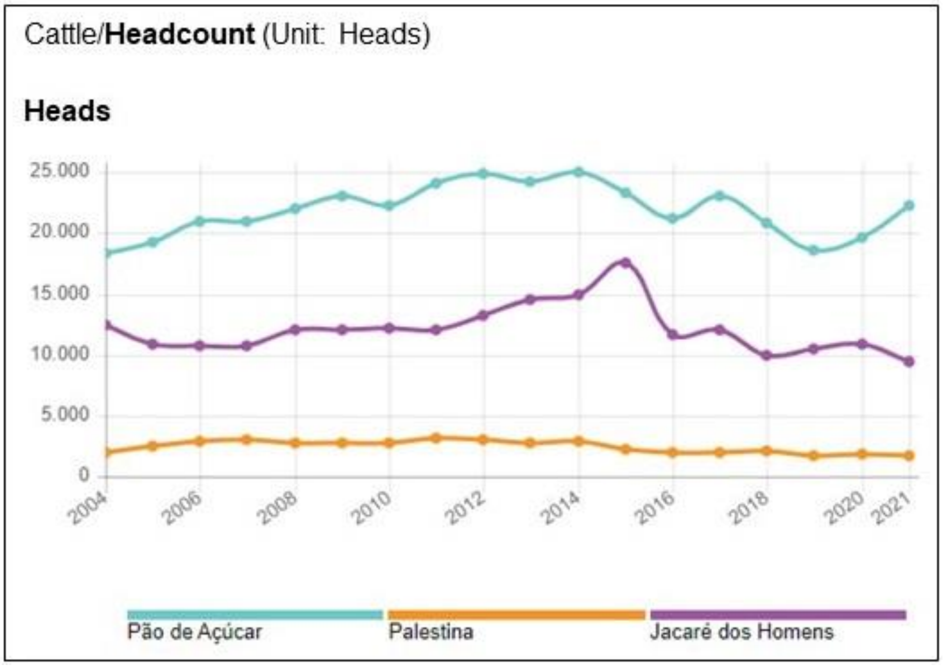
Located between the cities of Palestina, Jacaré dos Homens and Pão de Açúcar in the state of Alagoas/AL, the Tapuio river sub-basin covers an area of 91.70 km² (figure 1).

Located in the caatinga biome, the sub-basin has dry, open and deciduous forest vegetation (ROSS, 2009). According to Correia et al. (2011) the characteristic flora of this biome is made up of very hardy, resistant trees and shrubs that are not uniformly distributed due to climatic variations.

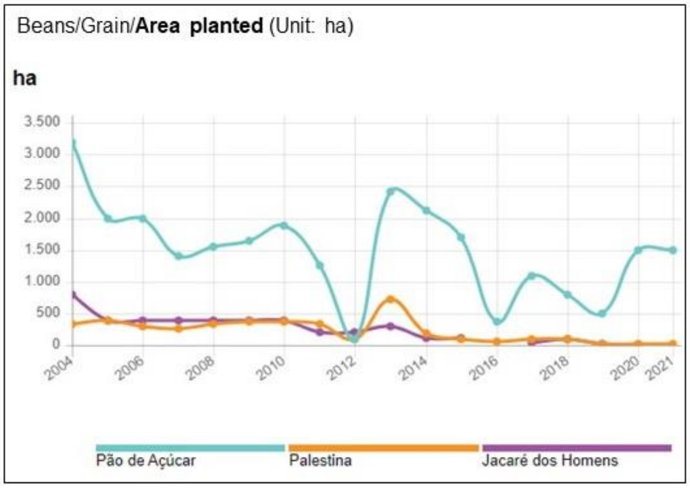
As for climatic aspects, it is located in Brazil's semi-arid region and has rainfall characteristics of climatic extremes, i.e. short periods of rain and great intensity while long periods of drought occur.

According to the IBGE (2022), the municipalities of Pão de Açúcar, Palestina and Jacaré dos Homens have a combined population of 33,231 inhabitants, with “Gross National Product (GNP)” (Produto Interno Bruto - PIB) of R$9,500.20, R$7,689.13 and R$12,178.27 (2020) and “Human Development Index (HDI)” (Indice de Desenvolvimento Humano – IDH) of 0.59, 055 and 058 (2010). They are ranked 30th, 98th and 93rd in terms of population in relation to the other municipalities in the state of Alagoas.

The municipalities' main sources of income come from farming and fishing (CBHSF, 2023). According to the IBGE (2021), the municipalities stand out for their production of cattle and temporary bean crops, as shown in graphs 1 and 2 below:



Graph 1. Number of cattle per unit in the cities of Pão de Açúcar, Palestina and Jacaré dos Homens/AL. Source: IBGE (2021).



Graph 2. Bean planting per hectare in the municipalities of Pão de Açúcar, Palestina and Jacaré dos Homens/AL.
Source: IBGE (2021).

In order to understand the relevance of the study on the subject of land use and the hydrological cycle, a word cloud (https://www.lens.org/) was generated to detect the main areas of knowledge that are currently academically addressing the subject in Brazil, of which geography, environmental science, human sciences and forestry stand out (figure 2).

The study was prompted by data observed during the IV Scientific Expedition of the Lower São Francisco where significant soil loss and siltation was detected in the vicinity of the Tapuio River (figure 3).

In order to understand how climate change directly affects the hydrological cycle in the Tapuio/AL river sub-basin in the lower São Francisco region, we used data on land use and cover, pedology, slope and climatological data (precipitation and temperature), which will be used as input for the SWAT hydrological model simulation.

With regard to land use and cover, data from MapBiomas Brasil belonging to collection 6 for the years 2000 and 2020 were used. These served as the basis for analysing changes in land use and cover, as shown in figure 4.

The pedological coverage was extracted from the Environmental Information Database - BDiA/IBGE (2022), which has coverage for the whole of Brazil and is available on a scale of 1:250,000, as can be seen in figure 5. The sub-basin is dominated by Neosolos Litólicos and Planossolos Háplicos soils, as can be seen in table 1.

Information on the slope of the terrain was obtained from the Digital Elevation Model (DEM) of the ASTER satellite with a spatial resolution of 30 x 30 metres. According to the classification of hierarchical categories by Ross (1994), the sub-basin has a weak slope (6 - 12%) occupying 34% of the area as shown in Table 2, justified by its location close to the outflow of the São Francisco River.

Finally, it was necessary to assess the impact of precipitation and temperature in relation to the other components mentioned above. Therefore, we collected a 19-year historical series (2001/01/01 to 2019/12/31) from the World Weather for Water Data Service (W3S)[2] application, of which, for simulation purposes, we will consider 3 years for warm-up (Graph 3).

With all the data duly processed, I used the SWAT (Soil and Water Assessment Tools) hydro-sedimentological model, which is a water and soil modelling tool that simulates certain environmental impacts on river basins, including evapotranspiration, surface runoff and sediment input (SOIL AND

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[2] Data platform that allows users to download climate data (precipitation, maximum temperature and minimum temperature) from a predefined region within any area around the world. The data can be downloaded in various formats compatible with hydrological models, such as SWAT and generic CSV format for other hydrological models.

WATER ASSESSMENT TOOLS, 2023). To simulate the hydrological cycles, based on the aforementioned input data, we will use the ArcSWAT 2012 version 10.25 add-on available for installation in the ArcGIS 10.8.2 Geographic Information System software.

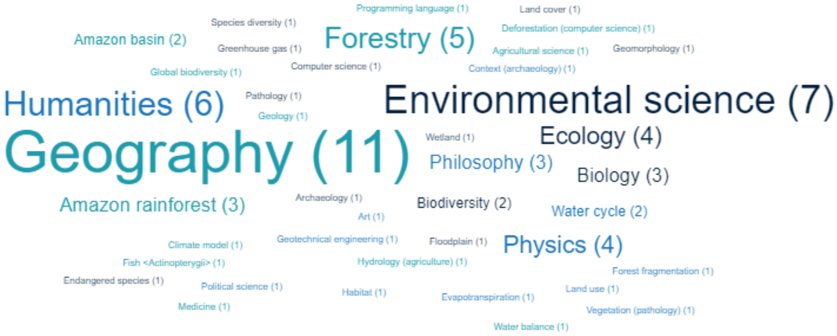


Figure 2. Word cloud of the main study areas of land use and hydrological cycle.
Source: Lens (2023).

Figure 3 - Erosion processes in the vicinity of the Tapuio River, identified during the IV Scientific Expedition of the Lower São Francisco. Source: Nadjacleia Vilar Almeida e Milena Dutra (2021).

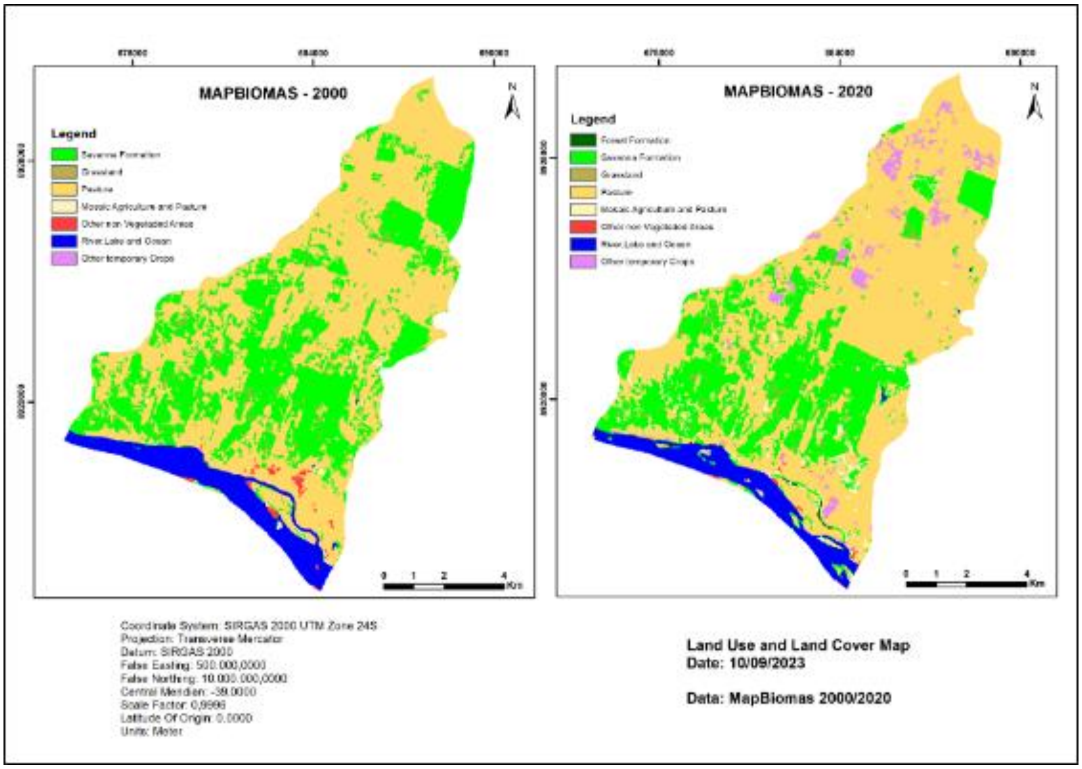


Figure 4 - Space-time dynamics of land cover and land use in the Tapuio river sub-basin, Alagoas, Brazil.
Source: Authors (2023).

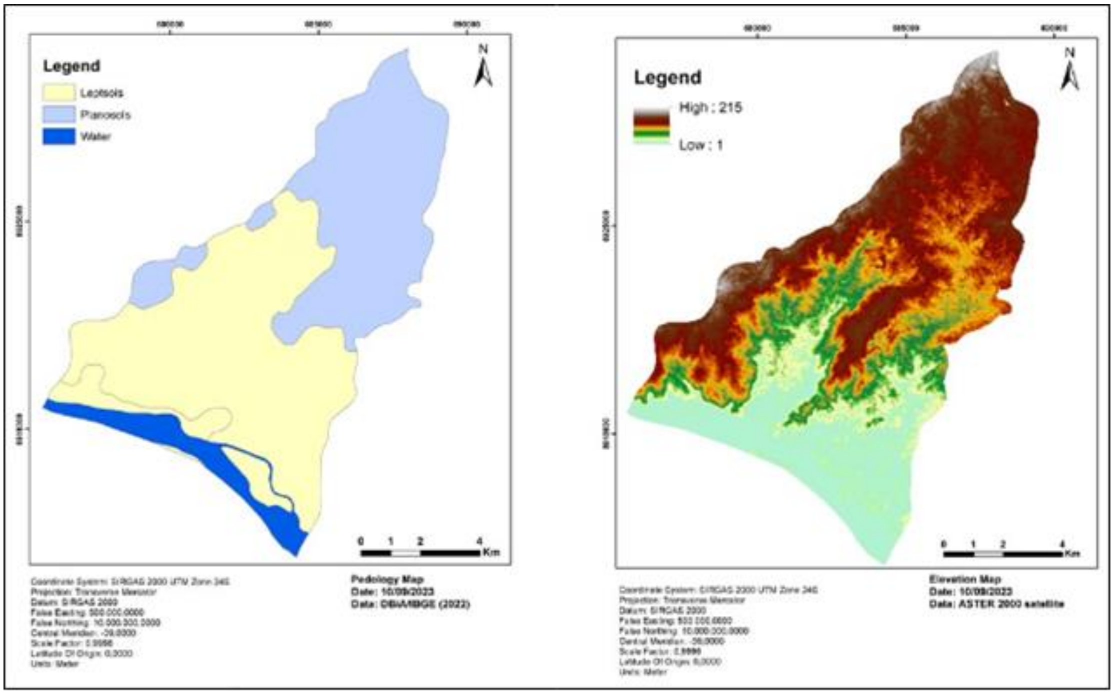


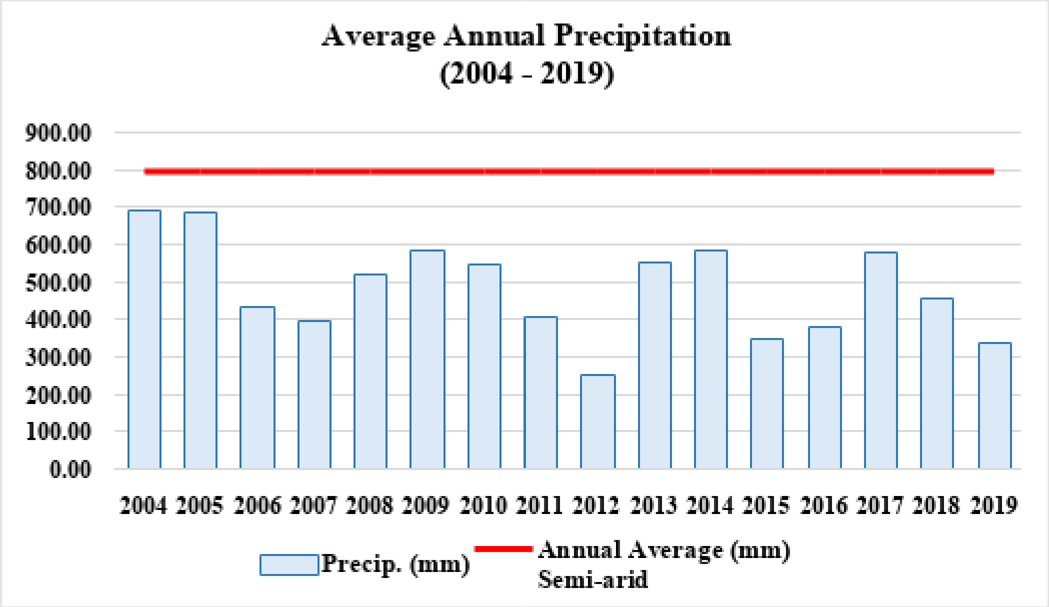
Figure 5 - Pedology and elevation of the Tapuio river sub-basin.
Source: Authors (2023).

Table 1. Percentage of area by soil type in the Tapuio River sub-basin.

Soils	Area (%)
Leptsols	58
Planosols	37
Water	5

Table 2. Percentage of area in relation to Ross's (1994) classification of hierarchical categories in the Tapuio River sub-basin.

Slope	Hierarchical Categories	Area (ha)	%
0 - 6%	Very Low	2.353,64	26
6 - 12%	Low	3.114,12	34
12 - 20%	Medium	2.521,97	28
20 - 30%	High	934,86	10
> 30%	Very high	245,84	3



Graph 3. Average annual rainfall for the period 2004 - 2019.
Source: World Weather for Water Data Service - W3S (2023).

3. Results and discussion

In the SWAT model simulation, it was possible to delineate the drainage network and 24 microbasins in the Tapuio River sub-basin based on inputs from the Digital Elevation Model (DEM) (Figure 6).

As a result of these simulations, microbasins 21 and 22 stood out from the analyses observed. In both simulated periods, watershed 22 showed the greatest interaction between the parameters: use classification 'pasture', plateau soil and slope between 6-12%. Watershed 22 corresponds to transect 3 (T3) observed in the field with erosion and gullies (figure 3). Microbasin 21, on the other hand, was indicated by the simulation as the most fragile microbasin based on the interactions of the 'non-vegetated area' use class, litholic neosol soil for both years. This indication is strongly reinforced by Correia et al. (2011) when he states that this type of soil does not have much depth and is therefore more susceptible to erosion.

The total number of Hydrological Responses Unit (HRU) simulated in the watersheds totalled 553 for the year 2000 and 662 for the year 2020. The responses of the hydrological units (HRU) showed changes in land use/cover, with a reduction in the savannah formation class (-8.04%) and growth in the Pasture (4.00%) and Temporary Crops (3.23%) classes for the periods analysed (Table 3).

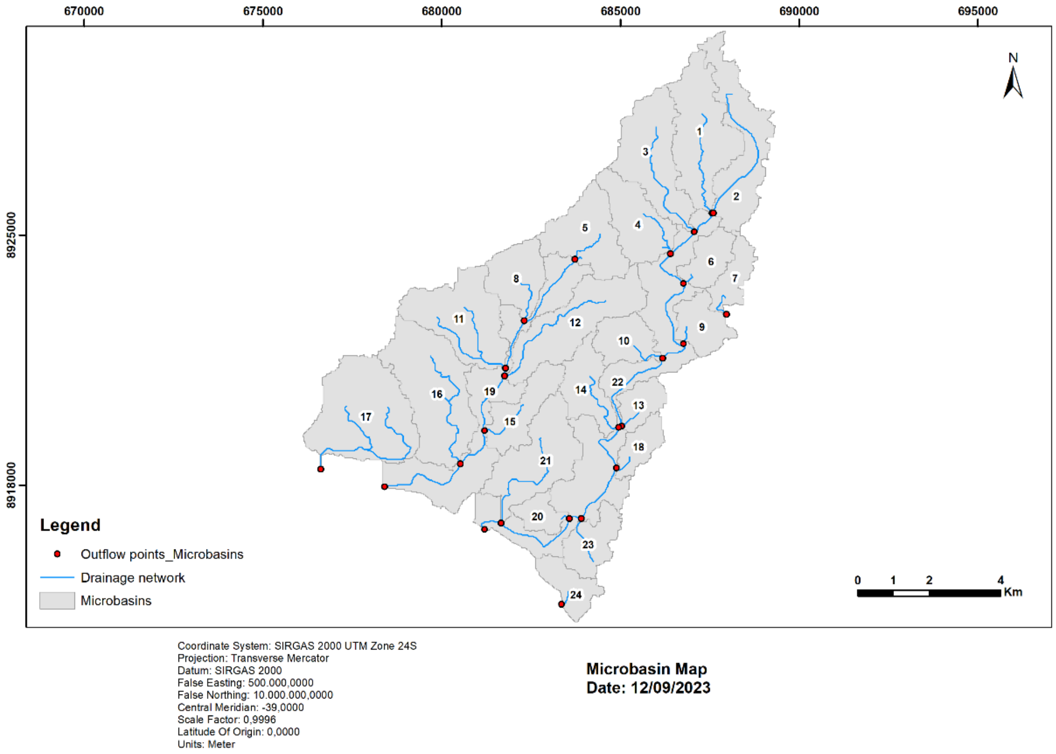


Figure 6 - Microbasins of the Tapuio river sub-basin, Alagoas, Brazil.

In microbasin 22 alone, 19 per cent of the savannah has been converted to pasture in the last 20 years. Deforestation and the advance of livestock farming in themselves contribute to climate change and consequently to an increase in the release of CO2 into the atmosphere (BARBOSA, 2014).

In the simulation of the hydrological cycle, changes were observed in the potential evapotranspiration rates (PET), surface runoff and sediment production between the periods analysed (figure 7).

According to Barros et al. (2012), the highest evapotranspiration in the state of Alagoas is in the sertão region, where averages oscillate between 1,400 and 1,500 (mm) per year. Compared to the years studied, PET showed a reduction of 0.42% (Graph 4), from the perspective of changing land use and cover. Even so, this is a very high average in relation to the parameters indicated for the region.

Microbasin 24 stands out as having the highest volume of potential evapotranspiration in the two simulated scenarios. The area is made up of 79% water mass and is located on the banks of the São Francisco River (Figure 8).

Microbasin 19 (Figure 8) showed the second greatest change in the Tapuio River sub-basin from the interactions of HRUs related to PET. In this microbasin, there was a 2% increase in agropastoral activities to the detriment of the reduction in native forest (caatinga) and a 6% decrease in water mass between 2000 and 2020.

Table 3. Extent of land cover and land use classes in the Tapuio River sub-basin.

Uso e Cobertura da Terra (MapBiomas)	2000 (ha)	2020 (ha)	Δ%
Savanna Formation	3.371,39	2.634,35	-8,04%
Grassland	106,80	107,56	0,01%
Pasture	5.120,13	5.486,86	4,00%
Mosaic Agriculture and Pasture	51,32	260,39	2,28%
Other temporary Crops	0,66	296,97	3,23%
River,Lake and Ocean	469,56	353,96	-1,26%
Forest Formation	0,00	18,24	0,20%
Other non Vegetaded Areas	50,56	12,09	-0,42%

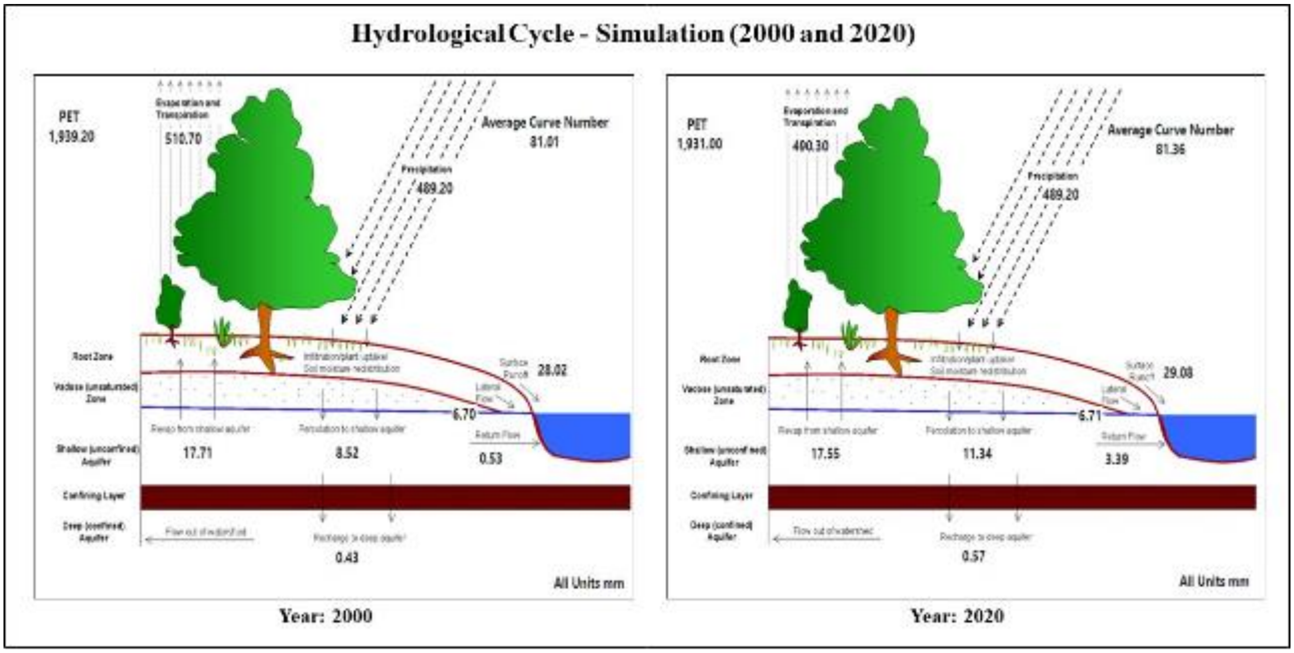


Figure 7. Simulation of the hydrological cycle in the years 2000 and 2020 in the Tapuio River sub-basin.

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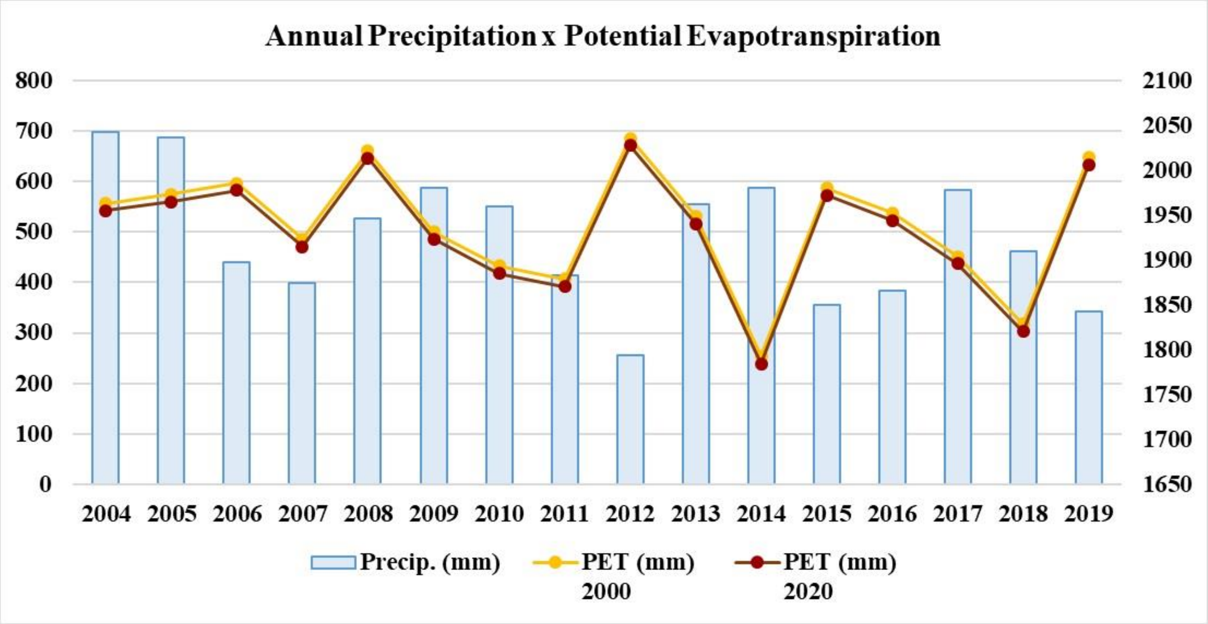


Graph 4. Potential evapotranspiration between land uses and land cover for the period 2000 and 2020 in the Tapuio River sub-basin.

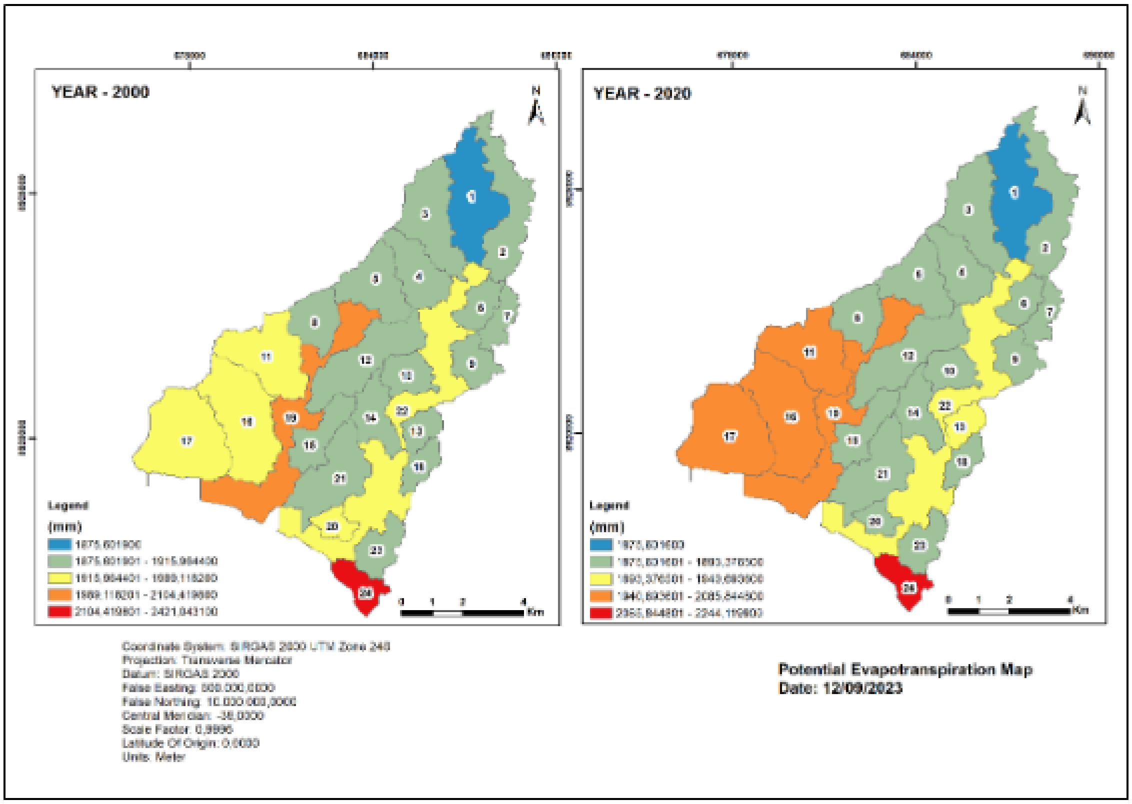
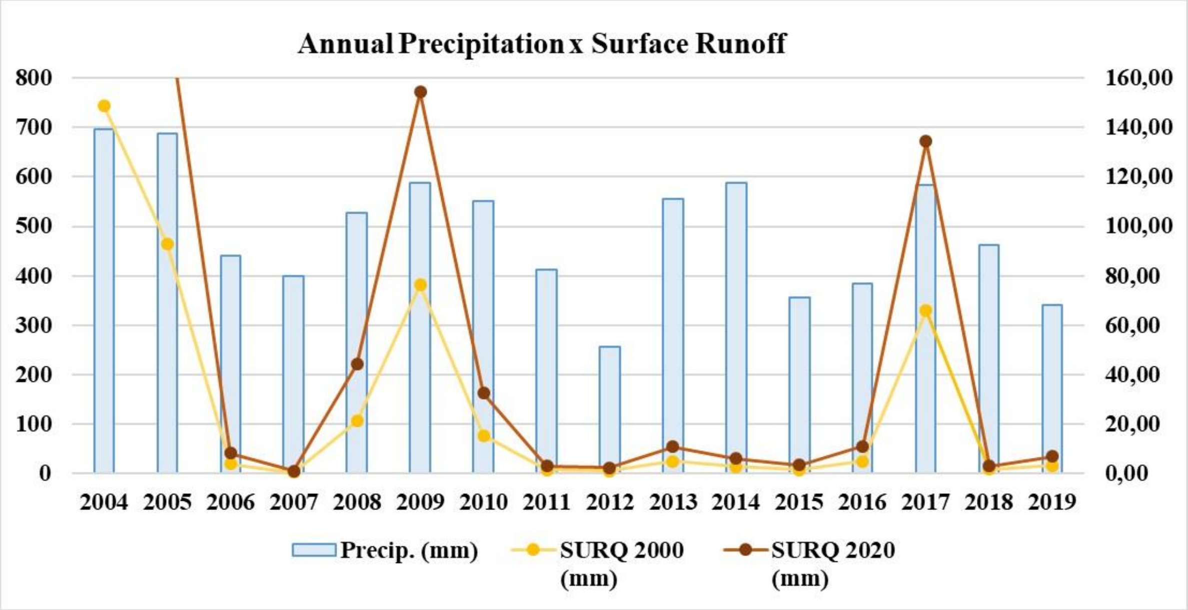


Figure 8. Potential evapotranspiration (PET) of the microbasins in the Tapuio River sub-basin.

The surface runoff generated by the model indicated an increase in flow of 4 per cent throughout the sub-basin (graph 5). This change in flow volume is explained by the replacement of native forest formations with areas of pasture and temporary crops. Vegetation acts as a natural obstacle and aids the infiltration process along rainwater routes, as well as reducing the kinetic energy of rainwater particles, reducing the impact on the soil and consequently erosion processes (TUCCI, 1993). According to Hörbe, Minella and Londero (2020) erosive dynamics favour the loss of the fertile layer and weaken the physical, chemical and biological aspects of the soil.



Graph 5. Surface runoff between land uses and land cover for the period 2000 and 2020 in the Tapuio River sub-basin.

Microbasin 20, for the year 2000, had the highest volume of surface runoff of the entire sub-basin, mainly due to the presence of the body of water. Microbasin 24, on the other hand, showed a greater volume of surface runoff in 2020 due to the conversion of the water class to pasture, mosaics of agriculture and pasture, indicating a picture of sediment deposition over the years and the consequent formation of sand banks, as well as a decrease in the depth of the main river (São Francisco).

According to Ross (1994), from the perspective of degrees of soil protection by vegetation cover, he states that temporary crops have low to no soil protection and these, coupled with pedology and the absence of conservation practices, favour surface run-off and, consequently, erosion processes.

The annual sediment input increased by 9%, corroborating the previously mentioned hypothesis that global warming negatively affects water cycling and that anthropogenic actions related to land use and cover play a fundamental role in this process (Graph 6). Temporary crops allow for greater exposure of the soil between harvest cycles and the planting of a new crop, favouring a marked loss of soil through precipitation.

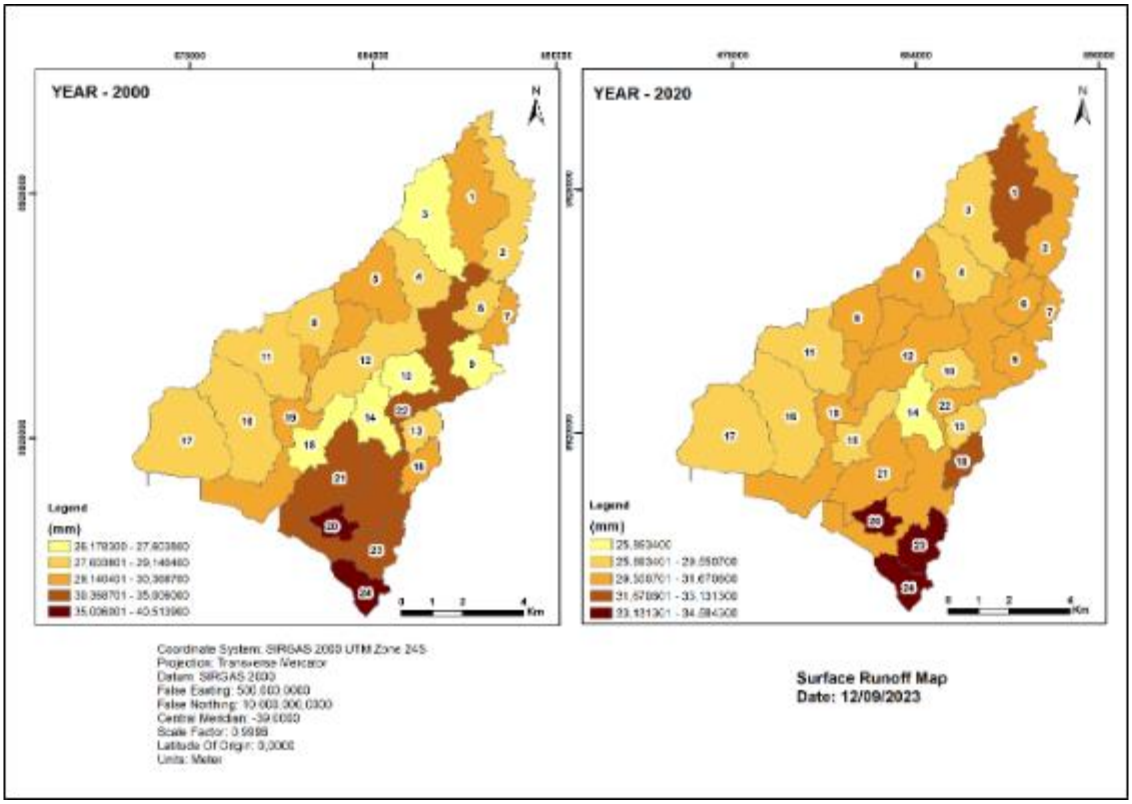
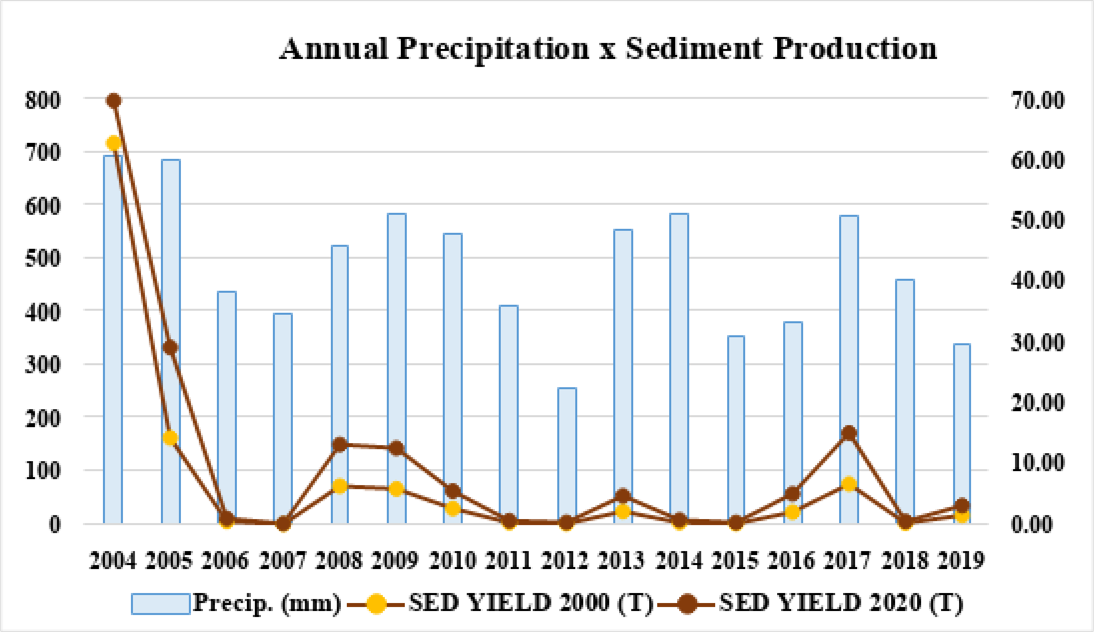


Figure 9. Surface runoff from the microbasins in the Tapuio River sub-basin.



Graph 6. Sediment production between land uses and land cover for the period 2000 and 2020 in the Tapuio River sub-basin.

The results at microbasin level for the sediment yield parameter showed that microbasin 21 in 2000 had an input of 10.37 t/ha -^{1} due to its total composition of 54% pasture, an aspect that changed in 2020 when there was a reduction in pasture areas for savannah formation. In 2020, the largest sediment-producing microbasin was 5, with an average of 10.83 t/ha -^{1} due to the conversion of the savannah formation class to temporary crops.

According to Righetto (1998), erosion processes generated within river basins are more easily transported to rivers.

Sediment production is also influenced by vegetation cover. According to Mishra et al. (2006), vegetation dissipates the energy of precipitation, increases porosity through the root system and reduces soil moisture due to evapotranspiration. Therefore, sediment production varies from watershed to watershed depending on the combination of various factors.

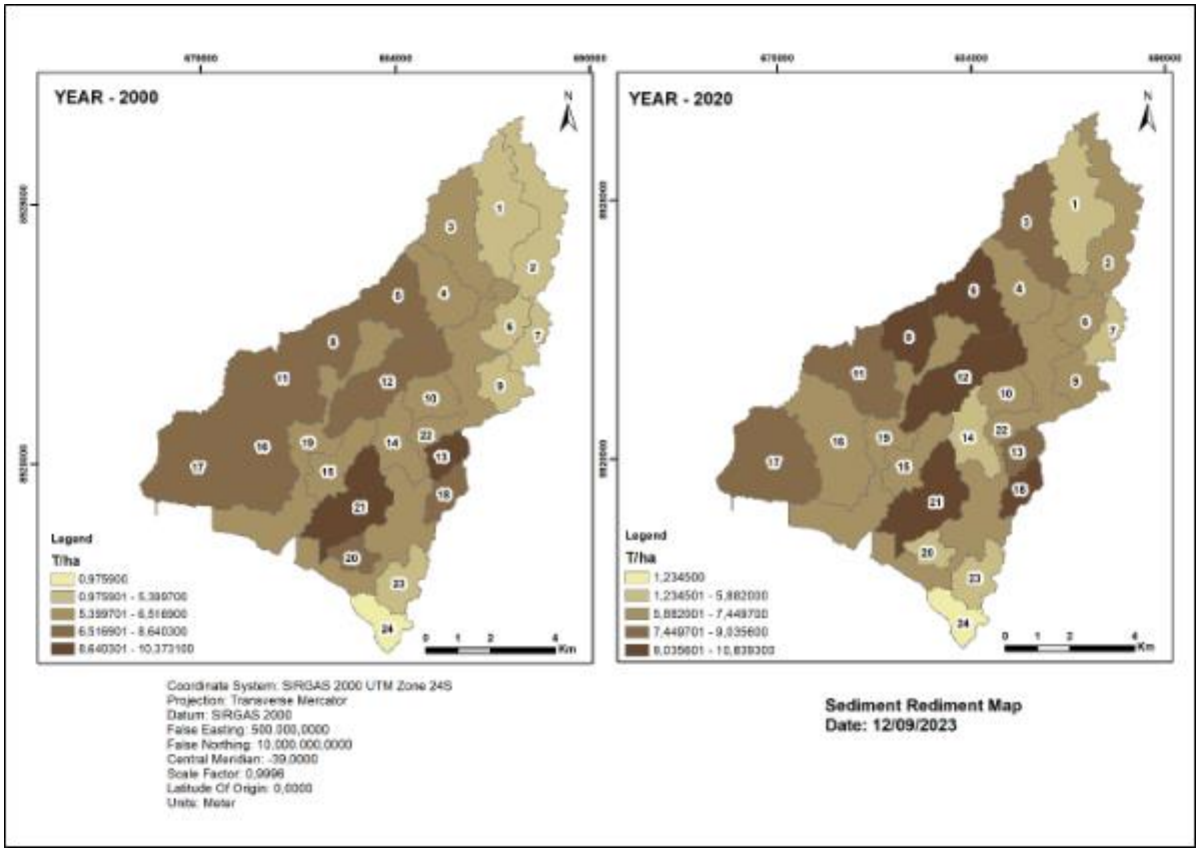


Figure 10. Sediment yield of the microbasins in the Tapuio River sub-basin.

Thus, analysing the hydrosedimentological cycle in an integrated manner is an important tool for managing river basins, since inadequate management, the suppression of vegetation and the disorderly occupation of space were shown in this study to be factors that contributed to changes in the hydrological dynamics of the Tapuio river sub-basin.

4. Conclusions

The ArcSWAT 2012 version 10.25 tool proved to be very efficient in generating hydrological unit (HRU) responses and simulating the hydrological cycles obtained from land use/cover change data for the years 2000 and 2020 in the Tapuio River sub-basin.

The changes that took place in the sub-basin studied pointed to the conversions of native vegetation to alternative land uses, such as temporary crops and pasture, as the main reason for the increase in surface runoff and the consequent increase in sediment volume, which grew by 11% between 2000 and 2020, especially in the microbasins where the changes were most significant. These changes have also led to a reduction in potential evapotranspiration, directly impacting the hydrological cycle because the removal/replacement of the original vegetation cover has reduced the system's ability to regulate itself, enabling temperatures to rise and conditioning the region to climatic extremes of drought. These scenarios are likely to worsen in the face of future indications of climate change, giving rise to the need for land use management to minimise the impacts on the Tapuio River sub-basin.

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