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Flow variability in the Araguaia River Hydrographic Basin influenced by precipitation in extreme years and deforestation

Variabilidade da vazão na Bacia Hidrográfica do Rio Araguaia influenciada pela precipitação em anos extremos e desmatamento

Dênis José Cardoso Gomes[1], *Max Miler Menezes Nascimento*[1], *Fabianne Mesquita Pereira*[1], *Gustavo Francesco de Morais Dias*[2], *Rafael Ribeiro Meireles*[1], *Luis Gelisson Nascimento de Souza*[2], *Ailson Renan Santos Picanço*[3], *Hebe Morganne Campos Ribeiro*[1]

ABSTRACT

The climatic extremes and the dynamics of land use and cover can cause changes in river flow. The objective of this work was to analyze the flow of the Araguaia River under the effects of extreme years associated with the dynamics of land use in the Araguaia Watershed (AW) from 1981 to 2019. The land use and land cover product were based on the MapBiomas Project classification, imported from the Google Earth Engine. The measured rainfall and flow data were obtained from the National Water Agency. In contrast, the estimated rainfall was based on the data Climate Hazards Group InfraRed Precipitation with Stations. The precipitation climatology showed the lowest values (1,464.9–1,720.4 mm) in the south-central sector, and the highest (1,720.4–2,014.6 mm) rainfall amounts were observed in the north sector. However, it was identified in the five pluviometric stations with a high variability of precipitation, with an emphasis on the extreme years. Such wet and dry years were marked by a large difference in water availability. There was an intense reduction of the Amazon and Cerrado biomes by 31,641.8 and 42,618.9 km², respectively, mainly due to the expansion of 18,936.1 km² of agricultural activities and 47,494 km² of pasture. The fluviometric variability showed a decreasing trend, mainly in the past 15 years. Public actions, such as the intensification of environmental policies, monitoring focusing on the most compromised and strategic areas such as the headwaters of the Araguaia River, can minimize the impacts caused by climate extremes and deforestation.

Keywords: ocean-atmosphere interactions; hydroclimatic variability; land use and cover.

RESUMO

Os extremos climáticos e a dinâmica de uso e cobertura do solo podem acarretar alterações na vazão dos rios. O objetivo deste trabalho foi analisar a vazão do rio Araguaia sob os efeitos de anos extremos associada à dinâmica do uso do solo na bacia hidrográfica do rio Araguaia no período de 1981 a 2019. O produto do uso e cobertura do solo foi baseado na classificação do Projeto MapBiomas, importado da plataforma *Google Earth Engine*. Os dados de precipitação e vazão medidas foram obtidos da Agência Nacional de Águas, enquanto a precipitação estimada se baseou nos dados *Climate Hazards Group InfraRed Precipitation with Station data*. A climatologia da precipitação apresentou os menores valores (1.464,9–1.720,4 mm) no setor centro-sul, e os maiores (1.720,4–2.014,6 mm) montantes pluviais foram vistos ao norte. Contudo, identificou-se nos cinco postos pluviométricos alta variabilidade de precipitação, com destaque para os anos extremos. Tais anos chuvosos e secos foram marcados por grande diferença na disponibilidade hídrica. Houve intensa redução dos biomas amazônico e cerrado em 31.641,8 e 42.618,9 km², respectivamente, principalmente em decorrência da expansão de 18.936,1 km² das atividades de agricultura e 47.494 km² de pasto. A variabilidade fluviométrica apresentou tendência de diminuição, principalmente nos últimos 15 anos. Ações públicas como intensificação de políticas ambientais, monitoramento com enfoque nas áreas mais comprometidas e estratégicas, como a cabeceira do rio Araguaia, podem minimizar os impactos causados por extremos climáticos e desmatamento.

Palavras-chave: interações oceano-atmosfera; variabilidade hidroclimática; uso e cobertura do solo.

[1]Universidade do Estado do Pará – Belém (PA), Brazil.

[2]Instituto Federal de Educação, Ciência e Tecnologia do Pará – Belém (PA), Brazil.

[3]Universidade Estadual de Campinas – Campinas (SP), Brazil.

Correspondence address: Dênis José Cardoso Gomes – Travessa Doutor Enéas Pinheiro, 2626 – Marco – CEP:66095-015 – Belém (PA), Brazil.
E-mail: deniss.feg@gmail.com

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Introduction

Climate change in recent decades has impacted the hydrological regime at different time scales and in different watersheds located in many parts of the Earth such as Africa (Coulibaly et al., 2018), America (Lu et al., 2015), Asia (Qiu et al., 2019), Australia (Speer et al., 2021), and Europe (Grusson et al., 2021). Cai et al. (2014) and Yun et al. (2021) suggested that such climate variations may contribute to the intensification of extreme events such as the El Niño Southern Oscillation (ENSO). Therefore, these phenomena of ocean-atmosphere interaction can cause fluctuations in precipitation patterns in Brazil (Natividade et al., 2017). In addition, the analysis and prognosis of this ENSO phenomenon are crucial for some basic sectors of society such as agricultural production (Sazib et al., 2020). To study these extreme events, the use of climate indicators such as the Multivariate ENOS Index version 2 (MEI) is recommended to detect the ENSO signals (Baddoo et al., 2015).

ENSO is the name referring to the El Niño and La Niña phenomena, which constitute the hot and cold phases, respectively, when there is anomalous heating and cooling of the sea surface temperature (SST) in the tropical Pacific, causing a decrease and an increase in atmospheric pressure in this region of the ocean (Pedreira Junior et al., 2020). Such thermal and barometric oscillations alter the circulation of winds, configuring in the northern Brazilian region and its surroundings as descending and ascending air movements, which induce a reduction and an increase in precipitation, respectively (Barichivich et al., 2018).

However, climate oscillations are not the only factor that influences regional hydrology, as human activities alter the landscape and interfere with natural ecosystems (Ekness and Randhir, 2015), which can affect the availability of some natural resources present in environments, i.e., terrestrial and aquatic. Changes in land use and cover usually originate from human settlements and agricultural activities that cause deforestation (Nkhoma et al., 2021).

Land use and land cover are supporting components to analyze socioeconomic development, which can strongly influence the transformations of rural systems (Liu, 2018; Long and Qu, 2018). The same authors also reported the effects in the economic and socio-environmental spheres, such as the loss and degradation of soil that affects biodiversity, the ability of ecosystems to meet human needs, the quality of the rural environment, as well as agricultural production and food security. In this way, such environmental degradation can induce changes in the hydrological processes of a watershed (Shao et al., 2018; França et al., 2021).

Soil use and cover can identify vegetation cover in hydrographic basins, where it plays a fundamental role in capturing, storing, and distributing water to springs and tributaries of the main channel (Llerena et al., 2007). In the watershed, all geoenvironmental components (geology, relief, vegetation cover, climate, and rivers) are integrated and interconnected, in such a way that changes in any of these elements can affect local stability and worsen its environmental vulnerability (Schineider et al., 2011). Thus, evaluating land use and occupation in hydrographic basins has been one of the most effective ways to identify and analyze impacts on the environment (Queiroz, 2011).

Remote sensing combined with geoprocessing is important tools to generate new information that represent the spatial variability of phenomena through the construction and interpretation of maps (Faustino et al., 2014). An example of the functionality of these geotechnologies is the mapping done by Souza Junior (2020) who reconstructed the past decades of deforestation using the MapBiomas product through Google Earth Engine. Calegario et al. (2019) used remote sensing to detect the advance of pasture areas, consequently indicating the alert for environmental degradation and possible limitations in the conservation of natural resources in the Limoeiro river basin. Another role of geoprocessing mapping is in the application of Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) data, widely used to observe the spatialization of precipitation (Belay et al., 2019; Oliveira-Júnior et al., 2021).

In Brazil, the national hydrographic division instituted by the National Water Resources Council (CNRH) established 12 hydrographic regions (ANA, 2021a). The Tocantins-Araguaia Hydrographic Region corresponds to more than 10% of the national territory, where the Amazon and Cerrado biomes are present (ANA, 2021b). In the region, the main activities linked to land are agriculture (cultures of rice and soy) and mining, where it is worth mentioning that agricultural expansion is one of the human activities that has contributed most to the reduction (deforestation) of the regional native vegetation (ANA, 2015). In recent decades, large tracts of land in the Araguaia Watershed (AW) have been undergoing an intense process of transformation of the natural landscape due to human action, associated with the advance of the agricultural frontier and changes in forms of occupation (Luiz et al., 2019; Assis and Bayer, 2020). Currently, the AW represents one of the most important river systems in Brazil, being considered a key region for the country's economic growth, with a perspective of strengthening for the next decades due to national and international demands for the production of commodities (Bayer et al., 2020).

In this sense, the objective of this work was to analyze the flow of the Araguaia River under the effects of extreme years associated with the dynamics of land use in the AW from 1981 to 2019.

Material and Method

Study area

Figure 1 represents the location of the AW in central Brazil, comprising an area of approximately 384,818.0 km² divided into sub-basins (Araguaia Upper, River of Death, Araguaia Middle, Canton of Araguaia, and Araguaia Lower) where consisting of approximately 1,365,220 inhabitants of the states of Goiás, Mato Grosso, Pará, and Tocantins (Brasil, 2006).

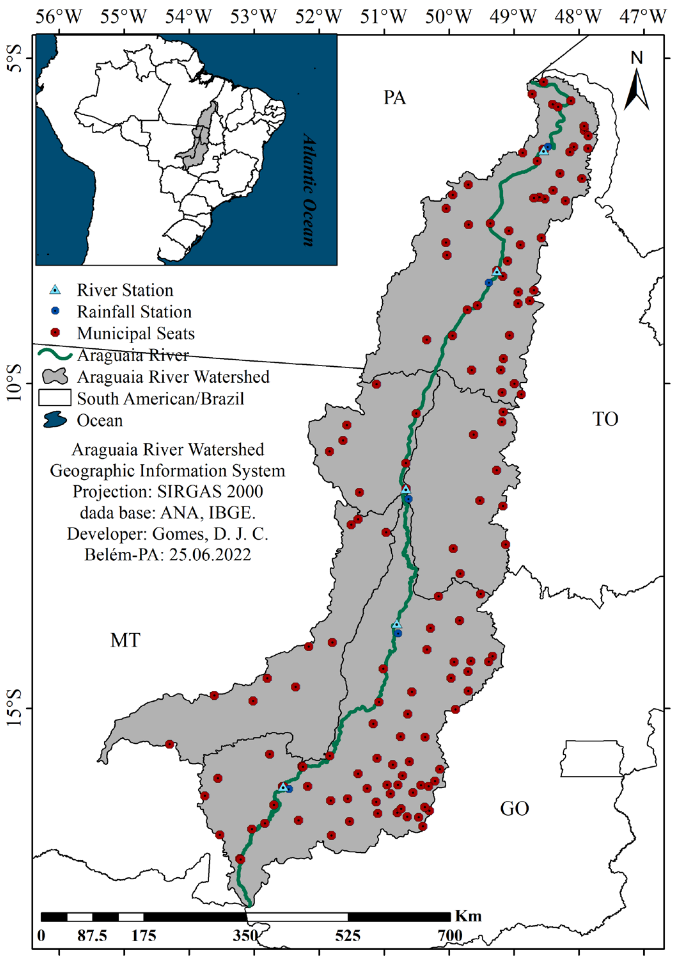

Figure 1 – Location of the study area: Araguaia River Watershed. (A) Araguaia Upper, (B) River of Deaths, (C) Canton of Araguaia, (D) Araguaia Middle, (E) Araguaia Lower.
Source: authors (2021).

The Araguaia River rises in Serra dos Caiapós (Mineiros-GO) and travels to its mouth where it flows into the Tocantins river (Gomes et al., 2019a). The AW comprises 204 municipalities in the states of Goiás, Mato Grosso, Tocantins, and Pará. The Araguaia River (2,110 km) supplies municipalities in the states of Pará (11), Goiás (11), Tocantins (19), and Mato Grosso (11).

The altitudes vary between 850 m at the springs and 100 m at the mouth, and it has a topographic difference of 750 m (EMBRAPA, 2022). After a distance of 720 km, it divides into two arms forming the Bananal Island, with an extension of 375 km, considered the largest river island in the world (Morais, 2006). The AW has an Aw climate classification, a hot climate with summer rains (Dubreuil et al., 2018), with average rainfall ranging from 1,450 mm to 1,850 mm, maximum air temperature of 35°C, and minimum air temperature of 22°C, and average relative humidity of 72% (INMET, 2021).

The Araguaia River is one of the main waterways in the country, encompassing the Cerrado biome and the Amazon Forest, two phytogeographic regions of notorious biodiversity (Lopes et al., 2017). It has a complex floodplain with the largest wetland in the Cerrado (Planície do Bananal that extends over 100,000 km²) and the Cerrado-Amazon ecotone with the greatest geodiversity of the biome, the great diversity of fish (approximately 416 species), and a high rate of endemism (Dagosta and Pinna, 2017).

Data acquisition and processing

The MEI climate index provided by the National Oceanic and Atmospheric Administration (NOAA, 2021) was acquired. The MEI is a combined index, which is the calculated value based on several atmospheric and oceanic components: atmospheric pressure, SST, solar radiation, and wind (NOAA, 2022). The reason is the complexity of the ENSO event that depends on the interaction of the variables; however, it generates a higher quality product in relation to the other indices (McGregor and Ebi, 2018). According to Shrestha and Kostaschuk (2005), when the MEI anomalies are greater (smaller) than +0.5 (-0.5) for at least five consecutive months, the El Niño (La Niña) phenomenon is observed.

The measured rainfall and flow were obtained from the National Water and Sanitation Agency (ANA, 2021c), where the continuous data series with the lowest number of failures in the 39-year period (1981–2019) of five stations was selected hydrological systems distributed along the Araguaia River. Filling in gaps was not applied, as in addition to having a low absence of measurements, it is not recommended due to the risk of inconsistency and subjectivity in the analysis (Mendes and Zucowski Junior, 2019; Nascimento et al., 2020). To represent the spatial distribution of precipitation in the AW, the CHIRPS dataset (Climate Hazards Group InfraRed Precipitation with Stations) with a high spatial resolution (0.05°–5 km) was used to estimate the rainfall regime (Funk et al., 2015; Costa et al., 2019).

Land use and cover were imported from the Google Earth Engine platform (MAPBIOMAS, 2021), producing the map in a Geographic Information System (GIS) environment to represent changes in land use (1985–2019). Based on the methodology applied by Dias et al. (2019), the Pearson correlation (r) was calculated between land use and cover and the flow in the AW with a significance level of 5%.

Through the program Hidro 1.3 (ANA, 2021c), the river data were visualized, organized in spreadsheets to be later treated, and generated figures representing the hydrological variations (Rodrigues et al., 2015). Subsequently, to observe the extreme events in the hydroclimatic variables in the AW over the years, it was calculated (Equation 1) with the measured precipitation the Rain Anomaly Index (RAI) developed by Rooy (1965) and applied in other studies (Gomes et al., 2021b; Raziei, 2021), to detect extreme rainfall events (Jorge and Lucena, 2018). Table 1 describes the classification referring to the intensity of precipitation represented by the RAI.

$$RAI = \pm \frac{p - p\prime}{e - p\prime} \quad (1)$$

Where:

p = the measured precipitation (mm/year);

p' = the average of the measured precipitation;

e = the 10 highest annual rainfall measured in the historical series.

Then, only the estimated precipitation (CHIRPS) of the extreme years of El Niño (1982–1983, 1987–1988, 1991–1992, 1997–1998, and 2015–2016) and La Niña (1988–1989, 1998–1999, 1999–1900, 2007–2008, and 2010–2011) to observe the distribution of rainfall in the AW (Souto et al., 2019). Thus, the pluviometric spatialization was carried out in a GIS environment (Gomes et al., 2021b).

Table 1 – Rainfall anomaly index classification.

RAI	Class
≥ 4	Extremely rainy
2 > 4	Very rainy
0 > 2	Rainy
0 < -2	Dry
-2 < -4	Very dry
≤-4	Extremely dry

Source: adapted from Jorge and Lucena (2018).

MEI was used to investigate the relationship between tropical Pacific ocean-atmosphere interaction oscillations and AW precipitation. The Shapiro-Wilk normality test for the hydroclimatological data (MEI, precipitation, and measured flow) was performed using the free access software BioEstat 5.3 (Santos et al., 2020), in which $p > 0.05$ was obtained for the data. MEI and measured precipitation (except for the Araguaia Upper-Middle), however, the flow data, were all non-normalized ($p < 0.05$) (Silva et al., 2021a). Therefore, for the parametric datasets, the Pearson correlation coefficient (r) was calculated, and for the non-parametric data, the Spearman's correlation coefficient (ρ) was calculated. Figure 2 shows the flowchart that helps to understand the steps taken.

Results and Discussion

Precipitation: estimated and observed

Figure 3 shows the spatial variability of rainfall and its respective anomalies. In the north-central region of the AW, the highest rainfall was estimated (1,720.4–2,014.6 mm). In this region, the Araguaia Lower recorded the largest (smallest) water surplus (deficit) in 1985 (2015) with 4.4 mm (-7 mm), being this year classified as extremely rainy (dry) due to the occurrence of La Nina (El Nino). In the Araguaia Sub-Middle, the biggest (minor) extreme positive (negative) event also occurred in 1985 (2015) with an anomalous value of 5.9 mm (-5.6 mm), possibly being the effects of the action of climatic phenomena originating from the tropical Pacific.

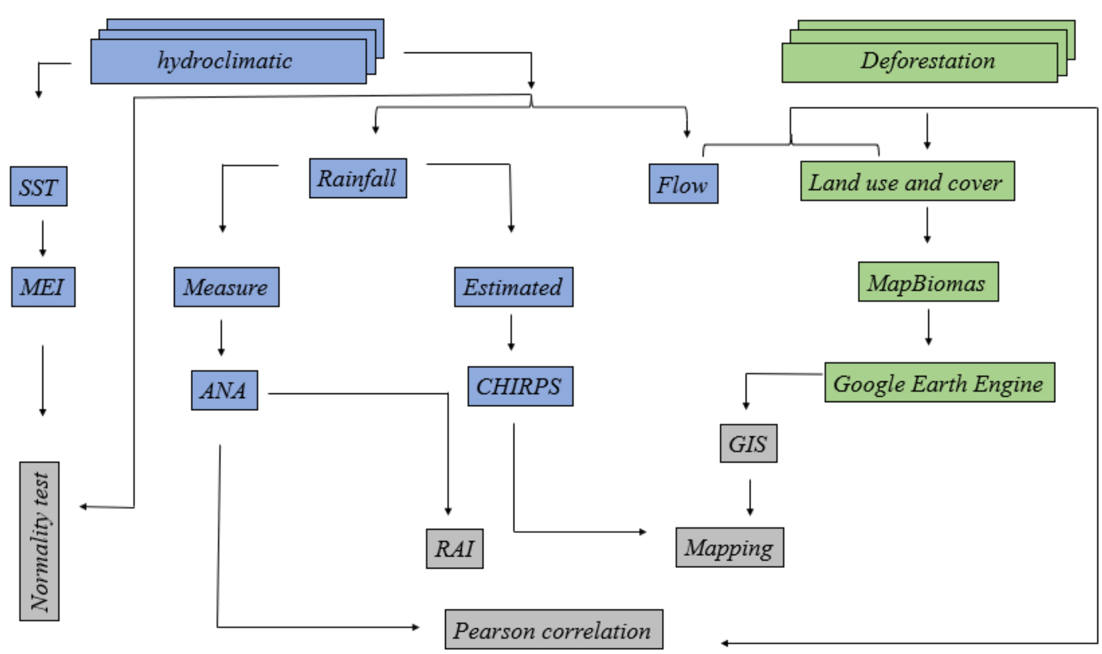

Figure 2 – Flowchart of data collection and processing.
Source: authors (2022).

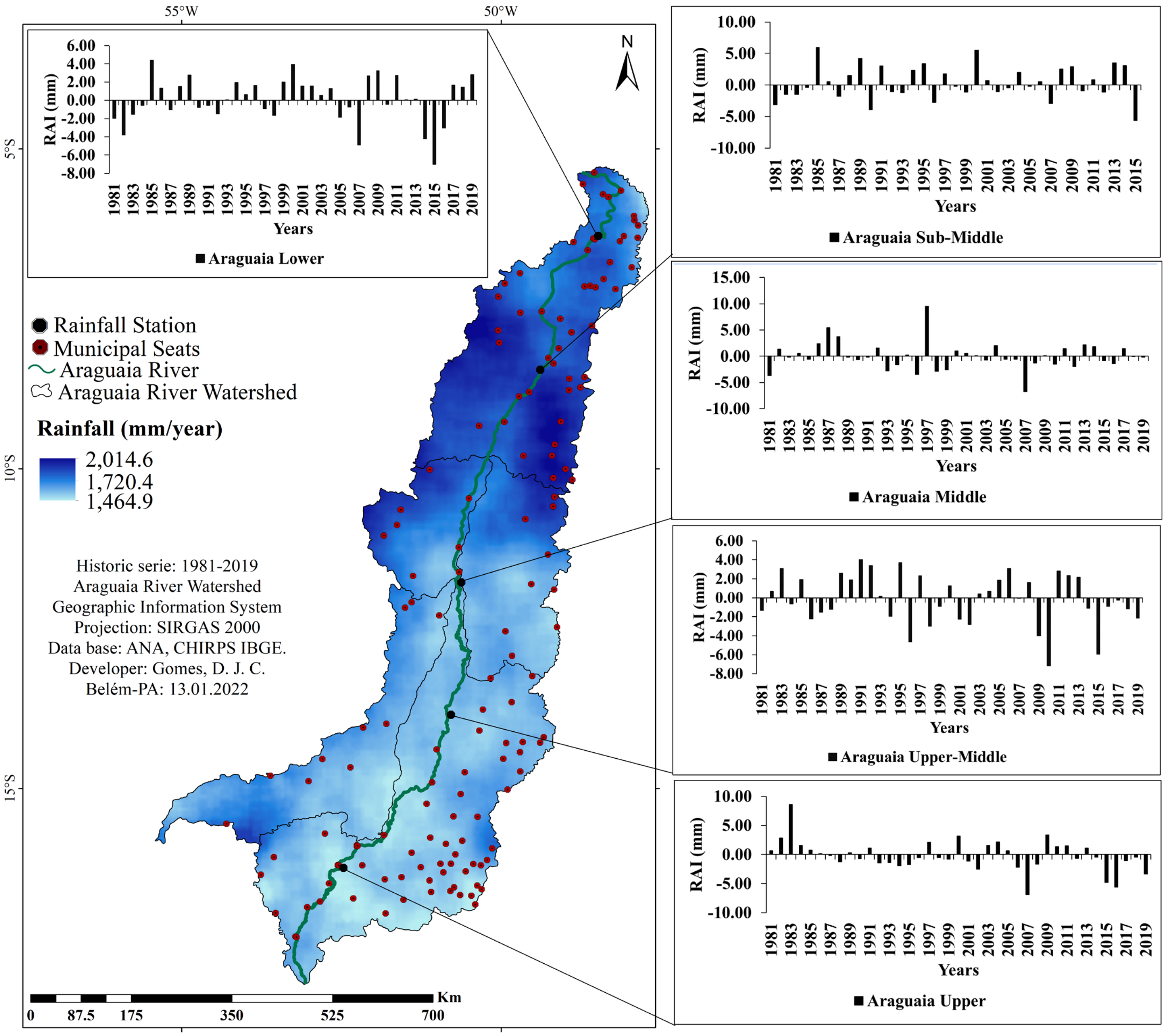

Figure 3 – Spatial (CHIRPS) and temporal variability of the RAI (ANA) from 1981 to 2019: Araguaia River Watershed.
Source: ANA (2021c), CHIRPS (2021).

The south-central region of the AW is characterized by the lowest rainfall volumes (1,464.9–1,720.4 mm). The Araguaia Middle has the highest (smallest) positive (negative) rainfall anomaly in 1997 (2007) with an anomalous value of 9.5 mm (-6.7 mm), which is classified as extremely rainy (dry). In the Araguaia Upper-Middle stretch, the value of water surplus (scarcity) was observed in 1991 (2010) with 4.0 mm (-7.2 mm) in the category of very rainy (extremely dry). In the region of the headwaters of the Araguaia River, the highest (lowest) positive (negative) water anomalous index was in 1983 (2007) with 8.6 mm (-6.8 mm), which is classified as extremely rainy (dry) in the year of climatic extremes.

Marengo et al. (2021) showed the importance of spatialized precipitation data (CHIRPS) when analyzing extreme drought in the Brazilian Pantanal region. This estimator helped in the observation of areas with a deficit in rainfall recharge, which contributes to the search for answers in relation to the cause of the reduction of rainfall in the region and the decrease in the level of the Araguaia River quotas. In the AW, the effects of the ENSO phenomenon were studied by Marcuzzo and Romero (2013) for the state of Goiás, where they detected relatively moderate signals with a slight tendency of sensitivity to El Niño events. For the state of Mato Grosso, ENSO signals are low (Oliveira et al., 2015), which means that the rainfall regime in this region is modulated by other factors, probably synoptic systems (Gomes et al., 2019a; Faggiani et al., 2020).

El Niño

The high spatiotemporal rainfall variability in El Niño years in the AW is observed in Figure 4. In El Niño (1982–1983), although there are no great differences in the volume of rainfall in the years, there is an expansion of areas with lower precipitation (1,323.4–1,342.1 mm) in Araguaia Lower and Middle. El Niño (1987–1988) contributed to the drought, as indicated by the increase in areas of reduced precipitation (1,194.5–1,330.1 mm) in the Araguaia Upper and River of Deaths regions.

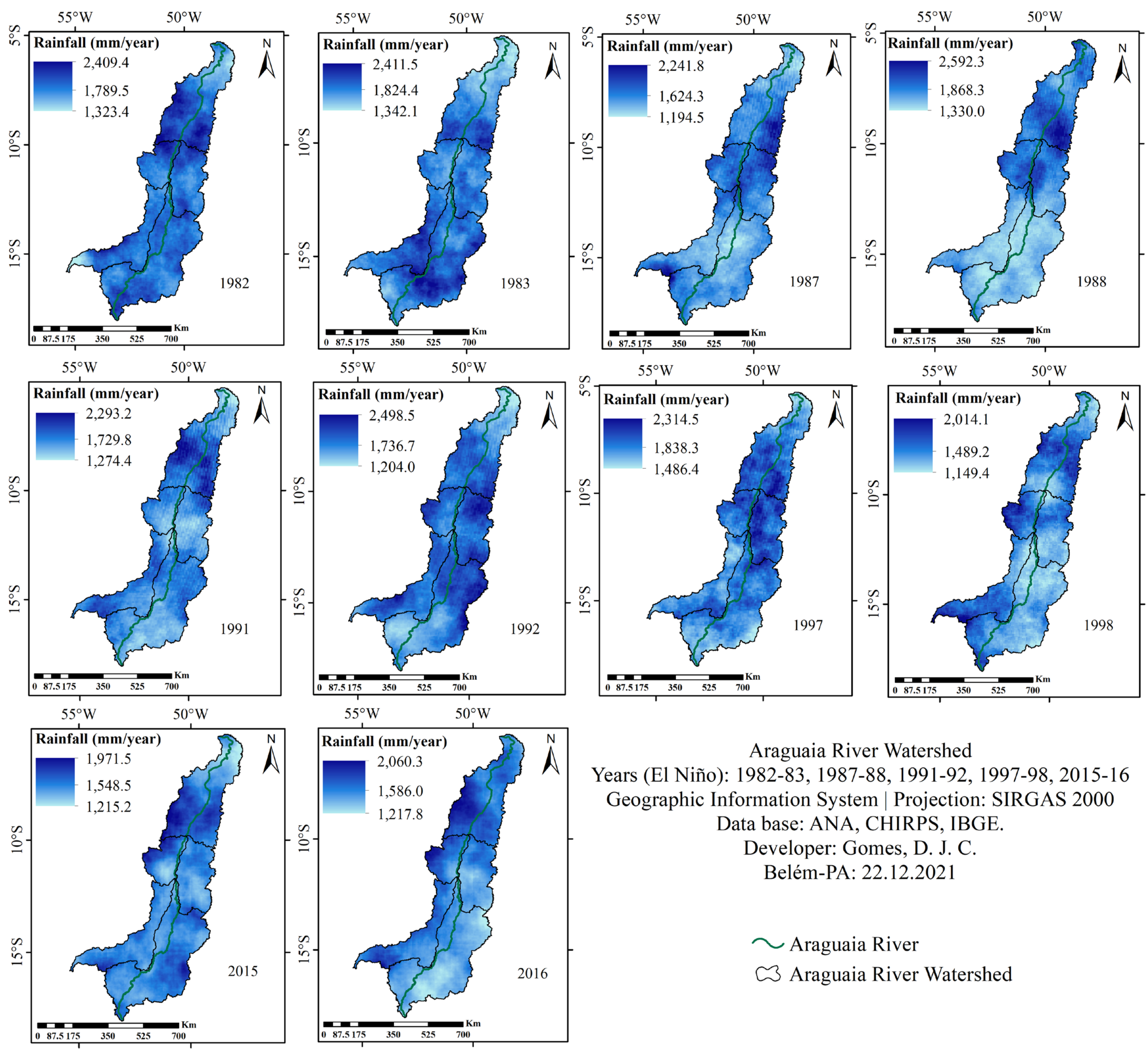

Figure 4 – Spatiotemporal rainfall distribution (extreme years: El Niño): Araguaia River Watershed.
Source: adapted from CHIRPS (2021).

The rainfall regime in El Niño (1991–1992) had the lowest rainfall (1,204–1,274.4 mm) in the Araguaia Upper and Middle, as well as at the mouth of the Araguaia River. However, El Niño (1997–1998) is characterized by strong signs of lower water recharge (1,149.4–1,486.4 mm) on the edges of the Araguaia Upper and River of Deaths, in addition to the river mouth region. In El Niño (2015–2016), rainfall variability is configured differently, with the lowest values (1,215.2 mm) in the stretch where the river empties and in the Araguaia Middle course, where this low volume of rainfall (1,217.8 mm) moves to the Upper-Middle Araguaia. The Integrated System on Natural Disasters (S_2ID, 2022) reported the performance of 23 drought events in the AW, which may be associated with El Niño episodes and their effects on regional water availability.

It is worth mentioning the shift in the rainfall distribution in the AW in El Niño years, which suggests the high spatial variability caused by this phenomenon. In their research, Raj et al. (2020) identified the distinct effects of El Niño on the rainfall pattern, that is, this phase of the phenomenon promotes an increase and a decrease in rainfall in different locations in the southern region of India. Delage and Power (2020) also observed different shapes in the distribution of rainfall in Australia during El Niño years. In Brazil, Correia Filho et al. (2022) analyzed the influence of the ENSO phenomenon on rainfall patterns in the Cerrado biome. This scenario of changes in the performance of El Niño is addressed by Capotondi and Sardeshmukh (2017), who point to the spatial increase in warming and anomalous intensity (SST) as the factors responsible for the different effects of the phenomenon that can generate more extreme drought events such as in the 2015–2016 El Niño (Jiménez-Muñoz et al., 2016), mainly in the Araguaia Lower region.

La Niña

Figure 5 presents the spatial and temporal variation of precipitation in La Niña years in the AW. In the years of the occurrence of La Niña (1988–1989), an increase can be observed with the highest amounts of rainfall (2,592.3–2,620.4 mm), mainly in the Araguaia Lower region. However, in La Niña (1998–1999), the maximum precipitation (2,014.1 mm) occurred in the central part of the Araguaia Lower, in the Araguaia Middle, and in the Southwest of the AW, where it is estimated a higher rainfall volume (2,236.4 mm) concentrated in Araguaia Lower, east of Araguaia Middle, and part of the northeast Canton of Araguaia in the following year.

The persistence of La Niña (1999–2000), despite the small reduction in precipitation (2,209.6 mm), also marked the shift of the rainfall regime to the central part, with a small patch in the Araguaia Upper. In La Niña (2007–2008), signs of the highest rainfall (1,783.8 mm) were observed in Araguaia Lower, Southwest of Araguaia Middle, and Northeast of Canton Araguaia, where there was a greater concentration of rains (2,310 mm) in Araguaia Lower in the following year. Maximum rainfall (1,921.5 mm) was observed in La Niña (2010–2011), east of Araguaia Lower, and north of Araguaia Middle, increasing (2,479.5 mm) in the following year, also expanding to North of the Canton of Araguaia. The Araguaia Lower region showed the trends of greater rainfall, the same characteristic recently observed by Espinoza et al. (2022) who identified positive rainfall anomalies in years impacted by La Niña. The same study reinforces the analysis of La Niña (2011–2012), where this episode of the phenomenon caused anomalies with the greater spatial distribution of rain covering a large part of the AW, showing that moderate intensity La Niña can eventually influence the rainfall regime from central Brazil.

According to the S_2ID records (2022), there was a decree of emergency situations due to the occurrence of 169 storm events in the municipalities of the AW. In some cases, the storms happened in areas climatologically with drought tendencies, which means that the AW region has a considerable susceptibility to such intense rain events and they are possibly aggravated when there are climatic extremes.

Table 2 describes the statistical values of Pearson's correlation and coefficient of determination between climatic indices from the tropical Pacific Ocean and rainfall measured at five points along the Araguaia River. All regions had positive and moderate correlations, with the exception of Araguaia Lower, which had a low classification. In this way, there is a low degree of explanation of the climatic oscillations and the pluviometric regime in the AW, which indicates the moderate signal of the ENSO events in the rain in the region of central Brazil. Carpenedo and Silva (2022) analyzed the teleconnection of the tropical Pacific with precipitation from the Cerrado and obtained similar results at some points in the AW.

Over the past few decades, Figure 6 identifies eight classes of land use and land cover in the AW, namely, agriculture, urban area, Cerrado, Amazon forest, water body, mining, pasture, and reforestation. In 1989, it was observed that most of the Amazon forest is composed of 93,296.6 km² of area, and is concentrated to the northwest of the AW in the Araguaia Middle and Lower. However, the predominance of cerrado and pasture areas stands out, with 126,226.7 and 154,276 km², respectively, along the AW. Then, agriculture with approximately 5,841.3 km² is located to the southwest of the AW. On a smaller scale, urban areas (372.5 km²), reforestation (1.3 km²), mining (4.7 km²), and water body (3,069.3 km²) are identified.

In 1999, the advance of pasture with an increase in its area to 191,603.9 km² can be detected throughout the entire region of the AW, mainly when it is observed the decrease of the Amazon and Cerrado classes, with 75,278.9 and 105,801 km², respectively. In addition, the expansion of agriculture to 8,724.6 km² in the Southwest, as in the River of Deaths region, may have contributed to the suppression of biomes. The other classes of smaller area also continue to increase their areas. In 2009, there is still a persistent increase in agropastoral activities, with the values of agriculture and pasture reaching approximately 14,110.5 and 209,118.2 km², respectively, as well as a decrease in the size of the Amazon forest areas to 62,061.9 km² and cerrado to 94,101.3 km². With the exception of urban areas, all other classes had an increase in their respective territorial extensions.

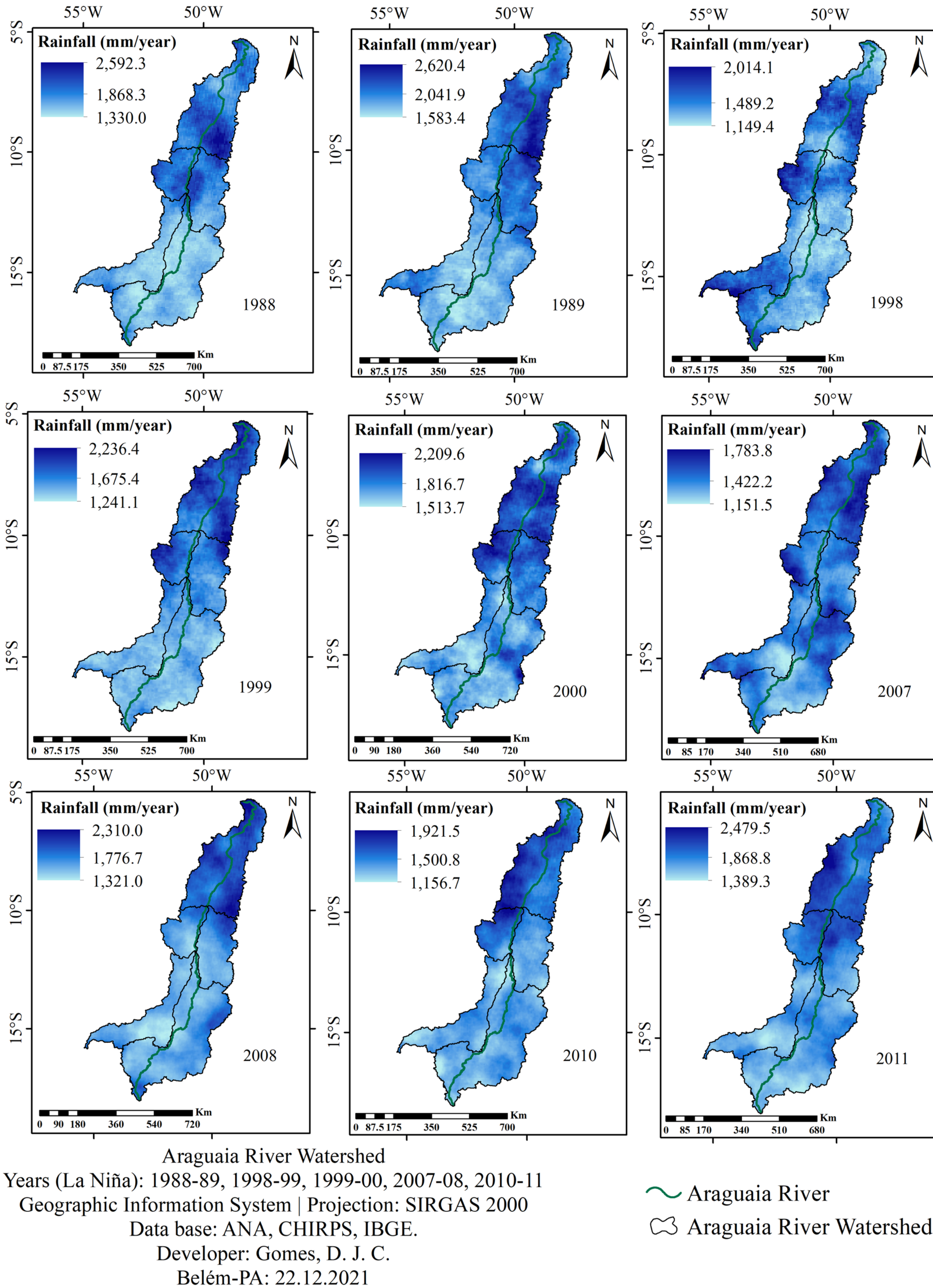

Figure 5 – Spatiotemporal rainfall distribution (extreme years: La Niña): Araguaia River Watershed.
Source: adapted from CHIRPS (2021).

Table 2 – Pearson correlation statistics (r) and coefficient of determination (r^2) between climatic variables: climatic indices × rainfall.

Climate (MEI) × Rainfall	Upper Araguaia	Upper-Middle Araguaia*	Middle Araguaia	Sub-Middle Araguaia	Lower Araguaia
r	0.58	0,53*	0.56	0.56	0.35
r^2	0.34	–	0.32	0.32	0.13

*Spearman's correlation coefficient (ρ).
Source: authors (2022).

Yao et al. (2021) used geotechnologies to map land use classes in a watershed in China and observed more significant changes, such as an increase in forests by 31 km² and a decrease in pasture areas by 29.5 km².

In 2019, intense environmental degradation can be observed from human actions, such as the advance in the SW-SE direction of agricultural areas with 24,777.4 km², in addition to some points in the region close to the border of the Araguaia Middle-Lower and Canton of Araguaia. Another issue to be highlighted is the pasture that reached high values with 201,770.0 km².

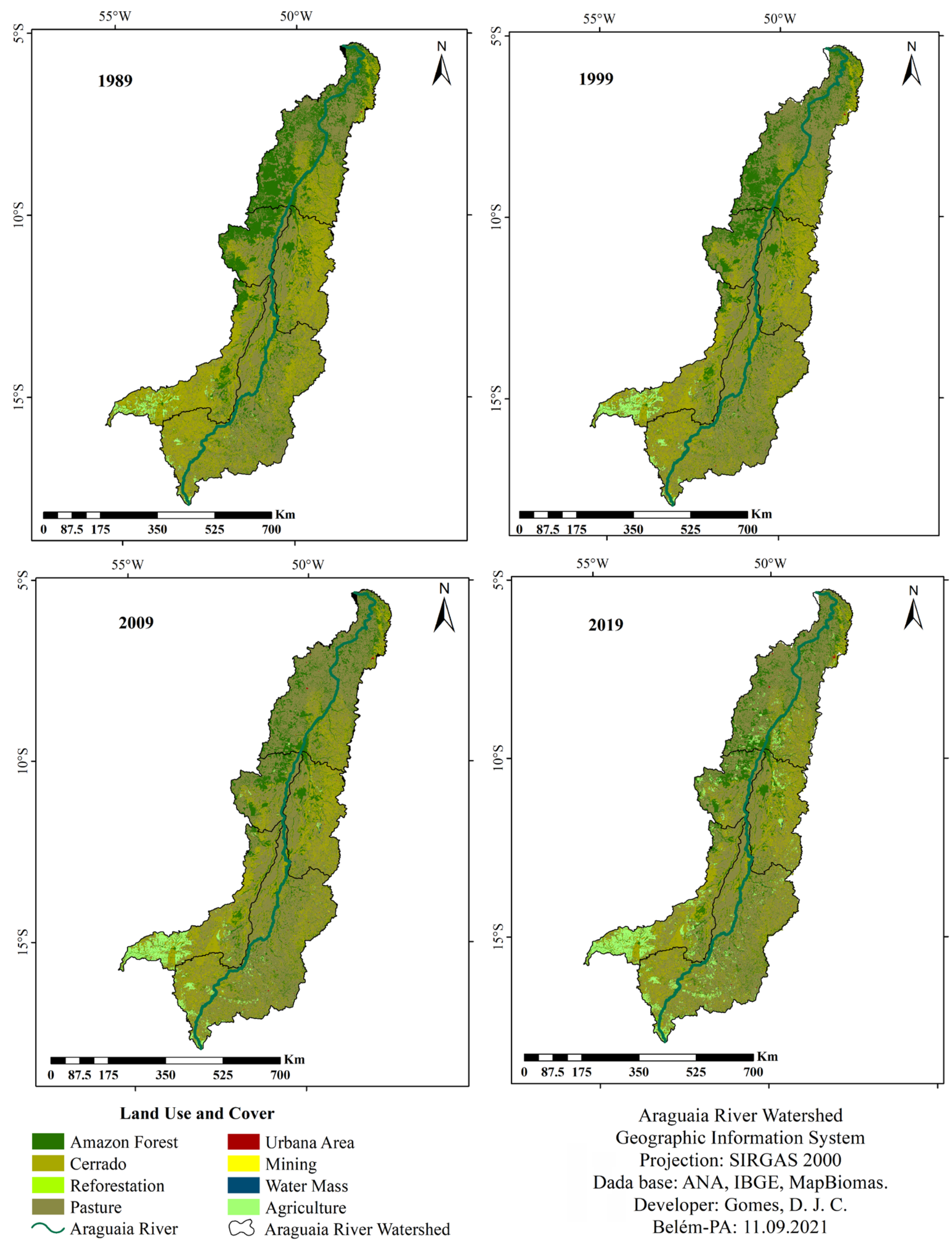

Figure 6 – Land use and cover (1989–2019): Araguaia River Watershed.
Source: MapBiomas (2021).

This scenario may be related to the considerable reduction of the areas of Amazon forest to 61,654.8 km² in the Northwest and of cerrado to 83,607.8 km² distributed in the AW, mainly in Araguaia Lower.

The progression to 219.4 km² of reforestation is less when compared to the deforested areas, and this cutting of the vegetation cover is a serious problem that can lead to changes in the hydrological cycle of the AW (Balbinot et al., 2008; Rosa et al., 2020). This can be seen in the increase to 3,180.7 km² in the water mass in recent decades. For the Araguaia Lower region, Oliveira et al. (2020) observed similar changes in land use and cover in relation to the advance of pasture and agriculture, with the expansion of the latter class being attributed to public policy incentives and government investments. In this way, the authors discussed how much this environmental degradation will affect local ecosystems, since native forests are being deforested with the two banks, right and left, of this stretch of the Araguaia River being marked by different forms of land use such as agriculture and pasture.

In the flow of the Araguaia River, decreasing trends were observed in the five (5) points analyzed. In Araguaia Upper (Figure 7), the highest flow occurred in 1982 with a value of 497.9 m³/s, while the lowest value occurred in 2015 with 139.3 m³/s. Such values are conditioned to positive (1982) and negative (2015) rainfall anomalies, with the latter driven by the El Niño event.

In Figure 8, the Araguaia Upper-Middle recorded the highest river discharge in 1983 (2,042.3 m³/s), decreasing until reaching a minimum value in 2017 (495.8 m³/s).

The water capacity in the extreme years of the Araguaia Upper-Medium influenced the flow in this stretch of the river. In the Araguaia Middle represented by Figure 9, high annual fluctuation is observed, with the highest fluvial discharge in 1991 (3,944.1 m³/s), until reaching the lowest extreme in 2016 (1,690.6 m³/s).

The Araguaia Sub-Middle region (Figure 10) also has large fluctuations in the flow values at this point of the Araguaia River, where the maximum peak was detected in 1997 with a flow of 6,998.1 m³/s, which may be related to climate extremes. In 2017, a minimum river flow value of 2,576.4 m³/s was observed.

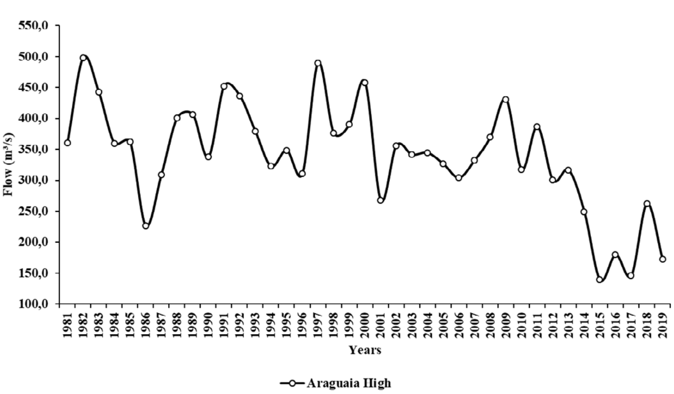

Figure 7 – Annual flow variability (1981–2019): Araguaia Upper.
Source: ANA (2021c).

Figure 11 shows Araguaia Lower with a high variability in river discharge with the highest extreme in 1997 with 7,641.1 m³/s, which may be associated with anomalies accumulated in previous years. The lowest river flow occurred in 2016 (3,012.1 m³/s), possibly due to the negative anomalies of water recharge.

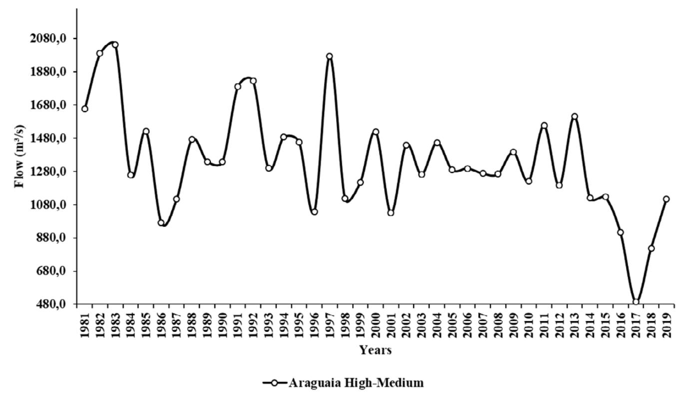

Figure 8 – Annual flow variability (1981–2019): Araguaia Upper-Middle.
Source: ANA (2021c).

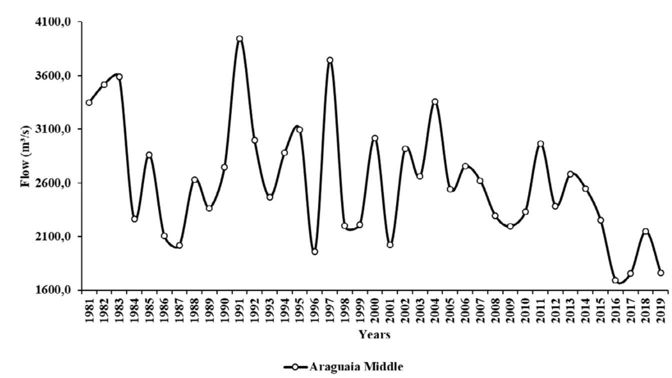

Figure 9 – Annual flow variability (1981–2019): Araguaia Middle.
Source: ANA (2021c).

Figure 10 – Annual variability of flow (1981–2019): Araguaia Sub-Middle.
Source: ANA (2021c).

The Spearman's correlation statistics (Table 3) between the hydrometeorological variables in the AW presents positive and moderate values, except for the Araguaia Upper where the hydrological components are strongly correlated, that is, the greater the volume of rainfall, the greater the flow of the Araguaia River.

The dynamics of land use and cover, especially in the Araguaia Upper, Araguaia Sub-Middle, and Araguaia Lower sub-regions, may be contributing to the reduction in the flow of the Araguaia River. Oliveira et al. (2014) confirmed this fluvial trend and claimed that these changes may be related to deforestation that reduces evapotranspiration. For Ho et al. (2016), there are trends of reduced precipitation in the AW between the months of March and November, in addition to the decrease in flow, in which the researchers attributed such declines to climate change. Rápalo et al. (2021), through hydro-environmental modeling, simulated scenarios under different conditions in a watershed adjacent to the Araguaia Upper and found that the recovery of vegetation cover favors hydrological stabilization, the opposite effect when agriculture and pasture are present. These changes in the natural water flow cause environmental disturbances in the Brazilian cerrado, such as increased environmental fragility related to soil erosion (Silva et al., 2021b), and this generates several other problems such as leaching (Rizinjirabake et al., 2019), water quality of water bodies (Girardi et al., 2016), and river silting (Moreira and Souza, 2018).

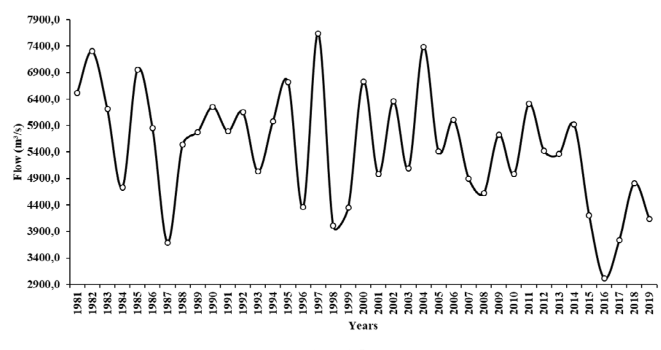

Figure 11 – Annual flow variability (1981–2019): Araguaia Lower.
Source: ANA (2021c).

Table 3 – Spearman's correlation statistics (ρ) between hydrometeorological variables: Rainfall × Flow.

	Upper Araguaia	Upper-Middle Araguaia	Middle Araguaia	Sub-Middle Araguaia	Lower Araguaia
ρ	0.71	0.66	0.56	0.50	0.65

Source: authors (2022).

The statistical relationship between the hydro-environmental variables (Table 4) describes the influence of environmental degradation. It is worth noting the high directly proportional and positive correlation between the Amazon forest × flow (r = 0.93), cerrado × flow (r = 0.90), pasture × flow (r = 0.85), and water mass × flow rate (r = 0.93). This scenario means that the greater the preservation of the biomes (Amazon forest and cerrado), the greater (in the same proportion) the flow in the Araguaia River.

The increase in river discharge may be the effect of replacing the Amazon forest and cerrado for pasture expansion, with possible long-term consequences for the regional hydrological cycle. Such hydro-environmental relationships are due to the fact that the soil of the areas destined for the activities usually becomes more compact, hindering the process of water infiltration and, consequently, increasing the surface runoff (Lulandala et al., 2021). The urban area × flow (r = 0.46) has a low direct and positive correlation, in which the increase in flow consists of a decrease in soil infiltration conditions. The correlation of agriculture ×flow (r = -0.31) and reforestation × flow (r = -0.16) is low and inversely proportional, that is, the larger the areas of both classes, the lower the fluvial flow. Mining is not correlated with the flow in the AW region.

In the Guamá River watershed, Silva et al. (2021c) highlighted the scenario of human actions such as deforestation and later the use of these lands for agricultural activities, where this problem becomes more critical when researchers found that the areas close to the source have a high degree of environmental degradation, compromising circumstances for the regional water availability, including flow. In their research in the Paraná River watershed, Lee et al. (2018) detected an increase in river discharge values due to the accelerated process of removing vegetation cover for other types of land use. Bayer et al. (2020) revealed the hydrological impacts that occur in the AW due to accelerated anthropic modification in the region, also pointing out that other consequences such as silting of some stretches of the river can cause serious damage to river biota. Such alterations in the natural landscape may be associated with the 15 cases of flooding and 7 floods, in addition to 15 soil erosion events in the AW (S_2ID, 2022).

However, such extreme episodes occur at the local level and under certain environmental conditions, that is, these amounts of rain, despite being intense, do not have enough water volume to reverse the regional water diagnosis. Ribeiro Neto et al. (2016) in their forecasts reported that in the next 80 years, the AW has severe trends in flow reduction. Scenarios show a drop in water recharge and, consequently, a reduction in the fluvial discharge flow. However, despite the results indicating decreasing trends in the flow of the AW, medium-term pro-

Table 4 – Pearson correlation statistics (r) between hydroenvironmental variables: Land use × flow.

	Forest Amazon	Cerrado	Agriculture	Pasture	Urban Area	Reforestation	Mining	Water Mass
Flow	0.93	0.90	-0.31	0.85	0.46	-0.16	0.02	0.93

Source: authors (2022).

jections of the flow indicated neutrality on this issue for this region (Lima et al., 2022). In addition, such hydrometeorological information is essential for improving rainfall and flow prediction models, such as the Box-Jenkins applied in Tocantins-Araguaia (Salame et al., 2019).

Barichivich et al. (2018) attributed the occurrence of Amazonian floods to atmospheric circulation, which indicates that the Araguaia Upper region especially may be susceptible to extreme hydrological events. Campos and Chaves (2020) detected decreasing trends in rainfall variability in the cerrado, the same results identified by Casaroli et al. (2018) in the municipality of Goiânia (GO). However, Silva Neto et al. (2020) observed greater events of intense rainfall with high erosivity in the regions of Parrot's Beak and Bananal island located in the Araguaia Upper and Middle, respectively. These findings showed how much precipitation variability, despite decreasing, has isolated the cases of extreme events that can cause natural disasters. This scenario worsens when research points to the influence of El Niño in the AW region (Alves et al., 2011; Gomes et al., 2019a).

Studies focused on the analysis of natural systems such as climate variability and anthropogenic factors such as land use dynamics show how much such forcing pressures river components (Silva et al., 2021c). Therefore, the results of this research suggest that the decrease in precipitation and increase in anthropized areas may be reducing the water flow of the Grande River. Martins and Galvani (2020) applied the SEBAL flow estimation algorithm in the Araguaia Upper region with the aid of simplified water balance and land use information and recommended its use for this purpose.

Recent findings by Anache et al. (2019) showed that the change in land use and cover, such as the removal of the cerrado for agropastoral purposes without sustainable planning, causes changes in surface runoff patterns and water balance, which can affect water availability in groundwater. Lopes et al. (2018) observed in Santa Catarina that the infiltration rate of water in the soil is higher in forested areas when compared to areas without forests. These human conditions, together with climate change, were the basis for developing impact projections of the erosivity of rains in the AW region, alerting to possible scenarios of soil erosion (Santos et al., 2022). According to Marengo et al. (2022), the transition zone between the Amazon and Cerrado biomes is marked by strong pressures from agricultural frontiers, and in the face of climate change, such adverse conditions cause a delay in the rainy season, decreased precipitation, humidity and evapotranspiration, and an increase in dry days.

Therefore, the use of geotechnologies to analyze the forms of use and land cover is essential for territorial planning at the hydrographic basin level with the purpose of a better multiple-use of water, aiming at its conservation and preservation (Oliveira-Andreoli et al., 2019). In addition, allied to climate information can provide valuable information for the creation of strategies in regional water management. Siqueira et al. (2021) studied three basins in the cerrado and commented that conservationist practices in the agricultural sector combined with reforestation in ciliary forests lead to attenuation of flow, even in the rainy season and under the effect of climate change. This may foster ideas for improved management of these aspects of this highly degraded area of the AW. In this way, the development and application of an integrated management of watersheds analyzing each geoenvironmental component (Alemu, 2016) can mitigate environmental impacts related to climate and human actions.

Conclusion

Weather extremes from the tropical Pacific have a moderate impact on AW precipitation. Thus, the rainfall regime is possibly modulated by other climatic mechanisms such as the Madden-Julian Oscillation and the Southern Annular Mode, as well as synoptic-scale atmospheric systems such as the South Atlantic Convergence Zone, Cold Fronts, and South Atlantic Subtropical Anticyclone, all influencing seasonally. The deforestation of the Amazon forest and cerrado due to the advance of agriculture and pasture activities interfere with the flow of the Araguaia River, where there is a reduction in the water flow, despite the gradual increase in the water mass in the AW. The downward trend in rainfall water recharge observed in recent years reinforces this fall in the fluvial flow of the Araguaia River.

Therefore, the landscape dynamics represented by changes in the use and cover of the AW's soil have evidence for greater and more significant impacts on the hydrological regime in relation to natural factors (climate fluctuations), such as areas with anthropic agriculture and pasture that potentiate erosive processes, carrying of sediments and silting of the Araguaia River. However, it is worth mentioning that the Araguaia Lower region presents serious risk conditions, as it is climatologically more rainy and sensitive to La Niña events. In this way, possible severe storms associated with climate change when reaching highly degraded areas due to the intense advance of land use and cover can generate negative environmental impacts on the balance of regional hydrological systems.

Deforestation for agricultural purposes has been a reality in recent decades and the hypothesis that the ENSO phenomenon will show greater signs of influence in central Brazil in the future cannot be disregarded. Therefore, this study serves as a subsidy for the management and planning of hydrographic basins, as well as to better assess the changes and processes that have taken place in this environment. Public actions such as the intensification of environmental policies and monitoring focusing on the most committed and strategic areas such as the headwaters and mouth of the river can minimize the impacts caused by anthropic and natural factors.

Authors' contribution:

Gomes, D.J.C.: Conceptualization, Data Curation, Formal Analysis, Funding, Acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing — First Draft, Writing — Review and Editing; Nascimento, M.M.M.: Funding, Investigation, Resources, Validation, Visualization, Writing — First Draft, Writing — Review and Editing; Pereira, F.M.: Data Curation, Funding, Investigation, Resources, Validation, Visualization; Dias, G.F.M.: Data Curation, Funding, Methodology, Resources, Validation, Visualization; Meireles, R.R.: Funding, Investigation, Visualization; Souza, LG.N.: Funding, Visualization; Picanço, A.R.S.: Funding, Visualization; Ribeiro, H.M.C.: Funding, Visualization, Validation, Supervision, Writing — Review and Editing.

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