UNIVERSIDADE DE BRASÍLIA - UnB

FACULDADE UnB PLANALTINA - FUP

PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS AMBIENTAIS - PPGCA

VARIAÇÕES HISTÓRICAS DA SUPERFÍCIE DE ÁGUA E DA VAZÃO HÍDRICA NA BACIA HIDROGRÁFICA DO RIO ARAGUAIA

ALEX DOS SANTOS TEIXEIRA

DISSERTAÇÃO DE MESTRADO EM CIÊNCIAS AMBIENTAIS

Planaltina-DF

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Orientador: Prof. Dr. Ludgero Cardoso Galli Vieira.

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“Natura non facit saltus”.

(Gottfried Wilhelm Leibniz)

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SUMÁRIO

VARIAÇÕES HISTÓRICAS DA SUPERFÍCIE DE ÁGUA E DA VAZÃO HÍDRICA NA BACIA HIDROGRÁFICA DO RIO ARAGUAIA

Resumo

Conciliar a conservação ambiental com a crescente demanda por alimentos, água e energia é um desafio global. O Brasil, um grande produtor agrícola, enfrenta os custos ambientais do desmatamento. A bacia do rio Araguaia, vital para o crescimento econômico do Brasil, passa por mudanças significativas no uso da terra. Avaliando dados de 1987 a 2019, estudamos as variações anuais da superfície da água, considerando o desmatamento, a agricultura, a pecuária e a irrigação por pivô central, e históricos da vazão hídrica de 1980 a 2020 de 21 estações de monitoramento. Observamos reduções notáveis nas áreas inundadas (coeficientes angulares de 130 a 2.276 ha/ano) e na vazão hídrica em toda a bacia (b = -13,84; t = -4,8; P < 0. 001) e suas subdivisões (Alto Araguaia: b = -3,32; t = -4,5; P < 0,001; Médio Araguaia: b = -8,70; t = -4,8; P < 0,001; Baixo Araguaia: b = -45,49, t = -4,7; P < 0,001) nos últimos anos. As reduções da vazão hídrica persistem durante todo o ano, com uma diminuição acentuada durante o período de estiagem ($F_{3,8}$ = 8,82; P = 0,006), alinhando-se com o aumento da demanda de água para a agricultura intensiva. Os afluentes e o canal principal apresentam processos de redução semelhantes (t = 0,16; g.l. = 19; P = 0,873). A garantia da vazão ecológica da bacia é imprescindível para atender as necessidades mínimas do ecossistema aquático.

Palavras-chave: vazão hídrica, desmatamento, vazão ambiental, vazão ecológica, impacto antropogênico, agricultura

HISTORICAL VARIATIONS IN WATER SURFACE AND WATER FLOW IN THE ARAGUAIA RIVER BASIN

Abstract

Reconciling environmental conservation with growing demands for food, water, and energy is a global challenge. Brazil, a major agricultural producer, grapples with deforestation's environmental costs. The Araguaia River basin, vital for Brazil's economic growth, undergoes significant land use changes. Assessing data from 1987 to 2019, we studied annual water surface variations, considering deforestation, agriculture, livestock farming land, and central pivot irrigation, and historical water flow series from 1980 to 2020 from 21 monitoring stations. We observed notable reductions in flooded areas (angular coefficients from 130 a 2,276 ha/year) and water flow the entire basin ($b = -13.84$; $t = -4.8$; $P < 0.001$) and its regions (Upper Araguaia: $b = -3.32$; $t = -4.5$; $P < 0.001$; Middle Araguaia: $b = -8.70$; $t = -4.8$; $P < 0.001$; Lower Araguaia: $b = -45.49$, $t = -4.7$; $P < 0.001$) over recent years. Water flow reductions persist year-round, with a marked decrease during low water periods ($F_{3,8} = 8.82$; $P = 0{,}006$), aligning with heightened water demand for intensive agriculture. Tributaries and the main channel show similar reduction processes ($t = 0.16$; g.l. = 19; $P = 0.873$). Ensuring the basin's ecological flow is imperative for the aquatic ecosystem's minimum requirements.

Keywords: water flow, deforestation, environmental flow, ecological flow, anthropogenic impact, agriculture

Apresentação Geral

Nas últimas quatro décadas, dois importantes biomas brasileiros, o Cerrado e a Amazônia, vêm experimentando uma evidente expansão de atividades antropogênicas como a construção de barragens hidrelétricas, abertura de novas áreas para o cultivo, implantação de sistemas de irrigação por pivô central e realização de atividades de mineração e aquicultura, que tem induzido extensivas mudanças na cobertura da terra, hidrologia e condições ambientais (Coe et al., 2017; Strassburg et al., 2017; Latrubesse et al., 2019).

Nesse contexto, a bacia hidrográfica do rio Araguaia - um dos principais cursos d'água do território brasileiro – que abrange os biomas Cerrado e Amazônia, vem passando por um aumento significativo do desmatamento ao longo dos anos (MapBiomas, 2022), reduzindo a floresta ripária (Swanson & Bohlman, 2021) e proporcionando um maior papel para os processos erosivos (Zema et al., 2022). Deste modo, dada a interconexão entre o uso da terra e os recursos hídricos (Weatherhead & Howden, 2009), vários impactos podem ser previstos e estudados.

Diante disso, o presente trabalho dissertativo de mestrado acadêmico, dividido em capítulo único **("Evidence of water surface and flow reduction in the main hydrographic basin of the Brazilian savannah (Cerrado biome): the Araguaia river")**, foi produzido a partir de dados públicos, abertos e gratuitos, acessados através do projeto MapBiomas e do Sistema Nacional de Informações sobre Recursos Hídricos (SNIRH), administrado pela Agência Nacional de Águas (ANA – Brasil), e tem como objetivo avaliar as variações históricas na área da superfície de água e na vazão hídrica das estações de monitoramento localizadas ao longo do canal do rio Araguaia e de seus afluentes.

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EVIDENCE OF WATER SURFACE AND FLOW REDUCTION IN THE MAIN HYDROGRAPHIC BASIN OF THE BRAZILIAN SAVANNAH (CERRADO BIOME): THE ARAGUAIA RIVER

EVIDÊNCIA DE REDUÇÃO DA SUPERFÍCIE DE ÁGUA E DA VAZÃO HÍDRICA NA PRINCIPAL BACIA HIDROGRÁFICA DA SAVANA BRASILEIRA (BIOMA CERRADO): O RIO ARAGUAIA

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Introduction

One of the greatest challenges for the current human population and future generations is to reconcile environmental conservation and maintenance of ecosystem services with their food, water, and energy demands (Whitman, 2019; Yoon, 2021). To meet a portion of this demand, Brazil has become one of the main agricultural producers in the world at the expense of deforesting extensive areas of native vegetation (Coelho et al., 2013; Schneider et al., 2021). In the last four decades, two important Brazilian biomes, the Cerrado and the Amazon, have been experiencing an evident expansion of hydroelectric dams, crop areas, irrigation central pivots, mining, and aquaculture activities, which have induced extensive changes in land cover, hydrology, and environmental conditions, compromising both their biodiversity and ecosystem services (Coe et al., 2017; Strassburg et al., 2017; Latrubesse et al., 2019).

In this context, the Araguaia River hydrographic basin – one of the main watercourses in the Brazilian territory – has become a region of extreme importance for the development of the country's economy, through a strengthening perspective for the coming years, in face of global demands to produce commodities (Bayer et al., 2020). The Araguaia River is the largest river in the Brazil wet-dry tropics (Latrubesse et al., 2009), covering the Cerrado and Amazon biomes, and whose ichthyofauna is one of the most species-rich of all water bodies in the Cerrado biome (Latrubesse et al., 2019). It is, also, one of the few large free-flowing rivers in South America. Besides, the Araguaia River watershed is home to the largest river island of theworld – Bananal Island – which is about 20.000 km^2 and supports the largest seasonal wetlands in the Cerrado biome. The exploitation of this basin goes beyond agricultural activities, as hydroelectric dams are planned in its southern portion (Latrubesse et al., 2019).

Deforestation in the Araguaia River basin has increased significantly over the years. In the late 1980s, the total area deforested was approximately 423.7 thousand hectares. In 2019, this number exceeded 9.5 million hectares (MapBiomas, 2022). In 1985, anthropic land use corresponded to 26.65% of the total area. In 2021, this number exceeded 51%, being largely used for pastures and soybean crops (MapBiomas, 2022). This major change in land use has reduced riparian forests (Swanson & Bohlman, 2021) and provided a greater role for erosion processes, in which sediment transport and deposition in watersheds can be visibly altered by anthropogenic activities such as deforestation, intensive agriculture, overgrazing, and forest fires (Zema et al., 2022).

Thus, given the inextricable interconnection between land use and water resources (Weatherhead & Howden, 2009), various impacts on the Araguaia River watershed can be predicted and assessed. Intensification of land use can lead to large soil losses through erosion (Zema et al., 2022), which are carried to water bodies by runoff (Chen et al., 2022), accelerating the process of channel siltation, thus altering the hydrological dynamics of rivers (Nearing et al., 1999; Coe et al., 2009). Increased siltation is related to decreasing water surface area (Brown et al., 2012; Sugianto et al., 2022) and decreasing water flow velocity

(Bukaveckas, 2007). The carried materials, mainly clays, make it difficult for the water to infiltrate into the water table of the channel, thus the flow rate tries to decrease (Bara et al., 2014). Nutrients carried from agricultural soils into surface and groundwater can affect human and aquatic organisms that depend on water for consumption and habitat (Easton & Petrovic, 2004). The uses of surface and groundwater for irrigation are factors that relate to the reduction of water flows (Latrubesse et al., 2019), as well as the use of water to produce agricultural commodities (Vos & Hinojosa, 2016).

In a context of global environmental changes, trends of vegetation reductions, and modifications in land use and the water cycle, particularly in parts of the Southern Hemisphere (Le & Bae, 2022; Le, 2023), and given the economic, environmental, and social importance of the Araguaia River basin, it is necessary to understand the temporal dynamics of anthropic impacts in this region to provide insights that contribute both to public management and the sustainable use of its water resources. In this context, we aimed to assess the historical variations in water surface area within the Araguaia River basin, as well as the water flow from monitoring stations located along the Araguaia River channel and its tributaries. With the observed increase in deforestation over the years, our expectations are (i) that both water surface and water flow are experiencing a substantial decline; (ii) the reduction in water flow is even more pronounced during the drier months of the year (low water period of the flood pulse); and (iii) the tributaries that supply the Araguaia River undergo an even more pronounced process of water flow reduction compared to the main river.

Materials and Methods

Study area

The Araguaia River is approximately 2,100 km long **(Figure 1)** and its watershed drains an area of about 375,000 km² (Latrubesse et al., 2009). Its course can be divided into three portions: Upper, Middle, and Lower Araguaia. The Upper Araguaia extends over 450 km, draining areas of Precambrian, Paleozoic, and Mesozoic crystalline rocks from the Paraná Sedimentary Basin (Latrubesse & Stevaux, 2002). The middle course of the Araguaia comprises 1,160 km in length and is characterized by the formation of Cenozoic, Tertiary, and Quaternary sediments (Latrubesse & Stevaux, 2002). In addition, the middle river course is home to the largest river island in the world, the Bananal island (Aquino et al., 2009). The lower river course is 500 km long, does not develop alluvial plains, and drains crystalline rocks of the Precambrian (Latrubesse & Stevaux, 2002).

According to the Köppen-Geiger (1948) classification system, the predominant climate in this region is of the Aw type, characterized by alternating periods of rain during the summer and drought during the winter, with average monthly temperatures that vary between 24° C and 26° C. The rains occur between October and April, while the drought extends from May to September (Latrubesse and Stevaux, 2002). Precipitation levels increase gradually from south to north, ranging from 1500 to 2200 mm/year (Latrubesse et al., 2009). The tributaries in upper watershed section contribute with 10.4% of the water discharge, while the middle section is responsible for 77.54%, and the lower section for 12.06% (Aquino et al., 2009).

Over the last decades, land use and land cover have undergone considerable changes in the region. In 1985, forest cover accounted for 59.04% of the total hydrographic basin area. In 2021 this area was reduced to 36.48% (MapBiomas, 2022). On the other hand, in this same period there was a significant increase in deforestation and the expansion of extensive areas for pasture and agriculture. In 1985, the area corresponding to pasture and agriculture comprised approximately 10 million hectares. In 2021, this area practically doubled in size, reaching almost 20 million hectares (MapBiomas, 2022).

Data base

We obtained data on cumulative annual deforestation, cumulative annual agricultural and livestock farming area, cumulative annual irrigated area with central pivots, and the annual variation in water surface area (which serves as our primary dependent variable). All datasets were measured in hectares and covered the period between 1987 and 2019, and was obtained from the MapBiomas project (https://mapbiomas.org/). MapBiomas consists of a collaborative research network, which produces annual mappings of land cover and land use, water surface monitoring and fires, based on monthly data, in Brazil since 1985, whose data are public, open, and free (Souza, 2020). For the information on the annual variation of water surface area, five regional cutouts of the Araguaia River basin, made available by the MapBiomas Project, were used: (1) Upper Araguaia and Rio Claro, (2) Upstream of Bananal Island, (3) Stretch from Bananal Island, (4) Downstream from Bananal Island, and (5) Lower Araguaia **(Figure 1)**. MapBiomas mapped the water surface in Brazil using the Landsat satellite at a spatial resolution of 30 meters.

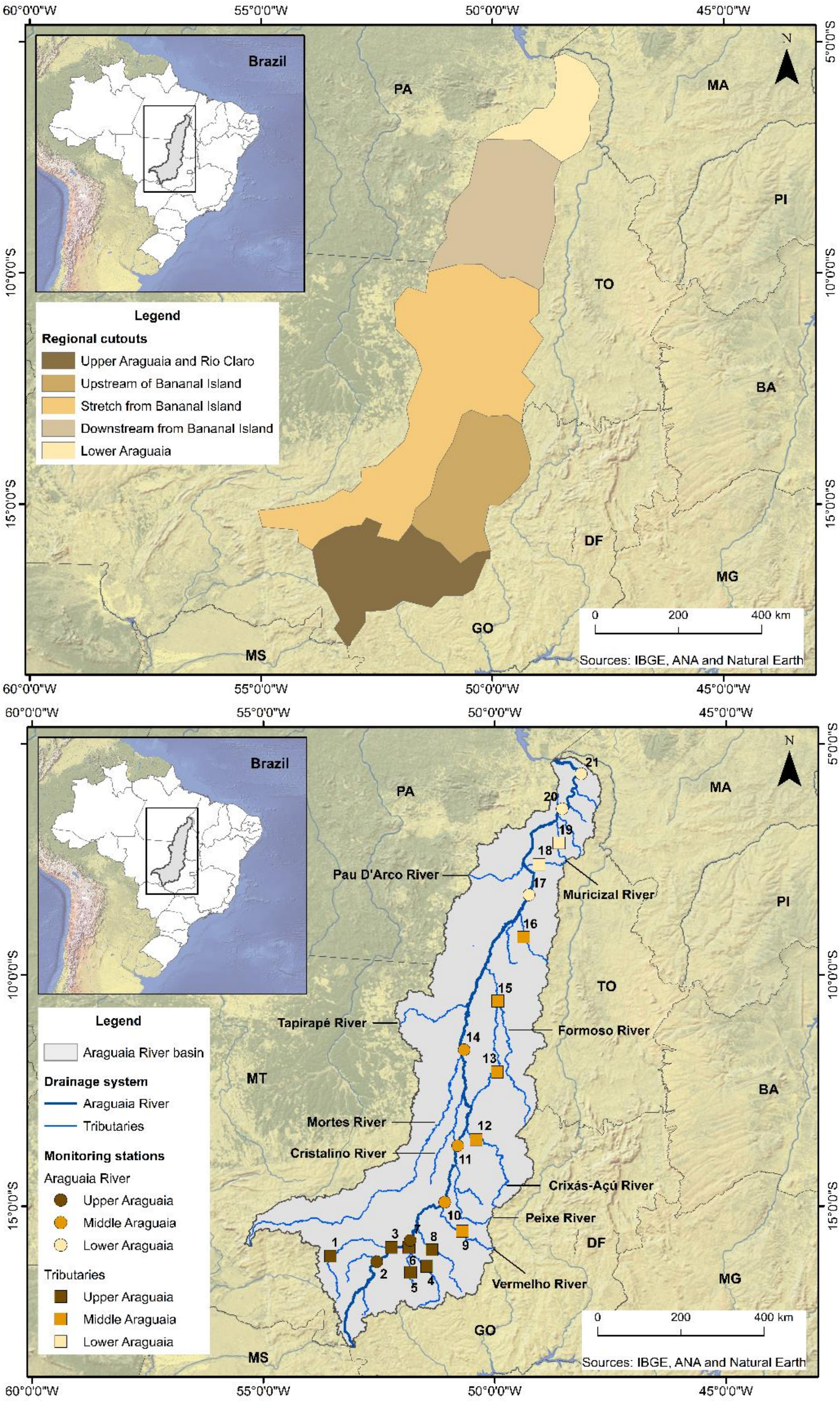


Figure 1. Location of five regional cutouts of the Araguaia River basin (drainage areas highlighted in the top map) and 21 monitoring stations in the Araguaia River hydrographic basin in Upper, Middle, and Lower Araguaia regions (bottom map).

We also used historical series of water flow (which serves as our secondary dependent variable), measured in cubic meters per second (m^3/s), spanning the period from 1980 and 2020. The data was obtained from 21 monitoring stations situated within the Araguaia River hydrographic basin **(Figure 1)**. This information is publicly accessible through the HidroWeb Portal (https://www.snirh.gov.br/hidroweb/), which is an integral tool of Brazil's National Information System on Water Resources (SNIRH) administered by the National Water Agency (ANA – Brazil). ANA coordinates the Brazilian National Hydrometeorological Network (RHN), which comprises over 4,600 monitoring sites responsible for gathering data on various parameters such as water levels, flows, water quality, and sediment transport across the national water network. Through ANA's HidroWeb Portal, we obtained data on monthly total precipitation (mm) from January 1980 to December 2020 for monitoring stations 10, 14, and 21 **(Figure 1)**.

Statistical analysis

To investigate the potential decrease in water surface and water flow over time (**hypothesis 1**), we conducted linear regression analyzes. This analytical approach assesses the predictive capability of a quantitative variable X (predictor or independent variable) on a single quantitative variable Y (response or dependent variable), assuming an approximately linear relationship between the two variables. This method was chosen due to its simplicity and ease of interpretation, making it accessible not only to the academic audience but also to managers and policymakers. However, it is crucial to acknowledge that, in regression analyses, identified relationships between variables X and Y may not always imply causal connections and may simply indicate spurious correlations. While we recognize the merits of more robust analyses, linear regression proved to be a more suitable option for facilitating understanding among diverse audiences without compromising the robustness of our findings.

Regarding the temporal dynamics of the water surface, we examined the total annual water surface area in five sections (drainage areas as highlighted in Figure 1) of the Araguaia River basin as the explained variable (Upper Araguaia and Rio Claro, Upstream of Bananal Island, Section of Bananal Island, Downstream of Bananal Island, and Lower Araguaia), with the period between 1987 and 2019 as the predictor variable. Subsequently, we performed separate linear regressions analyzes to explore the relationship between the temporal dynamics of the water surface in these five sections of the Araguaia River basin (response variable) and three predictor variables measured in hectares: (i) cumulative annual deforestation area, ii) cumulative annual agricultural and livestock farming area, and (iii) cumulative annual irrigated area with central pivots. All four datasets covered the period from 1987 to 2019.

To examine the temporal dynamics of water flow between 1980 and 2020, we employed two strategies. The first approach involved assessing the temporal dynamics of average annual flow (measured in m^3/s) separately for each of the 21 monitoring stations, textually highlighting the main discharge sites within each subdivision of the basin, namely: the Upper (monitoring stations 7 or 10), Middle (monitoring station number 17), and Lower Araguaia (monitoring stations 20 or 21). Therefore, the observations made at these specific locations become even more relevant as downstream water flow can exhibit an accumulative pattern influenced by upstream regions. The second strategy also focused on evaluating the temporal dynamics of the average annual flow but summarizing the response variable (water flow) through mean values across four groups of the 21 monitoring stations: the entire Araguaia River hydrographic basin (21 monitoring stations) and its subdivisions—Upper Araguaia (eight monitoring stations), Middle Araguaia (eight monitoring stations), and Lower Araguaia (five monitoring stations) **(Figure 1)**. The predictor variable considered in all these analyses was the period between 1980 and 2020.

We also used linear regression analyses to assess whether the reduction in water flow is even more pronounced in the drier months of the year (**hypothesis 2**). Thus, we calculated the average flows for each of the 12 months of the year, also considering the information obtained from all 21 monitoring stations, between 1980 and 2020 (response variable), with time as the predictor variable. Subsequently, we standardized the estimated flow loss of the month over the years (angular coefficient of the regression, *b*) by the average flow rate of the same month over the same period. These standardized flow reduction values were used to compare the flow losses between the phases of the flood pulse: flooding (November, December, and January), high water (February, March, and April), flushing (May, June, and July), and low water (August, September, and October), using analysis of variance (ANOVA) and Tukey test for all possible pairwise comparisons.

To assess whether the Araguaia River tributaries undergo an even more intense process of reduction in water flow than the main river (**hypothesis 3**), we carried out regression analyses with the average annual flows for each of the 21 monitoring stations as a response variable, and the years from 1980 to 2020 as the predictor variable. Subsequently, the estimated annual flow loss over the years by monitoring station (angular coefficient of the regression, *b*) was standardized by the average annual flow over the same period (non-significant angular coefficients were assumed to be zero). We used these standardized annual flow reduction values to compare flow losses between tributaries and the main river (Araguaia River channel) using a Student's t-test for independent samples.

Lastly, to evaluate whether the total monthly precipitation varied in the Araguaia River hydrographic basin, we conducted regression analyses using the average annual flows from three monitoring stations.

Validation

The results of the linear regression models were evaluated by the parameters *b*, *t*, *P*, and R^2. *b* is the angular coefficient (slope) of the linear regression, which indicates the effect of the predictor variable (independent) on the response variable (dependent). The greater the value of *b* (regardless of the sign), the greater the effect of the predictor variable on the response variable. The *t*-value is the Student's t-test statistic, used to test whether the *b*-values are statistically different from zero. *P* (*p*-value) is the probability of rejecting the null hypothesis (i.e., the relation between the variables equals zero). *P* values greater than 0.05 indicate that the model was not significant. The smaller the *p*-value, the greater the significance of the linear regression model. R^2 is the linear regression determination coefficient, measuring how much of the response variable (dependent) variance is explained by the predictor variable (independent). The higher the value of R^2, the greater the predictive power of the predictor variable over the response variable (Legendre and Legendre, 2012; Zar, 2010).

Results

Regarding the temporal dynamics of water surface area in the Araguaia River basin over the last decades (1987 to 2019), all five watershed spatial sections showed significant reductions (**Figure 2**). Moreover, these reductions in water surface area in each spatial section were strongly influenced by the cumulative deforestation area (ha), with coefficients of determination (R^2) ranging from 43.5% to 89.8%. Similarly, cumulative agriculture and livestock farming land (ha) accounted for the variations in water surface area, showing coefficients of determination (R^2) ranging from 41.4% to 89.5%. Additionally, the cumulative areas irrigated with central pivots (ha) exhibited a notable impact on water surface area, with coefficients of determination (R^2) ranging from 67% to 86.6% (**Figure 3** and **Table 1**).

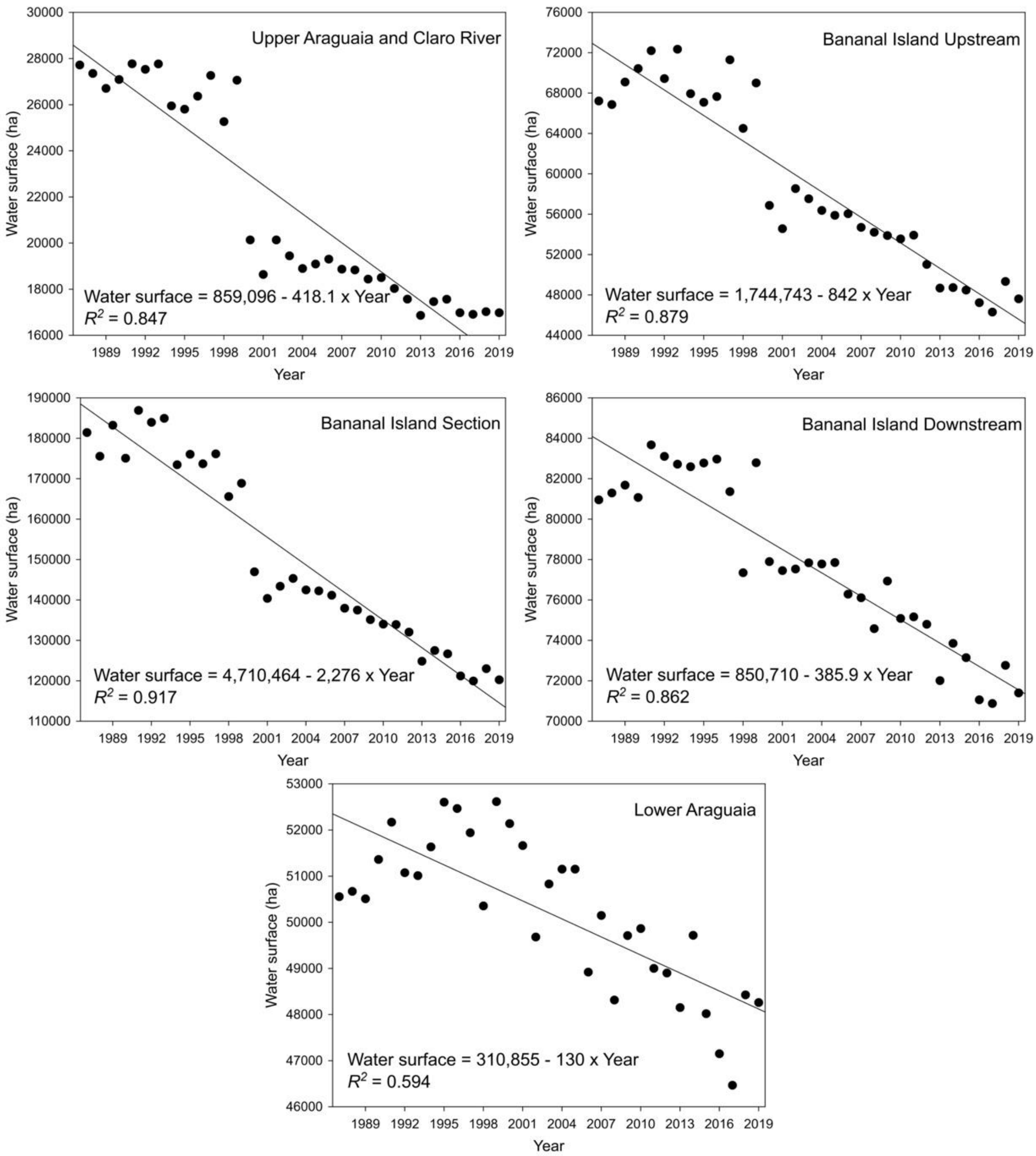


Figure 2. Graphical results of the regression analysis evaluating the temporal dynamics of water surface area (ha) in five spatial sections of the Araguaia River basin. All datasets are between 1987 and 2019.

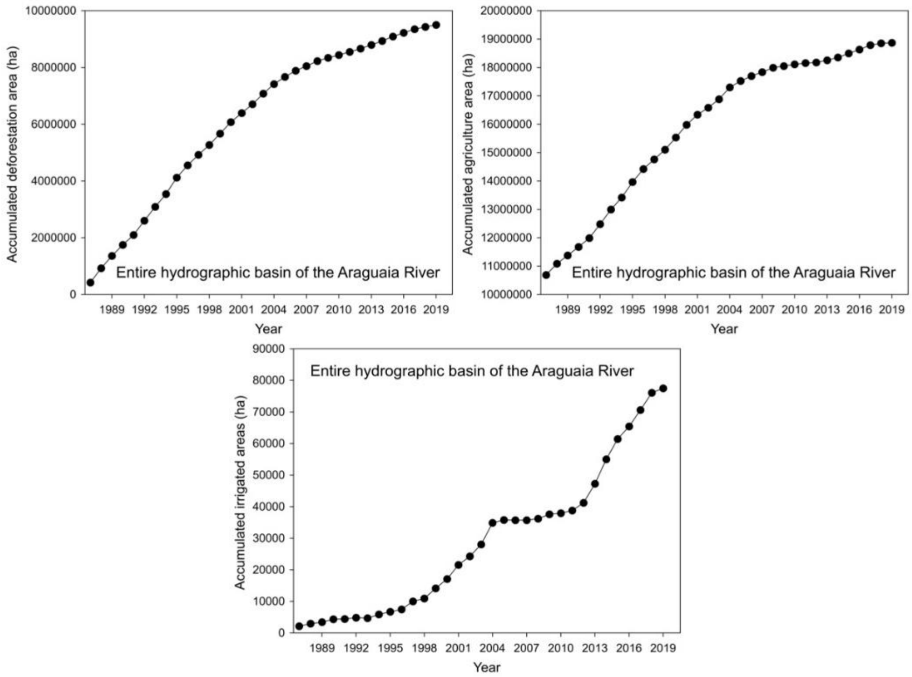


Figure 3. The cumulative deforestation area (ha), the cumulative agricultural and livestock farming area (ha), and the cumulative irrigated area with central pivots for the entire Araguaia River basin. All datasets are between 1987 and 2019.

Table 1. Results of the regression analyses evaluating the temporal dynamics of water surface area (ha) in five spatial sections of the Araguaia River basin, in relation to accumulated deforestation area (ha), accumulated annual agricultural and livestock farming area (ha), and accumulated annual irrigated area with central pivots (ha) between 1987 and 2019 for the five regional cutouts of the Araguaia River basin. ***b***: angular coefficient (slope) of the equation of the line. ***t***: Student's t test statistic, used to test whether ***b*** values are statistically different from zero. ***P*** (*p*-value): significance of linear regression models. ***R²***: coefficient of determination of linear regression models.

Hydrographic Basin	**Water Surface x Accumulated Deforestation**	**Water Surface x Accumulated Agriculture and Livestock Farming Land**	**Water Surface x Accumulated areas irrigated with central pivots**

	b	*t*	*P*	R^2	*b*	*t*	*P*	R^2	*b*	*t*	*P*	R^2
Upper Araguaia and Claro River	-0.0014	-14.5	< 0.001	0.871	-0.0015	-14.7	< 0.001	0.874	-0.1659	-10.4	< 0.001	0.778
Bananal Island Upstream	-0.0027	-12.2	< 0.001	0.827	-0.0029	-11.9	< 0.001	0.821	-0.3444	-13.5	< 0.001	0.854
Bananal Island Section	-0.0076	-16.6	< 0.001	0.898	-0.0081	-16.3	< 0.001	0.895	-0.9153	-13.8	< 0.001	0.860
Bananal Island Downstream	-0.0012	-9.9	< 0.001	0.760	-0.0013	-9.52	< 0.001	0.745	-0.1607	-14.2	< 0.001	0.866
Lower Araguaia	-0.0003	-4.9	< 0.001	0.435	-0.0003	-4.68	< 0.001	0.414	-0.0574	-7.9	< 0.001	0.670

The water flow data exhibited similar patterns of temporal dynamics as observed in the water surface area data. Among the 21 monitoring stations assessed, 18 showed reductions in water flow between 1980 and 2020 (**Table 2**). It is worth highlighting that all the monitoring stations that receive discharge from other points, located downstream in each section of the watershed, whether considering the entire Araguaia River hydrographic basin (monitoring station number 21) or its subdivisions Upper (monitoring stations 7 or 10), Middle (monitoring station number 17) and Lower Araguaia (monitoring stations 20 or 21), indicated temporal decreases in water flow.

Table 2. Water flow (minimum, maximum, and average) between 1980 and 2020 and results of the regression analysis evaluating the temporal dynamics of the average annual flow (m^3/s), by monitoring station. TR = monitoring station located in tributary; AR = monitoring station located in the Araguaia River channel. ***b***: angular coefficient (slope) of the equation of the line. ***t***: Student's t test statistic, used to test whether ***b*** values are statistically different from

zero. ***P*** (*p*-value): significance of linear regression models. ***R^2***: coefficient of determination of linear regression models.

Stations	***b***	***t***	***P***	***R^2***	**Water Flow (m^3/s)**			**Environment**
					Minimum	**Maximum**	**Average**	
1	-1.59	-6.6	< 0.001	0.526	47	176	104	TR
2	-4.56	-4.9	< 0.001	0.380	139	498	339	AR
3	-5.42	-3.8	< 0.001	0.275	443	906	646	TR
4	-1.48	-3.6	< 0.001	0.248	53	206	112	TR
5	-0.41	-3.8	< 0.001	0.270	10	48	26	TR
6	-3.08	-4.0	< 0.001	0.289	79	408	198	TR
7	-8.57	-3.9	< 0.001	0.284	502	1292	853	AR
8	-1.41	-2.9	0.006	0.176	69	259	132	TR
9	-1.55	-4.9	< 0.001	0.382	39	152	76	TR
10	-12.39	-4.1	< 0.001	0.306	813	1864	1300	AR
11	-14.64	-4.3	< 0.001	0.321	810	2042	1353	AR
12	-0.35	-0.5	0.596	0.007	109	303	191	TR
13	-3.85	-4.9	< 0.001	0.426	68	293	176	TR
14	-18.67	-2.6	0.015	0.144	1691	3944	2657	AR
15	-11.98	-5.7	< 0.001	0.455	180	1010	540	TR
16	-0.14	-3.1	0.003	0.203	16	32	24	TR
17	-47.59	-3.7	< 0.001	0.260	2613	7649	4817	AR

Stations	***b***	***t***	***P***	**R^2**	**Water Flow (m^3/s)**			**Environment**
					Minimum	**Maximum**	**Average**	
18	-0.18	-1.8	0.080	0.093	15	40	27	TR
19	-0.14	-1.3	0.212	0.040	13	58	32	TR
20	-49.02	-3.6	0.001	0.245	3012	8517	5532	AR
21	-42.27	-2.8	0.008	0.169	3016	8692	5897	AR

Similar results were also found when considering the average values of water flow in the four groupings of the 21 monitoring stations, indicating a reduction over the last decades (1980 to 2020). The angular coefficients of the regression analyses were significant for the entire Araguaia River basin (t = -4.8; P < 0.001), the Upper Araguaia region (t = -4.5; P < 0.001), the Middle Araguaia region (t = -4.8; P < 0.001), and the Lower Araguaia region (t = -4.7; P < 0.001) (**Figure 4**).

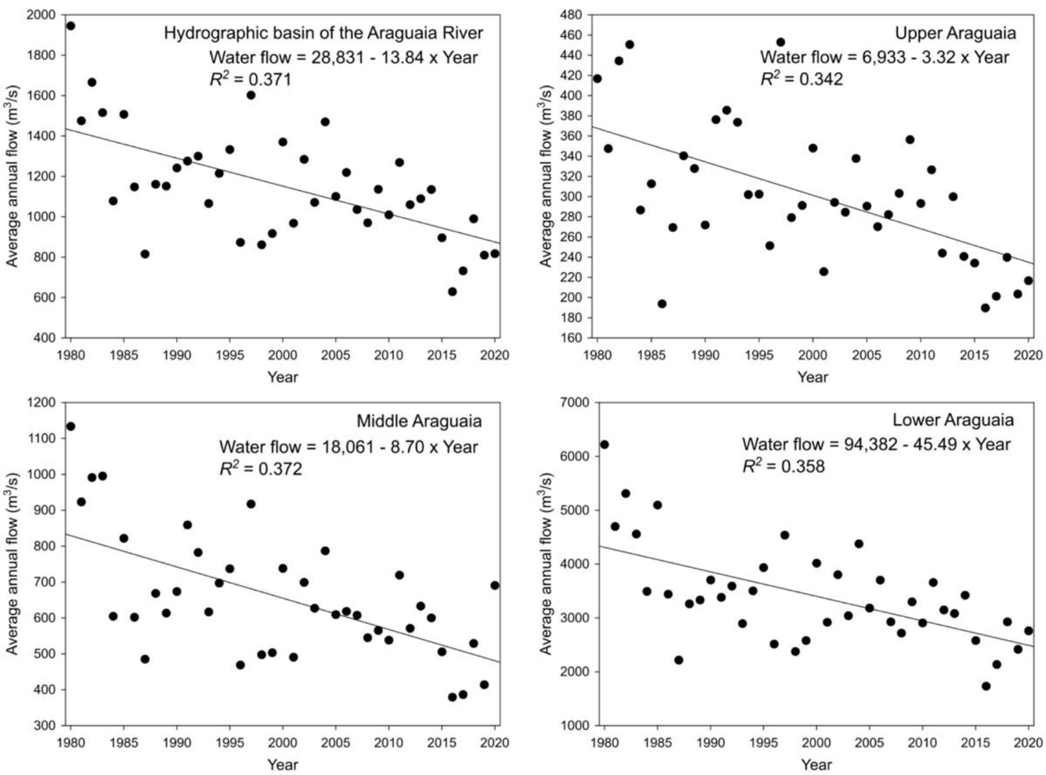
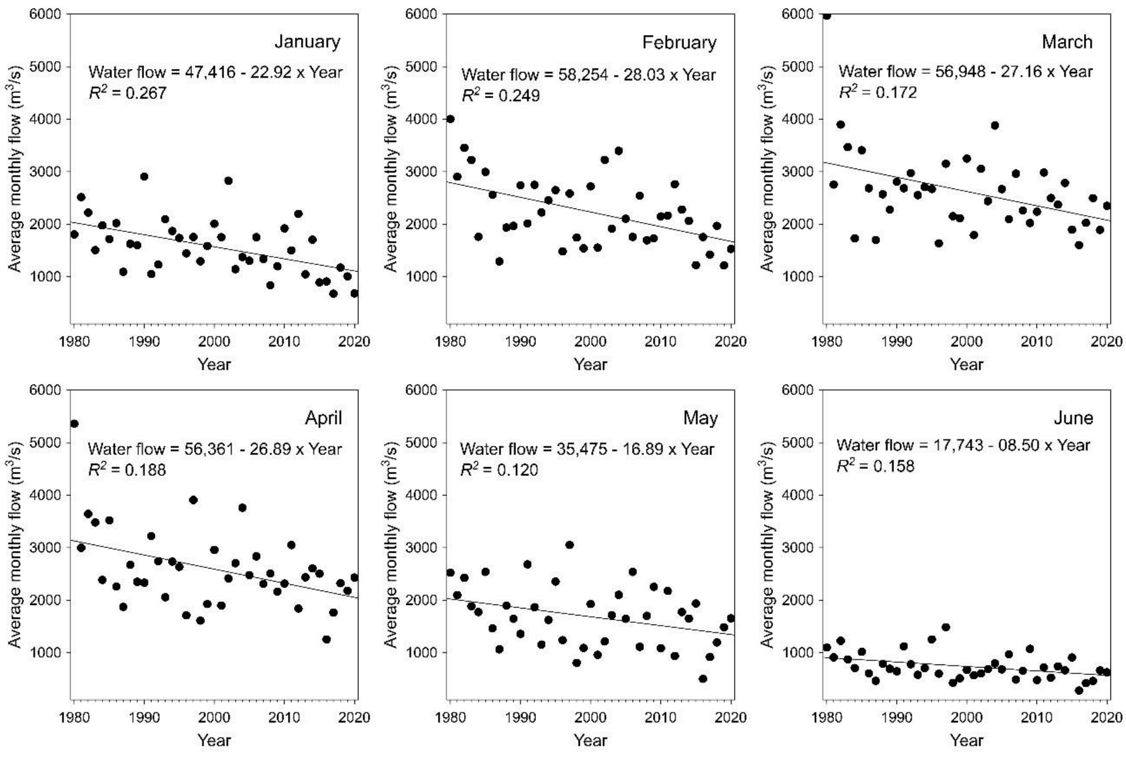


Figure 4. Graphical results of the regression analysis evaluating the temporal dynamics of the average annual flow (m^3/s) in the entire Araguaia River basin and its subdivisions (Upper, Middle, and Lower Araguaia) between 1980 and 2020.



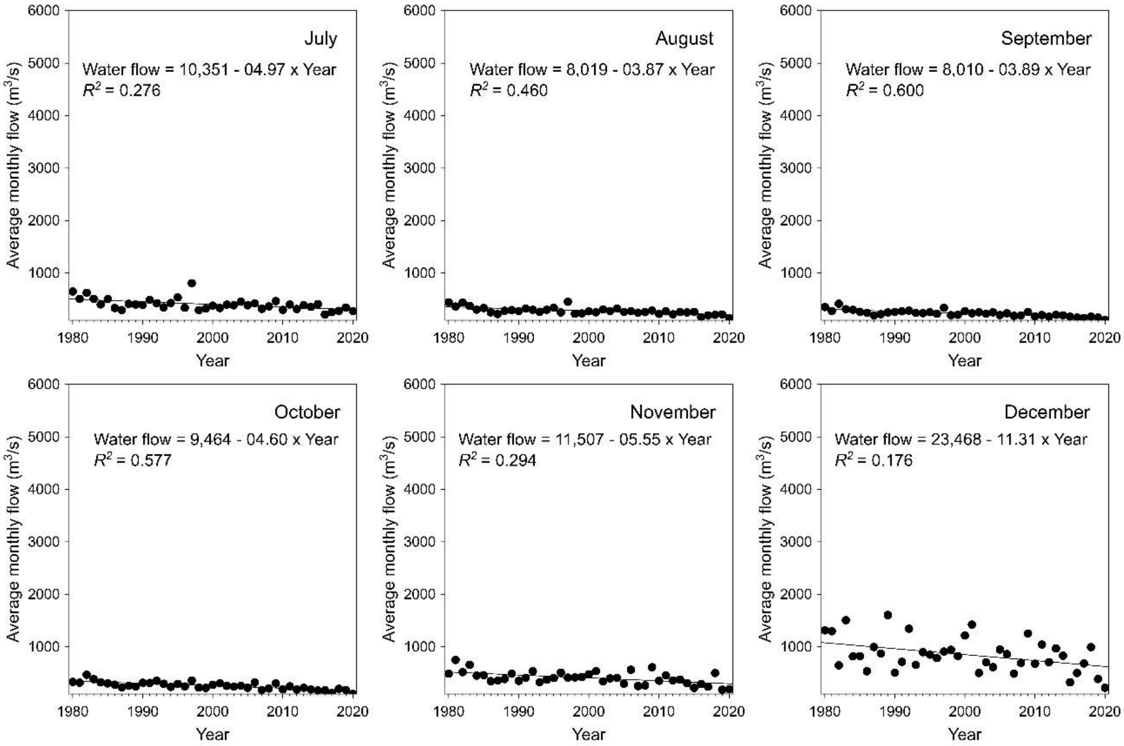


Figure 5. Results of the regression analysis evaluating the temporal dynamics of the average monthly flow (m^3/s), by months, in the entire Araguaia River basin, between 1980 and 2020.

The water flow in the Araguaia River basin has also reduced over the years (1980 to 2020) in all months, both in the low water phase (August, September, and October) and in the high water phase of the flood pulse (February, March, and April) (**Figure 5** and **Table 3**).

Table 3. Water flow (minimum, maximum, and average) throughout the Araguaia River basin, by month, between 1980 and 2020, and results of the regression analysis evaluating the temporal dynamics of the average monthly flow (m^3/s). ***b***: angular coefficient (slope) of the equation of the line. ***t***: Student's t test statistic, used to test whether ***b*** values are statistically different from zero. ***P*** (*p*-value): significance of linear regression models. ***R²***: coefficient of determination of linear regression models.

Months	***b***	***t***	***P***	***R²***	**Water Flow (m^3/s)**	**Flood Pulse Phases**

					Minimum	Maximum	Average	
January	-22.92	-3.8	< 0.001	0.267	678	2909	1570	Flooding
February	-28.03	-3.6	< 0.001	0.250	1217	4006	2232	High water
March	-27.16	-2.9	0.007	0.173	1605	5971	2623	High water
April	-26.89	-3.0	0.004	0.188	1254	5363	2591	High water
May	-16.89	-2.3	0.026	0.121	506	3054	1685	Flushing
June	-8.50	-2.7	0.009	0.159	283	1488	738	Flushing
July	-4.97	-3.9	< 0.001	0.276	210	809	403	Flushing
August	-3.87	-5.8	< 0.001	0.460	135	454	279	Low water
September	-3.89	-7.7	< 0.001	0.600	107	415	232	Low water
October	-4.60	-7.3	< 0.001	0.577	104	468	258	Low water
November	-5.55	-4.0	< 0.001	0.294	186	750	408	Flooding
December	-11.31	-2.9	0.006	0.176	220	1606	852	Flooding

The ANOVA results indicated a higher relative reduction in water flow during the low water phase of the flood pulse compared to the high water and flushing phases (**Figure 6**). However, the results of the independent samples t-test indicated no significant difference in the relative loss of water flow between the tributaries and the main river (t = 0.16; *g.l.* = 19; P = 0.873).

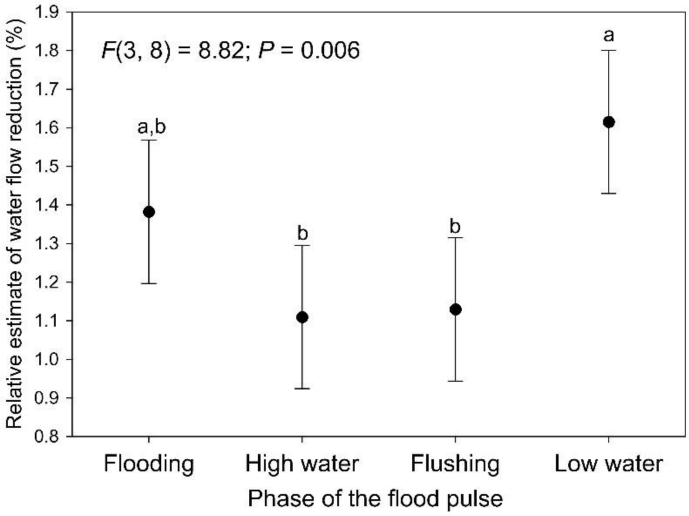


Figure 6. ANOVA result containing the values, in percent, of the estimated relative reduction in water flow over the years 1980-2020 by phases of the flood pulse (mean, minimum, and maximum values). Treatments with different letters showed significant differences.

Finally, the precipitation data do not indicate temporal reductions in the volume of rainfall between January 1980 and December at monitoring stations 21 (t = 0.17; P = 0.868), 14 (t = -1.25; P = 0.211), and 10 (t = -1.48; P = 0.140) (**Figure 7**).

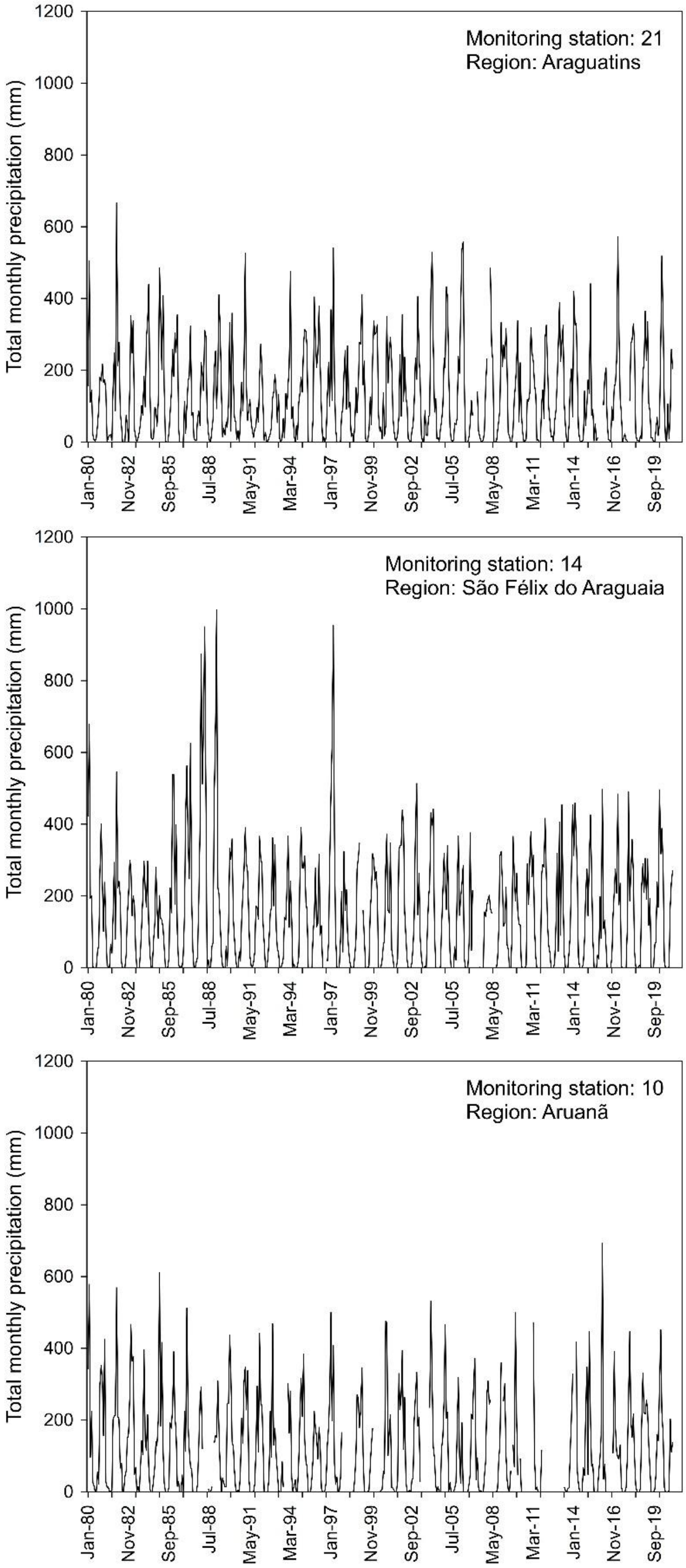


Figure 7. Total monthly precipitation (mm), obtained between January 1980 and December 2020, at three monitoring stations.

Discussion

Our results indicate a continuous process of reduction in flooded areas (between 1987 and 2019) and water flow (between 1980 and 2020) in the Araguaia River basin over the last decades, despite no significant changes in total monthly precipitation during the same period. These findings support our first hypothesis and demonstrate that this process has affected the entire watershed, including its spatial divisions (Upper, Middle, and Lower Araguaia) and sections (Upper Araguaia and Claro River, Bananal Island upstream, Bananal Island stretch, Bananal Island downstream, and Lower Araguaia). Additionally, our results confirm the second hypothesis, showing that the reduction in water flow is consistent throughout all months of the year, regardless of seasonal periods (flooding, high water, flushing, and low water), with a particularly significant decrease during the low water period. This period coincides with the increased demand for water due to the intense agricultural production in the region. However, contrary to our third hypothesis, the results indicate that the reduction in water flow over the years has occurred similarly throughout the watershed, without significant differences between the tributaries and the main river.

The Araguaia River basin has undergone significant anthropogenic pressure and land use changes in recent decades (MapBiomas, 2022). This is primarily driven by the expansion of agribusiness to meet the growing demand for beef, soy, and other commodities, resulting in increased water extraction from the watershed to support these activities (Latrubesse et al., 2019; Pelicice et al., 2021). Consequently, both water surface area and water flow in the Araguaia River basin have experienced significant reductions over the years, which aligns with findings from previous studies conducted in the basin (Rosin et al., 2015; Lima et al., 2022).

Analysis of water surface mapping reveals a decrease in water levels across all five spatial sections of the hydrographic basin, with the most pronounced reduction observed in the Bananal Island section, located within the Middle Araguaia. This section encompasses a vast drainage area (Latrubesse & Stevaux, 2002) and contributes nearly 80% of the basin's total water flow (Aquino et al., 2009). Furthermore, in almost all the monitoring station (18 out of 21) and within all the studied spatial regions of the basin (Upper, Middle, and Lower Araguaia), characterized by distinct hydrological and geomorphological features (Aquino et al., 2005), significant reductions in flows have been observed. These reductions demonstrate a decreasing trend in water flows over time, with more substantial reductions occurring as we move downstream from the Upper to the Lower Araguaia.

Siltation is an important factor that can result in decreased water flow in water bodies (Chen et al., 2022; Zema et al., 2022) and reduced water surface area in the watershed (Nearing et al., 1999; Coe et al., 2009; Brown et al., 2012; Sugianto et al., 2022). The increase in sedimentation of materials carried by surface runoff promotes an elevation of the water bodies channel, which favors a decrease in water current velocity (Bukaveckas, 2007; Sugianto et al., 2022). Even though there are few studies, they provide strong evidence of a significant increase in the sediment load in the course of the Araguaia River, resulting in short-term geomorphological responses associated with deforestation (Latrubesse et al., 2009; Suizu et al., 2022). For example, Latrubesse et al. (2009) estimated a 31% increase in bed load transport in a stretch of the Middle Araguaia during the 1990s.

In addition to deforestation and inadequate land management and use in urban and rural areas, another important factor possibly associated with the decrease in the flow and water surface is the withdrawal of water from water bodies for the irrigation of agricultural production, mainly to produce commodities (Vos and Hinojosa, 2016), a practice that has increased in the Araguaia River basin and in other Cerrado areas (Latrubesse et al., 2019). For example, there is an estimated increase of around 1700% of soybean planting areas, between 2008 and 2016, in the Bananal Island region (Moreira et al., 2019).

Other Brazilian River basins have also been undergoing similar processes of water resources loss (Getirana, 2016; Silva et al., 2021). For example, the São Francisco River basin, located in the northeastern Brazil and has a drainage area of approximately 630,00 km^2, has also been losing water flow over the years (Maneta et al., 2009; Paredes-Trejo et al., 2021). The main cause may be associated with the withdrawal of groundwater and surface water to meet the increased demands of various socioeconomic sectors (Maneta et al., 2009; Paredes-Trejo et al., 2021). Considering a larger spatial scale, there are indications that the effects of climate change may also collaborate with water reduction. Climate change is making the Cerrado Biome (Brazilian Savannah) warmer and drier. Between 1961 and 2019, the Cerrado Biome showed increases in maximum and minimum temperatures between 2.2-4.0°C and 2.4-2.8°C, respectively, and a reduction in relative humidity by about 15% (Hofmann et al., 2021).

Our findings suggest that the cumulative effect of deforestation, agriculture and livestock farming expansion, and irrigated activities using central pivots likely have a relationship with the reduction of water surface areas in the Araguaia watershed and the decrease in water flow in the Araguaia River and its tributaries. Deforestation leads to hydrological and geomorphological changes, such as increased runoff, river discharge, erosion, and sediment transport, which ultimately contribute to siltation and the reduction of water surface areas (Coe et al., 2011).

The decrease in water surface areas can be attributed to cumulative changes in various aspects, including the expansion of drainage areas, the proliferations of islands, the formation of side bars and mid-channel bars within the river system (Latrubesse et al., 2009). Furthermore, changes in water quality and characteristics in response to land use changes have been observed in various river basins across Brazil (Silva et al., 2021; Godoy & Lacerda, 2014; Spera et al., 2016; Sousa et al., 2021; Ferraz et al., 2022) and globally (Hurkmans et al., 2009; Booiji et al., 2019).

These findings highlight the interconnectedness between land use practices, hydrological processes, and the overall health of river ecosystems. The cumulative effects of deforestation, agriculture, and livestock farming, and irrigation activities can lead to substantial alterations in the water balance, morphology, and functioning of river systems, ultimately affecting water surface areas and water flow within the Araguaia River watershed.

Conclusion

Based on the interpretation of the results presented in this study, we objectively conclude that there is evidence suggesting a continuous process of water reductions in the Araguaia River, the main hydrographic basin of the Brazilian savannah. To demonstrate and evaluate the temporal trends of decreasing water surface area (from 1987 to 2019) and water flow (from 1980 to 2020), we employed simple graphical formats and hypothesis tests (linear regression). This approach not only enhances understanding of these temporal patterns within the national and international academic community but also makes the results more accessible to managers and policymakers. Moreover, it would be valuable to compare the results obtained in this study with those generated in future research where our hypotheses are also assessed using hydrological modeling methodologies. The decrease in flow and surface water in the Araguaia River basin may be associated with deforestation, the expansion of agricultural and livestock farming activities, and the establishment of irrigated areas through central. Consequently, considering the expected factors of an increasing world population, rising demand for food production, and advancing climate change, it is anticipated that this potential scenario of water reduction in the Araguaia River basin may worsen.

Finally, our study highlights two critical results that should be considered by governmental environmental control and monitoring agencies and can be valuable for public policy formulation. Firstly, both the tributaries and the main channel of the Araguaia River are experiencing similar reductions in water flow. Therefore, management and environmental conservation plans for the watershed should encompass not only the main river but also its tributaries. Secondly, although the reduction in water flow has increased throughout the year, the higher demand for irrigation in agricultural crops precisely in the drier months may have resulted in a greater relative water losses during the dry season. Therefore, it is necessary to ensure the ecological flow of the Araguaia River basin, enabling the residual water volume in the bed of the Araguaia River, in the bed of the tributaries, and in the hydrographic basin wetlands can minimally meet the demands of the aquatic ecosystem, and ensure the preservation of its flora and fauna.

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