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Temporal geomorphic modifications and climate change impacts on the lower course of the São Francisco River, Brazil

Maria Fernanda Oliveira Torres [a], Robério Anastácio Ferreira [b], Anderson Nascimento do Vasco [c], Renata Silva-Mann [d,*]

[a] Agriculture and Biodiversity Graduate Program, Federal University of Sergipe, São Cristóvão, Sergipe, Brazil
[b] Department of Forest Science, Federal University of Sergipe, São Cristóvão, Sergipe, Brazil
[c] Department of Agroecology, Federal Institute of Sergipe, São Cristóvão, Sergipe, Brazil
[d] Department of Agronomic Engineering, Federal University of Sergipe, São Cristóvão, Sergipe, Brazil

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ABSTRACT

Monitoring human intervention and understanding temporal geomorphic modifications in hydrographic basins require continuous data collection. This study aimed to investigate the geomorphological and hydroclimatic changes in the lower course of the São Francisco River, Brazil from 1986 to 2020, utilizing Cloud-based satellite image processing techniques for mapping and identifying flooded areas through the calculation of Modified Normalized Difference Water Index (MNDWI). The findings reveal a significant increase in sedimented areas within the river channel, occupying 10.64 km^2 in 2020, which represents a 22% increment compared to 1986. The river has experienced a territorial reduction of approximately 20%, with decreased Modified Normalized Difference Water Index values indicating shallowing due to possible sediment contributions. Rainfall and flow data exhibited a positive correlation with Modified Normalized Difference Water Index and a negative correlation with sedimentation values, indicating their influence on the river's geomorphology. Furthermore, the Alagoas bank displayed 96 transects, with an average penetration of 86.36 m into the river for each transect, highlighting hydrological and morphological changes. Overall, this study emphasizes the vulnerability of the São Francisco River.

1. Introduction

The assessment of environmental changes and their consequences for both human life and flora has become a matter of significant concern, especially when monitoring anthropic actions that jeopardize sustainability, particularly in underdeveloped countries (Nkhonjera et al., 2021). The São Francisco River, one of Brazil's major hydrographic basins, has consistently attracted attention due to environmental issues, specifically in its lower subunit located in the Northeast region. In this area, environmental and hydrological conditions have undergone changes influenced by human activities and climatic factors (Fernandes et al., 2021). Notably, El Niño has been identified as a significant contributor to prolonged droughts in the region, thereby impacting the river system (Dos Santos et al., 2022).

The São Francisco River plays a vital role in sustaining local communities through agriculture, fishing, and tourism, thus emphasizing its critical importance (Costa et al., 2021). This study examines the challenges faced in monitoring these environmental changes and anthropogenic impacts on the river, highlighting the need for sustainable management practices in the region.

* Corresponding author.
E-mail address: renatamann@academico.ufs.br (R. Silva-Mann).

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The São Francisco River, characterized by its vast size and width, exhibits course variations influenced by the presence of nine hydroelectric power plants that form a cascade system, thereby exerting control over its flow. However, these power plants also give rise to significant environmental impacts, including urban flooding and drastic flow reductions (Rood, 2020). These alterations, in turn, lead to notable changes in the river's geomorphology, fish migration rates, sediment deposition, and silting (Latrubesse, 2008; Silva et al., 2018; Jimenez et al., 2021; Cavalcante et al., 2020). Moreover, the reduction of riparian vegetation exacerbates marginal erosive processes, contributing to high sedimentation levels and further modifying the river channel and its banks (Hubble et al., 2010; Stevaux et al., 2013; Singh et al., 2021). This study provides a comprehensive assessment of the spatial and environmental impacts associated with the presence of hydroelectric power plants on the São Francisco River, shedding light on the need for sustainable management practices in the region.

Rainfall is a critical factor that can have negative implications for agriculture, water recharge, stream flow, and lead to drought, ultimately exacerbating poverty and triggering rural exodus (Malakar et al., 2018; Albert et al., 2021; AghaKouchak et al., 2021). Precipitation plays a vital role in the hydrological process by regulating the volume of water in rivers (Latrubesse et al., 2005; Segadelli et al., 2019; Nkhonjera et al., 2021). In the case of the lower São Francisco River, situated near its mouth, direct impacts such as heightened salinity and reduced flow have been observed (Holanda et al., 2007, 2011). However, our understanding of the changes occurring in the river channel remains limited, highlighting the need for further scientific investigation.

Our study seeks to address the existing gaps in environmental monitoring by examining the geomorphological and hydroclimatic transformations that have occurred in a specific section of the São Francisco River, spanning the states of Alagoas and Sergipe, from 1986 to 2020.

The studied section of the São Francisco River holds significant environmental importance due to various factors. It is characterized by rich biological diversity, with many unique species endemic to the region, crucial for wildlife preservation and ecosystem balance (Soares et al., 2023).

Moreover, the river plays a vital role in supporting local communities, particularly in areas with a low Human Development Index (HDI). It sustains activities like agriculture, fishing, and tourism, extravitism, providing livelihoods for thousands of people (Gomes et al., 2013).

The water resources of the Rio São Francisco are essential for domestic, agricultural, and industrial use, and it also serves as a source of water for hydroelectric power generation along its course (Bettencourt et al., 2022; Figueiredo et al., 2023).

The surrounding region of the river plays a critical role in regulating local and regional climates, influencing factors like temperature, humidity, and precipitation patterns.

Culturally and historically, the "Rio São Francisco" holds deep significance for the Brazilian people, celebrated in songs, legends, and local traditions, often referred to as the 'river of national integration".

However, the river faces significant environmental challenges, including dam construction, deforestation, pollution, and sedimentation, posing threats to the health and sustainability of its ecosystem.

Therefore, the São Francisco holds substantial environmental importance, not only for the communities directly dependent on it but also for the entire ecosystem and associated biodiversity. Consequently, conserving and sustainably managing the river are critically important for the well-being of current and future generations.

Our study aims to address existing gaps in environmental monitoring by examining the geomorphological and hydroclimatic transformations that have occurred in a specific section of the São Francisco River, spanning the states of Alagoas and Sergipe, from 1986 to 2020. To achieve this, we employed geoprocessing techniques, which provide crucial spatial data instrumental in our comprehensive assessment of the environmental impacts associated with the presence of hydroelectric power plants on the São Francisco River. The primary objective of this research is to generate valuable insights that can inform environmental management practices and contribute to the conservation of the river.

2. Material and methods

2.1. Area of study

The study area encompasses Santana do São Francisco, Neópolis, Igreja Nova, and Penedo, located between the states of Sergipe and Alagoas. These locations are approximately 37 km away from the mouth of the São Francisco River (Fig. 1). The dominant vegetation type in this region is the Atlantic Forest, with potential transitional areas of Caatinga or Restinga ecosystems (CBHSF, 2018).

The study region in Northeast Brazil has a tropical monsoon climate (Dubreuil et al., 2018) and is located in the Coastal Tablelands. The fluvial geomorphology of the region is shaped by climatic factors and human activities such as deforestation, hydroelectric plants, water reservoirs, and agriculture (Nogueira Junior et al., 2019).

To conduct this study, a systematic approach consisting of five stages was followed: i) Data access, involving the collection of relevant datasets; ii) Mining of precipitation and flow data, which encompassed the analysis of information related to precipitation and river flow; iii) Mapping using the Modified Normalized Difference Water Index (MNDWI), a remote sensing technique utilized for mapping water bodies; iv) Analysis of the variation in the riverbank line, focusing on examining changes occurring along the river's banks; v) Evaluation of spatiotemporal alterations, which involved assessing changes in both space and time.

2.2. Data mining

The study utilized Landsat 5 TM (L5) and 8 OLI (L8) satellite images obtained from the Google Earth Engine (GEE) platform, made available by the United States Geological Survey (USGS). These images were used to extract surface reflectance (SR) data from the

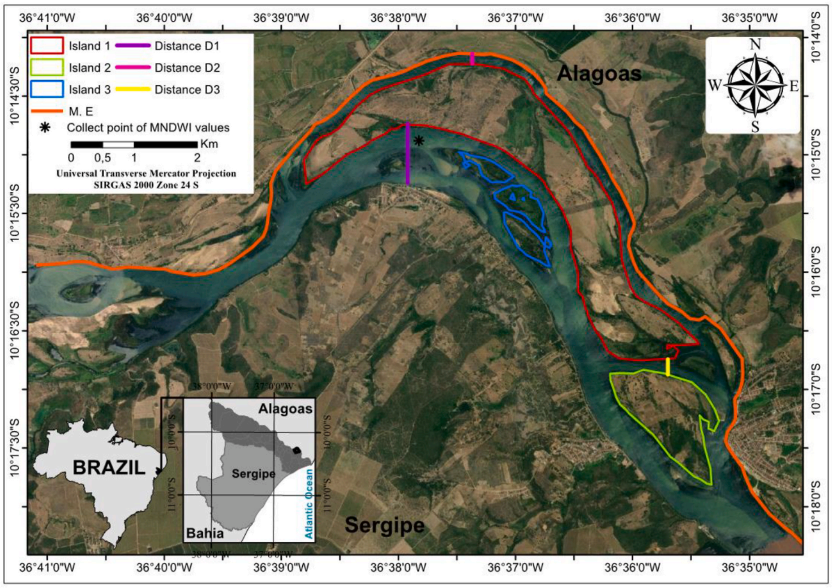

Fig. 1. The region.

green (0.50–0.60 μm – 60 m of resolution) and Shortwave Infrared (wavelength 1.55–1.75 μm – 30 m of resolution) bands. The temporal analysis of the Modified Normalized Difference Water Index (MNDWI) (Xu, 2006) was performed using these data.

2.2.1. MNDWI mapping

For the detection of islands, sandbanks, and rivers, MNDWI is a modification of the Normalized Difference Water Index (NDWI) proposed by McFeeters (1996), where the near-infrared band is replaced with the mid-infrared band in the equation to enhance the detection of water bodies. The MNDWI values range between −1 and 1, with positive values indicating the presence of water. This modification enables better differentiation between built-up areas and water bodies compared to NDWI, which often leads to overlapping results. The equation for calculating the MNDWI is as follows:

$$\mathrm{MNDWI} = \frac{Green\ band - shortwave\ infrared\ band}{Green\ band + shortwave\ infrared\ band} \quad \text{(Equation 1)}$$

Geospatial analysis utilized the GEE platform for separate acquisition of images from each satellite, following a consistent methodology. The study covered a six-year timeframe (1986–2020) at both long- and short-term scales. In 1986, a year prior to the commencement of the installation process of the Xingó power plant, it was the last year with the highest recorded minimum flow Hidroweb (Brasil, 2005) (http://hidroweb.ana.gov.br/). In 1995, one year after the start of Xingó power plant operation, a pattern of monitoring every five years was established, with a variation of approximately ±10 years depending on the availability and quality of satellite images. The calculation and retrieval of images were performed using the geospatial analysis platform GEE. These procedures were conducted separately for each satellite yet following the same methodology. Six different years were selected, spanning both long (± 10 years) and short (± 5 years) intervals, covering the period from 1986 to 2021. Table 1 displays the selected years and corresponding image counts for each satellite. Cloud-covered pixels were eliminated using a filter that applied the mass cloud function and the F mask algorithm, which references the Q60 band to identify and remove cloud-affected pixels. The images were obtained from the Google Earth Engine, where all available images for the year on the platform were filtered, and an average was taken from the sum of all, thus obtaining a product for each selected year.

The MNDWI function (eq. (1)) was applied to the L5 and L8 collections, computing MNDWI values for each year. The image collection was then reduced to retain the maximum-value image per year. Random sampling of MNDWI values was performed at (−36.6283

Table 1
Number of images selected in the GHG databases from 1986 to 2020, covering the area between the states of Alagoas and Sergipe (Zones 24 S – SIRGAS, 2000).

Satellite	Year	Number of images	Average flow for the period ($m^3.s^{-1}$)
Landsat 5 – TM (L5)	1986	08	2211.75
	1995	15	1722.87
	2000	06	2082.00
	2010	11	1981.55
Landsat 8 – OLI (L8)	2015	39	1020.90
	2020	27	1675.93

longitude, −10.249 latitude) within the river area. The resulting six products were classified into “water” and “non-water” classes, exported to a GIS environment, and shapefiles were edited to differentiate river areas, islands, and sandbanks.

To analyze changes over time, sedimented and eroded areas were estimated from 1986 to 2020, including the river, islands, sandbanks, merged margin, sedimented margin areas, and areas sedimented since 1986. A comprehensive temporal analysis assessed variations in the river's course and island size.

For potential trends in island junctions and sections with possible channel closure, distances were measured for three randomly allocated points: D1 (Sergipe bank to island 1), D2 (Alagoas bank to island 1), and D3 (islands 1 and 2). Locations are shown in Fig. 1. Measurements were conducted in ArcMap and exported to Excel for further analysis.

2.3. Historical patterns of precipitation and flow variation

2.3.1. Precipitation

To assess the impact of climate on water body regimes and daily precipitation, we used CHIRPS Daily (UCSB-CHG/CHIRPS/DAILY), a spatial precipitation product (Abdelmoneim et al., 2020). CHIRPS Daily is commonly used as a substitute for precipitation measurements in data-scarce regions (Le and Pricope, 2017). Annual precipitation data from 1986 to 2020 were extracted from CHIRPS Daily and exported to Excel as. csv files. This facilitated a comparison of precipitation data with corresponding flow values for further analysis.

2.3.2. Flow

Flow data used in this study was obtained from the National Water Agency (ANA) Hydrological Information System platform, known as Hidroweb (Brasil, 2005). Data from the Propriá conventional station (Code: 49,705,000; Coordinates: Lat = −10.21 and Long = −36.82) was collected for 34 years (1986–2020), therefore, the temporal resolution of the flow data was annual.

To explore the relationship between flow and precipitation, the acquired flow data was compared with annual precipitation data from the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS Daily) (UCSB-CHG/CHIRPS/DAILY). CHIRPS Daily is a reliable source of precipitation measurements, especially in data-sparse regions (Le and Pricope, 2017).

2.3.3. Principal Component Analysis – PCA

Principal Component Analysis (PCA) was conducted using the variables of Sedimented Areas, for the entire stretch of the channel, along with precipitation, flow, and MNDWI. The data were processed using the RStudio software to explore potential correlations and identify underlying patterns in the dataset.

2.3.4. Multitemporal mapping

The multi-temporal mapping was conducted using the Coastal Analysis System platform via the Satellite Imagery Engine (C.A.S.S.I.E.), which was integrated with the Google Earth Engine platform (C.A.S.S.I.E and COASTAL ANALYSIS VIA SATELLITE IMAGERY ENGINE, 2020) Google Earth Engine - GEE (Moore and Hansen, 2011). For this analysis, six satellite scenes were chosen for the same year, except for 2015, which was substituted with 2018. Due to the platform's limitations in applying a cloud filter, similar to what can be done in GEE, the presence of clouds in 2015 rendered the analysis unviable. Therefore, 2018 was deemed the most suitable alternative, as indicated in Table 2.

The mapping method focused specifically on the Margin of Alagoas (M.A.) (highlighted in orange in Fig. 1) due to significant observed changes in this area, due to the significant changes observed in this area through the products generated for each year of the study. A total of 96 equidistant transects, each spanning 200 m, were generated and subsequently classified into four distinct classes, following the approach described by Luijendijk et al. (2018).

Coastline analysis involved using linear regression to determine the linear regression rate (LRR) and endpoint rate (EPR). LRR calculated the average rate of shoreline movement over time, while EPR measured the distance traveled by the shoreline between the oldest and most recent images, considering the rate based on the most recent image.

The shoreline change envelope (SCE) method was also employed to assess margin variation within each transect. This method, described by Thieler et al. (2009), provides a comprehensive understanding of coastline fluctuations by evaluating the extent of change along each transect.

3. Results

Fig. 2A, B, and C illustrate the emergence of new islands and sandbanks between 1986 and 2020. These newly formed features highlight the dynamic nature of the study area's landscape and the changes occurring within the river system over the specified time.

Table 2
Classes from C.A.S.S.I.E platform for 96 transects found on the left margin line.

Class	change rate LRR (m.year^{-1})
Added	> +0.5
Stable	+0.5 to −0.5
Eroded	−0.5 to −1
Critically Eroded	< −1

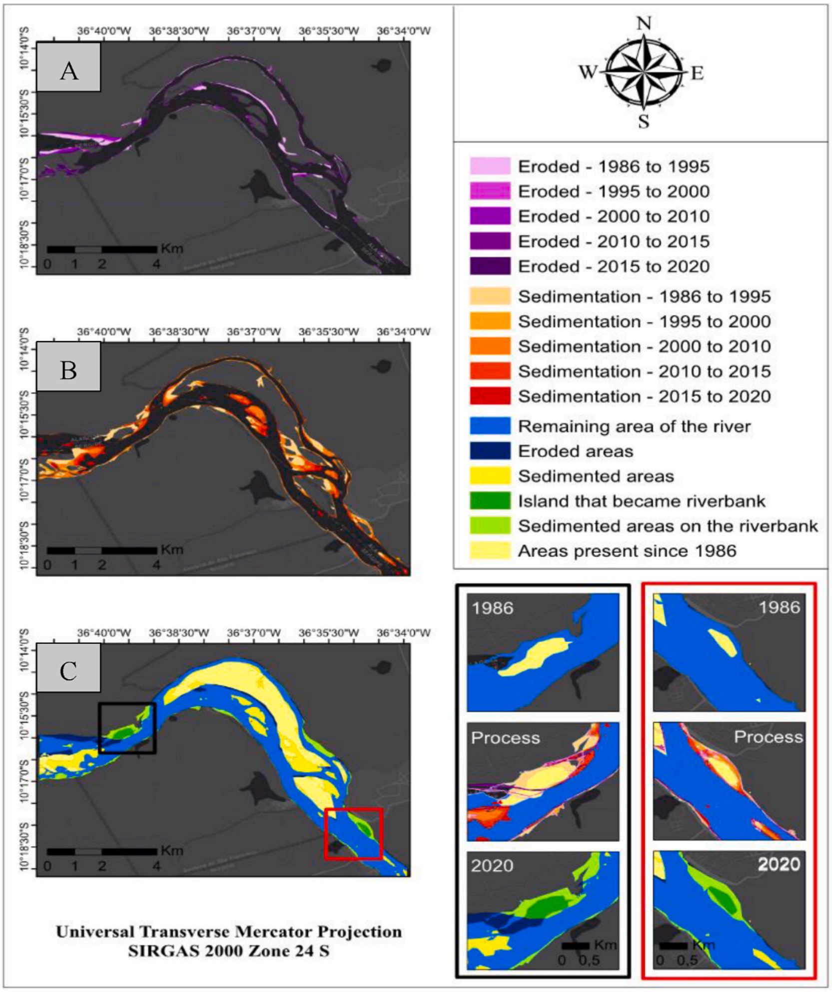

Fig. 2. Temporal analysis of the evolution of sedimentation on islands, sandbanks, and banks in the Lower São Francisco from 1986 to 2020. Panel A - geomorphological dynamics of eroded land; Panel B and C - temporal sedimentation of islands and sandbanks.

The islands and sandbanks within the river experienced expansion, increasing from 8.28 km^2 to 10.69 km^2 over the studied period. Notably, the merging of islands into the Alagoas bank, along with sedimentation on both banks, contributed to a marginal increase of approximately 1.92 km^2 (highlighted in green in Fig. 2). Although the islands on the Alagoas margin merged, the river islands remained visible above the water surface until 2020, thanks to the substantial sedimentation occurring in the area.

Moreover, there was a significant rise in sedimentary areas within the river channel from 2000 to 2015, amounting to approximately 1.11 km^2, as outlined in Table 3.

Within the sedimentation area, three islands accounted for 83% of the total, with Island 1 being the largest and experiencing the most significant increase in sediment accumulation in the eastern region, as depicted in Fig. 2. Its size expanded from 5.58 km^2 to 6.62 km^2, primarily due to the merging of three smaller nearby islands. Island 2 observed a smaller increase of 0.32 km^2, while Island 3, consisting of a complex of three small islands, exhibited a territorial growth of approximately 0.69 km^2.

The sedimentation process had a notable impact on the size and structure of the islands, with some experiencing growth, while others eroded or disappeared entirely. Out of the 1.36 km^2 of eroded sediments, 0.82 km^2 were contributed by islands and sandbanks that reintegrated into the river following erosion, while the remaining 0.54 km^2 accounted for bank erosion, as displayed in Fig. 3. These findings demonstrate the dynamic nature of the islands and sandbanks, undergoing constant changes in size and shape due to sedimentation and erosion processes (Guo et al., 2018; Wilkes et al., 2019; Szmańda et al., 2021; Chen, 2021)

As sedimentation and bank advancement occurred, the size of the river area proportionally decreased. In 1986, the river occupied an area of 19.4 km^2, as indicated in Table 1 and illustrated in Fig. 4. This highlights the impact of sedimentation and bank encroachment on the reduction of the river's spatial extent over time.

Over 34 years, the river's area decreased by approximately 20%, reaching 73.2% (14.20 km^2) of its original extent (Fig. 4). Geomorphological changes due to erosion affected 1.36 km^2 of the riverbed by 2020 (Fig. 2-A). The analysis of MNDWI images generally showed a decreasing trend in composition, except for 2015 (Table 3). These findings highlight significant alterations and ongoing processes impacting the river's area, emphasizing its dynamic geomorphology.

Table 3
Temporal analysis of sedimentation evolution of islands and sandbanks along the São Francisco River from 1986 to 2020.

		MNDWI[a]	Area (km²)						
			General	I 1	D I 1	I 2	D I 2	I 3	D I 3
Island (Year)	1986	0.80	8.28	5.58	–	1.28	–	0.00	–
	1995	0.73	8.58	5.84	0.26	1.40	0.12	0.06	0.06
	2000	0.64	9.08	6.14	0.30	1.44	0.04	0.09	0.03
	2010	0.60	9.47	6.34	0.20	1.47	0.03	0.29	0.20
	2015	0.66	10.58	6.65	0.31	1.58	0.11	0.68	0.39
	2020	0.59	10.69	6.62	−0.03	1.60	0.02	0.69	0.01
Addition of occupancy to the gutter	2.41	1.04		0.32		0.69			
	0.07	0.03							
Total - added per year				0.01		0.02			
River (1986 versus 2020)	Sedimented area	3.59							
	Marginal sedimented areas	1.92							
	Eroded areas	1.36							
	Remaining river area	14.20							
	Total area of the river in 1986	19.36							
	Total area of the river in 2020	15.56							

I - Islands 1, 2, and 3; D - the difference between the previous and the following study year for islands 1, 2, and 3. MNDWI - the value of the modified normalized difference water index collected for each year covered.
[a] Collection coordinate represented in Fig. 1; Longitude: 36.62854770023863; Latitude: 10.249887764485537.

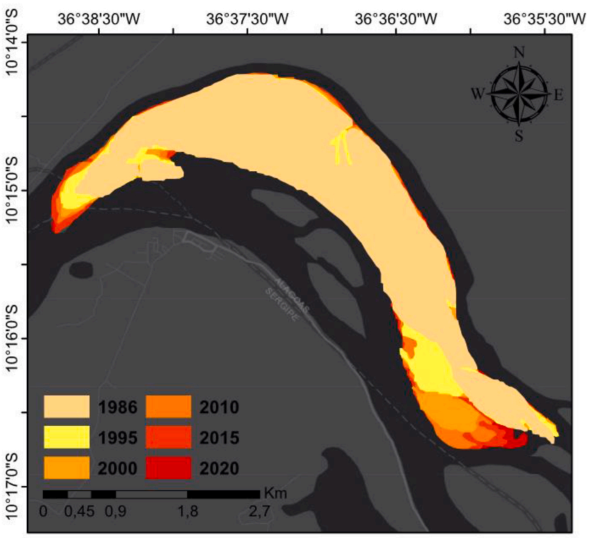

Fig. 3. Evolution of the sedimentation of island 1 in the São Francisco River from 1986 to 2020.

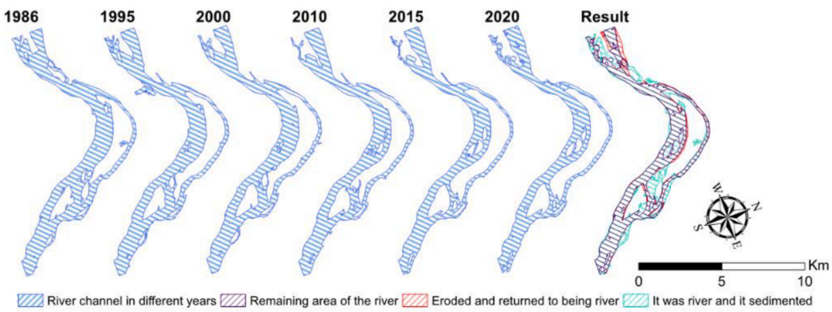

Fig. 4. Temporal analysis of the evolution of the river system in São Francisco River, from 1986 to 2020.

The anomaly observed in the 2015 MNDWI images may be due to factors like satellite image spatial resolution (Du et al., 2016) or natural erosion followed by sediment transport. Nonetheless, the overall trend from 1986 to 2020 indicates a linear reduction, indicating degraded water availability at the collection point. The decrease in water or wetland area, as indicated by MNDWI, suggests a shallower channel over the past 34 years.

The emergence and growth of islands and sandbanks in the river channel are influenced by various factors, including natural water erosion (Alekseevskiy et al., 2008; Barabas and Tkáč, 2019). Sediment aggregation affects the river's sediment transport capacity, influenced by flow changes resulting from precipitation events after the establishment of the Xingó Hydroelectric Power Plant (HPP). In the literature, it is noted that following the installation of this hydroelectric plant, there was a reduction of approximately 56% in the average flow of the river in its lower course. It is reported that around 30% of the decrease in its minimum flow during dry periods occurred between the years 1994 and 2012 (Vasco et al., 2021).

Historical hydrological changes were assessed by evaluating flow data from the Hidroweb platform and precipitation measurements from the CHIRPS dataset. Fig. 5 presents the analysis results, providing insights into the relationship between flow, precipitation, and sedimentation dynamics in the river system.

Throughout the study period, flow consistently remained below the historical average. Only in 2017 and 2019 did precipitation values exceed the historical average, indicating occasional increases in freshwater discharge during periods of reduced rainfall. The consistently low flow had a negative impact on the local riverside population, suggesting potential issues with the management of the Xingó Hydroelectric Power Plant (HPP) and its water release policies.

To understand the relationships between sedimentation, precipitation, flow, and MNDWI variables, a Principal Component Analysis (PCA) was conducted. PCA revealed that ACP1 and ACP2 accounted for over 95% of the variables, indicating their significant contribution. Four main components were identified (Fig. 6), providing insights into the interdependencies and patterns within the analyzed variables.

The application of the normalized Varimax method in the Principal Component Analysis (PCA) revealed that PCA1 and PCA2 account for more than 95% of the variation, as illustrated in Fig. 6. PCA1 explains 73.6% of the total variance, while PCA2 explains 21.3% of the variance.

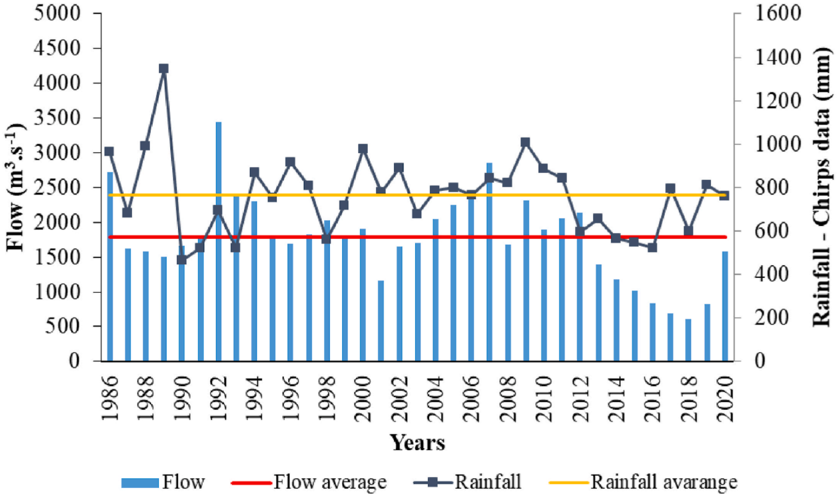

Fig. 5. Annual means of flow obtained from the nearest rainfall station, and accumulated rainfall. Red - 1781.22 m^3 s^{-1}. $year^{-1}$; yellow - 764.07 mm. $year^{-1}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

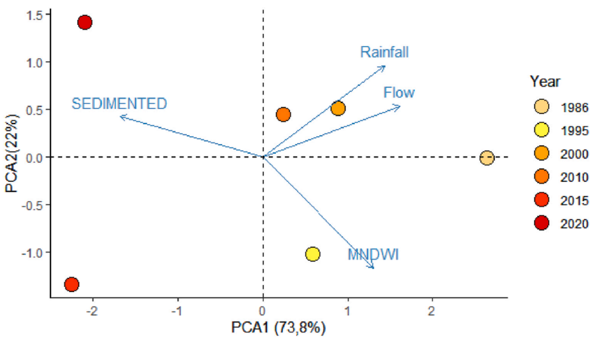

Fig. 6. Analysis of principal components of sedimentary areas (SED), MNDWI, precipitation (Precipit), and flow (Code: 49,705,000) (ANA, 2021), from 1986 to 2020.

PCA1 is primarily associated with MNDWI, flow, and precipitation variables, providing insights into the hydroclimatic conditions of the region. There is a positive correlation of flow, precipitation, and MNDWI in relation to PCA1. Conversely, sedimentation shows a negative correlation with these variables.

PCA2, on the other hand, focuses on the physical or geomorphological attributes of the region, specifically emphasizing the sedimented areas that visually alter the channel's geomorphology. High sedimentation levels are indicative of reduced rainfall, flow, and MNDWI, suggesting antagonistic interactions and spatial distances of these variables.

The PCA analysis provides a comprehensive understanding of the interplay of hydroclimatic conditions, sedimentation, and geomorphological changes within the study area. Changes in flow patterns have resulted in a reduction in the river's velocity, leading to sediment accumulation at various points in the fluvial system, including existing islands. This process has influenced the emergence of new islands over time (Montero and Latrubesse, 2013).

In 2015, an atypical data pattern was observed for hydroclimatic variables, characterized by lower precipitation and flow values, along with higher MNDWI compared to 2000 and 2010. This anomaly may be indicative of specific local conditions or environmental factors during that particular year.

Sedimentation has shown a consistent increase since 2000, which aligns with the data observed in 2000, 2010, 2015, and 2020. The progressive sedimentation process contributes to changes in the river's geomorphology and dynamics.

Furthermore, the distance between the margins of islands one and two has been decreasing over time, with an average proximity of 12.3 m per year. This trend suggests that if local conditions remain unchanged, the islands may merge in approximately 12 years (Fig. 7).

The distance between D1 and the Sergipe margin remained relatively stable until 2015, with an increase observed in 2020. In the case of D2, the distance experienced an initial increase until 1995, followed by a period of stability until 2000. Subsequently, there was a decrease until 2010, and it has since remained stable at less than 90 m. This trend suggests a potential closure of the channel over time.

Photographs depicting the surface of new sandbars or dams upstream of islands 1 and 3 are presented in Fig. 8, providing visual evidence of the formation of these new sandbanks as sedimented areas rise to the water surface. Notably, Fig. 8B showcases a newly identified sandbar, as depicted in Fig. 3-C, situated between island 1 on the right side and island 3.

The connection between the islands on the Alagoas margin represents a significant sedimentological change, as demonstrated in Fig. 9, particularly in the vicinity of point 2 as depicted in Fig. 1. The patterns observed in the transects reveal a consistent trend of increasing sedimentation, indicating a potential reduction in the distance at D2.

The left bank line of the river exhibits stability, erosion, and critically eroded areas, indicating island merging in 1986 (highlighted in light-yellow in Fig. 3). In 1995, the island in the eastern area merged with the margin, as shown in Fig. 9-C and Fig. 2-C (outlined in a red frame). Islands between transects 71 and 76 merged, while other regions experienced erosion, accretion, or remained stable.

The Alagoas margin shows accretion, with higher LRR and EPR mean values (Table 4). Among the transects, transect 10 displays the most significant SCE variation, with a margin area of 399.12 m compared to the initial year and an average of 86.36 m per transect.

Analysis of 96 transects (200 m each) revealed 36 exhibiting accretion, 12 as critically eroded, 8 with erosion, and 40 remaining stable. Critically eroded transects were divided into distinct sections. Erosion began in the mid-1990s and stabilized between 1995 and 2015. Accretion in some transects may result from merging small islands into the Alagoas bank, potentially influenced by climate change and altered flow patterns.

4. Discussion

The study monitored islands and sandbanks in Santana do São Francisco (SE), Penedo (AL), and Igreja Nova (AL) from 1986 to 2020. Initial geomorphology showed sedimentation, but significant changes occurred after 1995. Sedimentation increased by 0.3 km^2 from 1986 to 1995 and further by 0.5 km^2 from 1995 to 2000. The studies by Gautier et al. (2021) and Chen et al. (2018) are the ones

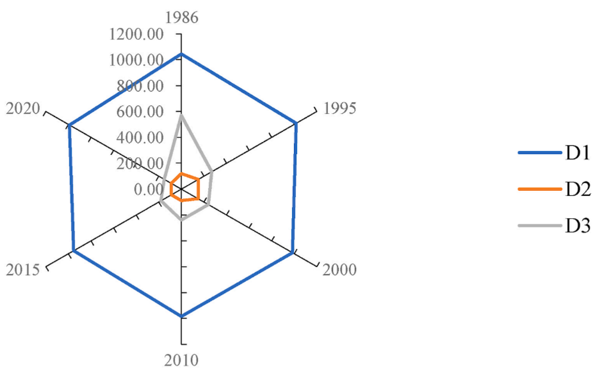

Fig. 7. Distance (m) of islands (right side) (D1), Alagoas (left side) (D2), and of island 2 (D3) from 1986 to 2020.

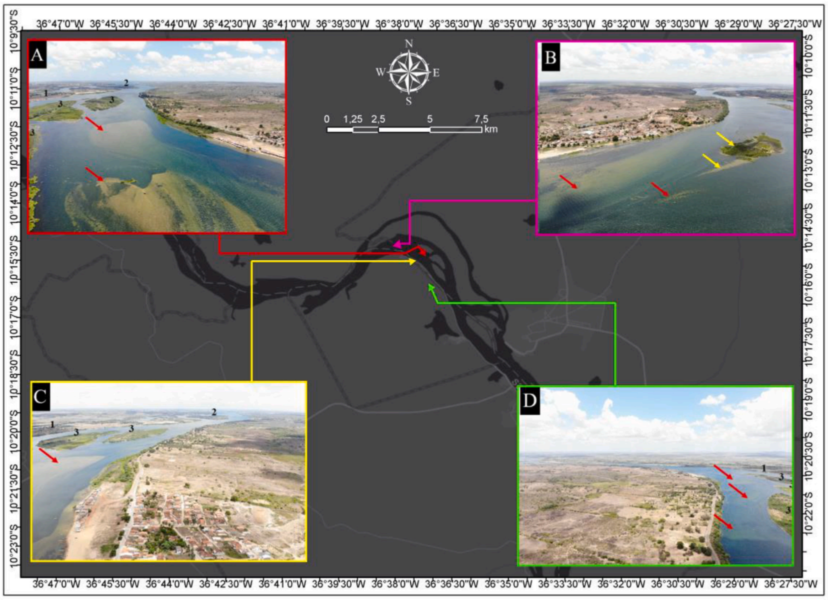

Fig. 8. The condition of the fluvial channel of the São Francisco River in 2020. Red arrows in A, B, C, and D = deposit of sediments. 1, 2 and 3 – islands. Yellow arrows in Fig. B = emergence of a new sandbar and submerged sediments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that most closely resemble the results obtained in this work. Human activities in the São Francisco River have contributed to increased discharge and sedimentation, impacting the river system (Sun et al., 2016; Holanda et al., 2021a,b). Hydropower production since the 1970s, particularly the Xingó HPP, has led to reduced water flow, affecting water availability for local communities (do Vasco et al., 2019; Santos et al., 2020). The construction of dams and reservoirs alters sediment transport, impacting channel morphology (Eaton et al., 2010; Wang et al., 2017; Chen et al., 2018; Talukdar and Pal, 2019; Nistor et al., 2021).

Sedimentation has resulted in the formation of islands and a reduction in water area. The MNDWI values indicate changes in the river's environment and its biological aspects (do Vasco et al., 2019; Santos et al., 2020). Sediment vertical increase and the classification of the river's channel influence island evolution and sediment dynamics (Leli et al., 2018, 2020; Mescolotti et al., 2021).

Anthropic interventions, including the river transposition project, impact the river system (Stolf et al., 2012; Torres et al., 2021). Changes in flow and precipitation have affected the water regime and sedimentation patterns (De Jong et al., 2018; Cavalcante et al., 2020). The presence of hydroelectric plants promotes changes in land cover that contribute even more to geomorphological changes (Genz and Luz, 2012; Pathan et al., 2021).

Riverbanks and coastlines undergo morphological changes due to erosion and sediment deposition (Kim et al., 2017; Duru, 2017). Vegetation plays a crucial role in channel narrowing and bank stability (Zen and Perona, 2020). In the section of the Permanent Preservation Area (APP) located in the municipality of Santana do São Francisco, under the jurisdiction of the state of Sergipe (on the right bank and opposite to the area under study), it is known that approximately 62% of its area is in a disturbed state. This condition is a result of alterations caused by agricultural activities, urban development, and deforestation. Consequently, the remaining vegetation is at risk of forest degradation and genetic erosion due to the reduced connectivity between the remaining forest fragments (Torres et al., 2021). Restoration of natural vegetation can reduce sediment transport and improve soil quality (Buendia et al., 2016; Dal Ferro et al., 2019; Silva et al., 2018).

5. Conclusions

The chosen base year, 1986, represented the last year with the highest flow before the installation of the Xingó hydroelectric plant, which occurred in 1987, and the commencement of its operations in 1994. Additionally, this year exhibited favorable characteristics in terms of satellite imagery compared to previous years, allowing for a more effective comparison with the subsequent years. From this year onward, various impacts were identified in this study, and their consequences, which were predominantly negative.

The study period from 1986 to 2020 has witnessed significant geomorphological, hydrological, and climatic changes in the study region, particularly in the São Francisco River channel. Ongoing monitoring of the channel's geomorphology is essential, along with timely intervention if necessary. Changes include channel narrowing, increased island sizes, and the proliferation of sandbanks.

The coastline has also experienced alterations, such as erosion in the western region. Islands have emerged on the left bank, while sedimentation has occurred on the right bank, resulting in reduced river flow due to suspended sediments, restricted channel flow, and silt transport. The accumulation of suspended sediments vertically within the river channel modifies its longitudinal profile. These changes in islands and sandbanks serve as ecological indicators of environmental disturbance, impacting navigation, local so-

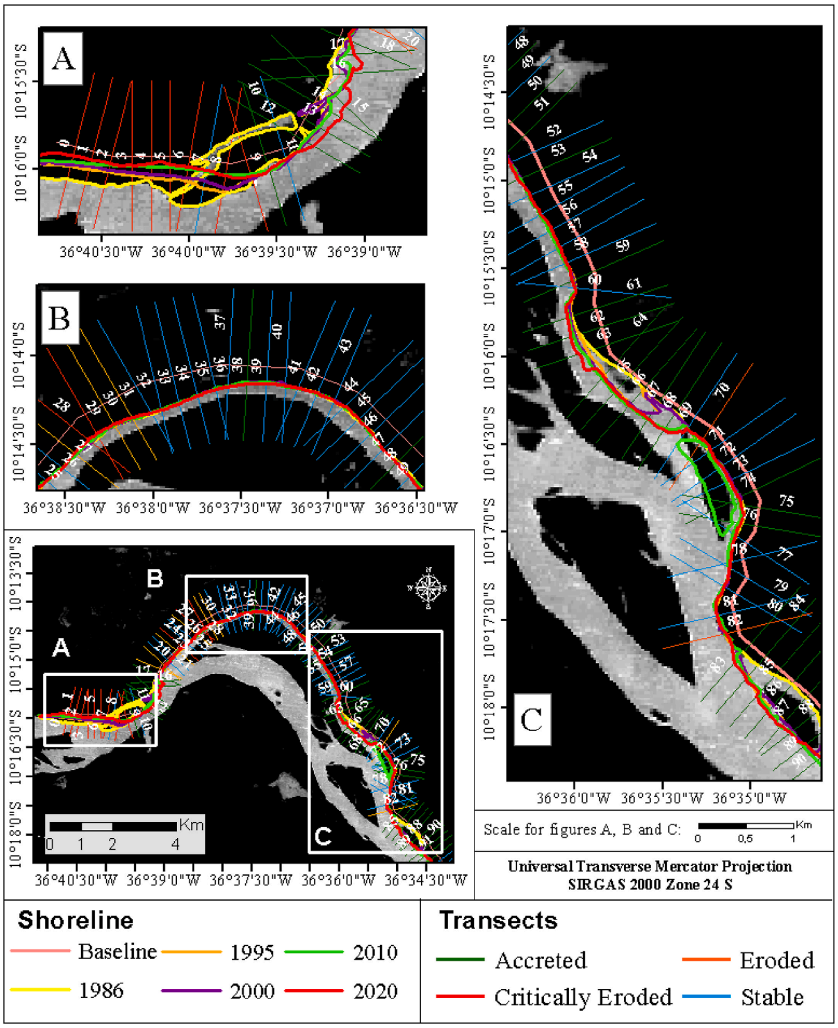

Fig. 9. Variation of the São Francisco River in the section of the fluvial channel and the transects from 1986 to 2020.

Table 4
Variation of the Alagoas margin by the method of the different rate of the line of the oldest margin by the most recent (EPR), rate of the point of change of the line by linear regression (LRR), variation of the lines within each transects (SCE), at the level of each class of transect and general in river channel from 1986 to 2020.

Transect		Addition	Critically Eroded	Eroded	Stable
		36	12	08	40
LRR (m.year^{-1})	min	0.51	−9.06	−0.93	−0.47
	max	9.99	−1.03	−0.54	0.43
	mean	3.56	−4.64	−0.71	0.04
EPR (m.year^{-1})	min	−0.43	0.00	−1.08	−0.57
	max	11.44	−0.87	−0.58	2.47
	mean	3.71	−4.59	−0.73	0.07
SCE (m)	min	19.88	−0.02	20.76	0.00
	max	399.12	319.18	41.74	281.04
	mean	142.43	172.60	29.45	21.40
General		LRR (m.year^{-1})	EPR (m.year^{-1})	SCE (m)	Transects
	min/max	−9.06/9.99	−9.29/11.44	0.0/399.12	96
	mean	0.712	0.79	86.36	
	Cv%	47.44	45.52	12.13	

Behavior: Accretion.

cioeconomic activities, channel stability, and the livelihoods of riverside communities reliant on the river as a natural resource (Farias et al., 2017; Barreto et al., 2019).

Overall, the study highlights the complex interactions between human activities, hydroclimatic factors, sedimentation, and geomorphological changes in the São Francisco River.

This study has highlighted significant gaps, particularly from a forestry perspective, as there is limited information available regarding the preservation of Permanent Preservation Areas (APP) along this river. Therefore, research aimed at assisting in the dynamics, identification, delineation, land use and land cover classification, restoration of degraded APP (Janssen et al., 2021), as well as genetic diversity studies (which aid in identifying species resistant to flood seasons and promote reforestation success), can support new environmental objectives for the region and contribute to environmental policy development.

The restoration of degraded APPs also serves as a mitigating agent against marginal erosive processes. In this context, these complementary studies are essential for promoting the conservation of the São Francisco River in its lower course.

Ethical Declaration

Dear Editor, We are enclosing herewith a manuscript entitled "**Spatial framework vulnerability in the riparian area of the lower course of the São Francisco River**".

We certify that the Research does not involve the use of animals or microorganisms. The authors agree with the Ethical Principles in Research in accord with Brazilian and international Laws.

The study received the consent of all authors and does not involve recruitment of patients, staff or use of animals. The study does not involve participants age 16 or over who are unable to give informed consent. The research does not involve potentially vulnerable groups. The study does not involve discussion of sensitive topics.

Authorship Statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication. Authorship contributions:

MFRT conducted research, analyzed data, and drafted the manuscript.

RAF provided guidance and supervision.

ANV contributed to data acquisition and provided insights.

RSM reviewed and edited the manuscript, offering critical feedback.

All authors actively contributed, reviewed, and approved the final version.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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