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STYLES AND FLUVIAL PATTERNS OF THE APODI-MOSSORÓ RIVER IN THE CRYSTALLINE BASEMENT AREA, SEMI-ARID POTIGUAR, BRAZIL

Estilos e padrões fluviais do Rio Apodi-Mossoró no embasamento cristalino do Semiárido Potiguar, Brasil

Estilos y patrones fluviales del Río Apodi-Mossoró en el área de basemento cristalino, semiárido potiguar, Brasil

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ABSTRACT

Watercourses are dynamic environments that play a fundamental role in landscape transformation due to their specific characteristics and associated fluvial changes. These bodies of water act as modifying agents with varied dynamics, styles, and forms. In semi-arid areas and crystalline basement regions, these modifications can naturally occur more slowly due to lithology and irregular rainfall. Thus, this study aims to classify the fluvial styles and patterns of the Apodi-Mossoró River, located on the Crystalline Basement in the Semi-arid region of the Brazilian state of Rio Grande do Norte. Methodologically, the research is characterized as analytical and descriptive with a qualitative-quantitative approach. It adopts the analysis of morphometric parameters of the area and a classification of fluvial styles considering valley configuration, planform, and geomorphological units for the interpretation of the study object. The results indicate that lithological structure, altimetry, and slope exert a significant influence on the morphometric indices of the watershed, acting as important controllers of the fluvial dynamics of the Apodi-Mossoró River. Regarding fluvial styles, confined valleys predominate in areas with higher slopes and altitudes, while unconfined and partially confined valleys occur at slope breaks, where there is lower flow energy capacity, favoring sediment deposition.

Keywords: Fluvial morphodynamics; Morphometry; Fluvial controllers; Fluvial geomorphology.

RESUMO

Os cursos d'água são ambientes dinâmicos que desempenham um papel fundamental na transformação da paisagem, devido às suas características específicas e às mudanças fluviais associadas. Esses corpos de água agem como agentes modificadores com dinâmicas, estilos e formas variadas. Em áreas semiáridas e de Embasamento Cristalino, essas modificações podem ocorrer naturalmente de forma mais lenta, em função da litologia e da irregularidade das chuvas. Assim, este trabalho tem como objetivo central, classificar os estilos e padrões fluviais no curso do rio Apodi-Mossoró localizado sobre o Embasamento Cristalino, no Semiárido no Estado brasileiro do Rio Grande do Norte. No quesito metodológico, a pesquisa caracterizada como analítica e descritiva com abordagem qualiquantitativa, adota para interpretação do objeto de estudo, a análise de parâmetros morfométricos da área, e uma classificação de estilos fluviais considerando a configuração de vale, forma em planta e unidades geomorfológicas. Os resultados indicam que a estrutura litológica, altimetria e declividade exercem uma influência significativa sobre os índices morfométricos da bacia hidrográfica, atuando como um importante controlador da dinâmica fluvial do rio Apodi-Mossoró. Quanto aos estilos fluviais, os vales confinados predominam em áreas de maiores declividades e altitudes, enquanto os vales não confinados e parcialmente confinados ocorrem a partir de rupturas de declive, onde há menor capacidade de energia de fluxo, favorecendo a deposição de sedimentos.

Palavras-chave: Morfodinâmica fluvial; Morfometria; Controladores fluviais; Geomorfologia fluvial.

RESUMEN

Los cursos de agua son ambientes dinámicos que desempeñan un papel fundamental en la transformación del paisaje, debido a sus características específicas y a los cambios fluviales asociados. Estos cuerpos de agua actúan como agentes modificadores con dinámicas, estilos y formas variadas. En áreas semiáridas y de basamento cristalino, estas modificaciones pueden ocurrir naturalmente de manera más lenta, debido a la litología y a la irregularidad de las lluvias. Así, este estudio tiene como objetivo principal clasificar los estilos y patrones fluviales del río Apodi-Mossoró, ubicado sobre el Embasamiento Cristalino en la región semiárida del estado brasileño de Río Grande del Norte. En cuanto a la metodología, la investigación, caracterizada como analítica y descriptiva con un enfoque cualicuantitativo, adopta para la interpretación del objeto de estudio el análisis de parámetros morfométricos del área y una clasificación de estilos fluviales considerando la configuración del valle, la forma en planta y las unidades geomorfológicas. Los resultados indican que la estructura litológica, la altimetría y la pendiente ejercen una influencia significativa sobre los índices morfométricos de la cuenca hidrográfica, actuando como un importante controlador de la dinámica fluvial del río Apodi-Mossoró. En cuanto a los estilos fluviales, los valles confinados predominan en áreas con mayores pendientes y altitudes, mientras que los valles no confinados y parcialmente confinados ocurren a partir de rupturas de pendiente, donde hay menor capacidad de energía de flujo, favoreciendo la deposición de sedimentos.

Palabras clave: Morfodinámica fluvial; Morfometría; Controladores fluviales; Geomorfología fluvial.

1 INTRODUCTION

In the Brazilian semi-arid region, water availability is characterized by irregular distribution, low rainfall rates, and prolonged periods of drought, which significantly influence local fluvial dynamics. This results in the predominance of intermittent and ephemeral rivers, whose flow depends heavily on the rainy season.

Lima and Girão (2020) emphasize that the region's main feature is not merely low rainfall, but rather the irregularity and unpredictability of precipitation, which, even in favorable years, may occur within short time intervals throughout the year. According to Menezes et al. (2010) and Rocha et al. (2020), the rainy season, marked by relatively low precipitation levels, is confined to a few months—typically three to four months per year—with an average annual rainfall of approximately 960 mm.

Thus, as water serves as the primary natural agent of force transmission and is responsible for the movement and sustenance of water bodies through surface runoff, fluvial morphodynamics result directly from drainage behavior. According to Marçal (2013), rivers are not static systems; their behavior is shaped by morphological adjustments induced by a series of erosional and depositional processes. In this context, studies such as those ones by Shibata and Ito (2014), Meslard (2022), and Fu et al. (2023) demonstrate that water acts as the principal shaping force of fluvial forms, providing the energy necessary for erosion and deposition processes, while also transporting and depositing material along watercourses, thereby creating environments with distinct characteristics.

According to Von Sperling (2007), there is a considerable complexity in accounting for the factors influencing behavior inherent to morphological modeling, given the diversity of fluvial configurations resulting from variations in topographic, geological, climatic, and hydrological conditions. The interplay of these factors imparts a dynamic character to channel configuration, linking channel-shaping processes to flow characteristics that operate differently across space and over time.

Multiple processes are involved in the formation and evolution of fluvial environments, where spatial and temporal changes occur across varying timescales. Brunsden and Thornes (1979) assert that each environment is defined by its own distinctive forms and features, which persist over time, taking into account both the period required for their establishment and their subsequent longevity. Thus, time acts as a modulator of the system, introducing disturbance processes that induce instability and, consequently, increase the landscape’s sensitivity to change.

In this context, several studies, such as those by Menezes and Salgado (2019), Souza and Branco (2021), and Franco, Souza, and Lima (2022), emphasize the importance of understanding fluvial styles, particularly for identifying areas within a watershed that are more sensitive to disturbances. These studies provide insights into how a watercourse may respond to environmental changes, offering valuable support for environmental planning and water resources management.

Among the works addressing these topics, the contributions of Brierley and Fryirs (2005) stand out for introducing fundamental concepts in river geomorphological analysis; Brierley et al. (2008) for advancing fluvial classification frameworks; and regional studies such as those by Souza and Correa (2015), Franco, Souza, and Lima (2022), and Souza, Santos, and Oliveira (2023), who applied these approaches to the Brazilian semi-arid context. More recent research, including studies by Rodrigues and Souza (2021), Wheeler et al. (2022), Fryirs and Brierley (2022), Rodrigues et al. (2023), and Branco and Souza (2024), further expands this discussion by exploring fluvial responses to various natural and anthropogenic impacts.

Thus, recognizing the spatial and scientific significance of studies on fluvial systems in semi-arid regions, this research focuses on the main river of the Apodi-Mossoró River Basin (BHRAM), specifically on the segment located within the Crystalline Basement, with the objective of classifying its fluvial patterns and styles. To achieve this, the study adopts the fluvial style classification framework proposed by Brierley and Fryirs (2005), which, according to Magalhães Júnior, Barros, and Cota (2020), is considered the most comprehensive. In addition to being flexible and applicable to different approaches and physiographically distinct environments, this framework enables the assessment of channel conditions, offering valuable insights for planning river rehabilitation actions by examining the evolution of fluvial valleys.

Accordingly, it is necessary to characterize the morphometric aspects of the portion of the Apodi-Mossoró River Basin (BHRAM) situated over the Crystalline Basement, comparing them with those of the segment located within the Sedimentary Basin, as well as with those of the entire BHRAM area. Subsequently, the fluvial styles of this section of the Apodi-Mossoró River should be identified and their relationships with the existing fluvial patterns discussed. Furthermore, it is important to note that the focus on understanding fluvial dynamics within the Crystalline Basement area is justified by the fundamental role this sub-basin plays in shaping and directing the fluvial drainage behavior of the Apodi-Mossoró River Basin.

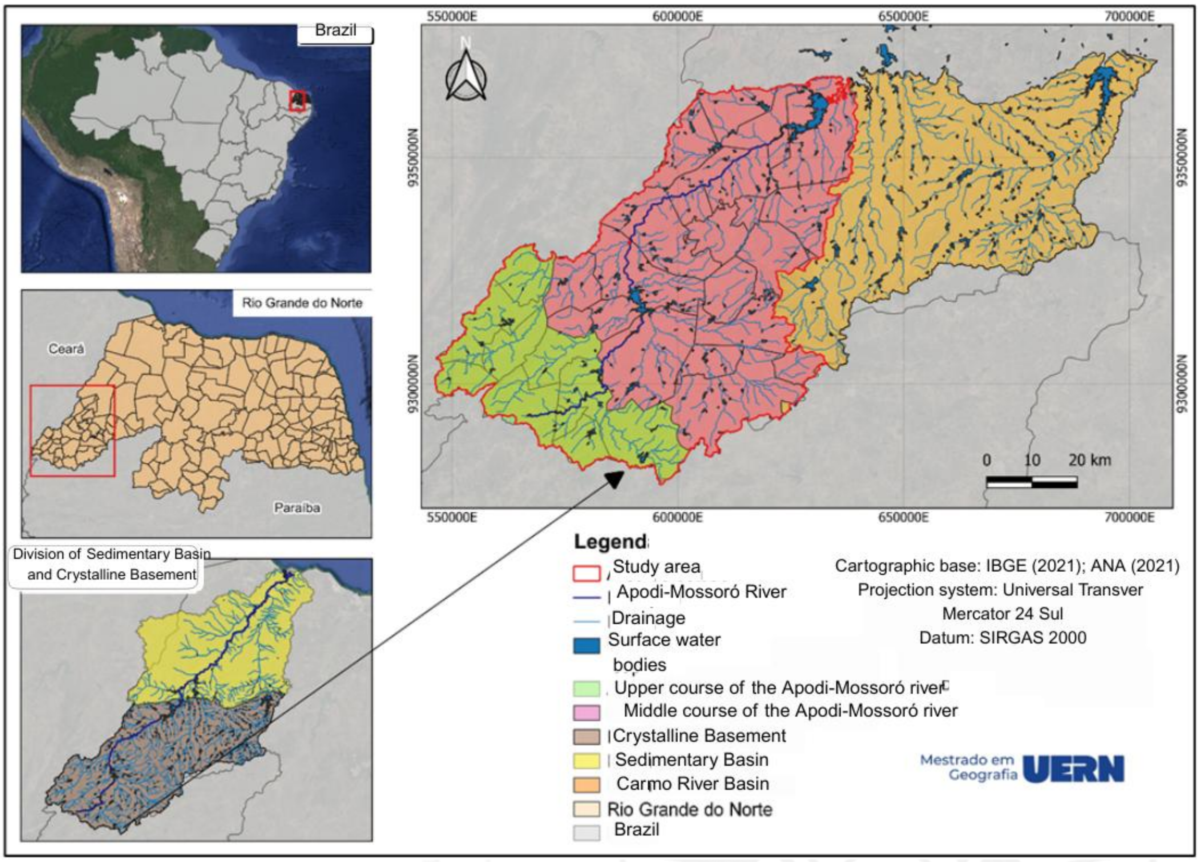
2 MATERIALS AND METHODS

2.1 Overview of the Study Area

The study area of this research is the Apodi-Mossoró River Basin (BHRAM), specifically the section of the Apodi-Mossoró River located within the territorial extent of the Crystalline Basement (Figure 01). This basin is situated in the Western Potiguar region, within the Northeastern Atlantic Hydrographic Region, in the state of Rio Grande do Norte, encompassing 52 municipalities.

From a geological perspective, BHRAM lies over a geological structure that defines two distinct domains: the Crystalline Basement in the southern half, characterized by Precambrian rocks along the upper and middle courses—where this study is focused—and the Sedimentary Basin in the northern half, composed of Mesozoic and Cenozoic rocks from the Potiguar Basin along the middle and lower courses (Maia, 2012).

Figure 01 – Location map of the Apodi-Mossoró River drainage area over the Crystalline Basement, Potiguar semi-arid region, Brazil



Source: Prepared by the Author (2025).

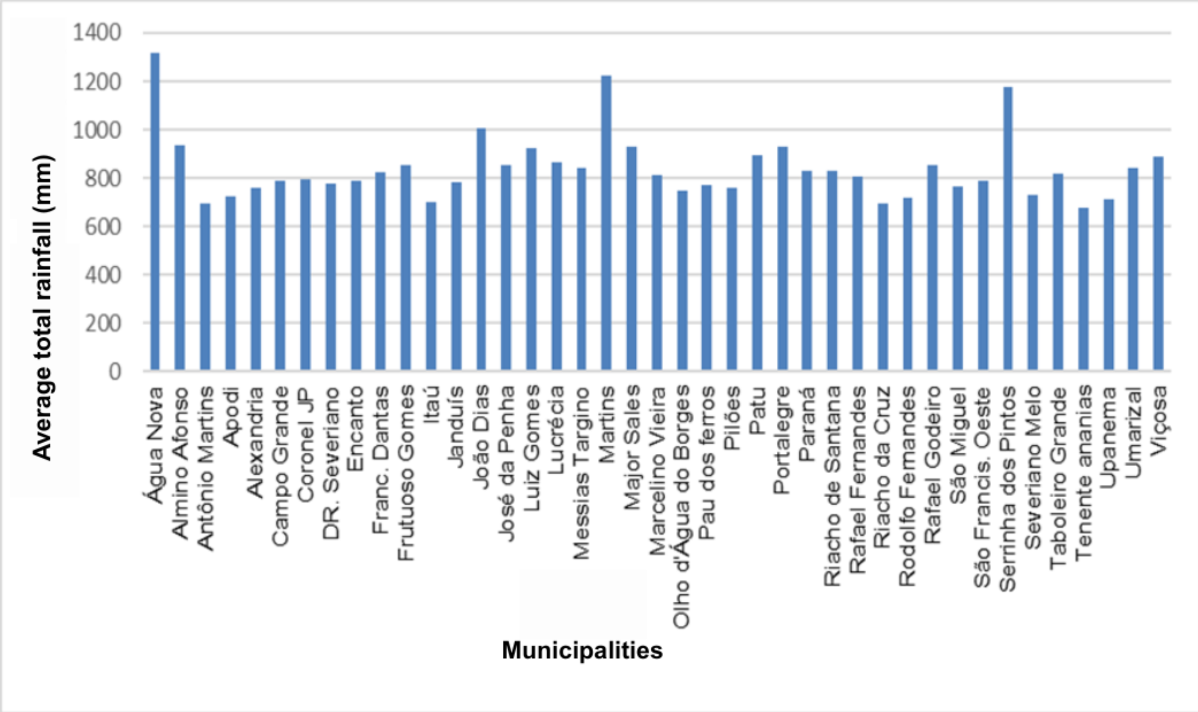
In this context, regarding the Crystalline Basement, the lower course of the Apodi-Mossoró River features a complex lithological composition, consisting of igneous and metamorphic rocks (coarse porphyritic monzogranites to syenogranites with amphibole and biotite, associated with diorites; leucocratic syenogranitic to monzogranitic granites; and migmatized granitic to granodioritic orthogneisses), influenced by structural fracturing that controls both the lithological arrangement and the drainage patterns (Souza, Souza, Souza, 2023). From this perspective, and directly related to the hydrological production framework of the basin, Lemos Filho, Espínola Sobrinho, and Oliveira Júnior (2022) assert that the Crystalline Basement favors a higher concentration of drainage channels and surface runoff gullies.

Similarly, the geological diversity that characterizes BHRAM, with formations of various ages, preserves important information regarding its natural history, which began millions of years ago. The geomorphology also exhibits diverse landscape configurations. The surface is marked by a complex framework resulting from evolutionary processes and landform development within the study area, including the presence of entirely crystalline residual massifs in the extreme west, such as the Pereiro Massif, and residual massifs with sedimentary cover, such as the Martins-Portalegre Massif, which stands out topographically within the vast sertanejo depression (Souza, Souza, Souza, 2023).

According to Souza (2023), the geological-geomorphological framework is dominated by a semi-arid climate, characterized by irregular rainfall patterns, high temperatures, and elevated evapotranspiration rates. The highest average annual precipitations, recorded at 1314.6 mm, 1221.3 mm, and 1178.4 mm, correspond to the municipalities of Água Nova, Martins, and Serrinha dos Pintos, respectively, while the lowest value, 678.9 mm, was observed in Tenente Ananias, as shown in Figure 02.

According to Diniz and Pereira (2015), the primary driver of rainfall in this region is the Intertropical Convergence Zone (ITCZ), which is responsible for the majority of precipitation recorded during the wetter months from February to May. Medeiros, Cavalcante, and Pinheiro (2018) further indicate that the atmospheric dynamics leading to higher rainfall indices are influenced by topographic factors, with areas of greater precipitation typically located at higher altitudes, over Precambrian rocks, where a high density of drainage channels is present.

Figure 02 – Graph of the average total precipitation (1973-2002) for municipalities located in the Crystalline Basement area of the Apodi-Mossoró River Basin.



Source: Prepared by the Author (2024) based on the data from EMPARN (2024)

The main river of the watershed has a length of 210 km, extending from its source in the mountainous region of Luís Gomes to its mouth, between the municipalities of Grossos and Areia Branca, in the state of Rio Grande do Norte. It covers an area of 14,276 km², corresponding to 26.8% of the estimated area of the state (Carvalho, 2022; Fontes, Filho, Costa, 2023; Souza, Souza, Souza, 2023).

In its upper and middle courses, where the Crystalline Basement is located, there is a high drainage density, resulting from its association with the Precambrian Basement (Silva; Carvalho, 2024). In this regard, the dendritic and sub-dendritic patterns arise from the impermeability of the crystalline rocks (Maia; Bezerra, 2012), as described by Carvalho (2011), who notes that crystalline terrains feature a higher number of surface watercourses and exhibit a scarcity of groundwater due to hydrogeological conditions.

2.2 Methodological procedures

This research is characterized as analytical and descriptive in terms of its objectives, as its purpose is to expose and identify the fluvial styles present in the Apodi-Mossoró River, as well as to analyze the fluvial morphodynamics based on these style patterns. The assessment of these locations will consider a quali-quantitative approach in examining the data collected.

The methodological procedures are primarily based on desk research, including a bibliographic survey, observation of satellite imagery, cartographic productions, classification of fluvial styles, collection of morphometric parameters for the river basin, and field research for observation, recognition, and photographic documentation.

For the creation of the maps, the software QGIS version 3.28.12 Firenze was used. The location map of the study area was constructed based on vector data from the Brazilian Institute of Geography and Statistics (IBGE) (2021) for the shapefiles of the state of Rio Grande do Norte and Brazil, the drainage shapefiles, watershed boundaries, and for the Crystalline Basement area, data from the National Water Agency (ANA) (2021) were utilized.

To understand the morphometric characteristics of the study area, the procedure was also applied to the area of the basin located within the sedimentary basin, in order to comprehend these characteristics within the broader context of the watershed. The parameters applied were based on studies by Villela and Matos (1975), Lima (2008), Pereira et al. (2019), and Cavalcante, Grigio, and Diodato (2021), which included the following parameters: form factor (Kf), circularity index (Ic), compactness coefficient (Kc), drainage density (Dd), and relief ratio (Rr) (Table 01), all of which were generated using QGIS version 3.28.12 Firenze.

Table 01 – Morphometric indices used in the characterization

Index	Definition	Descriptive Equation		Classification
Shape Factor (Kf)	It is defined based on the water concentration time within the watershed. The greater the shape factor, the higher the susceptibility to flooding	$F = A/L^2$	Where A, in km², is the basin area, and L is the length of the basin's main axis	<0,50 basin not susceptible to flooding 0,50 - 0,75 basin with moderate susceptibility to flooding 0,75 – 1,00 basin susceptible to flooding
Circularity Index (Ic)	It indicates a greater tendency toward circularity as the value approaches 1	$IC = 12{,}57 * A / P^2$	where A (km²) represents the basin area and P (km) denotes the basin perimeter	

Index	Definition	Descriptive Equation		Classification
Compactness Coefficient (Kc)	A value closer to 1 indicates a greater likelihood of the basin presenting irregularity and a flattened shape, thereby increasing its susceptibility to flooding	$KC = 0{,}28.\ P\ /\ \sqrt{A}$	P is the perimeter in km, and A is the area in km²	1,00 – 1,25 high propensity for flooding 1,25 – 1,50 moderate propensity for flooding >1,50 not susceptible to flooding
Drainage Density (Dd)	It represents the rate at which water leaves the basin	$Dd = Lt\ /A$	Where Lt represents the total length of all channels in km, and A denotes the basin area in km²	< 0,50 Low 0,50 – 2,00 Moderate 2,01 – 3,50 High >3,50 Very High
Relief Ratio (Rr)	It represents the altitude and velocity of water, leading to erosive processes	Rr = H/L'	Where H represents the difference between the maximum and minimum altitude, and L denotes the length of the basin's axis	

Source: Prepared from Villela and Matos (1975), Lima (2008), Pereira et. al (2019) and Cavalcante, Grígio e Diodato (2021).

To obtain these data, vector layers of the respective cuts, Digital Elevation Model (DEM) imagery, and vector layers of the main channel and drainage channels were used. First, a new layer was created to calculate the axial axis of the basin, disregarding the meanders, meaning a straight line was drawn from the upstream to downstream of the basin, using the main channel. Through this axis, it was possible to calculate the morphometric values.

In the next step, a new field for ‘area and perimeter’ was created in the basin layer using the ‘Field Calculator’ tool. In the main channel, the ‘Comp’ field, which represents the river length, was created. The ‘Comp’ field was also created in the axial axis layer and the drainage layer.

From the Digital Elevation Model (DEM) imagery, elevation values were obtained using the ‘Zonal Statistics’ tool, calculating the mean, minimum, maximum, and range statistics. With all the acquired data, these physical values were placed into the attribute table of the basin layer, and this entire process was also carried out for the Crystalline Basement clipping. Subsequently, index calculations were performed using the ‘Field

Calculator' with their respective equations, generating the morphometric information for analysis.

For the classification of river types, the river styles methodology developed by Brierley and Fryirs (2005) was adopted. This methodology proposes the classification of river segments with the aim of interpreting the shape, behavior, condition, and recovery potential of a river. It allows for the organization and differentiation of environmental characteristics into groups that can be compared and interpreted to better understand fluvial dynamics.

According to Pelech (2021), river styles, the typology of rivers themselves, are identified from channel segments, considering the valley configuration by identifying the degree of river confinement, analyzing the planform shape, and the geomorphological units, which were some of the items used in the analysis, along with fluvial morphology. Thus, the structure and definition of the river valley configuration used to identify the river styles in the study area can be demonstrated as shown in Table 02.

Table 02 – Analysis Variables for Defining River Styles

Confined Valley Configuration	Partially Confined Valley Configuration	Unconfined Valley Configuration
>90% of confined bank Absence of floodplains Channel planform Geomorphological Units	Between 10% and 90% of bank confinement Degree of lateral confinement Channel planform Geomorphological Units	<10% of bank confinement Absence or discontinuous channels Channel planform Geomorphological Units

Source: Brierley and Fryirs (2005), adapted by Rodrigues and Souza (2021).

For the definition of the geomorphological units in the study area, which are produced by the processes of erosion and sedimentation, the taxonomic basis for the geomorphological mapping of fluvial features proposed by Wheaton et al. (2015) was used, taking into account exclusively the geomorphological units recognized and present at the research sites (Table 01).

It is emphasized that, through the geomorphological classifications of rivers, it was possible to present their characteristics and functioning, which are considered one of the key factors in shaping the Earth's surface. In addition, it is highly relevant for identifying changes in the fluvial system and issues along the river channel, as demonstrated by Gomes and Magalhães Júnior (2018), Gomes and Magalhães Júnior (2020), Pelech (2021), and Marchioro and Ollero (2023), who work with the hydrogeomorphological classification of wetlands and rivers.

Table 01 – List of Geomorphological Units Analyzed in the Fluvial Context

Location	Taxonomic Levels		
	Level 1 (Vertical Situation)	**Level 2 (Form)**	**Level 3 (Specific Morphology)**
Outside the Channel	Active Floodplain	Concave	Secondary Channel
		Convex	Island
		Flat	Floodplain
Inside the Channel	Channel	Convex	In Channel
			Longitudinal Bar
			Cut-off Bar

Source: Adapted from Wheaton et al. (2015)

Thus, to begin the recognition of the river styles in the channel profile, the Apodi-Mossoró river was first analyzed under the Crystalline Basement using Google Earth imagery and, subsequently, field research was conducted. The vectorization of the channels for the river styles was carried out using the 'add path' tool in Google Earth, with the files saved in kml format, which was then converted to a vector file in QGIS. Also in Google Earth, the pre-identification of the valley configuration, channel planform, and geomorphological units present was executed. The images also allowed for the selection of 22 points to be visited during field research, considering locations with better access and landscape diversity.

Field research was conducted on April 30, July 2, and August 30, 2024, during the dry season of the region's hydrological year, in order to obtain better visibility of the fluvial channel morphology. A field sheet was used to record the characteristics observed in situ.

This sheet included the documentation of elements such as valley configuration, channel planform, bed morphology, geomorphological units, channel bars, and the processes occurring within the channel, following the model proposed by Brierley and Fryirs (2005), adapted by Magalhães Júnior and Barros (2020). Additionally, photographic records were made with UTM coordinate marking, altitudes, and timestamps, using the Timestamp Camera Free application.

3 RESULTS AND DISCUSSION

This section presents two topics related to the results and discussions. The first discusses the morphometric parameters found for the BHRAM and its distinct geological contexts (Crystalline Basement and Sedimentary Basin) as a means of understanding and comparing the proportions and physical characteristics of the watershed. The second and final topic focuses on the classification of the river styles and patterns found in the main river. Regarding the way this topic is presented and discussed for a better understanding of the fluvial sections, it was decided to follow the upstream-to-downstream order (from the upper course to the middle course).

3.1 Analysis of the Morphometric Characteristics of the Apodi-Mossoró River in the Crystalline Basement Area

The Apodi-Mossoró River watershed has a total area of 14,287 km², divided between the Crystalline Basement, which occupies 7,367 km², and the Sedimentary Basin, with 6,921 km². Despite similar areas and perimeters, the geological portions exhibit significantly distinct morphometric characteristics, as shown in Table 03.

Table 03 – Morphometric Characteristics of the Apodi-Mossoró River Watershed (BHAM)

Morphometric Characteristics	Apodi-Mossoró River Watershed (BHAM)	Portion of BHAM on the Crystalline Basement	Portion of BHAM on the Sedimentary Basin
A (A) (km²)	14.287,97	7.367,14	6.921,43
Perimeter (P) (Km)	868,58	716,36	656,52
Lowest elevation of the watercourse (m)	0,00	42,25	0,00
Highest elevation of the watercourse (m)	858,62	858,62	292,41
Length of the watercourse (L) (km)	220,54	94,69	119,36
Total length of watercourses (Lt) (km)	4.806,34	3.228,86	1.576,79
Compactness Coefficient (Kc)	2,03	2,33	2,20
Form Factor (Kf)	0,29	0,82	0,48
Circularity Index (Ic)	0,23	0,18	0,20
Drainage Density (Dd)	0,33	0,43	0,22
Relief Ratio (Rr)	0,0039	0,0086	0,0025

Source: Prepared by the author (2024).

The Crystalline Basement has morphometric characteristics that favor channel concentration and more direct runoff, which may result in rapid responses to precipitation events. In contrast, the Sedimentary Basin portion tends to naturally exhibit a greater infiltration capacity, influencing water retention and delayed runoff.

Regarding the compactness coefficient (Kc), which indicates the shape of the watershed, values close to 1 suggest a circular shape and a greater tendency for concentrated runoff and rapid hydrological responses, which increases the risk of flooding, as pointed out by Christofoletti (1980). In the case of the Apodi-Mossoró River Watershed (BHAM), the Kc value found was greater than 1, characterizing it as elongated. This shape favors a better distribution of water in the river channels during the rainy season, reducing the possibility of flooding due to the longer concentration time of the water. Upon examining the area corresponding exclusively to the Crystalline Basement, it was found that it does not have a circular shape, as it presents a value of 2.33, indicating that it naturally does not pose flooding risks.

Regarding the form factor (Kf) and the circularity index (Ic), BHAM presented low values, which aligns with the fact that the watershed has an elongated shape. This is corroborated by Peixoto et al. (2021), in their morphometric studies on the upper course of the Rio do Carmo/ RN watershed, where the form factor (Kf), combined with hydrological characteristics such as rainfall concentrated between 3 and 4 months and low water infiltration in the soil, results in highly variable runoff.

Padilha and Souza (2017), who performed morphometric characterization of a watershed, also obtained a low form factor value of 0.332, concluding that this occurs because an elongated watershed has a lower likelihood of experiencing intense rainfall at all points simultaneously. Pereira et al. (2019), when analyzing the morphometry of the Rio dos Patos/GO watershed, also identified an elongated shape in their study area, making it less susceptible to flooding and inundation under normal precipitation conditions, as it presented form factor values of 0.22 and a circularity index of 0.38.

For the Crystalline Basement, the form factor had a value of 0.82, which, according to the morphometric classification index, indicates susceptibility to flooding due to its longer water concentration time. This characteristic is attributed to the geological peculiarities of the area, marked by the predominance of igneous and metamorphic rocks with low permeability, which hinder water infiltration into the soil. However, the circularity index yielded a value of 0.1805, indicating its elongated shape, which reduces the likelihood of flooding. This means that, despite the form factor suggesting potential vulnerability to flooding, the elongated shape of the watershed, identified by the circularity index, acts as a mitigating factor, allowing water to spread along its tributaries and reducing the risk of immediate floods.

The drainage density of the watershed presented a value of 0.33, which is considered low according to the classification system, where values around 0.50 are classified as low and values between 2.01 and 3.50 as high. In their study on the morphometric analysis of the upper Paraíba River basin in the semi-arid region, Dornellas et al. (2020) also found a drainage density value of 0.74, similarly classified as low, which is characteristic of a low degree of relief dissection.

When considering the low drainage density value for the study area, it can be observed that the watershed exhibits an elongated shape and develops predominantly over flat terrains. However, in certain areas of the upper and middle courses, the relief becomes more undulating to strongly undulating, as it can be seen in the Portalegre, Martins, and Luiz Gomes mountain ranges, where the main source of the Apodi-Mossoró River is located. In these locations, the terrain displays slopes typical of mountainous and steep escarpment areas, with elevations exceeding 600 meters.

The drainage density for the Crystalline Basement was 0.43, with geological structures exerting control over the drainage pattern. According to Maia and Bezerra (2012), due to the impermeability of crystalline rocks, dendritic and sub-dendritic drainage patterns are typically formed, while parallel patterns result from drainage alignment with tectonic structures, particularly reliefs oriented along shear zone directions. Thus, the high complexity of geological structures, together with neotectonic movements, contributes to the formation of highly diversified landforms in the study area.

Maia (2022) emphasizes that, in the study area, the drainage system is controlled by incised valleys and ridges oriented NE–SW, and the morphology of residual massifs is aligned in the same direction. This configuration results from the Portalegre shear zone, or dextral strike-slip shear zone, which influences the development of a meandering channel behavior.

The relief ratio of the watershed was 0.0039. This low value reflects the general topographic characteristics, encompassing different geological contexts that influence the drainage pattern. Elements such as elevation and slope are key determinants of surface runoff velocity.

When compared with the values obtained for the Crystalline Basement, a higher value of 0.0086 was observed, attributed to the presence of more rugged terrain and higher elevations in that area. In locations with steeper slopes, the increase in surface runoff velocity, especially during precipitation events, it intensifies erosive processes and reduces infiltration capacity. As indicated by Silva, Melo, and Corrêa (2009), Moeini et al. (2015), Dragičević, Karleuša, and Ožanić (2019), Singh and Tirkey (2021), Kumar, Singh, and Saroha (2022), and Kim, Yoon, and Choi (2023), this phenomenon may be directly associated with the higher drainage density found in the area.

Celarino and Ladeira (2014), in their morphometric analysis of the Pardo River basin, located between the states of Minas Gerais and São Paulo, found that in the Paraná sedimentary basin area, drainage density values decreased due to lower slope gradients and higher infiltration rates. In the study conducted by Cardoso et al. (2006), most of the terrain was classified as strongly undulating, which reduced the potential for water infiltration into the soil.

From this perspective, based on the morphometric classification results of the Apodi-Mossoró River, it is understood that not only the lithological structure significantly influences its morphometric indices, but elevation and slope also act as important controls over fluvial dynamics and the distribution of water along the tributaries. Furthermore, morphometric parameters allow for the observation of watershed and watercourse proportions and features, enabling the differentiation and characterization of various areas. This, in turn, facilitates better understanding and forecasting of issues related to floods and inundations, supporting hydrological and environmental planning efforts.

3.2 Classification of Fluvial Styles and Patterns of the Apodi-Mossoró River in the Crystalline Basement Area

In general, fluvial compartmentalization and the classification of fluvial styles enable a clearer analysis of sediment production and anthropogenic activities, serving as key tools for planning purposes (Santos, Nascimento, and Barros, 2023). Accordingly, along the main course of the Apodi-Mossoró River within the Crystalline Basement section, three valley confinement patterns were identified: confined, partially confined, and unconfined. The unconfined valley configuration was predominant, extending approximately 68 km, as shown in Table 04.

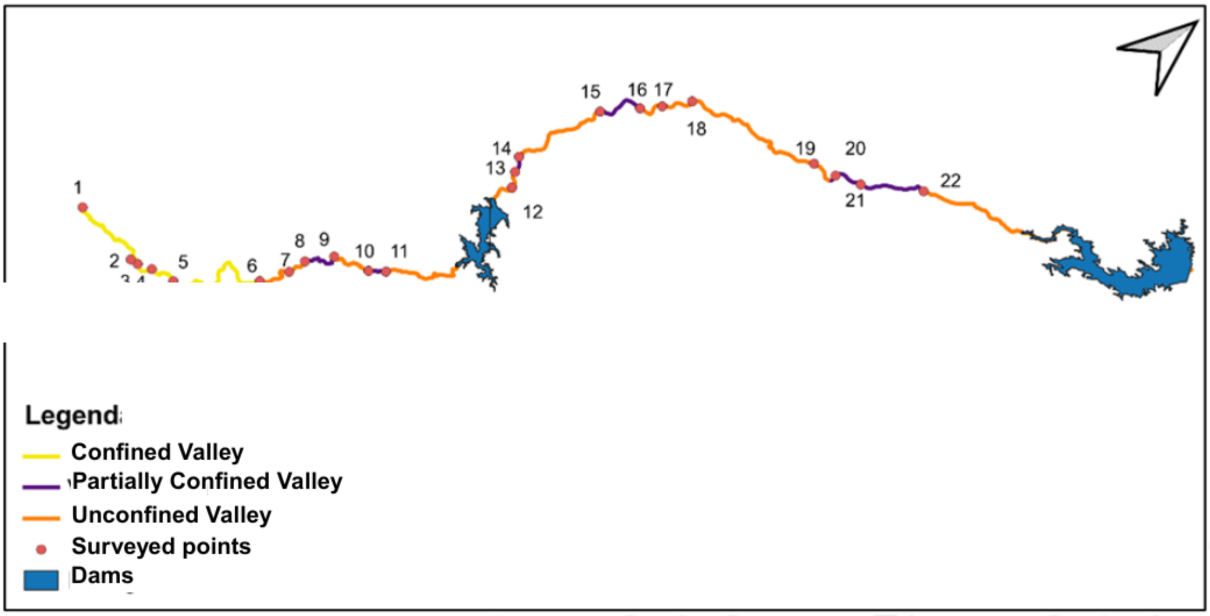
Table 04 – Extent of Fluvial Styles Compartmentalized into Three Valley Confinement Patterns

Fluvial Compartmentalization	Extent (Km)
Confined	14,95
Partially Confined	16,16
Unconfined	68,39

Source: Prepared by the author (2024).

The fluvial styles identified encompassed 22 analyzed points. As shown in Figure 03, along the distribution of styles, there is one reach with a confined valley, four reaches with partially confined valleys, and four reaches with unconfined valleys.

Figure 03 – Planform profile of the Apodi-Mossoró River bed (RN) and the corresponding fluvial styles over the Crystalline Basement



Source: Prepared by the author (2024).

Relief is recognized as a key landscape-shaping factor, responsible for determining fluvial forms and behaviors, closely associated with topography and slope. Santana and Marçal (2020) emphasize that relief not only enables the occurrence of diverse fluvial features but also exerts control over the fluvial system and influences the configuration of fluvial valleys.

When considering the topographic conditions and the classification of the upper course, where the landscape is predominantly characterized by strongly undulating (20–

45%) to mountainous (45–75%) relief, with altitudes ranging from 500 to 600 meters, it was observed that confined valley fluvial styles were more prevalent throughout the Crystalline Basement portion of the basin. This finding indicates a condition of geomorphological stability, marked by a consistent fluvial pattern with low susceptibility to adjustments.

Given its location in higher elevation areas, sections with greater flow velocity are predominant, particularly between February and May, when channel discharge is at its peak. This process can intensify erosive activity, especially in areas with lacking vegetative cover, and consequently, they transport coarser sediments downstream.

The confined styles in the upper course of the river were concentrated between segments 1 and 6, with elevations ranging from 552 to 274 meters. The marked presence of this fluvial style may be associated with the greater occurrence of impoundments along this channel, influencing the development of controlled margins and a reduced presence of floodplains, thereby contributing to the valley confinement (Figure 04).

Figure 04 – Segment 3–4 with impoundment interference and confined valley

Source: Prepared by the author (2024).

Furthermore, this section is located in more incised valleys with steeper slopes. In this reach, a lentic water behavior, or water accumulation, was identified, primarily due to the presence of dams that interfere with the river's flow capacity and promote greater sediment deposition, with sediments being retained. It is important to note that these observations were made during the dry season and under low river discharge conditions, when sediment accumulation and deposition within the riverbed were predominant.

Immediately following the confined valley style, due to the abrupt change in slope and elevation, the non-confined and partially confined valley styles become predominant. These areas are characterized by increased fluvial material transport and deposition, the development of floodplains, and the presence of geomorphological units such as islands and bars, associated with variations in flow velocity within the fluvial channel.

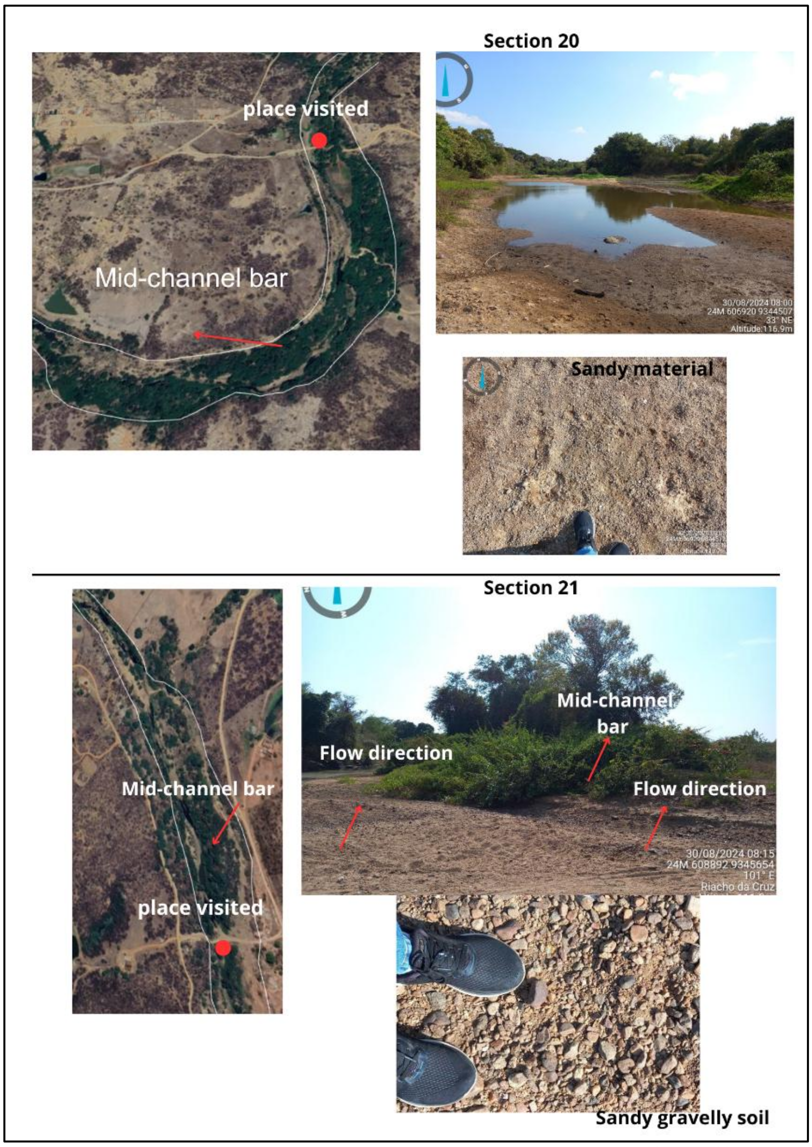
The partially confined fluvial style is distributed across five reaches (8-9; 10-11; 13-14; 15-16; 20-22). The processes occurring within the channel include the transport of finer materials and the deposition of coarse sediments, resulting from variations in flow characteristics. The prevailing bed morphology is colluvial, except for reaches 13-14 and 20-21, where the bed consists of colluvial material and exposed rock, with colluvial-sandy and sandy-gravelly characteristics. This style exhibits lateral discontinuities along its margins, primarily caused by unpaved roads, which interfere with the flow of water, sediment, and overbank flooding.

Regarding geomorphological units, reaches 13-14, 15-16, and 20-22 stand out due to the presence of vegetated, convex islands. In the colluvial-rocky reach, island formation occurs from sediment accumulation between exposed rock outcrops, with vegetated islands considered stable forms that take time to consolidate. Notably, reaches 20-21 (Figure 05) are characterized by the presence of vegetated islands, and the fluvial channel adopts an anastomosing form. This occurs as the channel attempts to bypass the geomorphological unit, resulting in the channel splitting to dissipate energy and solid discharge.

Regarding the Non-Confining styles, they exhibit discontinuities on both banks, with the identification of geomorphological units such as floodplains and vegetated islands. Along the river channel, a fluvial pattern is observed between reaches 11-13 and 16-20. According to Rodrigues and Souza (2021), flow in this fluvial style is prone to overflow during flood periods due to the lack of controls on the banks. These reaches flow through terrains with predominantly flat to gently undulating slopes, which define the floodplain.

In this fluvial style, a decrease in river velocity is predominant, which is characterized, according to Von Sperling (2007), by the formation of sediment deposits, leading to bed aggradation and widening, as well as facilitating the formation of geomorphological units such as channel bars and vegetated islands. These features may influence the diversion of the river channel and its planform shape.

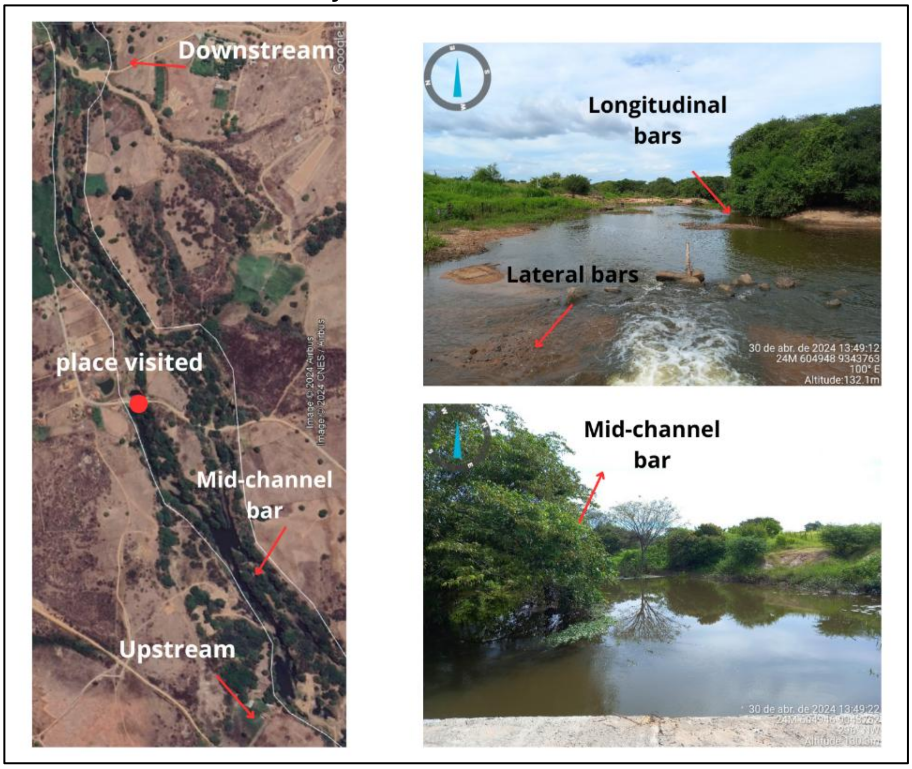
Figure 05 – Partially Confined Style of Reach 20-21 and its Elevation Profile



Source: Prepared by the author (2024).

It is noteworthy that reach 19-20 (Figure 06) contains convex gravel bars, both lateral and longitudinal, due to a bridge over the river that interferes with the transport capacity, with sediment accumulation being predominant near the culverts. Furthermore, this reach features an island with large vegetation, which alters its behavior, resulting in an anastomosed channel form with multiple channels.

Figure 06 – Unconfined Style of Section 19-20 and its Elevation Profile



Source: Prepared by the author (2024).

On this matter, Souza, Santos, and Oliveira (2023) emphasize the adaptability of different river styles in the upper course of the Paraíba River, noting that the unconfined sections exhibit characteristics of lower energy in the channel. In these areas, fine sand transport and suspended sediment predominates.

Additionally, it is highlighted that during high-magnitude flood events, the flow overflows, inundating the floodplains, which leads to lateral valley expansion, a decrease in specific energy, and a reduction in erosive potential. Under these conditions, depositional processes become predominant, shaping the geomorphological pattern and promoting the expansion of floodplain areas.

5 CONCLUDING REMARKS

The erosional, transport, and depositional processes exert a significant influence on the behavior, characterization, and specific attributes of each fluvial style identified in the Apodi-Mossoró River, particularly in the channel sections located over the Crystalline Basement area. The morphometric analysis enabled the preliminary recognition of the features that shape the fluvial morphology within this segment, as well as their influence on fluvial dynamics, which is directly linked to the distribution, behavior, and orientation of the drainage network.

In the analyzed sections, it was possible to identify three patterns of confined valleys, considering variations in slope, elevation, and the environmental conditions through which the river channels convey water and sediments. The characteristics of the fluvial geomorphological units were essential for differentiating the fluvial styles. In areas with higher elevations and steeper slopes, the predominance of confined valleys was observed. It was marked by margin control and the absence of broader geomorphological units, due to the greater flow velocity, which intensifies erosional processes.

Based on the identification of geomorphological units, such as bars and islands—which were more prevalent in the downstream sections and areas of lower elevation—a subtle change in fluvial behavior was observed, characterized by the development of multi-channel forms and anastomosed channels in the middle course of the river. It was thus understood that these sections experience a reduction in flow velocity and a corresponding loss of flow energy. As this occurs, heavier and gravelly materials are deposited, which over time evolve into stable bars and subsequently into islands, prompting the river to adapt and modify its course.

Finally, it is important to highlight that future studies incorporating additional natural and anthropogenic elements into the analysis - such as rainfall patterns, lithologies, topography, soil types, and land use - may yield more detailed results that could better explain the modifications in the observed fluvial patterns, as well as identify areas susceptible to fluvial changes. In this regard, it is suggested that research of this nature can be fundamental for territorial planning and water resources management, contributing to the identification of priority areas for interventions, such as erosion control measures and soil conservation actions.

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