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Research Article

Parameterization of flow intermittency and river styles in two hydrographic basins in the semiarid region of Paraíba

Parametrização de intermitência de fluxo e estilos fluviais em duas bacias hidrográficas no semiárido paraibano

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Abstract: This study parameterizes the behavior of intermittent rivers under similar morphoclimatic conditions in the Brazilian semi-arid region, focusing on the Paraíba and Piranhas River basins, impacted by SFIP. Methodologically, the base flow index (BFI) and the analysis of river styles (River Styles - RS) were integrated to characterize the perenniality and intermittency of rivers and to understand the geomorphological variability of river stretches. The BFI indicated that both rivers have perenniality of less than 5%, with the Paraíba River exhibiting a higher intermittency than the Piranhas River, corroborating analyses of frequency and duration of flow. The fluvial styles identified include confined (rocky and gravel) and partially confined stretches, with variability in geological and morphological controls. The fluvial style matrix revealed distinctive attributes, such as bed texture and connectivity, emphasizing the influence of hydrogeomorphological dynamics on fluvial stretches. The results contribute to the understanding of intermittent rivers in semi-arid environments, providing subsidies for hydrological analysis and water resources management in similar regions. Thus, this work is important to deepen studies in semi-arid river environments by providing a qualitative and quantitative proposal for analyzing intermittency and river behavior.

Keywords: non-perennial rivers; semi-arid river dynamics; river styles.

Resumo: Este estudo parametriza o comportamento de rios intermitentes em condições morfoclimáticas semelhantes no semiárido brasileiro, com foco nas bacias dos rios Paraíba e Piranhas, impactados pelo PISF. Metodologicamente, foram integrados o índice de fluxo base (BFI) e a análise de estilos fluviais (River Styles - RS) para caracterizar a perenidade e a intermitência dos rios e compreender a variabilidade geomorfológica dos trechos fluviais. O BFI indicou que ambos os rios apresentam perenidade inferior a 5%, com o Rio Paraíba exibindo uma intermitência superior ao Rio Piranhas, corroborando com as análises de frequência e duração de fluxo. Os estilos fluviais identificados incluem trechos confinados (rochoso e cascalhento) e parcialmente confinados, com variabilidade nos controles geológicos e morfológicos. A matriz de estilos fluviais revelou atributos distintivos, como textura do leito e conectividade, enfatizando a influência das dinâmicas hidrogeomorfológicas sobre os trechos fluviais. Os resultados contribuem para a compreensão dos rios intermitentes em ambientes semiáridos, fornecendo subsídios para análises hidrológicas e gestão de recursos hídricos em regiões similares. Assim, este trabalho é importante para aprofundar estudos em ambientes fluviais semiáridos a partir do fornecimento de uma proposta qualiquantitativa de análise de intermitência e comportamento fluvial.

Palavras-chave: rios não perenes; dinâmica fluvial semiárida; estilos fluviais.

1. Introdution

The permanence of river flow is influenced by factors such as the duration, frequency, and magnitude of rainfall. However, a more comprehensive understanding must include geological elements, which help explain hydrological responses in flow patterns (COSTIGAN et al., 2016; ZIPPER et al., 2022). In dry environments, non-perennial hydrological regimes prevail, characterized by ephemeral and intermittent channels that exhibit temporal and spatial discontinuities in flow. These non-perennial rivers have concentrated discharges over short periods, especially in response to rainfall events (CONESA-GARCÍA et al., 2020; FORTESA et al., 2021; SUTFIN et al., 2014).

In intermittent channels, flow is seasonal and depends on groundwater recharge during the rainy period, ceasing during dry seasons and resulting in hydrological disconnection (CHARLTON, 2008a; COSTIGAN et al., 2016). Ephemeral channels, on the other hand, exhibit brief flows that may last from hours to days, and their dynamics are affected by storms that only partially cover the basin, causing runoff losses (SUTFIN et al., 2014). Thus, rivers in dry areas directly reflect the variability of the rainfall regime, where intermittent channels have hydrology strongly linked to alluvial deposits, while ephemeral channels are associated with immediate runoff following rainfall (ANDRADE & FERNANDEZ, 2023; SANDERCOCK; HOOKE; MANT, 2007).

Given that water scarcity in the channel is frequent and seasonal, such dynamics can be considered its "normal functioning," as any level of water discharge that connects inundated segments and generates flow in the channel acts like a flood that performs mechanical work (SOUZA; ALMEIDA, 2015; DORNELLAS et al., 2020). In this way, sediment transport in natural semi-arid environments occurs only during part of the year, specifically during flood events. Without flow, the channel loses competence, leading to sediment deposition until the next discharge-generating event can remobilize bed material (SOUZA; ALMEIDA, 2015; DORNELLAS et al., 2020; KARAMITOPOULOS et al., 2022).

This pulsed discharge reduces channel incision processes and, consequently, the evolution of the longitudinal profile toward an equilibrium form (CHEN et al., 2019). However, equilibrium morphologies are rarely found in nature in a linear way, and a steady-state condition is generally absent in natural environments. On the contrary, the perspective of non-equilibrium or disequilibrium in dryland fluvial systems, that is, the predominance of morphological instability, can be understood as the most appropriate interpretive framework (CHEN et al., 2019; PHILLIPS, 2011).

Considering this, understanding fluvial regimes and characteristics is crucial, as it allows us to assess the influence of the catchment area and its adaptation to either climatic changes or anthropogenic disturbances in the channel (DEVIA et al., 2015; ELTNER et al., 2020). Efficient and cost-effective monitoring and mapping tools are essential and represent a current prerequisite in research for the development and evolution of scientific projects (DEWAN et al., 2017; LANGAT et al., 2019; LARNED et al., 2011).

In addition to traditional measurements using gauging stations or manual devices, remote sensing employs image-based approaches as alternatives in unmonitored areas. These are flexible methods for inferring runoff, as they do not require a minimum amount of water in the bed to identify flow energy through modeling (ELTNER; SARDEMANN; GRUNDMANN, 2020). Beyond automated mapping techniques, there are also desktop and field-based approaches, such as the River Styles methodology. This is a qualitative and quantitative approach that aims to characterize homogeneous river reaches based on channel attributes that are summarized and analyzed, enabling a better understanding of fluvial dynamics and morphology (BRIERLEY, 2010; BRIERLEY & FRYIRS, 2005).

The aim of this study is to analyze the intermittency of river channels and its relationship with different river styles in the upper basins of the Paraíba and Piranhas rivers, considering that these are naturally temporary channels that have been the focus of inter-basin water transfer projects in northeastern Brazil. These basins were selected because they began receiving water from the São Francisco River transposition (since 2017 in the Paraíba River and since 2021 in the Piranhas River), and they are being directly impacted hydro-geomorphologically by this artificial water input. Moreover, they contain similar fluvial segments that recur in various regions across the Brazilian Northeast.

2. Area characterization

The study area encompasses the upper course of the Paraíba River (Cariri region of Paraíba) and the upper course of the Piranhas River (Sertão region of Paraíba) (Figure 1).

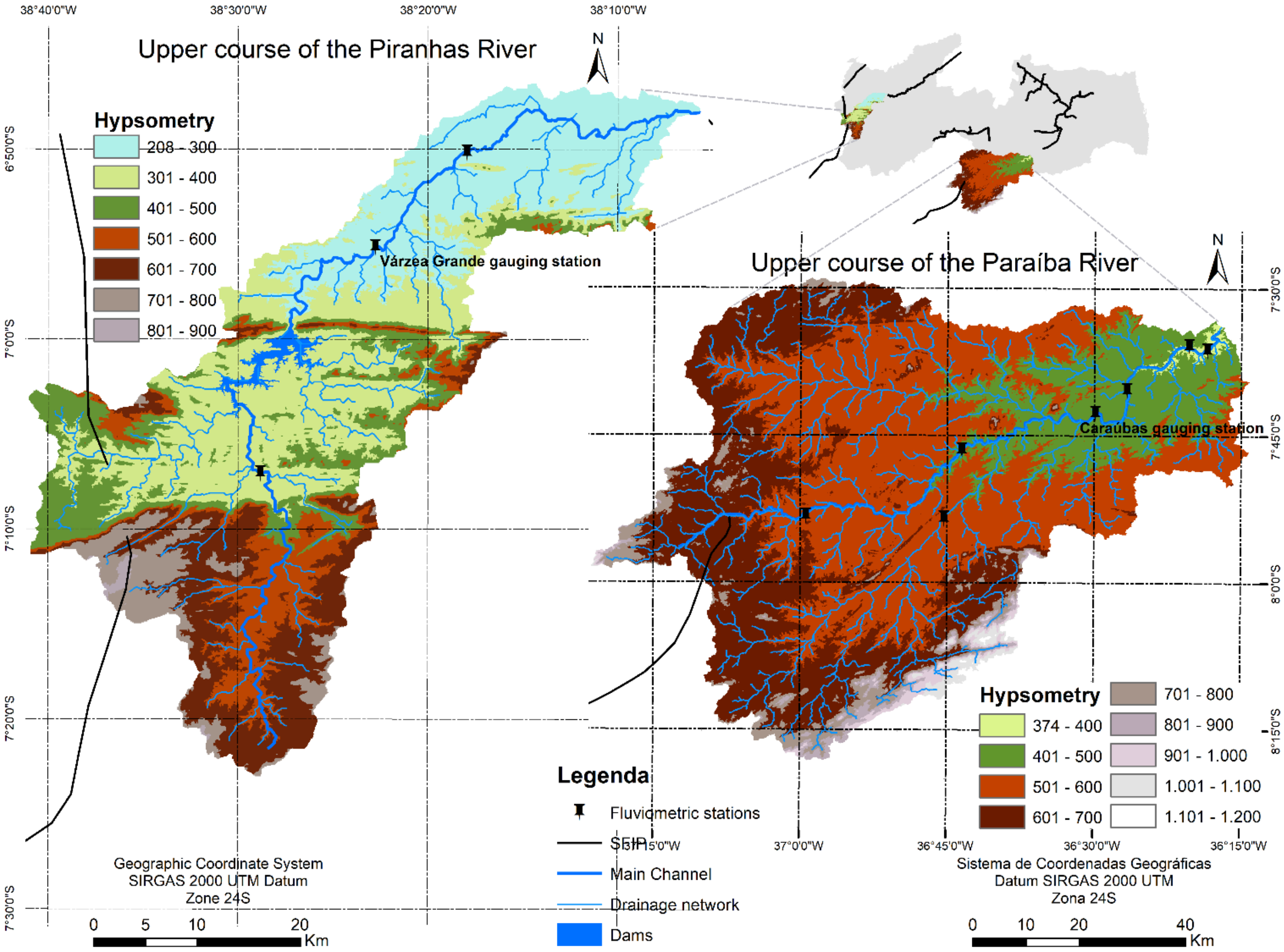


Figure 1. Location map of the study areas, including their respective DEMs, drainage networks, and the locations of identified streamflow gauging stations. Source: Author (2023).

The upper course of the Paraíba River extends for 167 km and drains a basin area of 6,226 km², with an altimetric variation of 798 m. The lowest elevation is 374 m at the river mouth, while the highest point reaches 1,172 m in the headwater areas, which lie within the crystalline geology of the Borborema Plateau. The upper course of the Piranhas River is 121 km long, covering a basin area of 1,548 km², with an altimetric amplitude of 670 m—ranging from a minimum elevation of 206 m at the river mouth to a maximum of 876 m near the headwaters, within the Sertaneja Depression zone (Table 1).

Table 1. Main characteristics of the upper course basins of the Paraíba River (UCPAR) and the Piranhas River (UCPIR). Source: Author (2023).

	UCPIR	**UCPAR**
	Climatic	
Climate zone	Semi-arid tropical	Semi-arid tropical
Average precipitation (mm)	500 mm to 900 mm	250 mm to 900 mm
	Watershed	
Drainage area (km²)	1548 km²	6226 km²
Length (km)	121 km	167 km
Lithology	Igneous and metamorphic	Igneous and metamorphic
Altimetric range	670 m	798 m

The climate in both basins is typically semi-arid, with rainfall concentrated during part of the year and a dry season prevailing during the remainder. According to Rodrigues (2020), the upper Piranhas River basin receives rainfall mainly between January and April (four months), with December representing the pre-rainy season, and an annual average precipitation of 900 mm. The Paraíba River basin experiences rainfall concentration over 3 to 4 months, with an average annual precipitation ranging between 250 mm and 900 mm (DORNELLAS et al., 2020). What characterizes these regions as semi-arid is the negative water balance between precipitation and evapotranspiration, the latter exceeding 2,000 mm per year (LIMA et al., 2021). Thus, although rainfall volumes may be considerable when compared to other semi-arid regions worldwide, the Brazilian semi-arid region experiences a persistent water deficit due to high evapotranspiration rates.

The geology of the Paraíba River basin is predominantly composed of rocks forming the shield of the Borborema Plateau, situated in the Borborema Province—a set of Precambrian structures deformed by the Brasiliano orogeny over an area of approximately 450,000 km². The drainage network in this region is structurally controlled (CORDEIRO et al., 2024). In contrast, the bedrock of the upper Piranhas River basin ranges from the Phanerozoic to the Archean, with a predominance of Proterozoic rocks. The lower parts of the Piranhas basin are primarily composed of younger sedimentary rocks, while the higher and transitional surfaces are older and crystalline. Furthermore, the orientation of the drainage network is influenced by major ductile and brittle deformation structures trending NE–SW and E–W. These structural controls result from lithostructural conditioning of the landscape developed since the end of the Brasiliano Cycle (CORDEIRO et al., 2024).

As shown in Table 2, not all streamflow gauging stations have long-term data records. The exceptions are the Caraúbas station on the Paraíba River and the Várzea Grande station on the Piranhas River (Figure 1), which began operations in 1970 and 1962, respectively. The remaining stations began monitoring activities from 2015 onward. Therefore, the Várzea Grande and Caraúbas stations will serve as the primary sources for specific methodological procedures in this study (Table 2).

Table 2. Streamflow gauging stations in the studied basins and their respective data time spans. Source: ANA (2023).

Station	Code	River	Municipality	Streamflow data period	Cross-section profile	Drainage area (km²)
PARAÍBA RIVER						
Caraúbas	38830000	Paraíba River	Caraúbas	1970 - 2022	1990 - 2019	5,030
Sítio Conceição	38812000	Paraíba River	Sumé	2017 - 2021	1999 - 2019	1240
Açude Poções	38801000	Paraíba River	Monteiro	Only Flow stage	No data	651
Pisf Sítio Porteiras	38831000	Paraíba River	São Domingos do Cariri	Only Apenas descarga	No data	No data
Açude Epitácio Pessoa Montante	38855050	Paraíba River	Cabaceiras	Only Flow stage and Discharge	No data	No data
PIRANHAS RIVER						
São José De Piranhas	37200000	Piranhas River	São José de Piranhas	Only Flow stage	No data	400
São João Do Rio Do Peixe	37220001	Piranhas River	São João do rio do Peixe	Only Flow stage	No data	No data
Fazenda Pau D'árco	37230100	Piranhas River	Sousa	2022 - 2023	2022	1440
São Domingos De Pombal	37300000	Piranhas River	Pombal	2022 - 2023	2022	5400
Várzea Grande	37220000	Piranhas River	São João do rio do Peixe	1962 - 2022	1985 - 2022	1110
Camalaú – Montante	38800500	Umbuzeiro River – tributary of the Paraíba River	Camalaú	2015 - 2022	2011 - 2022	1500

3. Materials and methods

This study is based on the characterization of flow permanence and, subsequently, the analysis of non-perennial river reaches to understand how and where changes occur in the fluvial environment, as shown in Figure 2.

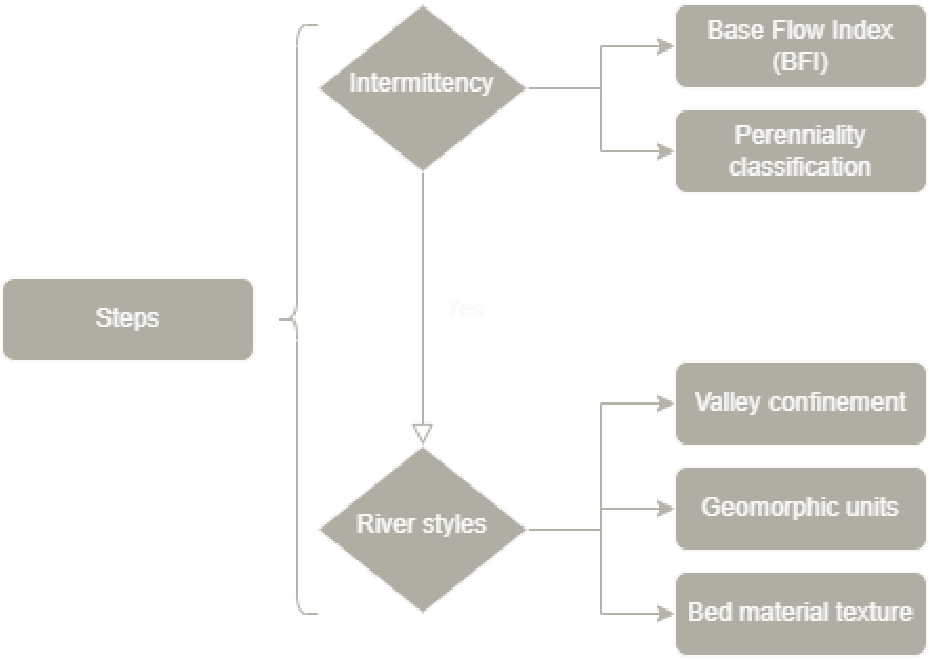


Figure 2. Flowchart of the research steps. Source: authorial (2024).

To achieve this, the key question is how to integrate the methodologies for a more robust analysis.

Flow Permanence: Even in intermittent rivers, analyzing flow permanence can provide insights into baseflow contribution during dry periods and help define intermittency. Since intermittent rivers in the semi-arid region exhibit seasonal flow, flow permanence and the Base Flow Index (BFI) can help identify periods when groundwater sustains the river, distinguishing it from ephemeral rivers (which only flow following precipitation events).

River Styles (RS): Once the flow permanence and intermittency of rivers are classified, RS can be used to analyze the geomorphological and functional characteristics of different river reaches, including non-perennial ones. RS focuses on how river reaches respond to changes in flow, sediment, and terrain structure. It enables understanding of the spatial variability of rivers, based on factors such as morphology, connectivity, and erosion and deposition processes. These stages are conducted after the flow permanence analysis and the characterization of River Styles. Thus, the BFI can be used to quantify intermittency and characterize hydrological dynamics throughout the year, while RS can interpret the effects of this dynamic on the morphology of river segments. Functional connectivity highlights the percentages and specific points of change in river reaches.

Flow Permanence/Intermittency

To analyze flow permanence, it was necessary to obtain discharge data for the studied rivers and define certain metrics as outlined in Table 3. This table summarizes the main metrics used to assess flow permanence, contributing to a robust classification of the studied river regimes.

Table 3. Metrics used in the analysis of flow permanence. Source: authors (2025).

Metric	Definition and Calculation	Reference
Base Flow Index (BFI)	Ratio between the mean low flow (Q_low) and the annual mean flow (Q). The higher the value, the greater the flow stability.	Sawicz et al., 2014; Zhao et al., 2023
Zero Flow Duration	Total number of days with no flow in a year, indicating the persistence of intermittency.	Oueslati et al., 2015
Zero Flow Frequency	Number of consecutive events with no flow, allowing the evaluation of interannual intermittency patterns.	Oueslati et al., 2015
Intermittency Classification	Dispersion analysis of Mean Frequency (mFREQ) versus Mean Duration (mDUR), categorizing rivers into three subclasses of intermittency.	Snelder et al., 2013
Principal Component Analysis (PCA)	Dimensionality reduction through linear combinations of variables, optimizing variance and providing clearer interpretations of hydrological variables.	Johnson, 2002

In this context, the Várzea Grande and Caraúbas stations are the methodological basis in some steps.

The definition of the river regime in the upper course of the Paraíba and Piranhas rivers required analyzing at least 15 years of data (EIDMANN & GALLEN, 2023). Therefore, in this initial stage, the discharge data analysis period was from January 1970 to December 2021 (Piranhas River) and 2021 (Paraíba River), totaling over 50 years of discharge data analysis for both stations. For this, the approach proposed by Sawicz et al., 2014 and Zhao et al., 2023 was used, which includes the calculation of the Base Flow Index (BFI) in Equation 1, defined by the ratio:

$$BFI = \frac{\overline{Q_{low}}}{Q}100 \tag{1}$$

Here, $\overline{Q_{low}}$ represents the average low flow during the considered period, and Q is the annual average flow. To define the average low flow, a threshold method is applied, where the minimum flow is defined to separate the base flow from total flow, and this minimum flow corresponds to flows that occur more than 25% of the time in the analyzed period. Given this, results nearly 100% indicate stable, sustained flow throughout the year, while values near 0% suggest sporadic or transient flow.

This study also applied the analysis proposed by Oueslati et al. (2015). The analysis of flow intermittency considers metrics such as the duration and frequency of zero-flow days. Notably, the number of no-flow days is crucial for classifying non-perennial rivers (Oueslati et al., 2015). The duration of zero-flow events is quantified annually by the total number of no-flow days, offering insights into the persistence of flow within a year. Frequency refers to the number of consecutive zero-flow days, allowing the analysis of interannual variations in stream intermittency. The intermittency classification, based on a scatter plot of mean frequency (mFREQ) versus mean duration (mDUR) (Snelder et al., 2013), identified three distinct subclasses. Subclass 1 is characterized by zero-flow periods with low frequency and short duration, while subclass 2 has long-duration events with low frequency. Lastly, subclass 3 is marked by high-frequency and long-duration zero-flow periods.

To complement the analysis, a hydrograph analysis was conducted, correlating rainfall and discharge data between the Várzea Grande (Piranhas River) and Caraúbas (Paraíba River) stations and their nearest and most temporally complete rain gauge stations, Bonito de Santa Fé and Monteiro, respectively. However, it is important to note that the analysis period was from 2008 to 2020, due to the availability of rainfall data for this time span, enabling an understanding of the discharge response time to rainfall events during this period.

Principal Component Analysis

One application of principal component analysis (PCA) is dimensionality reduction, and since the patterns and trends of the variable set are maintained in the components, it can offer new interpretations (JOHNSON, 2002). Algebraically, the principal components are linear combinations of p random variables $X_1, X_2,...,X_p$, and the combinations represent, geometrically, a new coordinate system obtained by rotating the original system using $X_1, X_2,...,X_p$ as coordinate axes. Thus, the new coordinates represent the directions in which variance is maximized (Equation 2).

$$\begin{aligned} Y_1 &= a_{11}X_1 + \dots + a_{1p}X_p \\ &\vdots \\ Y_p &= a_{p1}X_1 + \dots + a_{pp}X_p \end{aligned} \tag{2}$$

Where the random vector $X' = \{X_1, X_2,\dots,X_p\}$ has a covariance matrix Σ (or correlation matrix ϱ) with eigenvalues $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_p \geq 0$ (Equation 3). Therefore, calculating variance and covariance yields:

$$\begin{aligned} Var(Y_i) &= a_i' \textstyle\sum a_i \quad i = 1,2,3,\dots,p \\ Cov(Y_i, Y_k) &= a_i' \textstyle\sum a_k \quad i,k = 1,2,3,\dots,p \end{aligned} \tag{3}$$

The principal components are the uncorrelated linear combinations $Y_1,\dots,Y_p$ where variance is maximized. Thus, the first principal component is the linear combination $a_1'X$ that maximizes $Var(a_1'X)$ subject to $a_1'a_1 = 1$ (Equation 4). In the i-th step, we have:

$$\begin{gathered} i - éi - th\, principal\ component\ =\ linear\ combination\ of\ a\_i\^{}'\ X\ that\ maximizes \\ Var(a_i')\ sujeitoa\ a_i' a_i\ =\ 1\ e \\ Cov(a_i' X, a_k'\, X)\ =\ 0\ \forall\ k\ <\ i \end{gathered} \tag{4}$$

River Styles

To define river styles at the channel scale, it is necessary to assess three river variables: valley setting, geomorphic units, and bed material texture (Table 4).

Table 4. Variables assessed to determine valley setting. Source: Adapted from Brierley and Fryirs (2005).

CONFIGURATION OF CONFINED VALLEY	**CONFIGURATION OF PARTIALLY CONFINED VALLEY**	**CONFIGURATION OF NON-CONFINED VALLEY**	
(>90% CONFINED MARGIN)	(BETWEEN 10% AND 90% MARGIN CONFINEMENT)	(<10% MARGIN CONFINEMENT)	
PRESENCE/ABSENCE OF FLOODPLAINS	DEGREE OF LATERAL CONFINEMENT AND VALLEY CONFIGURATION (STRAIGHT - IRREGULAR - SINUOUS)	ABSENCE OR DISCONTINUOUS CHANNELS	PRESENCE OF CONTINUOUS CHANNELS
GEOMORPHIC UNITS	CHANNEL PLAN FORM	GEOMORPHIC UNITS	GEOMORPHIC UNITS
BED MATERIAL TEXTURE	GEOMORPHIC UNITS	SURFACE MATERIAL TEXTURE	BED MATERIAL TEXTURE
	BED MATERIAL TEXTURE		

Valley setting is the entry point for defining river style and is determined by the degree of channel confinement, expressed by the presence or absence of floodplains along river courses. Thus, channels may be confined, partially confined, or unconfined. Confined channels generally exhibit less than 10% floodplain on both channel margins. Partially confined channels have between 10% and 90% floodplain on both margins, so these floodplains may be alternating or discontinuous along the river course. Unconfined channels show less than 10% margin confinement, with continuous floodplains along the margins, and may include both continuous and discontinuous channels (BRIERLEY; FRYIRS, 2005). In this context, a UAV (Unmanned Aerial Vehicle) was used to generate information about valley width and to topographically represent geomorphic units according to their height variations within the fluvial environment.

Geomorphic units are a key tool for interpreting channel characteristics and behavior. They are the main interpretive parameter within the river styles framework. The criteria used are: number of channels, sinuosity, bars, and islands (BRIERLEY; FRYIRS, 2005). Since this procedure is conducted both in the office and in the field, it is important to note that the identification of the number of channels, sinuosity, bars, and islands will use the most recent Google Earth satellite images that allow clear visualization of the channel planform. During fieldwork, a drone will be used to allow detailed identification of geomorphic units and the generation of a detailed river styles map at the reach scale.

Bed material texture is another analysis procedure for determining styles and is based on the grain size of sediment present in the riverbed. The Wentworth scale (1992) was used to define grain size. Fieldwork initially involved collecting sediments from the bed of different river styles. In the lab, grain size analysis was performed using sieving for coarse sediments and pipetting for fine sediments (GALE and HOARE, 1991, apud SILVA and SOUZA, 2017). For this, 100 g of each sample (11 samples in total) were weighed and placed in 500 ml glass beakers with water and 20 g of dispersant (sodium hexametaphosphate). The samples were stirred continuously for 20 minutes to break up grain fractions, then left to settle for 24 hours. Afterward, the samples were washed and placed in an oven at 70ºC for 10 hours. Finally, they were processed with a ROTAP electromagnetic sieve shaker to determine grain size distribution. Five classes are used: Bedrock; Boulder (>256 mm); Gravel (2–256 mm); Sand (0.0625–2 mm); Silt and Clay (<0.0625 mm). After defining and characterizing the river styles, it will be possible to produce one styles map for the upper basin of the Paraíba and Piranhas rivers, based on the variables that drive variations in river reaches.

4. Results

4.1. Flow Perenniality and Principal Components

To determine the Base Flow Index (BFI), it was necessary to define the streamflows above the 25% exceedance threshold in the historical series (EIDMANN & GALLEN, 2023). In this way, discharges above 3.37 m³/s in the Paraíba River and 2.28 m³/s in the Piranhas River were considered. Thus, the variables used in the equation could be defined, as shown in Table 5.

Table 5. Variables analyzed to define BFI. UCPIR – Upper Course of the Piranhas River; UCPAR – Upper Course of the Paraíba River. Source: Author (2023).

	UCPIR	UCPAR
Average Low Flows	0.56	0.244
Average Annual Flows	1,75	5,33
BFI (%)	31,87	4,57

The BFI indicated that the flow perenniality of the Piranhas and Paraíba rivers is closer to 0% than to 100%, showing that these are intermittent rivers, as they spend most of the year with zero flow, especially the Paraíba River, which showed a 4.57% annual flow permanence, being classified as strongly intermittent. The number of days with discharge equal to or below the minimum flow was 12,998 for the Piranhas River and 14,952 for the Paraíba River between January 1970 and December 2021. Therefore, the difference in minimum flow days between the two rivers represents an approximate 15% increase in the number of days for the Paraíba River compared to the Piranhas River. This results in a difference of 1,954 minimum-flow days between the stations analyzed. The analysis of flow intermittence subclass reveals that most years analyzed fall into subclass 3 at the Caraúbas station, located on the Paraíba River, characterized by a high frequency and long duration of intermittence (Figure 3).

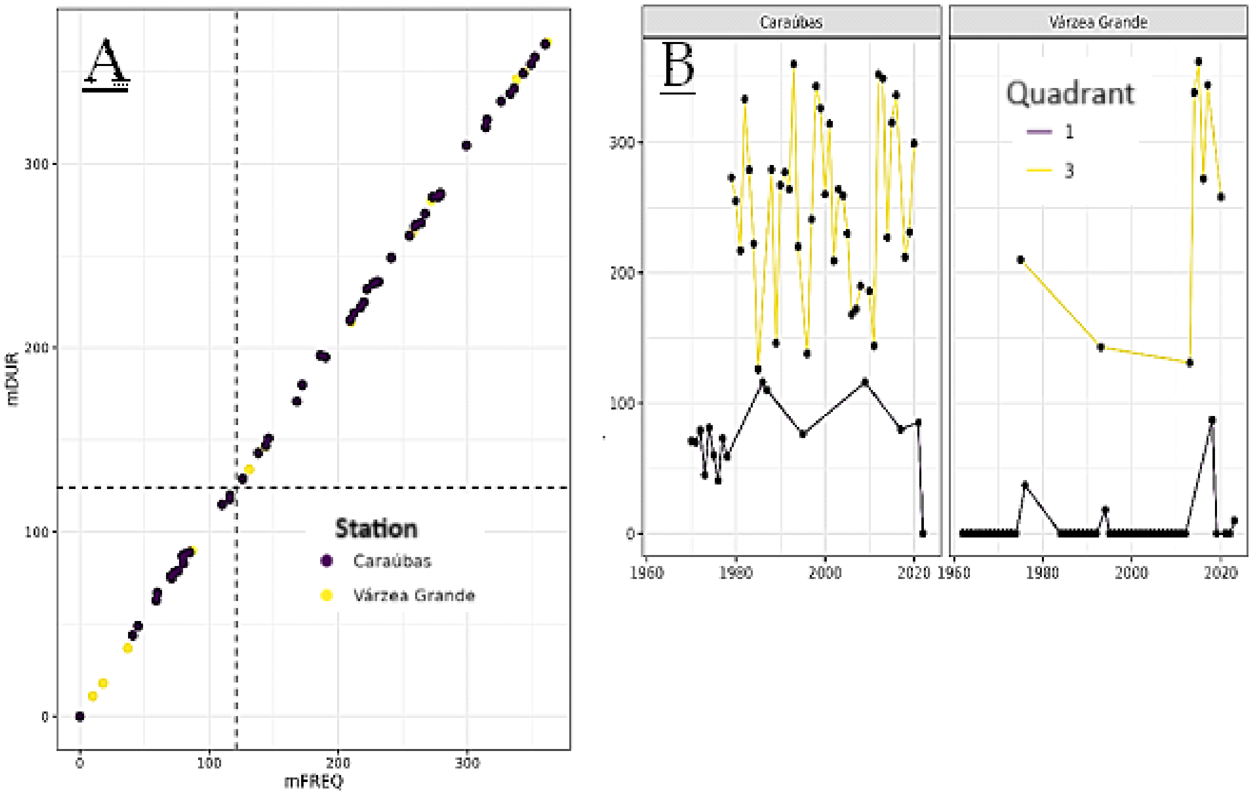
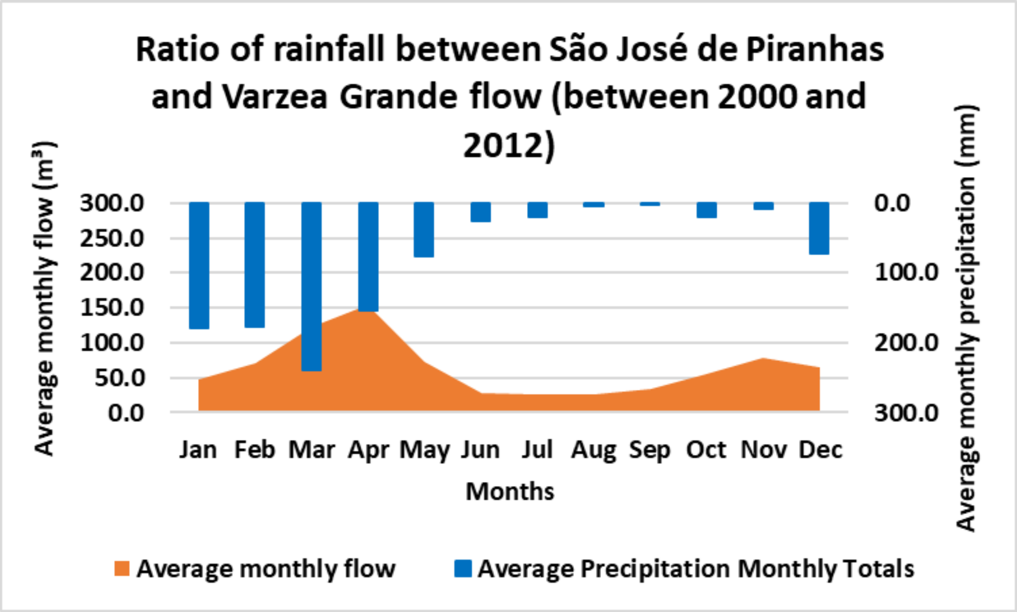


Figure 3. mDUR and mFREQ for the Caraúbas and Várzea Grande gauging stations. A: interpolation of mDUR and mFREQ results by quadrants. B: separation of mDUR and mFREQ by station. Source: Author (2023).

On the other hand, at the Várzea Grande station, most of the analyzed years fall into subclass 1, indicating that the Paraíba River exhibits higher flow intermittence than the Piranhas River, reinforcing the BFI assessment. Thus, the duration of zero-flow periods shows that most years in the Paraíba River register more than 120 days without interannual flow, with a frequency of over 120 consecutive days without discharge. Consequently, the Paraíba River concentrates most of its years in subclass 3, in comparison to the Piranhas River, and is classified as highly intermittent, while the latter may be considered less prone to strong intermittence.

It is important to highlight that, when comparing rainfall and discharge data, it is evident that the channels are hydrogeomorphologically conditioned by water input from precipitation, considering that the predominantly crystalline substrates of the basins act as enhancers of surface runoff, generating immediate discharge responses to rainfall (Figure 4).



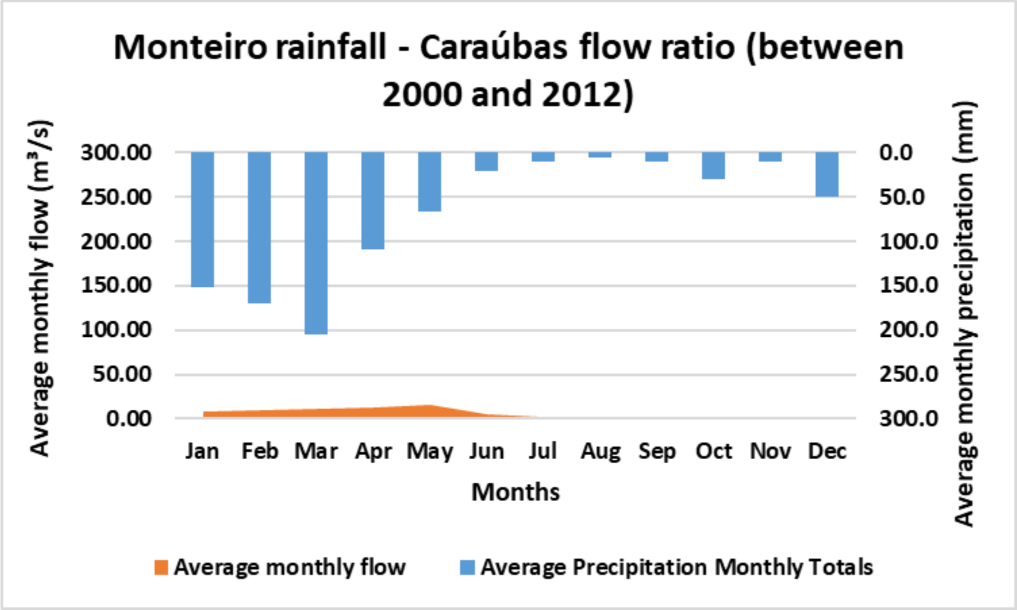


Figure 4. Hydrographs of the Várzea Grande (Piranhas River) and Caraúbas (Paraíba River) stations with their respective nearest rain gauges.

According to Figure 4, discharge events are closely related to rainfall events in both basins, with the upper Piranhas River basin showing higher discharge values that can reach up to 20.6 m³/s in April, shortly after the rainiest month, March. These values, combined with the crystalline structural characteristics and higher historical monthly average rainfall, confirm the flow perenniality indicated by the BFI, characterizing the Paraíba River as more intermittent.

In general, the Paraíba and Piranhas rivers are correctly categorized as intermittent, with most of the year showing low flow persistence, with values below 1 m³/s and most years falling into subclass 3 (strongly intermittent).

The first component explains approximately 100% of the variation, while the second explains a much smaller proportion. Due to this discrepancy, it is not possible to observe how the stations behave in relation to the second component (Figure 5).

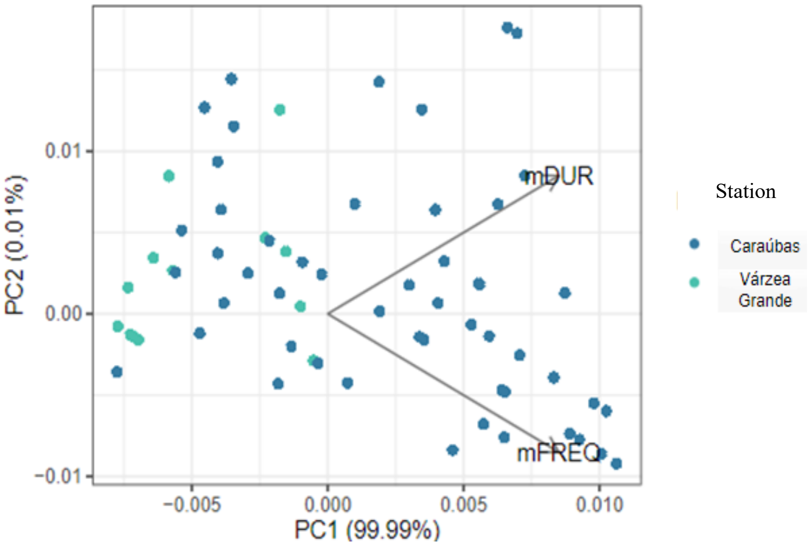


Figure 5. PC1 and PC2 for the Várzea Grande and Caraúbas stations. Source: Authors (2024).

Thus, the first component is the focus. It is evident that the frequency and duration vectors are directly proportional to the first component. Observations from Caraúbas show a pattern of higher frequency and duration, although some outliers indicate lower duration. In contrast, observations from Várzea Grande show lower frequency and duration.

Flow permanence in the Piranhas and Paraíba rivers indicates that both have prolonged periods of low discharge throughout the year, with about 80% of the time showing flows below 20 m³/s (Figure 6). For a more detailed analysis, the flow duration curves reveal that, between 1970 and 2021/2022, both rivers had most years with flows below 1 m³/s. Specifically, the Piranhas River had a 52% flow permanence below 1 m³/s, while the Paraíba River reached 65%.

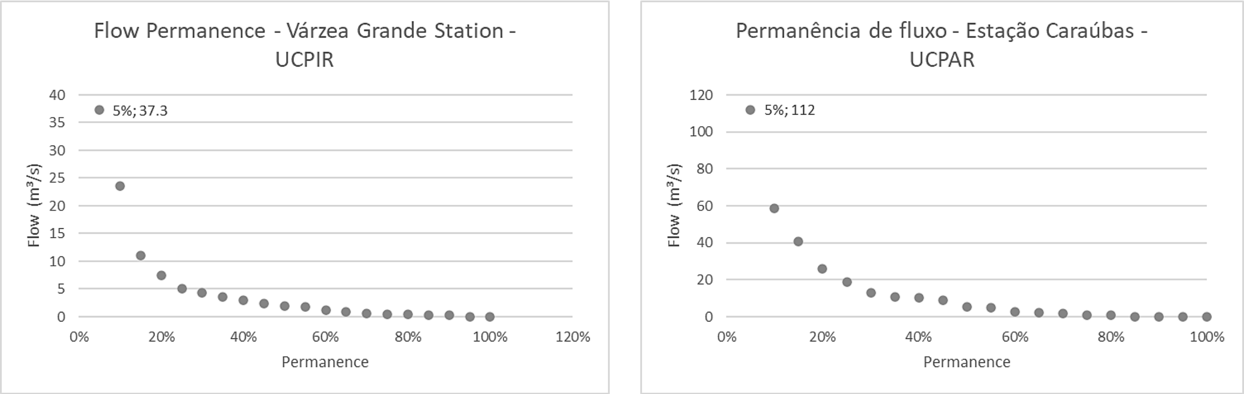
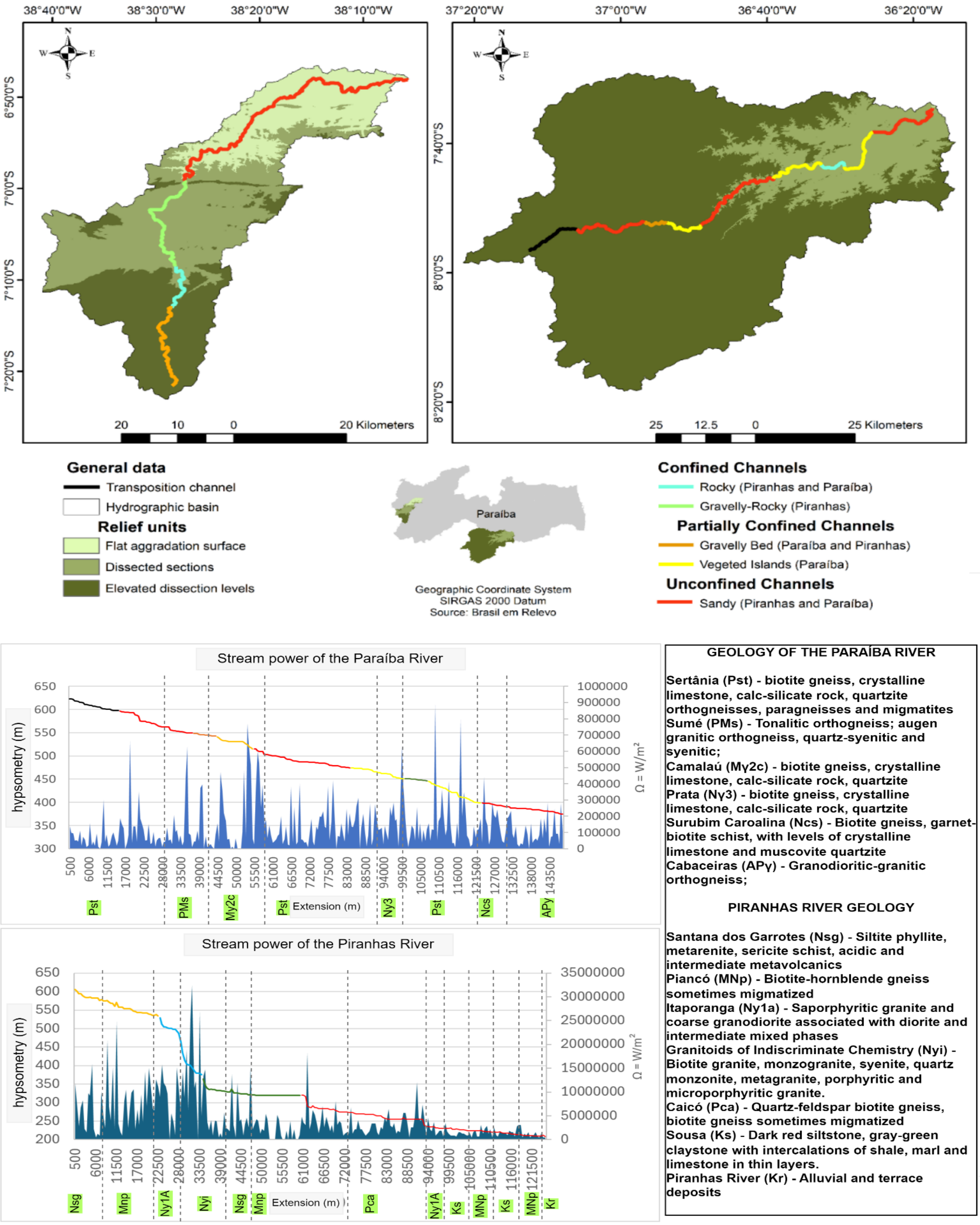


Figure 6. Flow duration for the Caraúbas and Várzea Grande stations between 1970 and 2022. Source: Authors (2024).

4.2. River Styles

This section presents a general characterization of the river styles of both basins, followed by a discussion of the identified styles and their relationship with the existing literature on the topic (Figure 7).



GEOLOGY OF THE PARAÍBA RIVER

Sertânia (Pst) - biotite gneiss, crystalline limestone, calc-silicate rock, quartzite orthogneisses, paragneisses and migmatites
Sumé (PMs) - Tonalitic orthogneiss; augen granitic orthogneiss, quartz-syenitic and syenitic;
Camalaú (Mγ2c) - biotite gneiss, crystalline limestone, calc-silicate rock, quartzite
Prata (Nγ3) - biotite gneiss, crystalline limestone, calc-silicate rock, quartzite
Surubim Caroalina (Ncs) - Biotite gneiss, garnet-biotite schist, with levels of crystalline limestone and muscovite quartzite
Cabaceiras (APγ) - Granodioritic-granitic orthogneiss;

PIRANHAS RIVER GEOLOGY

Santana dos Garrotes (Nsg) - Siltite phyllite, metarenite, sericite schist, acidic and intermediate metavolcanics
Piancó (MNp) - Biotite-hornblende gneiss sometimes migmatized
Itaporanga (Ny1a) - Saporphyritic granite and coarse granodiorite associated with diorite and intermediate mixed phases
Granitoids of Indiscriminate Chemistry (Nyi) - Biotite granite, monzogranite, syenite, quartz monzonite, metagranite, porphyritic and microporphyritic granite.
Caicó (Pca) - Quartz-feldspar biotite gneiss, biotite gneiss sometimes migmatized
Sousa (Ks) - Dark red siltstone, gray-green claystone with intercalations of shale, marl and limestone in thin layers.
Piranhas River (Kr) - Alluvial and terrace deposits

Figure 7. River styles of the upper courses of the Paraíba and Piranhas rivers, flow energy in each basin, and their geological controls. Source: Author (2024).

After defining the river styles, a matrix of general characteristics and controls was constructed, allowing the description of distinguishing attributes between them. The nomenclature of the styles was defined based on their morphology and dominant processes, that is, the characteristics and behavior of each reach (Table 6).

Table 6. Matrix of river styles in the UCPAR (Upper Course of the Paraíba River) and UCPIR (Upper Course of the Piranhas River). Source: Authors (2024).

RIVER STYLE					
Name	**Rochy**	**Gravelly-Rocky**	**Vegetated islands**	**Gravelly Bed**	**Sandy**
Valley characteristics	Confined		Partially confined		Unconfined
Plan shape	Single channel	Single channel	Section and islands with vegetation	Single channel	Single channel
Geomorphic units	No floodplains and entirely rocky bed	Rocky outcrops	Vegeted islands	Discontinuous floodplains and boulders	Continuous floodplains, bars and islands
Texture of bed material	Rocky	Gravel and sand	Sandy	Gravelly	Sandy
RIVER CONTROLS					
Catchment area (km²)	296 km²	325 km²	128 km² in the Piranhas River	59 km²	781 km²
Relief unit	Dissected pediments (301 m – 500 m)	Dissected pediments (301 m – 500 m)	High dissection levels (501 m – 856 m) and Dissected pediments (301 m – 500 m)	High dissection levels (501 m – 856 m)	Flattened surface of aggradation (206 m – 300 m)
Slope (%)	1,3%	0,08%	0,1%	0,3%	0,05%
Average flow energy (W/s)	103258,1	123611,99	180246,7	89210,09	119389,02

The two confined river styles identified in the basins – Rocky Confined and Gravelly-Sandy Confined – share common features that allow for an integrated analysis. Both styles exhibit single channels and banks with no floodplains, reinforcing their confined condition in the fluvial environment of the basin. The main distinction between them lies in slope and bed material composition. The Rocky Confined style is marked by a fully rocky and scored bed, including abrasion potholes, and is located in a slope-break area, which intensifies flow energy and increases velocity (Figure 6). On the other hand, the Gravelly-Sandy Confined style has a sandy layer over the crystalline bed, providing a different texture. These subtle variations do not change the confined configuration of the observed river styles, allowing a unified analysis that highlights confinement characteristics and substrate variation. It is important to note that the Gravelly Confined style is exclusive to the Piranhas River.

The confined river styles transition from a resistant crystalline rock complex to one with lower resistance to erosion and weathering processes, as seen in the Rocky Confined style, with flow running over gneiss and migmatite (resistant rocks) to granodiorite (a conglomerate of less resistant rocks), creating a slope break where the reach descends from 550 m to 370 m over approximately 8 km. This generates energy and scouring capacity, preventing the formation of depositional geomorphic units (Figure 8).

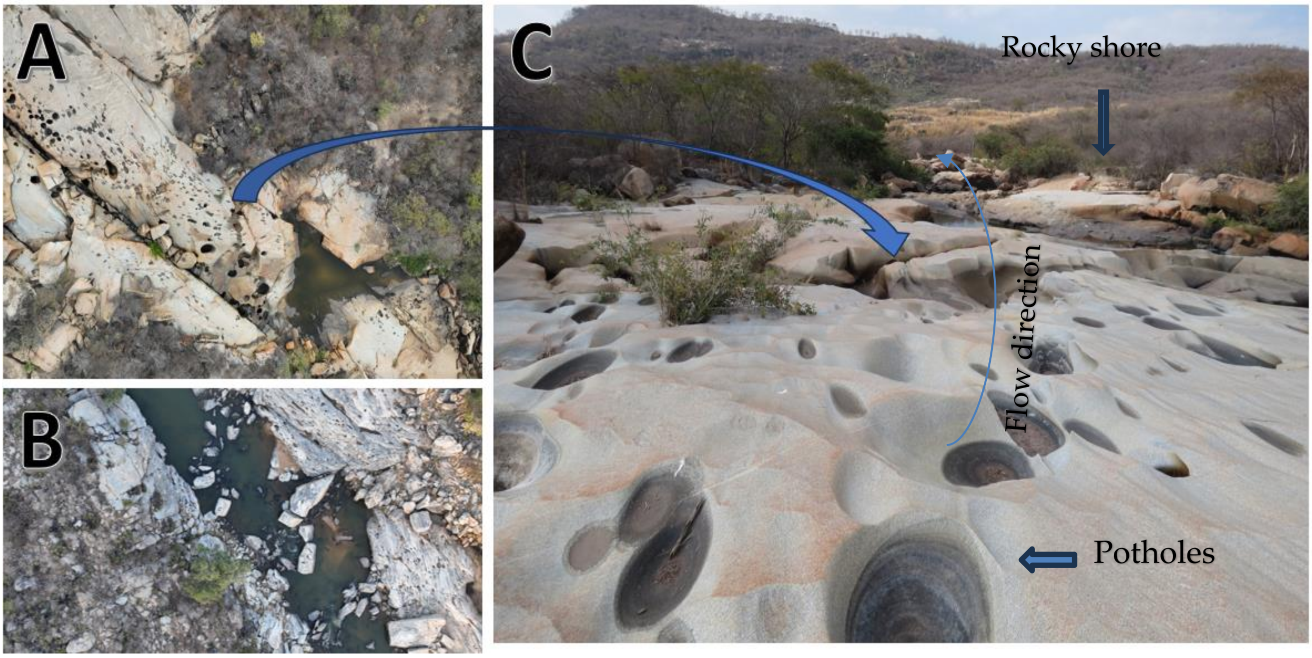


Figure 8. Rocky Confined Styles. A – Reach in the Piranhas River. B – Reach in the Paraíba River. C – Zoom on abrasion potholes. Source: Authors (2024).

Partially confined styles (Gravel-bed and Vegetated Islands) are located in two relief units: Elevated Dissected Terraces and Dissected Pediments. What attributes this type of characteristic to these reaches is the presence of depositional geomorphic units in the fluvial environment, especially floodplains that occupy more than 10% of the riverbanks. In this sense, moderate energy combined with a higher sediment contribution from headwater zones conditions the morphology of these reaches (Figure 9). It is also noted that the partially confined reaches are exclusively distributed over crystalline geological formations, which favors the possibility that depositional controls are due to surface hydrogeomorphological dynamics and the pulsed flow of non-perennial rivers.

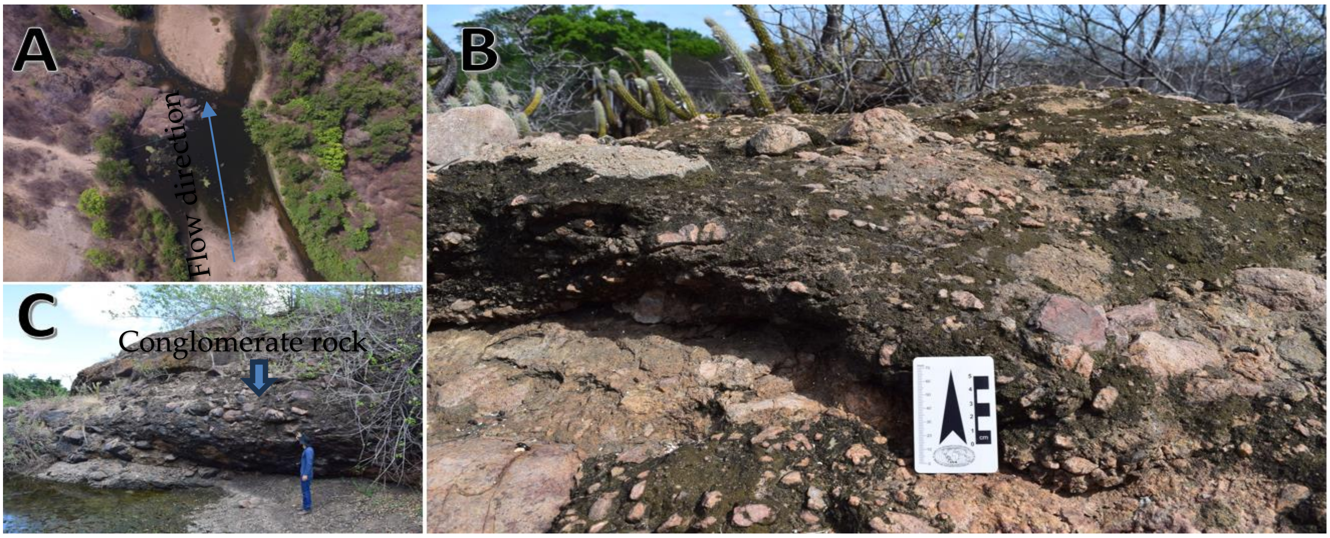


Figure 9. Partially confined styles with gravel beds and vegetated islands. A – Plan view. B – Conglomerate formation on one bank. C – View of the downstream confined margin. Source: Authors (2024).

Unconfined fluvial styles exhibit depositional characteristics along their entire extent, especially the presence of floodplains occupying more than 90% of the river margins. In this context, these reaches are characterized by low flow energy and large contributing areas. This style is almost exclusively associated with the Dissected Pediments relief unit, which is predominantly defined by a flattened landscape. In the Paraíba River, this style also occurs near headwater areas, where the presence of sandy material is noticeable along the reach. This is related to the pulsed flow dynamics of the channel, which during the rainy season can transport most of the sediment, but toward the end of the rainy period and the beginning of the dry season, loses flow competence and ends up depositing this material on the riverbed (Figure 10 and Table 6).

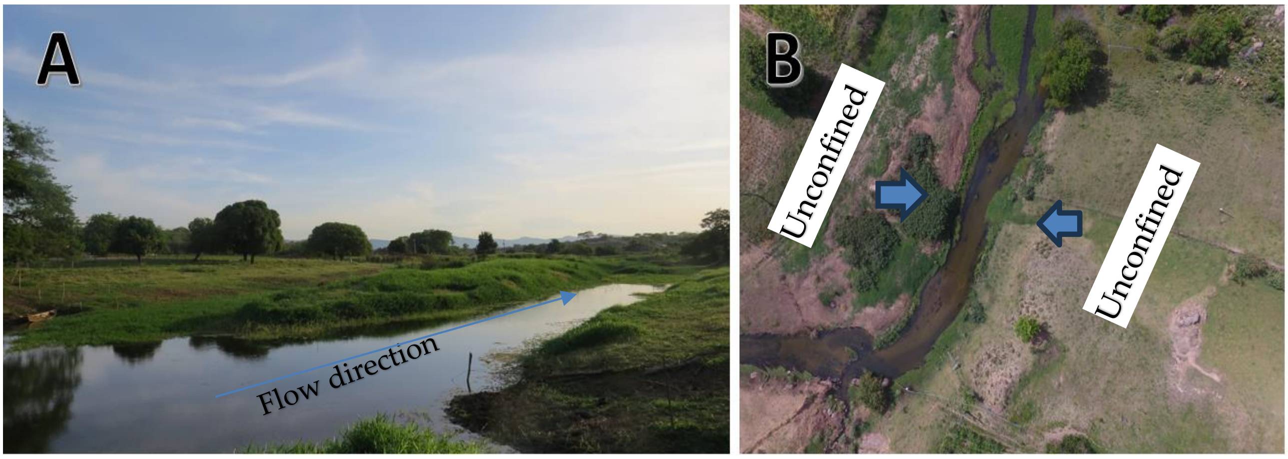


Figure 10. Unconfined Fluvial Style. A – Downstream horizontal view. B – Planform view. Source: Authors (2024).

In general, the boundary between one fluvial style and another was defined through changes in the geomorphic units present in the fluvial environment, a key attribute in defining river styles. Ultimately, the attribute selected to distinguish the styles was bed material texture.

5. Discussion

Since many rivers in dryland areas exhibit downstream reductions in discharge, flow power, and sediment transport, features related to the fluvial environment and environmental controls, their channels and floodplains may vary along the longitudinal profile (BRIERLEY; FRYIRS, 2013; FRYIRS; BRIERLEY, 2013). Channel adjustment, such as changes in pattern, formation of geomorphic units, and flooding, occurs more frequently in partially confined and unconfined middle and lower reaches (GRAVES et al., 2024; RODRIGUES; SOUZA; XAVIER, 2021), as observed in the partially confined and unconfined channels of the basins, which have depositional characteristics. According to Brierley and Fryirs (2005), alluvial reaches are more prone to change and adjustment driven by alterations in environmental controls; therefore, partially confined and unconfined styles tend to be more resilient and adaptable than confined styles (RODRIGUES et al., 2023; RODRIGUES; SOUZA; XAVIER, 2021).

Confined fluvial styles are generally associated with steep landforms, where the slope increases flow energy and, consequently, a river's capacity to transport coarser sediment particles. This causes the channel thalweg to incise the bed and wash over the channel surface, inhibiting the formation of geomorphic units parallel to the channels, such as floodplains. Thus, the absence of floodplains assigns a confined character to the fluvial environment, without flow overflow and with mechanical transport processes prevailing over sediment deposition (BRIERLEY; FRYIRS, 2013, 2005; FRYIRS; BRIERLEY, 2013).

The geomorphology of rivers in drylands ranges from confined bedrock rivers with straight, narrow channels and little to no floodplain (GRAVES et al., 2024)—as occurs in the confined sections of the studied basins—to sinuous, partially confined rivers with single or multi-thread channels and floodplains, to unconfined alluvial rivers with one or multiple continuous, braided or discontinuous channels and extensive floodplains (GRAVES et al., 2024; RODRIGUES et al., 2023; TOOTH, 2000).

The bedrock channels of the basins confined reaches present potholes, which are geomorphological features formed on crystalline rocks, sometimes on sedimentary rocks as well, but especially on crystalline outcrops in fluvial systems. They result from the combined interaction of hydraulic dynamics and fluvial incision processes on a geological time scale ($>10^3$ years), governed by Quaternary climatic variations (DIAS et al., 2024; LIMA, 2010). In Northeastern Brazil, these features are associated with energetic collisions between detrital sediments transported by rivers and their discontinuous topographic beds, generating vertical circular abrasion and consequently forming such morphologies, as seen in the Rocky Confined styles found in both river basins.

Regarding the morphology of partially confined and unconfined styles, it is important to note that flow discontinuity can occur in the same reach that, for part of the year, presents continuous flow. This is because rainfall variability in the Brazilian semi-arid region causes precipitation to be concentrated in only a portion of the year, and considering that non-perennial rivers lack subsurface recharge, their fluvial reaches may become discontinuous at the beginning of the dry season, with isolated wet zones that eventually become fully dry during peak dry season (COSTIGAN et al., 2017; JAEGER et al., 2017; LARKIN et al., 2020; TOOTH, 2000).

In addition, low flow permanence is also a determining factor in non-perennial rivers, where headwater reaches in erosive areas may become unconfined, considering that concentrated rainfall in a short period will cause dissection of the terrain. However, the abrupt interruption of rain events reduces the channel's transport competence and forces it to deposit material on the bed and margins, with finer materials settling along the banks and coarser materials remaining in the fluvial environment (BOAS; MARÇAL, 2013; CHARLTON, 2008b; FERGUSON; LEWIN; HARDY, 2022; POEPPL; KEESSTRA; MAROULIS, 2017; RODRIGUES; SOUZA, 2020). This situation occurs in the unconfined fluvial style in the headwaters of the Paraíba River, where low flow permanence—over 80% of the year with low or zero discharge and an extremely low BFI—conditions sediment accumulation within the fluvial environment, forming alluvial channels due to the lack of mechanical transport during the dry period.

It is worth noting that some studies analyze drainage networks in watersheds with a structural focus, where these upper areas of the Paraíba and Piranhas rivers are designated as erosive zones (CORDEIRO et al., 2024). In this sense, reach/segment scale studies show that fluvial behavior can deviate from structural generalizations, highlighting that variables such as rainfall patterns, terrain slope, catchment area, landscape position, land use and land cover, among others, are just as significant as geological structure in the fluvial morphodynamics of non-perennial rivers (CHARLTON, 2008b; CHEN; OLDEN, 2017; FERGUSON; LEWIN; HARDY, 2022).

6. Conclusions

The results of this research emphasize the importance of an integrated analysis between flow permanence, using the BFI index, and the classification of fluvial styles in watersheds located in semi-arid regions. The application of these methodologies enabled a detailed characterization of intermittent river reaches and their hydrological and geomorphological dynamics. It was observed that the Paraíba and Piranhas rivers exhibit distinct patterns of intermittence, with the Paraíba River being more prone to prolonged periods of minimal flow, supporting its classification as strongly intermittent.

Additionally, the identification of confined and unconfined fluvial styles highlighted the direct influence of factors such as slope, bed material composition, and functional connectivity, allowing the association of geomorphological features with the hydrological responses of each reach.

Overall, the data underscore the relevance of considering geomorphological and hydrological variability to understand the dynamics of rivers in dryland environments. The integrated analysis carried out in this study contributes to the advancement of knowledge on flow intermittence and fluvial styles, offering a robust scientific basis for future research and water resource management in semi-arid regions. The approach also reinforces the need to integrate geomorphological and hydrological aspects in the classification and monitoring of watersheds, especially under scenarios of climate change and increased hydrological variability, which may intensify the challenges faced by these fluvial systems.

A gap in the geomorphological literature is how the internal processes responsible for morphological changes in dryland river channels are linked to external events and how the timing of periodic floods alters channel morphology over time. Relatively little is known about the rates and patterns of these fluvial adjustment processes and how they affect the morphodynamics and associated biological communities.

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