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Fluvial connectivity in the Brazilian semi-arid, Araripe sedimentary plateau

Conectividade fluvial no semiárido brasileiro, planalto sedimentar do Araripe

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Abstract: This article aims at identifying and describing short-term connectivity scenarios in a semi-arid watershed in northeastern Brazil. The emergence of different decadal connectivity patterns is discussed, addressing the role of recent climatic inputs in triggering cut-and-fill erosive-depositional patterns within a valley bottom. A confluence stretch between a tributary and the stem channel was selected in order to analyze changes in connectivity and dysconnectivity patterns in response to climatic inputs from 2004 to 2014. The climatic behavior was assessed using the Rainfall Anomaly Index, which established dry and wet years, hence highlighting the relationship between connected and unconnected channel phases and a decennial precipitation dynamic. The years of 2004, 2008 and 2011 stand out as the rainiest and with the highest RAI values, in contrast to 2012, with a total rainfall of less than 600 mm and a RAI value below -2. The discrepancy between the 2012 rainfall total and the 2013/2014 biennium points to the relevance of this period for the reworking of alluvial deposits and connectivity resumption in the watershed. In the ephemeral drainages, connectivity is dramatically interrupted every dry season, creating fluvial disconnection. Dysconnectivity is characteristic of tropical semi-arid fluvial environments, but at landscape scale it may attest to the longevity of dry conditions, hence shall be addressed at time intervals ranging from a few days to thousands and tens of thousands of years.

Keywords: Dryland watershed; Landscape connectivity; Sediment cascade.

Resumo: O artigo tem como objetivo identificar e descrever cenários de conectividade de curto prazo numa bacia semiárida do nordeste do Brasil. O surgimento de diferentes padrões de conectividade em escala de década é discutido, abordando o papel dos recentes inputs climáticos no desencadeamento de padrões de corte e preenchimento erosivo-deposicional em fundo de vale. Um trecho de confluência de um tributário com um canal principal foi selecionado com a finalidade de analisar mudanças nos padrões de conectividade em resposta aos inputs climáticos entre 2004 e 2014. O comportamento climático foi acessado usando o Índice de Anomalia de Chuva, que estabeleceu anos secos e úmidos, evidenciando a relação entre fases de conectividade e desconectividade dos canais e a dinâmica de precipitação decenal. Os anos de 2004, 2008 e 2011 destacam-se como os mais chuvosos e com os maiores valores IAC em contraste com o ano de 2012, cujo total de precipitação esteve abaixo dos 600 mm e o valor de IAC foi mais baixo que –2. A discrepância entre os totais de precipitação de 2012 e o biênio 2013/2014 confere a estes uma relevância para a análise de retrabalhamento dos depósitos aluviais da bacia. Em drenagens efêmeras, conectividade é dramaticamente interrompida pela estação seca, criando cenários de desconexão. Desconectividade é característica dos ambientes fluviais tropicais semiáridos, portanto deve ser abordada em intervalos que abrangem desde alguns dias a dezenas ou milhares de anos.

Palavras-chave: Bacia hidrográfica semiárida; Conectividade da paisagem; Sedimentação em cascata.

Introduction

The dynamics of river discontinuities along the supply, transport, and deposition of matter and energy continuum have been a classic concern for landscape studies (Cossart *et al*., 2017). Two main investigation aspects arise: understanding the spatial distribution of sediments in different landscape compartments (cascade sedimentation) (Baartman *et al*., 2013) and identifying the geomorphic responses to energy inputs over time (sensitivity) (Brunsden & Thornes, 1979).

The study of river connectivity seeks to identify discontinuities, often controlled by barriers, that modify the base level and the water/sediment flows (Fryirs *et al*., 2007). The behavior and morphology of these discontinuities are not geographically homogeneous, varying according to the morphoclimatic regions of the globe. Especially for tropical semi-arid environments, river connectivity is essentially controlled by the extreme temporal variability of flow, followed by the concentrated and irregular rainfall regimes (Graf, 1988; Souza *et al*., 2016).

The concept of connectivity in geomorphology represents an attempt to understand the continuum between production, transport, and deposition in the landscape. It takes into account the volume of sediment supplied upstream from a certain point and the relationship between the elements responsible for the redistribution of the sediment between the components of the hydrological system. Thus, landscape connectivity can be understood as the transfer of energy, matter (sediment), and even organisms, between two relief compartments or within the same compartment.

In this context, the hydraulic conditions of channels and ephemeral fluvial plains (typical in semi-arid environments) are commonly characterized by unstable and non-uniform flow activity. Under semi-arid conditions, the loss of downstream transmission results in various sediment transport and deposition scenarios (Bull, 1997; Tooth, 2000). Thus, sheet deposition is episodic, and transport and deposition occur only during or shortly after high-intensity precipitation events (Mabesoone *et al*., 1981; Daniels, 2003).

The result of the behavior described above is the prevalence of cut-and-fill surface processes operating in different temporal scales (from the Holocene to a few decades), with internal controlling factors inherent to the watershed itself (Schumm & Hardley, 1957) or external, such as climate change (Harvey & Pederson, 2011). In addition, it is necessary to consider that the semi-arid environment presents a variety of regional and local landscapes according to lithology, vegetation cover, relief, land use, and the geomorphic evolutionary context.

In semi-arid environments, alluvial and colluvial deposits are prone to cyclic channel entrenching and reworking, primarily due to the lack of a protective perennial vegetation cover. Mabesoone *et al*. (1981) identified that in the semi-arid Northeast of Brazil, fluvial plains and adjacent lower colluvial ramps were characterized by the ubiquitous presence of cut-and-fill sedimentary structures. According to the author, these are characterized by the presence of an upturned concave erosive incision cut through the underlying layer by a high-energy current – forming a channel – and later filled by coarse sediments transported by the old channel (paleo-channel). Such features represent a guideline for interpreting the evolution of alluvial/colluvial deposits in the study area.

This article identifies and describes the short-term connectivity scenarios in a semi-arid watershed in northeastern Brazil. Previously, evolutionary models based on hillslope morphostratigraphy had been proposed for a time-lapse encompassing from the Upper Pleistocene to the onset of the Holocene. Thus, the emergence of different decadal connectivity patterns is discussed, addressing the role of recent climatic inputs in triggering cut-and-fill erosive-depositional patterns within a valley bottom.

By its turn, landscape dysconnectivity corresponds to the moments, expressed in sectors of the landscape, in which the transfer of sediment towards the common outlet, or base level, ceases to occur, retaining the sediment in different positions of the relief, subject to different controls and time scales of storage and evacuation.

The Araripe Plateau, in the northeast of Brazil, is a sub-humid landscape located within a semi-arid regional context, marked by a complex geomorphic history and subject to divergent approaches regarding its long-term evolution (Peulvast & Claudino Sales, 2004; Marques *et al*., 2014). Nevertheless, the geomorphic evidence present in the area records a sequence of cut-and-fill morphologies, from the lower hillslopes to the fluvial plains, whose earliest records date back to the Upper Pleistocene (Lima *et al*., 2021a).

1. Materials and Methods

1.1. Study Area

The Salamanca River watershed covers an area of 295 km² south of Ceará State, Northeastern Brazil. The drainage network headwaters are located along the northern escarpment of the Araripe Sedimentary Plateau. Most streams follow a SW-NE trend towards the Cariri Valley, an elongated E-W-oriented peripheral depression established in the geologic contact between the Mesozoic Araripe basin to the south and the Proterozoic crystalline basement to the North.

The Araripe Plateau is a table-like landform elongated in the E-W direction, structured on the post-rift sequences of the Araripe Sedimentary Basin, characterized by sub-horizontal strata with a slight westward dip (Assine, 2007). The landform has a level summit surface ranging from 900 to 1,000 m in elevation, limited by steep erosive escarpments of tens of meters, structured in the Lower Cretaceous Exu Formation sandstones. This lithology poses a much stronger erosion resistance than the underlying pellitic layers. Consequently, the sedimentary rocks that form the plateau contribute more weathered material to hillslope deposits and alluvial plains, unlike the metamorphic complexes in the vicinity.

The northeastern sector of the Plateau is marked by a sequence of drainage headwaters arranged in semi-circular hollows from where the main streams originate. Gentle slopes covered by colluvial-alluvial deposits form the relief downstream of the headwaters. The hillslope segments are distributed in staggered levels, with downstream incised sectors evolving into topographic shoulders. Further north relief forms turn into a dissected hilly surface that marks the limit between the Plateau itself and the Cariri Valley (Vale do Cariri) peripheral depression at an average altitude of 400 meters (Figure 1).

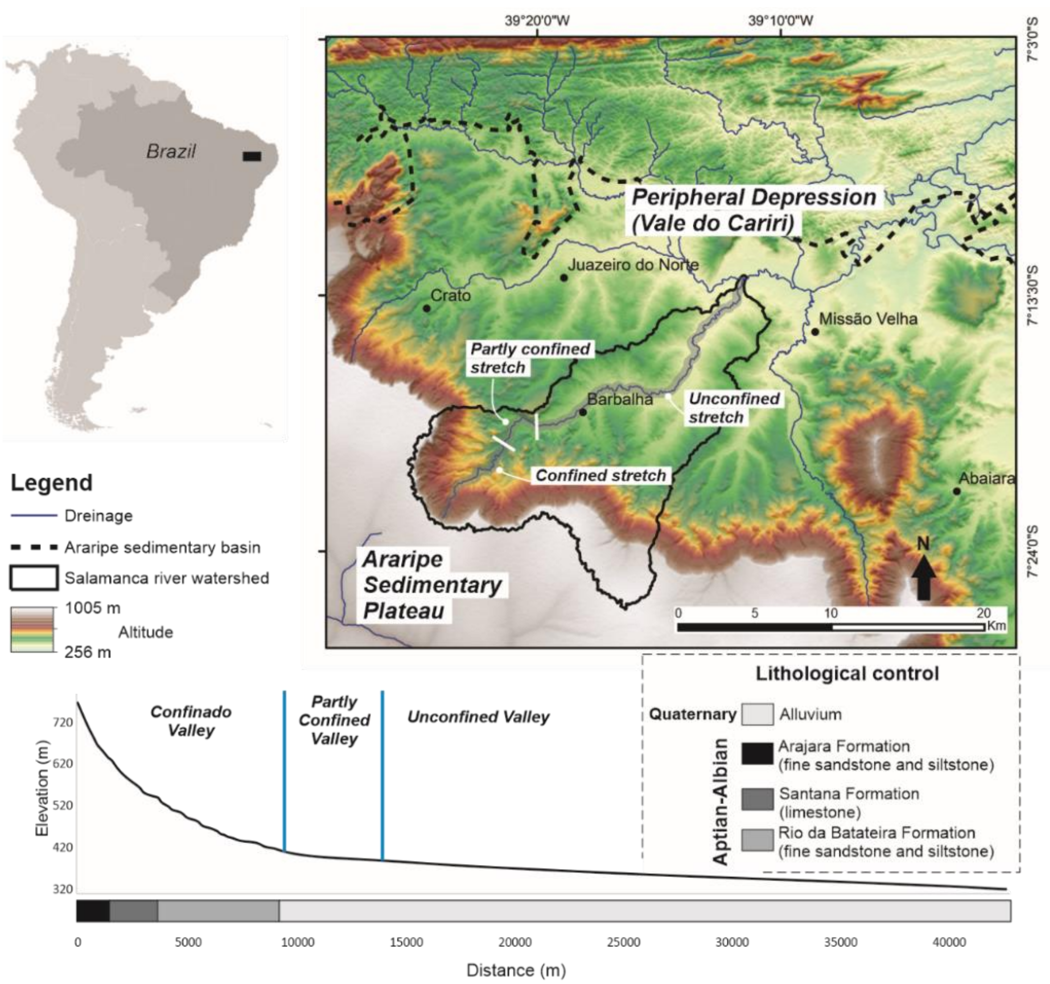

Figure 1: Location of the Salamanca River watershed. Longitudinal profile of the river displaying valley confinement pattern and lithological controls. Lithology distribution according to Ponte & Ponte Filho (1996).

Significant land use changes occurred since the establishment of Portuguese settlements in the early 18th century when floodplains were converted into sugarcane plantations. However, from the decade of 1990 onwards, this activity has gradually given in to irrigated fruit growing. Recently, the area was impacted by the construction of a canal cutting through the eastern sectors of the Plateau as part of the engineering works aiming to transpose water from the São Francisco River, the only perennial stream in the region, to the ephemeral and intermittent watersheds to the north.

1.2. Connectivity scenarios and morphostratigraphy

Along the channel stretches, the valleys present different confinement configurations related to the fluvial morphology and the lithological characteristics of the entrenched material: sedimentary rock from the Araripe basin (mostly sandstone) or unconsolidated Quaternary sediments, hence resulting in different connectivity patterns.

The type of valley confinement, defined by the presence of an alluvial plain or lack thereof, varies according to the morphostructural setting of the landscape, in accordance with the position of the regional knick-point and the dominance of erosion or deposition. Thus, the prevalence of confined stretches in the Salamanca River coincides with valleys incised into the Araripe Plateau morphostructure. In contrast, the partially confined and non-confined sections mainly occur in the Vale do Cariri Peripheral Depression (Figure 2).

The drainage network of the Salamanca River displays a subparallel SW-NE trending pattern controlled by the regional distribution of faults and fracture zones. The ephemeral regime of the watershed reflects the regional semi-arid climate. However, locally the streams are also affected by man-induced interferences such as the building of dams and reservoirs. The mapping of the dysconnectivity elements of the Salamanca River watershed explores the distribution and controls operating on the flow transmission along the stem channel and its main tributaries (Figure 2).

Transmission barriers prevent sediment from reaching the channel network and thus interrupt the lateral connection (hillslope to channel) within the watershed. In the case of the semi-arid Northeast, these forms have a residence time ranging from decades to tens of thousands of years, depending on their position in the landscape. The forms located on the hillslopes are those that accumulate first along the drainage basin. Next, there are forms directly related to fluvial dynamics, such as alluvial fans ahead of low-order drainages, usually in the transition (knickpoints) from the hillslope compartment to the low-lying pediments.

Dysconnectivity often cannot be accessed only at the scale of remote sensors, demanding fieldwork for the in-situ identification of morphostratigraphic relationships that indicate and reveal the type of connectivity loss.

The headwaters of the Salamanca River are arranged around a large topographic amphitheater. First-order drainages emerge from entrenched sedimentary deposits at the base of the escarpment or from talus deposits further downhill. To the east of the watershed, streams are adapted to fractures, cutting directly through the bedrock, the sandstone of the Exu Formation, which structures the summit surface of the Plateau.

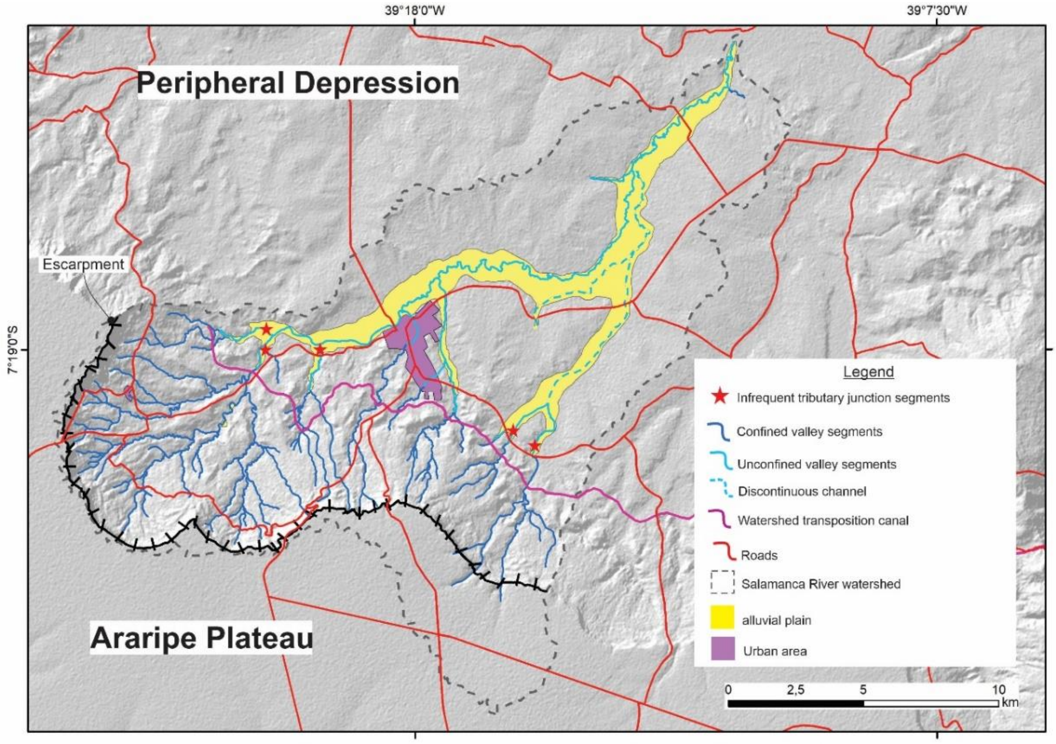

Figure 2: Distribution of fluvial dysconnectivity elements in the Salamanca River watershed.

The relief in headwater areas can be separated into two morphological units: hollows and hillslopes. The hollows present an amphitheater planform geometry and a concave longitudinal profile. They are supported by Mesozoic lithologies capped by Quaternary unconsolidated surface coverings (Lima & Corrêa, 2018; Lima *et al*., 2021b). Downstream of the escarpment, topographic hollows are filled by Upper Pleistocene/Holocene colluvial deposits. However, colluvium deposition was not synchronous all over the concave morphology upper slope sectors, which resulted in different geomorphic configurations reflecting various stages of sediment filling.

Some of the upper hollows with the thickest colluvial filling are characterized by the lack of drainage incision – unchanneled zero-order catchments. In contrast, other hollows at the same sector of the hillslope/escarpment show little colluvial sediment storage being actively dissected first-order channels. Both morphologies display an altimetric amplitude of approximately 120 m and are located along the northeastern escarpment of the Plateau (Figures 3 and 4). This configuration indicates the occurrence of different paleo-connectivity scenarios along the catchments, which point to certain randomness of surface dynamics operation, both at spatial and temporal scales. It is believed that changes in climatic inputs have operated as significant triggers of colluvial deposition in the area since the late Quaternary (Figure 4), as reported for several other hillslope environments in the semi-arid Northeast of Brazil (Gurgel *et al*., 2013; Fonseca *et al*., 2020; Lima *et al*., 2021a).

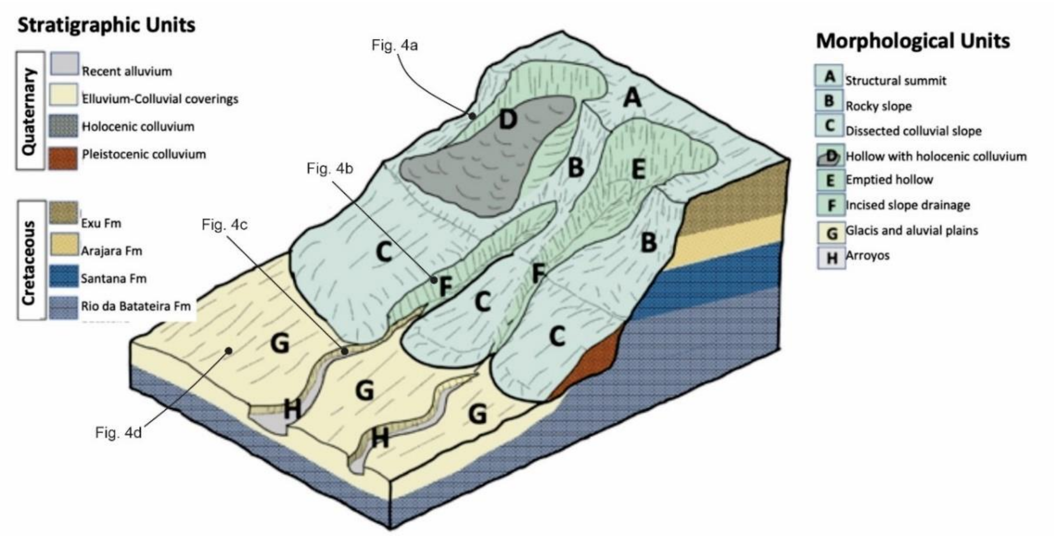

Figure 3: Illustration of topographic hollows along the Araripe Plateau northeastern escarpment and their morphostratigraphic framework.

Fluvial dynamics in headwater stretches are dominated by channel incision, with little lateral erosion. Current connectivity has established confined valleys that cut through unconsolidated sediments. Consequently, river instability occurs through the reworking of talus deposits and occasional channel obliteration (Figure 4a). In addition, gravel bars, boulders, and woody debris from the semi-deciduous forest upstream behave as flow impediments within the channel beds. Fluvial connectivity is also affected by land use activities. Streams are dammed or diverted for small-scale agriculture and domestic usage. In addition, water from the springs is used for recreational purposes by resorts and spas.

Downstream of the headwaters, channel stretches exhibit a gorge-valley configuration, with rocky beds, steep side-slopes, and the absence of alluvial plains (Figure 4b). The incised channel is confined to the sandstones of the Mesozoic Rio da Batateira or Barbalha Formations. The essentially erosive fluvial structure and the valley configuration, in addition to the high slope of the stretch, favor flow acceleration and an increase in connectivity along the acceleration zone, with a predominance of vertical erosion. The scant deposition along the riverbed attests to the high-energy fluvial environment.

Despite this essentially erosive, bedrock incised channel morphology, partly entrenched rudaceous sediments are found in some sectors. Nevertheless, not forming alluvial plains *per se*, these occurrences point to episodes of valley-bottom filling by gravitational flows derived from adjacent hillslopes. These deposits have been interpreted by Lima and Corrêa (2018) and Lima (2021a) as resulting from the generalized Holocenic colluviation in the northeastern sector of the Araripe plateau. In many areas, fracture zones have facilitated the entrenchment, beyond the deposits, further into the underlying bedrock, thus originating new incision patterns (Figure 4c).

Sediment transfer in the landscape was not uniform over time. Sedimentation pulses reflect cyclic (annual, decadal, secular, and even millennial) or stochastic (punctual) inputs simultaneously. It is known that, especially in semi-arid climates, the events that trigger the transport of sediments on hillslopes and from hillslopes to the valley floors operate at different scales along the tributaries and the segments of the main channel (longitudinal transport). In this way, landscape dysconnectivity operates in temporal intervals of different lengths, which are reflected in the residence time of sediments in the temporary storage areas in which they are found.

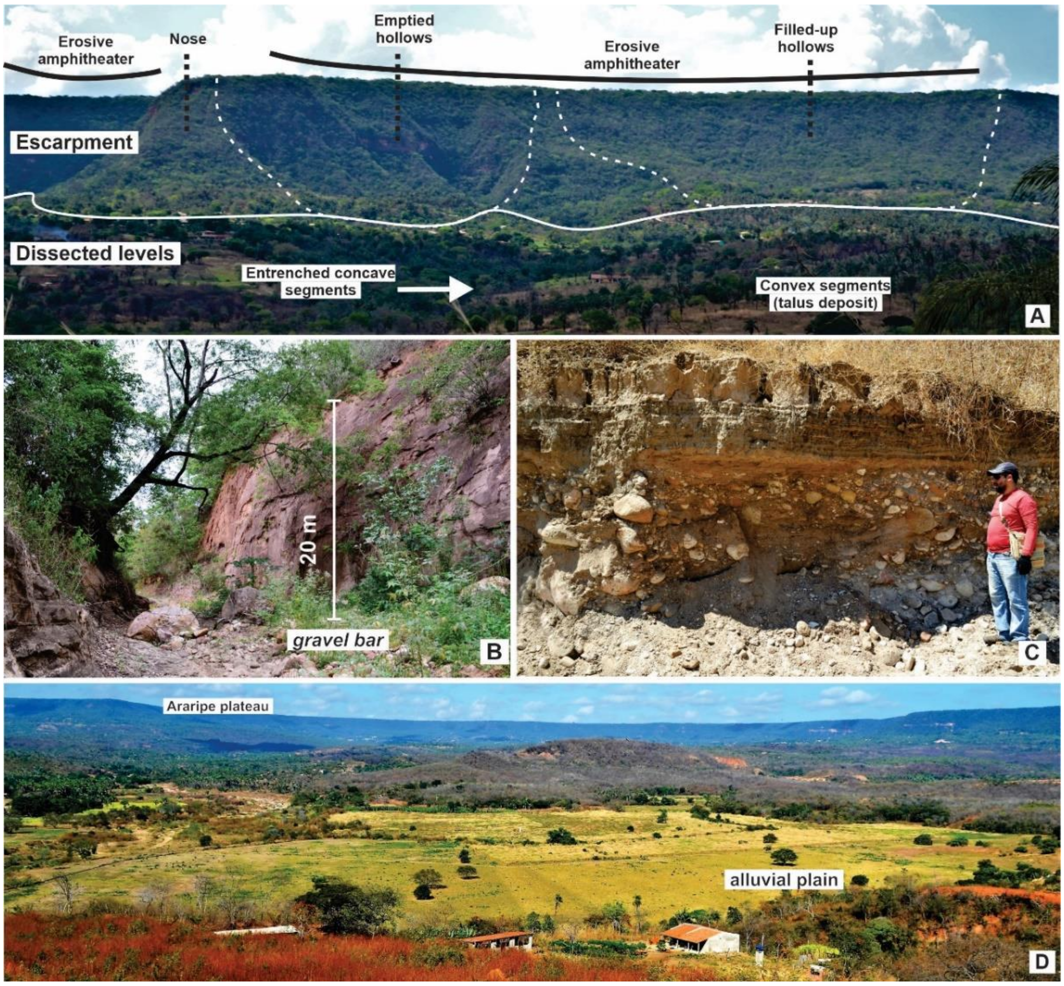

Figure 4: River connectivity scenarios along the relief compartments of the Salamanca River watershed. Drainage headwaters (a), gorge-valley stretches (b), outcrop in river terrace (c) and alluvial plain in the peripheral depression (d).

Morphostratigraphic records from the Salamanca River watershed reveal recurring events of sediment deposition and channel incision dating back to 40 Ka BP (Lima & Corrêa, 2018). Colluvio-alluvial coverings respond to changes in hydrologic dynamics in sync with shifting climatic patterns and base level changes throughout the late Quaternary, resulting in hillslope sedimentation and drainage entrenchment at the valley bottoms.

Expansion and shrinkage of the semi-deciduous forest from the upper Pleistocene onwards at the Plateau’s summit and upper slopes were addressed by Pessenda *et al*. (2010). The paleo-vegetation dynamics findings establish a linkage between the behavior of the vegetation cover and hillslope erosive stability. In this regard, one can postulate that Pleistocene-Holocene transition rudaceous deposits are related to a sparser vegetation cover and the surface exposition of talus deposits under increased seasonal torrentiality (Lima e Corrêa, 2018).

Upper Holocene valley bottom deposits record the last episodes of drainage obliteration and entrenchment as sub-humid conditions resumed (Lima *et al*., 2021a). These last phases of generalized valley bottom sedimentation, followed by channel incision, demonstrate the pulsatile character of Salamanca River paleo-connectivity. Such behavior indicates a close relationship between the origin of colluvial-alluvial deposits and climatic triggers modulated by the expansion/shrinkage of the vegetation cover. However, it is essential to remark that the resulting cut-and-fill features did not lead to the complete depletion of older sediment storage. On the contrary, those that remained filling the bottoms of topographic hollows, forming discontinuous pocket plains, fluvial terraces, and colluvial ramps, nowadays behave as buffers and barriers to sediment redistribution within the watershed.

The overall base level lowering during the Upper Holocene produced fluvial terraces along continuous and discontinuous alluvial plains (Figure 4c). The spatialization and lithostratigraphy of these sediment coverings reveal processes of local relief inversion, channel incision, and sediment reworking, as well as transport energy oscillation within the valley bottoms. Due to the low production of regolith in the crystalline areas of the semi-arid Northeast, these forms are more common in the sedimentary basins such as the study area.

1.3. Anthropogenic dysconnectivity

The Salamanca River watershed's most remarkable anthropogenic dysconnectivity feature is the Ceará State Water-belt Project (CAC) canal. It is a hydraulic engineering work built for transposing water from the perennial São Francisco River to supply the ephemeral or intermittent watersheds of Ceará State. It constitutes an addition to the original Transposition Project of the Waters of the São Francisco River (SRH, 2010).

The Araripe Plateau forms the regional divide between the watershed of the São Francisco River, to the south and the Jaguaribe River, to the north. The canal borders the lower slopes of the plateau to the east between the 415- and 486-meter contour lines. The water flow is driven by a gravitational system of open canals, tunnels (under topographic heights), and siphons whenever it intercepts watercourses, highways, and urban areas (Figure 6). The dynamics of the watershed transposition canal are not like that of a river channel, mainly due to the lack of lateral and vertical processes. CAC, therefore, constitutes a major artificial dysconnectivity element.

Some geo-ecological issues are also associated with the implementation of the CAC, such as the transfer of exotic species and the overall impact on water quality, environmental and hydrological conditions of the São Francisco River, which demand long-term hydro-sedimentological and ecological monitoring plans. Other drawbacks are related to the removal of traditional communities and the reparation of socioenvironmental damage, as identified by Brito (2016), for the CAC sections that cut through the study area.

Considering its longitudinal dynamics, the Salamanca River undergoes flow modification through the obstruction of lower-order channels. Lateral disconnection occurs on the hillslopes and between hillslope units and glacis (pediment ramps on sedimentary bedrock) by interrupting the laminar flow, modifying water collection and sedimentation downstream. At the headwaters and upper-slope sectors, unconsolidated deposits are reworked into the channel, thus creating episodic dysconnectivity events that may last until the stream flow entrenches the deposits.

1.4. Materials and Methods

The methodological procedures adopted in this research followed a flow of steps initiated with the mapping of fluvial impediments, followed by the classification and identification of the associated environmental controls. Google Earth Pro images were used for the mapping, in addition to digital elevation models (DEM) extracted from ALOS/PALSAR images with a spatial resolution of 12.5 m. Detailed erosive and depositional morphologies were identified during comprehensive fieldwork on the Salamanca River and its main tributaries. The classification of fluvial impediments, described in figure 2 and table II, followed the categories proposed by Fryirs *et al*. (2007), who established a taxonomy for the Australian passive-margin tectonic context based on their pattern of distribution through various landscape compartments and active river-connecting processes.

The construction of its longitudinal profile assisted in identifying Salamanca River's connectivity scenarios as a tool to define the pattern of valley confinement. The analysis initially followed the proposal of Brierley and Fryrs (2005) through the delimitation of Confined, Partially Confined, and Unconfined channel segments based on the presence or absence of alluvial plains. However, in addition to the valley's morphology, the connectivity pattern may change according to the material bordering the channel, resulting in distinct geomorphic responses and susceptibility to the obliteration of the flow path, both in the lateral or longitudinal directions (Lima *et al*., 2021a; Lima *et al*., 2021b).

In confluence segments between a tributary and the main channel, the role of roads as disconnectivity anthropic elements was also highlighted. This assessment was carried out by analyzing satellite images from decadal sequences, which allowed the reconstruction of the current channel dynamics in an unconfined valley sector. This analysis resulted in a summary table of the morphological elements, controls, and time scale of disconnectivity (Table II), as well as a conceptual representation of the connectivity patterns of the Salamanca River watershed (Figure 10).

1.5. Recent climatic dynamics

Precipitation data provided by the State of Ceará Foundation of Meteorology and Water Resources - FUNCEME from 1974 to 2014 were used. For its relevance for the

Salamanca River, due to its spatial proximity, data from the Barbalha Municipality meteorological station, located a -7.307472 and -39.301601, were used.

The annual precipitation totals show a significant interannual variability that directly interferes with the river flow and the accumulation and obliteration of alluvial deposits. In order to establish which years can be considered dry or wet and, therefore, when the most significant disconnection/connection events between the tributaries and the main stem occurred, the Rainfall Anomaly Index (RAI) was applied. as proposed by Rooy (1965). The index allows measuring the deviation in precipitation values concerning normal conditions from total annual precipitation historical data. The calculation of the RAI was conducted as follows:

$$RAI = 3 \times \left[\frac{(N - \bar{N})}{\bar{M} - \bar{N}}\right]$$

for positive anomalies, that is, for years whose total precipitation is above the series average and,

$$RAI = -3 \times \left[\frac{(N - \bar{N})}{\bar{X} - \bar{N}}\right]$$

for negative anomalies, that is, for years whose total precipitation is below the series average, where:

N = Total annual rainfall (mm);
N = Average annual precipitation of the series (mm);
M = Average of the 10 highest total annual rainfall (mm);
X = Average of the 10 lowest total annual rainfall (mm).

Thus, the classification of annual rainfall by RAI values varies from extremely wet to extremely dry, according to table I.

Table I: RAI values and their respective classes.

Rainfall anomaly index (RAI)	
RAI Values	**Class**
above 4	Extremely wet
2 to 4	Very wet
0 to 2	Wet
0 to -2	Dry
-2 to -4	Very dry
Below -4	Extremely dry

2. Results

2.1. Recent connectivity

The integration of long-term morphostratigraphic elements with contemporary channel dynamics led to the construction of a synthesis table in which landscape morphologies are linked to a corresponding type of dysconnectivity within a given timeframe (Table II).

Table II: Timescales of connectivity elements in the Salamanca River watershed.

Morphological elements	Type of barrier/form	Dysconnectivity process	Timescale	Environmental controls
Infilled Hollows (catchments)	Buffer Zone/ plane, concave	Channel obliteration by colluvio-alluvial deposits	Late Quaternary	Lithologic; climatic; stochastic
Occasional plains (pocket plains)	Buffer zone/ Plane, confined on unconsolidated deposits	Lateral impediment, with high susceptibility of channel obliteration by entrenched material reworking	Holocene	Lithologic; climatic; base level
Gravel and sand bars	Cover Zone/ Inside channel, elongated	Limit sediment reworking in sub-surface	Years	Slope; sediment availability
Wood debris	Barrier/ Irregular	Longitudinal impediment and upslope sediment accumulation	Years and decades	Climatic; biogeographic
River resorts	Barrier/ Irregular	Partial impediment of the flow	Permanent	Anthropogenic
Gorge valley	Acceleration Zone/ Narrow, confined in sandstone	Accelerate flow, increasing incision	---	Lihtologic; gradient
Watershed transposition canal	Buffer and barrier zone/ Partly open canal	Laminar flow impediment on slopes and interception of lower order channel flow	Permanent	Anthropogenic
Floodout	Barrier/ Plane, fan shape, unconfined	Longitudinal impediment and flow dissipation	Decades	Climatic; base level
Alluvial plain	Buffer Zone/ Plane, unconfined	Slope-channel transmission lateral impediment	Holocene	Climatic; sediment availability
Fluvial terrace	Buffer Zone / Plane, elevated paleo-plain	Slope-channel transmission lateral impediment	Holocene	Climatic; base level lowering
Aggraded tributaries	Buffer Zone / Plane or fan shape	Valley fill and infrequent merging with main channel	Years	Climatic; sediment availability
Discontinuous channel plain	Buffer Zone / Plane, unconfined	Channel with limited incision and transport capacity	Decades to centuries	Climatic; Anthropogenic
Glacis	Buffer Zone / Slightly undulated	Slope transmission impediment	Late Quaternary	Climatic; lithologic
Roads	Buffer and barrier Zone/ Irregular	Lateral slope-floodplain-channel and longitudinal flow impediment and long-term floodplain lateral adjustment limitation	Permanent	Anthropogenic

The fluvial morphologies of the partially confined and non-confined stretches of the Salamanca River consist of a sequence of arroyos (channeled sections), floodouts (unchanneled fan-shaped sections), and floodplains with discontinuous channels.

Floodouts and arroyos are common features in ephemeral drainages affected by changes in base level and transport and flow capacity in semi-arid regimes (Bull, 1997; Tooth, 2000). In addition, the longitudinal damming of the flow frequently occurs in sectors of tributary-main stem confluences (Figure 5).

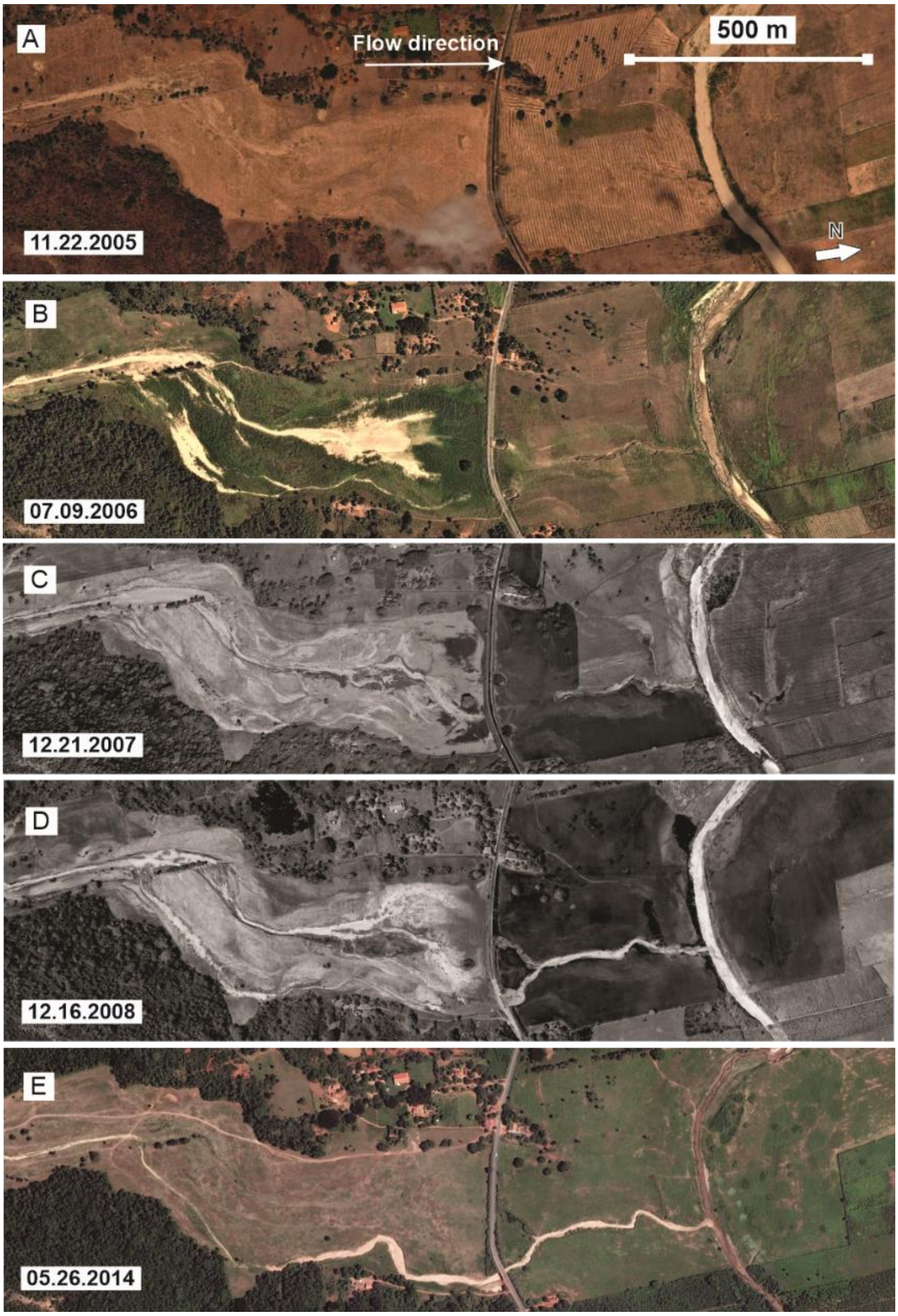

Figure 5: Tributary–main channel fluvial connectivity dynamics within a decadal timeframe marked by the intense lateral activity in a partly confined valley. Tributary of the Salamanca River, located in the transition between the partially confined and the unconfined valley, where a stretch of the plain is intercepted by a paved road, built on the limit of the valley confinement patterns. Disconnected pattern (A, B, C, D) connected pattern (E). Images source: Google Earth Pro.

In higher magnitude rainfall events, flooding, lateral migration, and multi-channels formation processes are intensified in the partially confined segment of the valley, controlled by changes in slope and water/sediment flow from the Plateau. Downstream, a road built on a wet passage on higher topographic level, also limits longitudinal flow transmission, leading to episodes of fluvial dysconnectivity (2005-2007).

Like the CAC canal, the road represents an anthropogenic disconnection element that, associated with the sedimentary cut-and-fill processes, promotes a peculiar river connectivity dynamic. In some SW-NE trending channel stretches, roads promote slope-channel dysconnectivity or, as Blanton and Marcus (2009) put it, behave as a marginal dike, intercepting the slope-floodplain connection, thus limiting the lateral delivery of materials to the fluvial plain.

2.2. Climatic control

The total annual rainfall at Barbalha Station from 1974 to 2019 varied from 540.5 mm to 2,147.5 mm (Figure 6), with an annual average of 1,053.4 mm, a value considered high in the context of the Brazilian semiarid region (Figure 6). Wetter conditions, in this case, reveal the orographic effect's interference since the Salamanca River headwaters lie at an altitude of 980 meters asl.

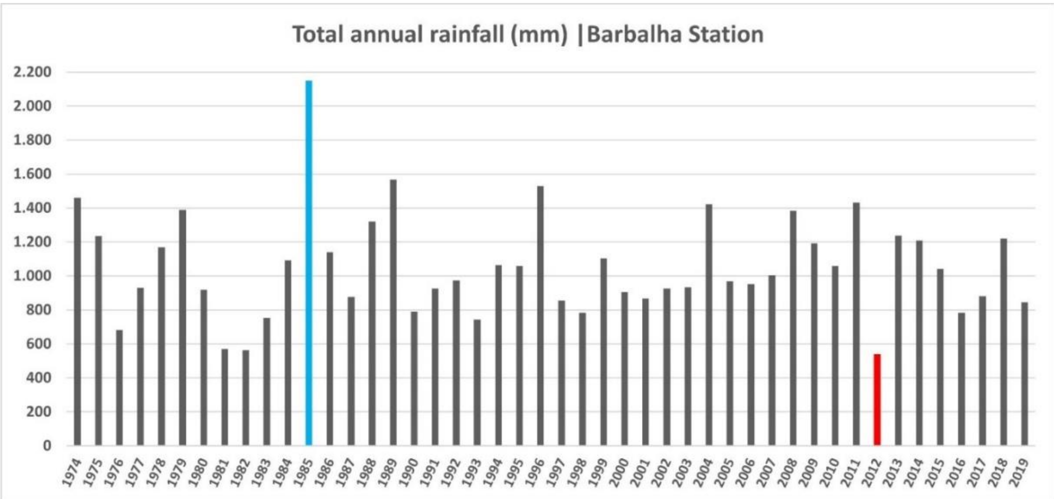

Figure 6: Total annual rainfall (mm), on Barbalha Station. **Source:** FUNCEME.

The annual rainfall totals also show a critical interannual variability that directly interferes with river flow and the accumulation and obliteration of alluvial deposits. In their turn, the RAI values obtained for the Barbalha station range from 7.53 in 1985 to – 4.43 in 2012, years classified as extremely wet and extremely dry, respectively (Figure 7).

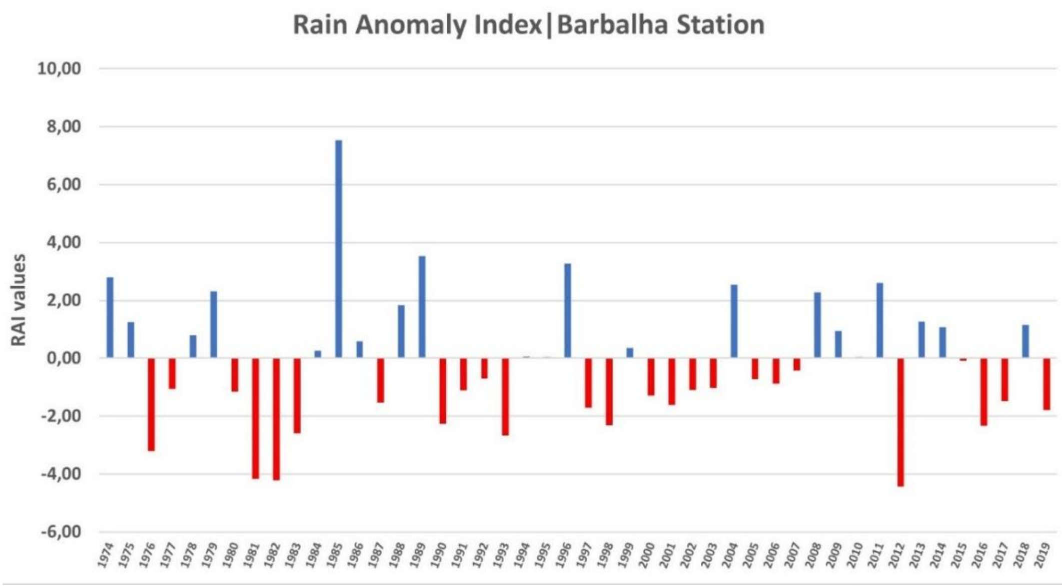

Figure 7: Rain Anomaly Index for the 1974-2019 series, Barbalha Station.

Considering the historical series and the existence of relationships between the occurrence of rainfall and the fluvial depositional dynamics, those years classified as very or extremely wet (RAI > 2) that occur after very or extremely dry years (RAI < 2) stand out. Periods of abundant rain that follow periods of drought, sometimes long ones, find a landscape whose surface coverings are more susceptible to erosion. Thus, identifying dry and wet phases within the available data series is particularly important for elucidating the cut-and-fill dynamics in the fluvial deposits of the region.

In this context, 1984 and 1985 stand out, following the dry period from 1980 to 1983 (Figures 6 and 7). This exceptional drought affected the entire Brazilian semi-arid region, which recorded below-average rainfall and high agricultural losses (Marengo *et al*., 2016). Although more discreetly, 2013 and 2014 stand out as wet years that followed the extremely dry year of 2012 (Figures 6 and 7). However, 2013 and 2014 are part of an extensive decadal dry period reported throughout the Brazilian semi-arid region (Marengo *et al*., 2016).

The interannual variability of rainfall in the Brazilian semi-arid region has been linked to global scale phenomena such as El Niño/Southern Oscillation and Atlantic Dipole (Hanstenrath & Heller, 1977; Ropelewski & Halpert, 1987; Servain, 1991; Nobre & Shukla, 1996; Brahmanada Rao *et al*., 1997; Souza & Nobre, 1998; Haylock *et al*., 2006; Andreoli & Kayano, 2007; Polzin & Hastenrath, 2014). In addition, anomalies in sea surface temperature in the Pacific and Tropical Atlantic oceans – capable of altering the position of the Walker Cell as well as the Intertropical Convergence Zone, interfere to a greater or lesser extent with the occurrence of dry or rainy periods in the Brazilian semi-arid region.

Evidence of climatic teleconnections was observed mainly in 1982/1983 and in 1992, when severe droughts were recorded throughout the region, concomitantly with the warm phase of ENSO and the positive phase of the Atlantic Dipole. On the other hand, the very humid years of 1985, 1996, 2008, and 2011 registered the occurrence of ENSO in its cold phase and Negative Dipole, which has been reported as favorable to triggering periods of more significant rainfall. However, the importance of ENSO interference was questioned by Kane (2001), who proposed the existence of more complex mechanisms involved in triggering dry and wet periods in the region.

The period from 2004 to 2014 was chosen due to the availability of good-resolution orbital images for the study area. Thus, remote sensing imagery interpretation was applied to analyze sedimentary reworking processes and possible linkages with the rainfall dynamics in this time interval. A graph containing the annual precipitation totals and the RAI values calculated for the 1974 – 2019 series was prepared (Figure 8). The years 2004, 2008, and 2011 stand out as the rainiest and with the highest RAI values, in contrast to 2012, with a total rainfall of less than 600 mm and a RAI value below -2. The occurrence of drought between 2012 and 2015 reported throughout the Brazilian semi-arid region (Marengo *et al*., 2016) was not evidenced by the calculation of the RAI for the Barbalha Station since in the years 2013 and 2014 total rainfall was above 1,200 mm, with RAI values slightly above 1, thus being wet years. The discrepancy between the total rainfall for 2012 and the biennium 2013/2014 points to a possible relevance of this period for analyzing alluvial deposits reworking in the watershed.

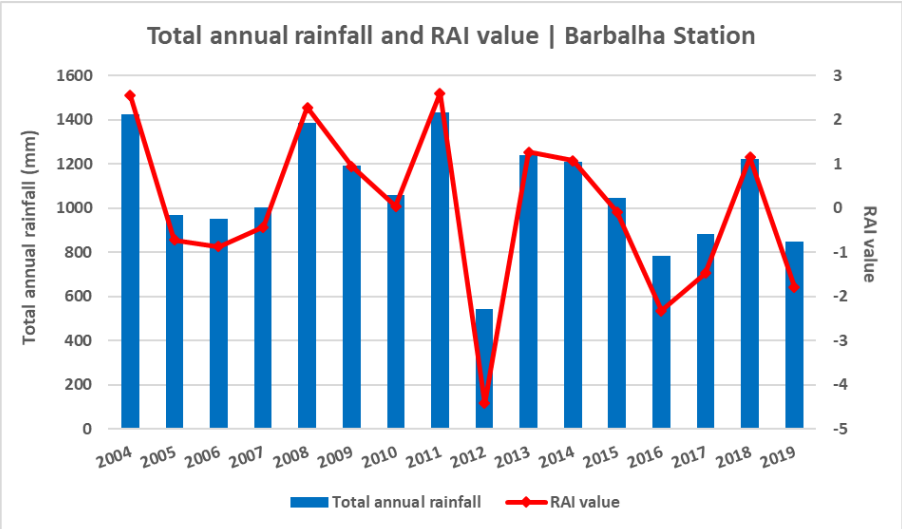

Figure 8: Total rainfall (mm) and RAI values between 2004 and 2019.

Although the interannual variability in precipitation is crucial to elucidate the erosive-depositional dynamics in the semi-arid fluvial environment, isolated extreme precipitation events can also affect transport and accumulation processes in these environments. Therefore, the extreme events that occurred in the (2004–2014) series were identified, considering as extreme those that exceeded 50 mm in 24 hours (Santos *et al*., 2012; Mascioli *et al*., 2016; Marengo *et al*., 2020; Cotterill *et al*., 2021) (Figure 9).

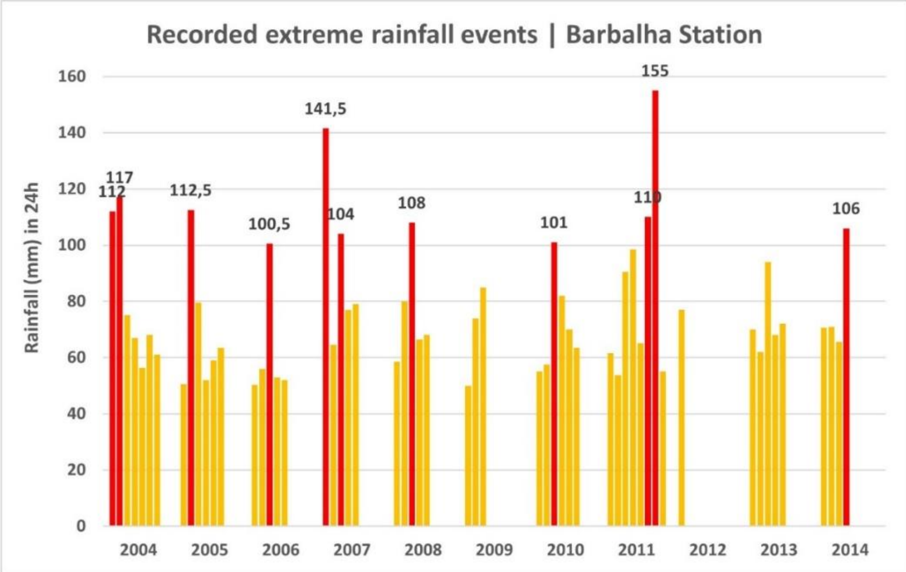

Figure 9: Recorded extreme rainfall events from 2004 to 2014 to Barbalha Station.

According to the graph above, the occurrence of at least one extreme precipitation event per year was verified. In 2004 and 2011, the highest number of such events was recorded, in contrast to 2012 – the driest year in the series, with only one extreme event.

Table III: Precipitation data, RAI, ONI index, Dipole index, number of extreme events and months with extreme events.

Year	Total (P)	RAI	ONI			ENSO Class	Anomalies Servain			Dipole class	Qt. Ext.	Months with extreme events
			DJF	JFM	FMA		Mar	Apr	May			
2004	1423,1	Very wet	0,4	0,3	0,2	Neutral	1.01	1.94	0.71	Neutral	7	01, 02, 03, 05
2005	969,7	Dry	0,6	0,6	0,4	Neutral	0.34	1.54	2.06	Positive dipole	6	01, 03, 12
2006	951,9	Dry	-0,9	-0,8	-0,6	ENSO cold	-0,64	0.17	0.23	Neutral	5	02, 03
2007	1.003,80	Dry	0,7	0,2	-0,1	Neutral	0.99	0.76	-0.14	Positive dipole	5	02, 04, 12
2008	1.384,50	Very wet	-1,6	-1,5	-1,3	ENSO cold	-0.22	-0.97	-0.71	Negative dipole	5	01, 02, 03, 12
2009	1.191	Wet	-0.8	-0.8	-0.6	ENSO cold	-1.50	-1.40	-1.85	Negative dipole	3	04, 05, 12
2010	1.059,90	Wet	1,5	1,2	0,8	ENSO Warm	0.66	1.10	0.95	Neutral	6	01, 03, 04, 06, 12
2011	1.431,20	Very wet	-1,4	-1,2	-0,9	ENSO cold	-0,71	-0,20	0,02	Negative dipole	8	01, 02, 03, 10
2012	540,5	Very dry	-0,9	-0,7	-0,6	ENSO cold	0.23	0.32	0.80	Positive dipole	1	03
2013	1.238,10	Wet	-0,4	-0,4	-0,3	Neutral	1.19	0.67	0.68	Positive dipole	5	01, 03, 05, 06, 11
2014	1.209,10	wet	-0,4	-0,5	-0,3	Neutral	-0.87	-0.87	-1.16	Positive dipole	4	02, 03

These data show that, in addition to being frequent, extreme precipitation events can occur even in years considered dry, although they occur in more significant numbers during wet years. This scenario reveals the need to address rainfall variability from both annual and daily scales, as single rainfall events alone can trigger the reworking of alluvial deposits.

3. Discussion

The lithology of the Araripe sedimentary basin exerts several controls over the fluvial systems of the Salamanca River watershed, among them the availability of sediments, the distribution of alluvial plains, and the hillslope-channel linkage dynamics. In the geological context of the Brazilian drylands, summit surfaces and low-lying pediments structured in metamorphic complexes and Proterozoic plutonic rocks predominate. Under such semi-arid conditions, those crystalline lithologies almost entirely lack in situ regolith covers; residual soils are generally scant and thin. Remobilized surface coverings, such as colluvium ramps and fluvial plains, are spatially limited and discontinuous.

In the sedimentary basins of the region, the predominance of siliciclastic rocks, subject to physical weathering, accelerates the rates of regolith production and, consequently, increases the availability of sediments for run-off detachment and other types of surface processes. Thus, the greater availability of unconsolidated material in the sedimentary basins accounts for the higher entrapment of sediments in the river systems, contributing to the filling of valley bottoms by recurrent cut-and-fill episodes (Mabesoone *et al*., 1981).

The lithological and tectonic structures also favor the genesis and maintenance of staggered surfaces on the hillslopes of sedimentary plateaux, resulting in the creation of a series of foot-slope accommodation spaces, which facilitate the development of discontinuous fluvial plains (pocket plains). The evolution of these aggradation landforms reflects the operation of the semi-arid climatic regime, with spasmodic sedimentation in response to high-magnitude precipitation inputs followed by long dry intervals when fluvial transport is significantly reduced.

Thus, remobilized surface coverings in the area represent relics of landscape paleoconectivity and testify to the rejuvenation of the drainage system during the Holocene (Lima *et al*., 2021a). They also represent sources of sediment as well as promote lateral and longitudinal dysconnectivity over various geomorphic units, such as catchment hollows, pocket plains, alluvial fans and terraces, floodplains, and channel bars. Such a set of morphologies highlights the role of inherited deposition structures on current drainage adjustments.

The current fluvial dynamics are controlled by the cut-and-fill processes associated with the semi-arid hydrological regime. In these scenarios, sheet-flow deposition over the plains is episodic, and transport and sedimentation occur only during or shortly after high-intensity precipitation events (Daniels, 2003). Hence, the morphologies of the Salamanca River resulting from cut-and-fill processes, such as arroyos (channeled stretches) and floodouts (unchanneled stretches), can be dealt with as a continuum of erosion-transport-filling in ephemeral rivers in association with regional controls, especially climate and lithology.

The contemporary reworking of floodplain sediments had extreme precipitation events as triggering mechanisms, which caused complex incision and sedimentation responses (Table IV). Along the channel segments, it was observed that the cut-and-fill structures occur on a surface inherited from depositional processes dating back to the Upper Pleistocene (Figure 10).

Table IV: Floodplain sediments reworking timeframe from 2004 to 2014.

Phases	Climatic forcings	Number of Extreme events	Image Date	*cut-and-fill* Processes
T0	2004			
	1142 mm, very wet, no tropical Pacific SST anomalies, neutral Dipole	7 extreme events between January and May	Images not available	Images not available
	2005			
	969,7 mm, dry, no tropical Pacific SST anomalies, Positive Dipole	6 extreme events in January, May and December	November	Images not available
T1: sediment filling	2006			
	951,9 mm, dry, Cold Enso, neutral Dipole	5 extreme events in February and March	July and September	Accumulation
T2: sediment cutting	2007			
	1003,8 mm, dry, no tropical Pacific SST anomalies, Positive Dipole	5 extreme events in February, April and December	December	Incision
	2008			
	1384,5 mm, very wet, cold ENSO, Positive Dipole	5 extreme events in January, February, March and December	December	Incision (mostly downstream of the road)
T3: sediment filling	2009			
	1191 mm, wet, cold ENSO, Negative dipole	3 extreme events in March, May and December	August	Accumulation
?	2010			
	1059, 9 mm, wet, warm ENSO, Neutral Dipole	6 extreme events in January, March, April, June and December	Images not available	Images not available
	2011			
	1431,2 mm very wet, cold ENSO, Negative dipole	8 extreme events in January, February, March and October	Images not available	Images not available
T4: sediment filling	2012			
	540,5 mm, very dry, cold ENSO, Positive Dipole	1 extreme event in March	March	Accumulation
T5: sediment cutting and channel development	2013			
	1238,1 mm, wet, no tropical Pacific SST anomalies, Positive Dipole	5 extreme events in January, March, May, June, and November	April, August, September, October	Incision and channel development (downstream of the road)
	2014			
	1209,1 mm, wet, no tropical Pacific SST anomalies, Positive Dipole	4 extreme events in February and March	May and August	Incision and channel development (downstream of the road)

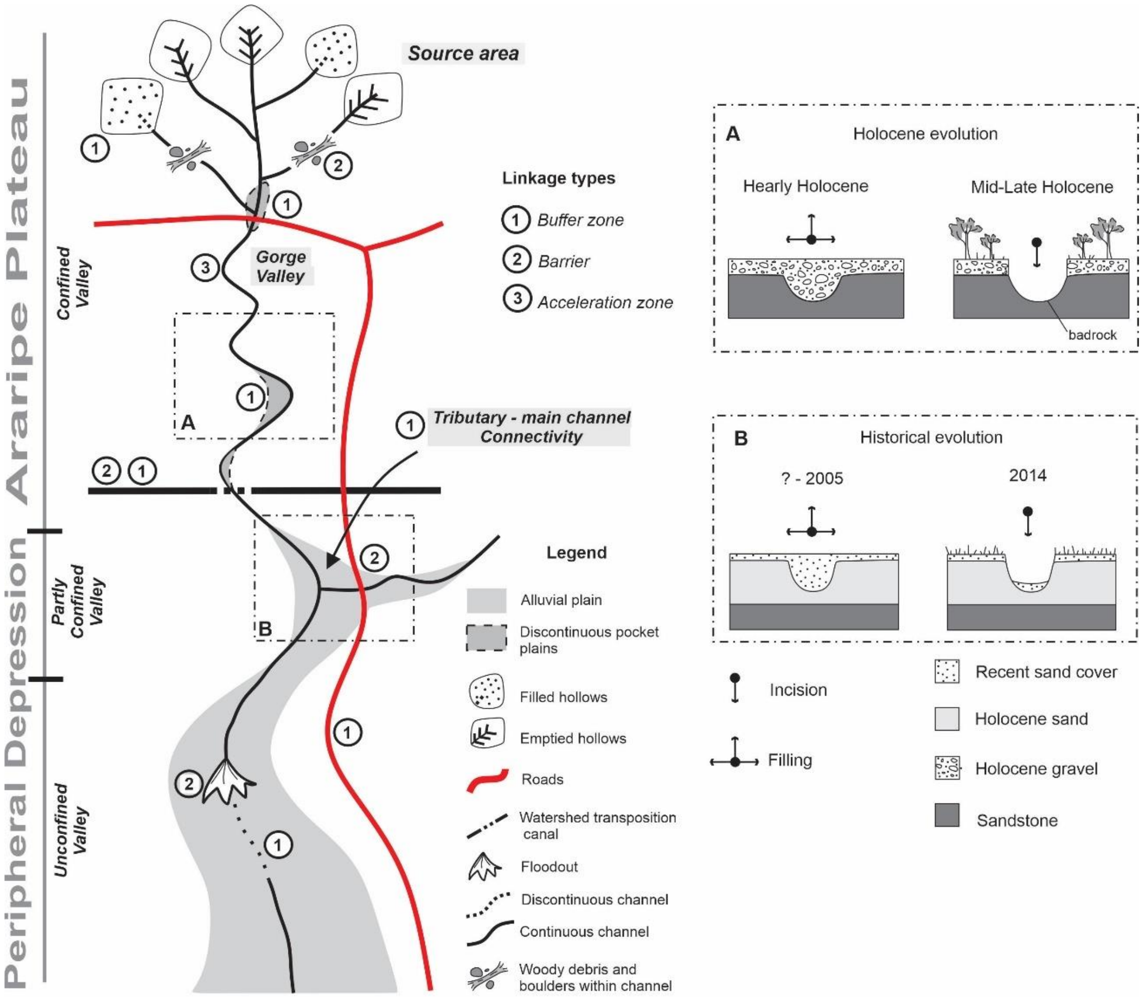

Figure 10: Synthesis of the fluvial connectivity system of the Salamanca River watershed.

Conclusion

The semi-arid region of Northeast Brazil is a complex mosaic of landscapes; as an expression of this diversity, the Araripe Plateau constitutes a regional geomorphological landmark, geologically distinct from the crystalline terrains surrounding it. In this morphostructural setting and under a transitional tropical sub-humid to the semi-arid environment, the Salamanca River watershed presents a diversity of fluvial connectivity scenarios, recorded in the landscape by colluvial and alluvial sediments and cut-and-fill structures since the Upper Pleistocene. The aggradational landforms and surface coverings reflect a history of climatic and hydrological oscillations.

Landscape connectivity governs sediment availability, transport, and storage (deposition) sites, typically addressed at the watershed scale. Therefore, in the ephemeral drainages of the study area, connectivity is dramatically interrupted with each dry season, creating disconnection. Dysconnectivity, described as the temporal inability of sediment to be removed from the geomorphological system, as we have seen, frequently occurs in semi-arid drainages; notwithstanding, at the landscape scale, it reflects increasing time intervals that can range from a few days to thousands and tens of thousands of years.

It is essential to highlight that the observed scenarios attest to a complex surface dynamic operating in a lower-order watershed. The frequency of connections depends on the types of impediments and geomorphic responses to energy inputs, especially climatic triggers, mediated by bedrock lithology and anthropogenic interference. This aspect was demonstrated in the section of channel confluence in which the valley filling, given the amount of sediment supply from the plateau in response to high precipitation events, is partially blocked by a road, hence artificially changing the local base level.

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