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Small river structures and their effects on landscape connectivity - lower course of the Piancó river - Brazilian semi-arid region

Pequenas estruturas em rios e seus efeitos na conectividade da paisagem – baixo curso do rio Piancó – semiárido brasileiro

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Abstract

This study investigates landscape connectivity in semi-arid fluvial systems, focusing on the effects of anthropogenic structures on water and sediment transmission. The research was conducted in the lower course of the Piancó River basin, where twenty-four anthropogenic structures were identified and characterized, including fords and dams (both rudimentary and engineered). The disordered distribution of these structures highlights the lack of planning in human interventions. The analysis demonstrated that engineered dams, in particular, disconnect the eastern portion of the basin from the effective catchment area (ECA), affecting hydrological and sediment dynamics. It is concluded that anthropogenic structures exert significant local influence on fluvial channels, necessitating continuous monitoring and an integrated approach with other research to better understand the impacts. It is recommended that preliminary connectivity mapping be incorporated in the initial stages of fluvial geomorphology research to improve the precision and effectiveness of analyses.

Keywords:
Sediment flow; Sections of the landscape; Anthropic impacts; River channel; Semi-arid landscape.

Resumo

Este estudo investiga a conectividade da paisagem longitudinal em sistemas fluviais semiáridos, com foco nos efeitos das estruturas antrópicas na transmissão de água e sedimentos. A pesquisa foi realizada na bacia hidrográfica do baixo curso do rio Piancó, onde foram identificadas e caracterizadas vinte e quatro estruturas antrópicas, incluindo passagens molhadas e barragens (rústicas e de engenharia). Os elementos foram analisados A distribuição desordenada dessas estruturas destaca a falta de planejamento nas intervenções humanas. A análise demonstrou que a barragem de engenharia, em particular, desconecta a porção leste da bacia da área de captação

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efetiva (ACE), afetando a dinâmica hídrica e desconectando a conectividade sedimentar. Conclui-se que as estruturas antrópicas exercem influência significativa e local nos canais fluviais, o que demanda monitoramento e abordagem integrada com outras pesquisas para entender melhor os efeitos. A recomendação é que mapeamentos preliminares de conectividade sejam incorporados nas etapas iniciais de pesquisas em geomorfologia fluvial para melhorar a precisão e a eficácia das análises.
Palavras-chave:
Fluxo de sedimentos; Seções da paisagem; Impactos antrópicos; Canal fluvial; Estruturas antrópicas.

I. INTRODUCTION

The history of dryland occupation around the world highlights the application of social technologies to improve the use of water resources, thus enabling the occupation of these territories. In the Brazilian semiarid region, occupation has always depended heavily on the efficient use of water, with interventions such as dams, pipelines, river transpositions and public policies (DANTAS; DA SILVA; SANTOS, 2020). This history has made the semiarid region of the northeast one of the regions with the largest number of dams in the world (VIEIRA, 2003).

Drylands possess a complex environmental context in their dynamics, being the scene of the interaction of various factors, such as irregular rainfall, episodic behavior, high evapotranspiration rates, and significant sediment movement (GRAF, 1988; BULL; KIRKBY, 2002a, 2002b). In these areas, the predominance of river systems composed of non-perennial rivers stands out (BUSCH et al., 2020; MESSAGER et al., 2021), in which the morphological work of these systems is strongly linked to episodic flow events in the river channel (HOOKE, 2016), with spatio-temporal variations in magnitude and frequency (BULL et al., 2000; CORRÊA et al., 2010; SOUZA; ALMEIDA, 2015). This opens a field of action for approaches and concepts that analyze the dynamics of transmission and behaviors of these environments, in which landscape connectivity is emphasized.

This emerges as a framework for analyzing environmental dynamics, especially in the river system, in order to investigate the potential for transmission and movement of matter and energy (input and output) at various scales of analysis (BRIERLEY; FRYIRS; JAIN, 2006), between sections of the system, ranging from morphological changes within the river channel (HOOKE, 2003; SANDERCOCK; HOOKE, 2011; WOHL; SCAMARDO, 2021), by channel segments (WOHL; SCAMARDO, 2021; HOOKE, 2023), sections of the landscape (SOUZA; CORRÊA; BRIERLEY, 2016; HOOKE; SOUZA; MARCHAMALO, 2021), and sub-basins of tributaries to large hydrographic basins (FRYIRS et al., 2007b, 2007a; WOHL, 2017).

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In the Brazilian context, studies on landscape connectivity, specifically river connectivity, have been gaining application in several national contexts (SOUZA; CORREA, 2012; SOUZA; CORRÊA; BRIERLEY, 2016; DUARTE; MARÇAL, 2017; FRANCO; SOUZA, 2019; CASTELO BRANCO, 2020; SOUZA; BRANCO, 2020; ZANANDREA et al., 2020; LIMA; MARÇAL; CORRÊA, 2021; ABATTI et al., 2023). These studies investigate structural and functional connectivity, evaluating the sediment transport process. Others evaluate connectivity in association with methodology or theoretical concepts that address susceptibility to change.

Studying connectivity implies understanding disconnections (BRIERLEY; FRYIRS; JAIN, 2006), such as the coupling and decoupling of sections of the landscape (HARVEY, 2001, 2002, 2012). For example, in the work of Fryirs et al., (2007b), the authors recognize three categories of elements (buffers, barriers and blankets), whether natural or anthropogenic, that interfere in the transmission of water and sediments in the river system, in transmission dimensions (lateral, longitudinal and vertical).

Specifically regarding the longitudinal dimension, barriers are significant, represented by interruption elements that interfere in the longitudinal dynamics of the river channel, altering the upstream-downstream relationship. They comprise rocky sills, dams (of varying sizes), highways and roads. The effects of these interruption elements can vary, ranging from partial or total, or temporary or permanent disconnections (FRYIRS et al., 2007b). Thus, each longitudinal interruption element, with its specific construction characteristics, has the potential to generate different manifestations in the transmission behavior (FRYIRS, 2013; SOUZA; CORRÊA; BRIERLEY, 2016; CASTELO BRANCO et al., 2023).

In addition to the characterization and differentiation of interruption elements, spatial distribution also gains interest when working with landscape connectivity, being one of the main factors for delimiting the Effective Catchment Area (ACE) (FRYIRS et al., 2007a). It can be understood as the portion that will contribute matter and energy to the downstream portions of the river system, that is, the areas that have the potential to supply water and sediments from upstream to downstream in scenarios varying in magnitude and frequency (FRYIRS et al., 2007b, 2007a; SOUZA; CORREA, 2012) of flow in the channel.

Exploring the longitudinal interruption elements a little further, dams, as the most significant representatives, have the potential to significantly alter river dynamics (COELHO, 2008; SCORDO et al., 2023). The release of water downstream, when the dammed volume exceeds the storage capacity, generates flow in the channel again, so that the flow relationship will not be linked just to flow events, but also to the dam limit. When sediment movement occurs, this suffers the most significant effects, especially on bedload sediments (FRYIRS et al., 2007a, 2007b), with less significant effects on suspended sediments.

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There are other types of interruption elements of smaller size, such as water crossings (CAVALCANTE et al., 2014; CASTELO BRANCO et al., 2023) and check dams (CASTILLO et al., 2007; ABBASI et al., 2019; LUCAS-BORJA et al., 2019). The effects on the river system can vary so that these elements also generate impeding results, restricting the flow of water and sediments; however, the transmission reaches connection stages (connected and partially connected) more easily. These lose effectiveness through more significant or extreme events (HOOKE, 2016; SOUZA; CORRÊA; BRIERLEY, 2016; CASTELO BRANCO et al., 2023) capable of remobilizing significant amounts of water and sediments (HOOKE, 2019).

Despite the growing interest in works focused on the quantification and measurement of river connectivity, both sedimentological and hydrological, (BRACKEN; CROKE, 2007; BORSELLI; CASSI; TORRI, 2008; CAVALLI et al., 2013; BRACKEN et al., 2015; WOHL, 2017; HECKMANN et al., 2018; ZANANDREA et al., 2020), especially from the perspective of functional connectivity (HECKMANN et al., 2018; ZANANDREA; MICHEL; KOBIYAMA, 2020; HOOKE; SOUZA; MARCHAMALO, 2021; ABATTI et al., 2023), we understand that the structural perspective needs to be considered especially when working with the distribution of interruption elements, resulting from historical anthropic processes in river systems, as is the case of the Brazilian tropical semiarid region.

Based on these considerations, this work aims to analyze how anthropogenic interruption elements affect longitudinal connectivity in rivers in a watershed in the semiarid region of Paraíba. The goal was to examine the spatial distribution of these structures, their typologies and construction characteristics, as well as the behavior of the river system in three scenarios of magnitude of flow events in the channel, recognizing their effects on the Effective Catchment Area (ACE), in addition to seeking to develop a model of the relationship between anthropogenic structures and the magnitude of events.

II. ÁREA DE ESTUDO

The Piancó River Watershed (BHRP) has a total area of approximately 9,242.75 km^2, whose lower course (BHBXP), a sub-basin with a perennial channel, has an estimated area of 768 km^2 (Figure 1). It is located in the sertaneja depression (CORRÊA et al., 2010), marked by a crystalline basement, a predominantly flat and gently undulating relief, containing granitic intrusions from the Neoproterozoic, and with incipient alluvial deposits associated with the principal channel (MEDEIROS, 2008).

The terrain presents altimetric homogeneity, with predominance of terrains with altitudes between 169 m and 300 m, and topographic changes recorded in the south of the basin due to a mountain range complex

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(ARAÚJO, 2018), with higher areas of altitudes starting from 300 m and reaching 800 m. Regarding the slope, it presents a mostly flat and gently undulating landscape, with steeper areas associated with drainage headwaters with higher altimetric levels (CASTELO BRANCO et al., 2023).

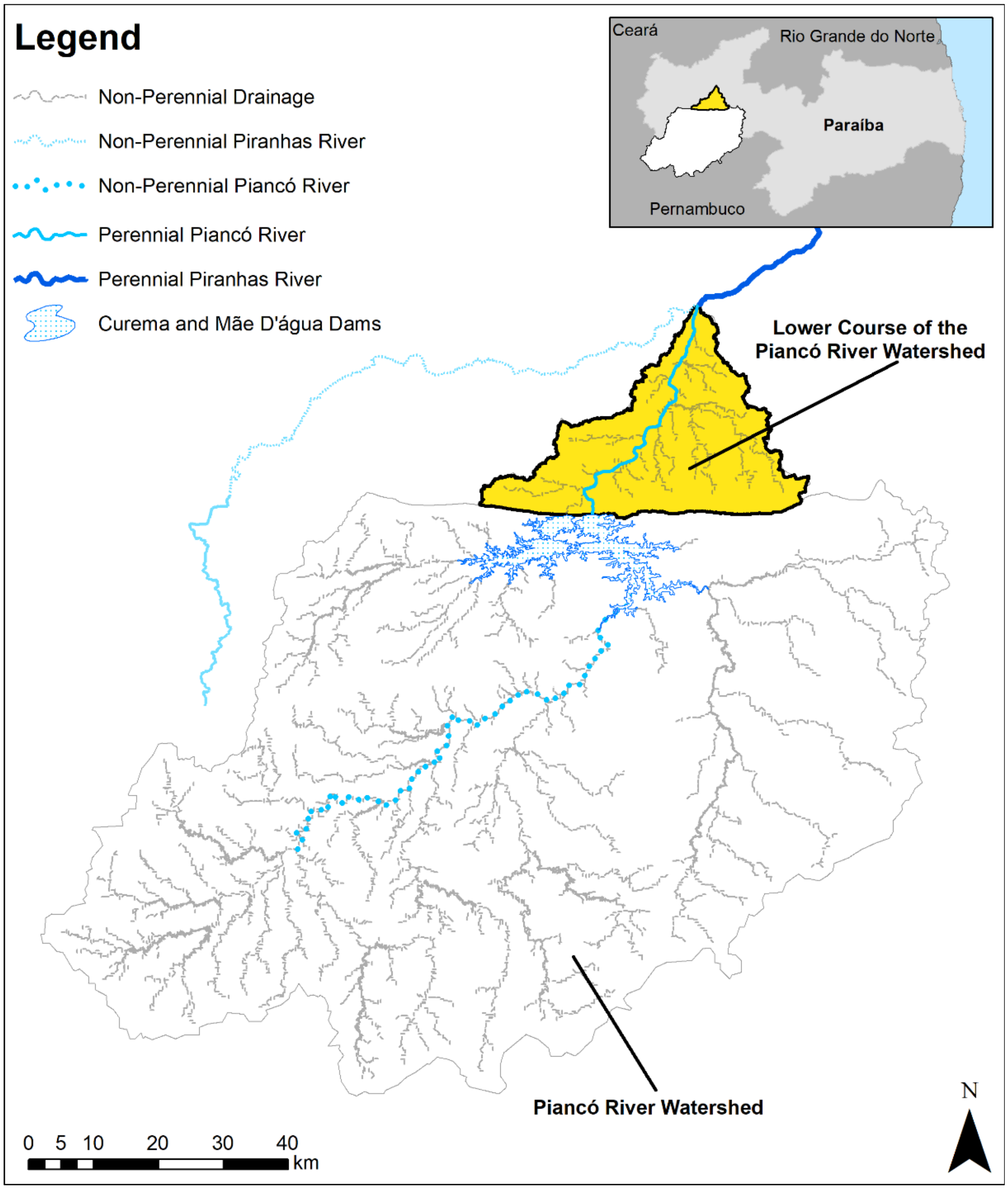

Figure 1 - Location of the Lower Piancó River Watershed. Source: Prepared by the authors, 2023.

III. Materials and Methods

The analysis of landscape connectivity was carried out based on the considerations of Brierley, Fryirs and Jain, (2006); Fryirs et al. (2007a, 2007b); and Fryirs (2013), starting with the identification of interruption elements in an office environment, followed by field activities for validation and characterization of the

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elements, analysis and treatment of the collected data, ending with the delimitation of the ACE, organized in five stages (Figure 2).

Since the focus of the work is on the anthropogenic longitudinal interruption elements, that is, the barriers (DUARTE; MARÇAL, 2017), it was decided to disregard the disconnecting features and elements of natural origin (FRYIRS et al., 2007a). This preference was due to the understanding that anthropogenic structures are capable of generating significant modifications (CORRÊA, 2012) on the river channels, and considering the effort (in-office and field activities) to locate and reach natural elements within the basin. The anthropogenic elements stand out, almost always associated with access roads and/or anthropogenic occupations.

The initial survey of the interruption elements was carried out through the delimitation of the BHBXP hydrography, which was examined sequentially through the sub-basins of the tributaries, in which the interruption elements were indicated using the Google Earth Pro software.

The field activities supported the preliminary recognition procedures, validating the previous survey, and detailing the construction characteristics and the effects generated (Table 1) of the longitudinal interruption elements. Thus, the typologies of the elements were analyzed considering the specificities and site in which they were installed.

Table 1 - Data collected and verified in the characterization of interruption elements.

TYPOLOGY	VERIFIED DATA
Dams **Small-sized rudimentary** **Medium-sized rudimentary** **Engineered**	• Characteristics of the channel upstream and downstream; • Channel level for the height of the interruption; • If there is a barrier, it prevents/interrupts the flow in the channel; • Component materials of the dam (bucket and spillway); • If they were broken/damaged.
Bridges	• Construction and width of the water passage; • If there is a barrier, it prevents/interrupts the flow in the channel; • There are dams adjacent to the structure.
Water crossings	• Characteristics of the upstream and downstream channel; • If there is a barrier, it prevents/interrupts the flow in the channel; • Level of the channel bed for the height of the interruption; • The type of component material; • The structure and shape of the device.

Source: Prepared by the authors, 2023.

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Field-data control was performed using a GARMIN Etrex30 GPS. Preliminary data and field points were also managed using the AlpineQuest Off-Road Explorer PRO software, for use on mobile devices with the Android operating system. In total, twenty-four interruption elements were mapped and visited.

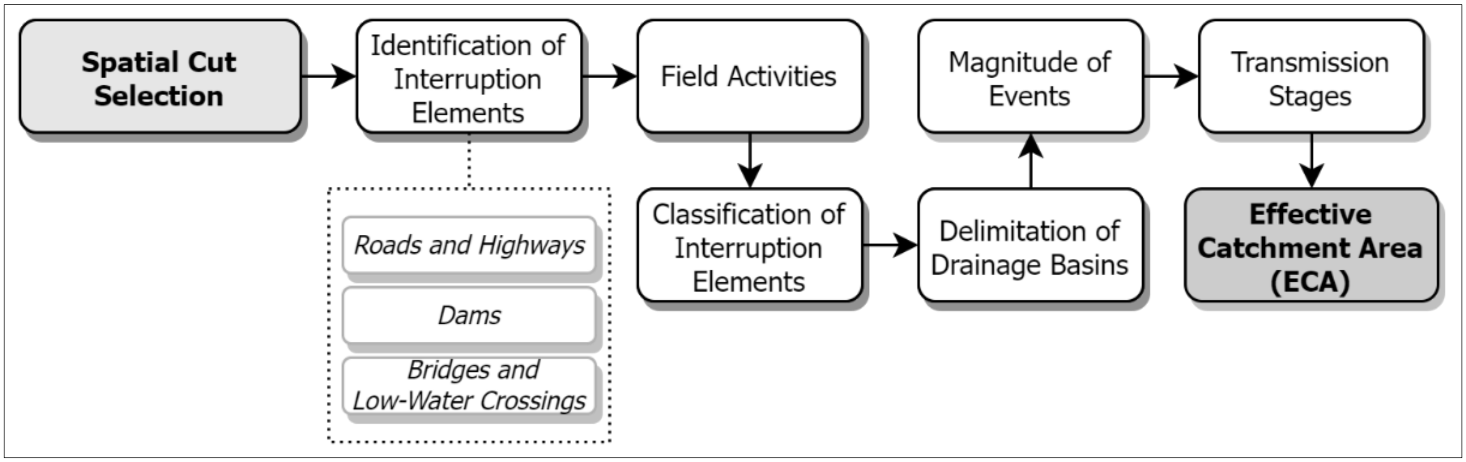

Figure 2 - Flowchart of recognition of interruption elements and delimitation of effective BCH catchment areas. Source: Adapted from: Fryirs, (2013); Fryirs et al. (2007b), (2007a); Souza et al. (2016). Prepared by the authors, 2023.

Following this, after data and information integration, the drainage basins of each mapped impediment were delimited (Figure 2), intentionally ignoring the sub-basins of the tributaries and the main channel. Through the spatialization of the interruption elements in the river channel, the drainage basins were delimited in a GIS environment, using the ArcMap software, version 10.1, with the *Arc Hydro Tools* package. In this way, we sought to understand which areas present potential connections and disconnections within the basin.

Finally, the behavior of the river channel and its interaction with the interruption elements, through the drainage basins of each element, were evaluated based on scenarios of magnitude of flow events (Table 2). These areas were then classified into three transmission stages based on the behavior of the structures in each potential scenario. Next, the ACE (FRYIRS et al., 2007a; SOUZA; CORRÊA; BRIERLEY, 2016) of BHBXP was delimited, based on three transmission stages (Table 2) (SOUZA; CORREA, 2012).

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Table 2 - Magnitudes of channel flow events and transmission stages.

MAGNITUDE	CHARACTERISTICS
Low Magnitude	Incipient flow, without reaching the banks of the river channel, with low sediment movement capacity and reduced process development capacity.
Moderate Magnitude	Flow filling the channel bed, reaching the level of full banks, with sufficient competence to mobilize sediments and develop geomorphic work in the channel bed.
High Magnitude	Large volume flow, exceeding the marginal limits, invading the floodplains, with a high capacity for sediment mobilization and great potential for developing intra and extra channel fluvial work, encompassing extreme events.
STAGES OF TRANSMISSION	**CHARACTERISTICS**
Connected	There is longitudinal transmission, so that the impeding effects of anthropic structures have little influence on the flow, thus allowing water and sediments to pass through without major difficulties.
Partially connected	There is partial transmission of water and sediments, so that the structure exerts an influence on the transmission capacity, restricting it.
Disconnected	There is no longitudinal flow, with the effects of the impediments subverting the flow of the channel, retaining all the flow upstream, generating accumulation.

Source: Adapted from: Fryirs et al., (2007b); Souza; Corrêa; Brierley, (2016); Hooke, (2019).

Considering the disorderly distribution of the longitudinal interruption elements within the basin, it was decided to analyze its drainage basins individually, allowing the filtering of possible inconsistencies, such as catchment areas connected upstream of large disconnection elements. In other words, the connected status of the drainage basin alone does not mean that this area is part of the ACE of the watershed.

IV. Results and discussion

Based on the delimitation of the interruption elements, the presence of bridges, water crossings, rudimentary and engineered dams (Figure 3) was verified within the watershed of the lower course of the Piancó River. The distribution of the elements presents differences between the main channel and its tributaries, as most of the dams (rudimentary and engineering) are installed in the tributaries and the water crossings are concentrated in the main channel and in the confluences (Figure 4B).

As for the water crossings, these small structures, almost always associated with rural roads (Figure 4A), are scattered throughout the BHBXP, from headwater areas and along the main channel, used to connect rural communities and farms in the region. The bridges are connected to highways (state and federal) that cross the basin (Figure 4A), installed both over the main channel and its tributaries.

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The basin has a chain of impediments in tributaries in the southeast portion, with rudimentary and medium-sized dams practically side-by-side (i.e., reaching parallel river courses) or subsequent ones, which are still covered by the catchment area of an engineered dam downstream, close to the main channel (Figure 4B). There is a noted social search for the capture of river courses, through the use of dams, aiming at future use in various anthropic activities, without any utilization planning or facilities management, as evidenced by the disorderly spatialization in the spatial cutout in question.

The quantity and distribution of interruption elements within the basin are noteworthy, which is consistent with the observations of Cavalcante and Cunha (2014) and Vieira (2003) regarding the massive frequency of river interventions in the semiarid region of northeastern Brazil. The presence of dams close to the headwater areas is also observed in the highest areas of the basin, close to the sertanejo mountain range complex, where sediment production processes predominate.

Once the interruption elements were identified, their drainage basins were demarcated, taking as a limit the existence of another impeding structure upstream or the topographic dividers of the watershed itself (Figure 4C). As a consequence, the size of the catchment areas varied considerably, since their delimitation followed the disordered spatialization of the elements within the basin, as previously mentioned.

By analyzing the construction characteristics of the impediment elements and the characteristics of the river channel, as well as the magnitude of the flow events, we sought to understand how the river dynamics and the capacity to transmit water and sediments from the bedload are related to these structures. Thus, each drainage basin was classified into the three transmission stages (Table 3), considering the transmission potential from upstream to downstream from the interruption element.

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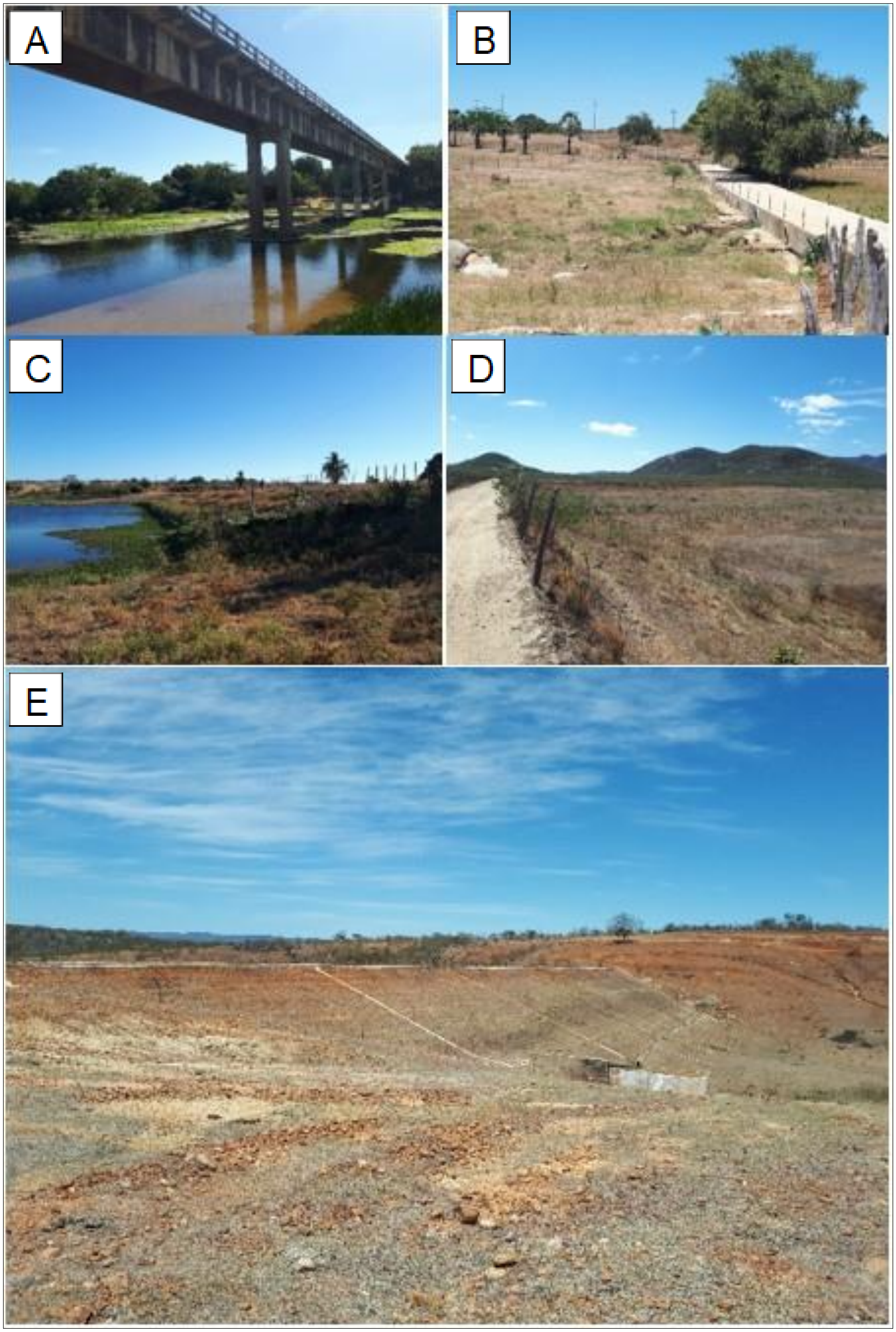

Figure 3 - Details of the anthropogenic impediments found within the lower Piancó River watershed. A – Bridge, B – Water crossing, C – Small rudimentary dam, D – Medium rudimentary dam and, E – Engineered dam. Source: Prepared by the authors, 2018.

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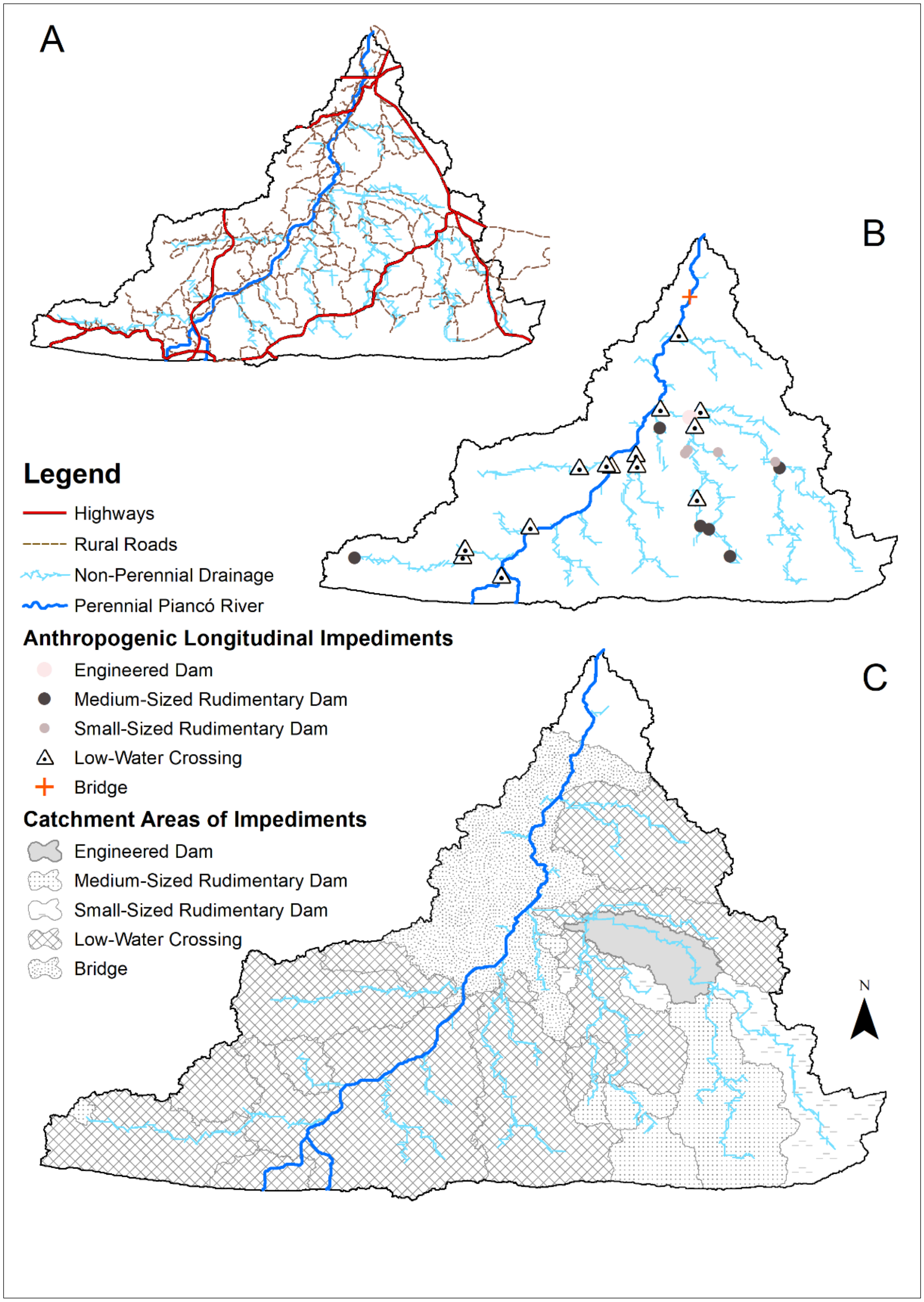

Figure 4 - Map of anthropogenic longitudinal impediments. A – Rural roads and highways within the basin; B – Distribution of longitudinal anthropogenic impediments in the basin; C – Catchment areas of anthropogenic elements and their associations upstream and downstream.
Source: Prepared by the authors, 2023.

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Each type of interruption element presents specific transmission stages in each of the three magnitude scenarios. As can be seen, smaller elements (e.g. water crossings) or with specific characteristics (e.g. bridges) allow the flow of channels to pass through or do not represent major restrictions on the transport of water and sediments. Compared to dams, these generate greater restrictive effects, acting as major transmission limiters.

Table 3 - Behavior of anthropogenic impediments in the scenarios and characteristics verified.

Impeding Element	Low Magnitude	Moderate Magnitude	High Magnitude	NOTES
BRIDGES	Partially connected	Connected	Connected	In low-magnitude events, the foundations inserted in the channel generate effects that lightly impede transmission. They have the potential to constrict flow in moderate and high-magnitude events, however, they do not generate restrictions on the transmission of water or sediments.
WATER CROSSINGS	Partially connected	Partially connected	Connected	In low- and moderate-magnitude events, they can interfere with the transport of bedload sediments, causing sedimentation upstream and erosion downstream of the structure. In high-magnitude events, their effects are overcome by the flow, with widespread mobilization of bedload sediments, thus exerting little resistance to transmission, however, they can become clogged.
SMALL RUDIMENTARY DAMS	Disconnected	Partially connected	Connected	In low-magnitude events, they trap sediments. In moderate-magnitude events, the flow can overcome the spillway, where suspended sediments are transported. In extreme and high-magnitude events, the flow can break the structure, causing the trapped sediments to be remobilized.
MEDIUM RUDIMENTARY DAMS	Disconnected	Disconnected	Partially connected	Capable of withstanding low- and moderate-magnitude events, trapping sediments, whether suspended or on the bottom. In extreme and high-water events, the flow can overcome it, but only when the structure ruptures can the sediments be reworked.
ENGINEERED DAMS	Disconnected	Disconnected	Disconnected	It can withstand events of varying magnitudes, but only the flow (with suspended sediments) can overcome the dams in extreme events, but the bedload sediments remain retained. Only when the dam ruptures can the sediments be reworked, but the chances of ruptures occurring are minimal when compared to rudimentary dams.

Source: Prepared by the authors, 2023

It is observed that bridges have a low capacity to interfere in the dynamics of longitudinal transmission, exerting restrictive effects in low magnitude events, in which the channel flow has not reached higher levels

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such as that of full banks. This is particularly true when the foundation of these structures is inserted in the channel bed, creating an impediment feature (Figure 3A) that, although not very expressive, generates effects on the transmission dynamics.

Water crossings exert a more significant impact during low- and moderate-magnitude events, restricting the flow of sediments, especially bedload sediments, which are notably retained upstream (Figure 5 A and B). In addition, these structures also affect water movement by slowing the flow velocity in the channel, potentially causing upstream accumulations that can obstruct normal flow (see Table 3).

However, during high-magnitude events, river dynamics can overcome the restraining effects imposed by water crossings. This occurs due to the considerable volume of water and sediment transported, resulting in widespread sedimentation and erosion along the channel stretch. In some cases, this force can even lead to the rupture of the structures themselves, although this outcome depends on several factors, such as construction methods and materials used, in addition to the flow volume.

Analyzing the water crossings and their conjunctures, it was found that, when clogged, these structures lose their effectiveness to impede in less expressive span events (e.g. low and medium flow). In other words, when the retained sediment volume fills the upstream portion, the impeding effects of these structures tend to be attenuated (Figure 5 C and D). However, the simple observation of colmatation does not allow us to affirm such behavior, therefore, it is necessary that each impediment be analyzed individually.

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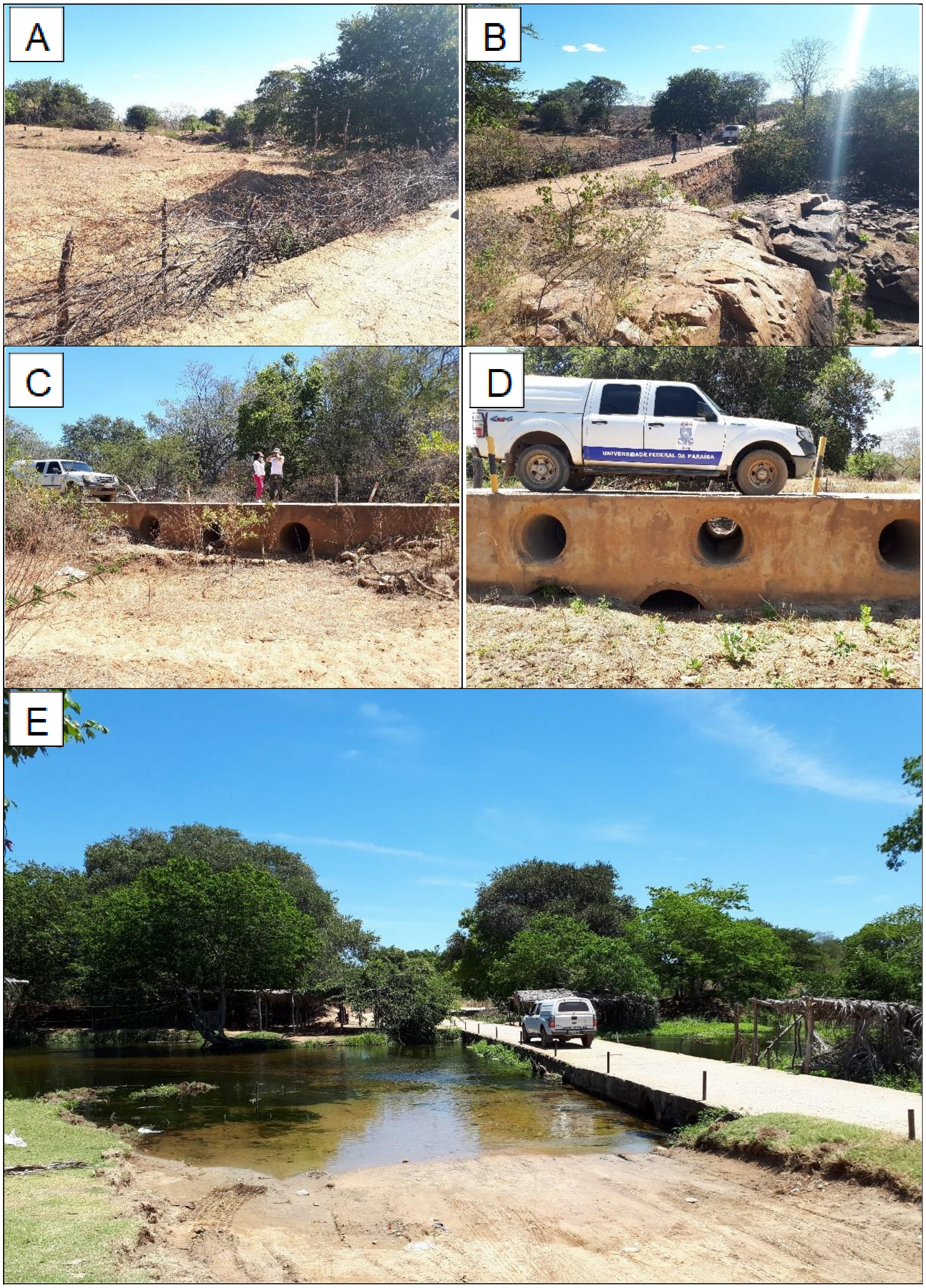

Figure 5 - Water crossings observed within the lower Piancó River watershed. A-B: Water crossing without drainage galleries, installed in a rocky outcrop, with sedimentation upstream (A) and erosion downstream (B). C-D: Water crossings, installed in alluvium, composed of galleries in the middle of their structure, presenting sediment retention at the height of the flow passages. E: Water crossings installed in the main channel of the Piancó River, presenting galleries for intermediate flow passage, and presenting sediment retention upstream (left) and erosion downstream (right). Source: Authors' collection, 2018.

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The structural and construction characteristics of water crossings present peculiarities. The presence of galleries (Figure 5D and E) in the body of the structure allows the flow to pass through at less significant flow rates. On the other hand, when these spaces are not present, they generate greater restrictive effects (Figure 5A and B) that can only be overflowed at more expressive flow rates, or when clogged. These characteristics have the potential to mitigate or aggravate the undesirable effects of these structures (e.g. sediment retention upstream and erosion processes downstream).

In a way, water crossings have effects more similar to dams than bridges, given the potential for sediment retention, changes in the local dynamics of the river system, as well as the potential to generate changes in the local base level (Figure 5 A, B and E).

As for dams (rudimentary or engineering), these are structures that are recognized as having varied effects on the river system. Therefore, a common behavior of this typology is recorded here, as they act as sediment traps (BRIERLEY; FRYIRS; JAIN, 2006; GRAF, 2006; FRYIRS et al., 2007b; COELHO, 2008; CORRÊA, 2012; CAVALCANTE; CUNHA, 2014), especially bedload sediments (FRYIRS et al., 2007a; SOUZA; CORRÊA; BRIERLEY, 2016).

Rudimentary dams, small or medium, share materials and differ mainly in construction processes and in the volume of water stored, affecting the areas of the drainage basins. Small dams are connected to smaller watercourses and, even releasing flow, have the possibility of transferring suspended sediments and dissolved materials. Medium dams serve larger basins and have reinforced structures. Engineered dams, with more robust technological inputs (see Figure 3E), capture water from large areas of the watershed, releasing large volumes of water only when that accumulated exceeds the spillway capacity, and are integrated into human supply systems, influencing the dammed volume.

Thus, it is understood that dams have a high capacity to disconnect the river system, sometimes serving as "landscape dividers" by disrupting the transmission of bottom sediments and substantially restricting water transmission within the basin. Finally, the ACE was delimited for each magnitude and transmission stages, considering the catchment areas up to the connection with the chosen reference outlet. The areas were summarized (see Table 4) relating the magnitudes and transmission stages, with the areas (km²) being computed for each stage, based on the total area of the watershed, in each magnitude scenario.

Regarding the magnitude scenarios and their respective stages (Table 4), the predominance of the partially connected stage is observed in moderate- and low-magnitude scenarios, with water and sediment transmission occurring, even under the effects of the structures, especially in the bedload sediments.

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In the high magnitude scenario, the flow has the potential to subvert the restrictive effects of the smaller interruption elements (e.g. water crossings, bridges and rudimentary dams). This can be seen in the transmission stages, where 70% of the basin has a connected status, with only 3% of the basin, associated with the restrictive effects of the engineering dam, having a disconnected status (Table 4; Figure 6E).

Analyzing the magnitude scenarios, it is noticeable the gradual migration from partially connected to connected sections and disconnected to connected areas, thus occurring a loss of potential to impede anthropic structures, such as small and medium rudimentary dams, since water crossings and bridges start from partially connected and connected.

Table 4 - Synthesis of areas classified in the transmission stages weighted by the magnitude scenarios of fluvial flow events.

STAGES / MAGNITUDES	Disconnected	Partially Connected	Connected
High Magnitude	24,92 km²	202,96 km²	540,78 km²
Moderate Magnitude	116,07 km²	517,12 km²	135,47 km²
Low Magnitude	170,11 km²	463,08 km²	135,47 km2

Source: the authors, 2023.

As mentioned, an increase in the catchment area and a gradual transfer from partially connected to connected areas can be observed, while the scenarios evolve from low magnitude to moderate magnitude (Figure 6A and C). This changes considerably in the high magnitude scenario, with small structures (bridges and water crossings) losing their impediment effects, and rudimentary dams releasing flow, thus predominating the connected stage (Figure 6E).

It is noted that some sections remain disconnected, cutting off the upstream catchment areas, consequently influencing the delimitation of the effective catchment area, which is explained by the engineered dam that massively retains water and sediments mobilized upstream of that point.

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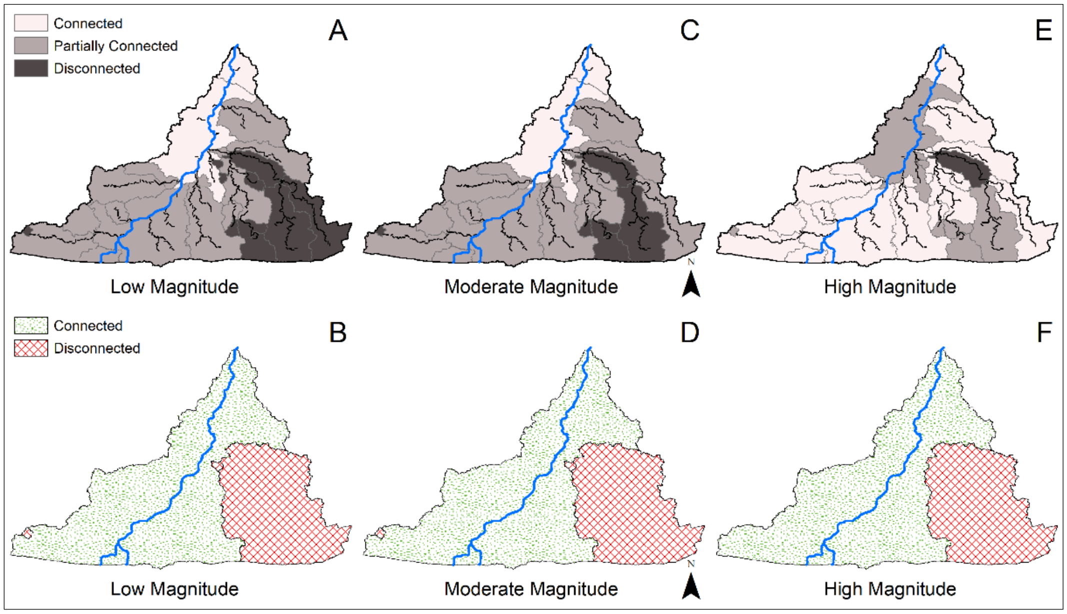

Figure 6 - A, C, and E - Transmission stage between catchment areas of the interruption elements; B, D and F – Effective Catchment Area of the river basin at each magnitude stage. Source: Prepared by the authors, 2023.

The predominance of the recognized transmission capacity, especially in moderate- and high-magnitude scenarios, needs to be understood with caution, since it does not mean that if there is transmission, the transported material will leave a point in the basin and be delivered to the reference outlet; as already highlighted by Fryirs et al. (2007a) and Fryirs et al. (2007b), there are several disconnection factors within the river system. However, from the point of view of the effects of longitudinal anthropic elements, the flow passage makes water and sediment transmission potentially possible.

The transmission stages in moderate- and high-magnitude scenarios need to be analyzed and understood. Therefore, the potential transmission potential assumed in these stages is recognized; however, the residence time and factors for sediment transport may vary for the most part (FRYIRS et al., 2007b, 2007a; SOUZA; CORRÊA; BRIERLEY, 2016). Thus, it is understood that the effects of the interruption elements lose their efficacy, but this does not mean that sediment transmission will be free and unimpeded.

Based on the behavior of the impediments in the face of the magnitude scenarios, and consequently the transmission stages, it was possible to trace the effective catchment area of the basin (Figure 5B, D and F), with areas that will contribute to the outlet, allowing the identification of the disconnected areas that have little transmission potential to the rest of the system. It can be noted, therefore, that, even with sections classified as connected and partially connected within the disconnected area, these stretches will remain disconnected from the rest of the sections due to the presence of a disconnecting impediment, as is the case of the

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engineering dam near the center of the watershed. Subsequently, other elements such as medium-sized dams contribute to the potential restriction of transmission capacity.

The ACE for BHBXP was then measured (Table 5) for the three flow magnitudes, being considered connected for the catchment areas that presented "connected" and "partially connected" transmission stages, which did not present sections in the "disconnected" stage downstream. In relation to the areas with the presence of disconnecting elements verified, these sections were then classified as disconnected stretches. Thus, for the low and moderate magnitude scenarios, an area of approximately 520.65 km² was identified, while for the high magnitude scenario an increase to 523.83 km² was observed, considering the conversion of medium rudimentary dams to partially connected.

Table 5 - Summary of the effective catchment areas of the Piancó River watershed for each scenario of magnitude of flow events.

MAGNITUDES	EFFECTIVE CATCHMENT AREA (ECA)	
	Connected	Disconnected
High Magnitude	523,83 km²	244,85 km²
Moderate Magnitude	520,65 km²	248,02 km²
Low Magnitude	520,65 km²	248,02 km²

Source: Prepared the authors, 2023.

With the results obtained, a conceptual model for landscape connectivity in river systems from a longitudinal perspective (Figure 7) was developed, focusing on flow magnitudes and the effects of anthropogenic impediments. The model takes into account dams and water crossings, their differences and similarities in river dynamics, causing sedimentation upstream and erosion downstream, in addition to altering the local base level. Initially, the model focuses on non-perennial channels, highlighting that perennialization alters river dynamics, exemplified by the Piancó River in its lower course.

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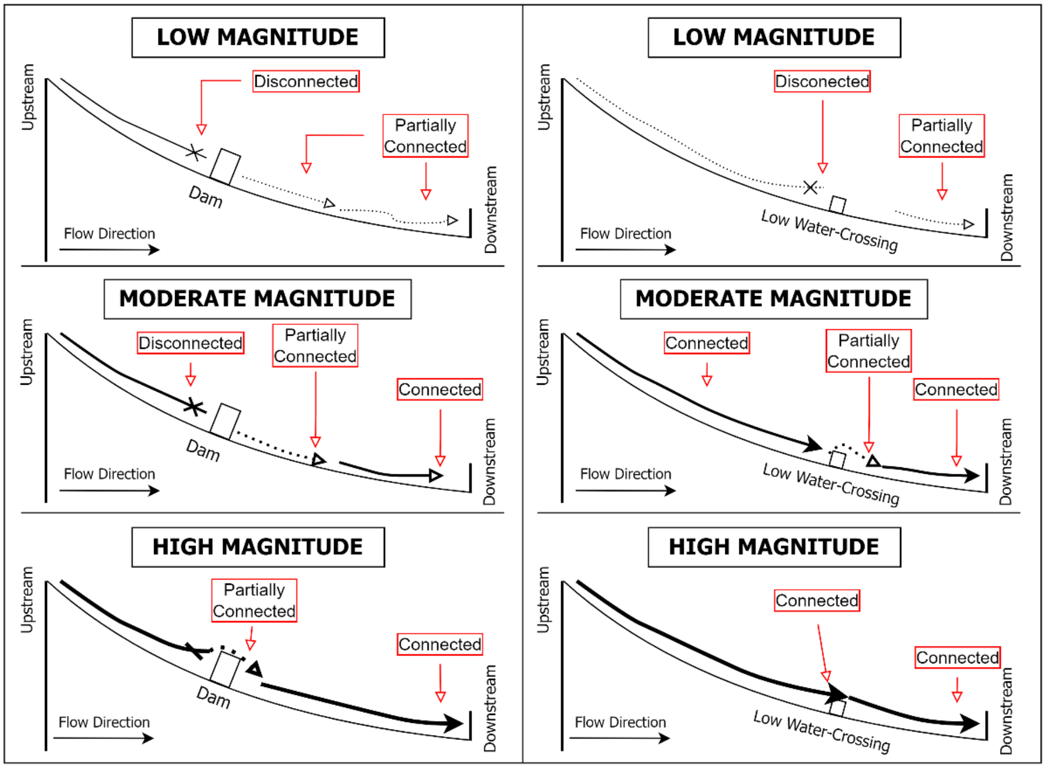

Figure 7 - Model of longitudinal connectivity for impeding elements for dams and water crossings and the behavior of these structures with flow scenarios in the river channel. Source: Prepared by the authors, 2024.

In low-magnitude events, structures can interrupt the flow of water and sediment, with the potential for immediate partial connections to the downstream water. In moderate magnitude events, changes are noted, with dams still restricting transmission, while smaller structures (water crossings) begin to allow the passage of water and sediment, improving the downstream river connection. For high magnitude events, dams release water, although the passage of bedload sediments remains limited, but smaller structures have their impact reduced due to the volume of water, favoring erosion and sediment deposition.

A caveat is made regarding the release of flow by dams; for this to occur, the dammed volume must be greater than the storage limit. It is worth highlighting the need to understand the river dynamics after the occurrence of magnitude scenarios, especially those of moderate and high magnitude, what features and how large structures (dams) and small structures (water crossings and bridges) will present themselves in these situations.

Furthermore, these elements, especially dams, have the potential to interfere with sediment storage time (KUO; BRIERLEY, 2013), both upstream and downstream (SOUZA; CORRÊA; BRIERLEY, 2016). These effects can be extended to water crossings (CAVALCANTE et al., 2014; CASTELO BRANCO et al., 2023), potentially altering the sediment balance in terms of erosion and depositional processes. However, these processes are

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also potentially compromised due to the disorderly excess of dams interfering with the transmission of water and sediments. In other words, in addition to breaking or hindering (as in the case of water crossings) the transmission of sediments, they also alter the water-flow energy, both enhancing and stifling flow events (COELHO, 2008). This is corroborated by the analyses of Rodrigues et al. (2023) when applying the Fluvial Styles classification, developed by Brierley and Fryirs (2005), in a semi-arid watershed, where they observed the impact of the dam on the sensitivity of the river channel in fluvial-style downstream of the structure. Although this river stretch was predisposed to receive a considerable amount of flow energy and sediments, it faced the restrictive effects caused by the impediment.

Specific studies on the morphological effects of wetlands, although incipient, offer relevant contributions that align with previous findings on transmission. Cavalcante et al. (2014) highlight the concern with the disorderly linking of wetlands in the development of the morphology of river channels and their banks, resulting in erosion processes and alterations that have the potential to generate changes beyond the local scope.

Studies that address the effects of small structures, specifically check dams, such as those by Castillo et al., (2007), Boix-Fayos et al., (2008), Abbasi et al., (2019) and Lucas-Borja et al., (2019), have recognized effects (positive and adverse) that are similar to those of water crossings, such as changes in sediment balance, sediment retention and filling of the upstream portion, with progressive passage of sediments, in addition to the incision of the river channel downstream, combined with a reduction in the supply of sediments. However, these structures have different social purposes because they aim to control erosion processes, flood control and debris transport.

These characteristics of small structures favor future work, such as on the stock of sediments retained upstream and the sediment balance of ACEs, as well as on restrictive and impeding effects generated by the structures, with potential for investigating the adjustment processes and sediment supply through monitoring.

V. Conclusions

Throughout the work and the examination of the interruption elements, the effects perceived involve sediment retention upstream and channel incision downstream of the structures. A predominance of connected or partially-connected stages was observed, with a reduction in disconnected areas as the magnitude of the flow increases, although the presence of a large dam keeps a significant portion of the lower Piancó River watershed in a disconnected stage.

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The development of a conceptual model allows the exploration of behavior in future investigations, so that it is possible to recognize how each element of the typologies addressed and the river channels will behave. It is important to include landscape connectivity analyses in initial geomorphological research to avoid inaccurate assessments of river dynamics. The application of conceptual scenarios and the effective delimitation of catchment areas help to understand the interactions between river dynamics and human interventions. It is recommended that future research consider the spatial distribution of small structures both upstream and downstream, assessing their effects from the beginning of preliminary analyses.

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