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Research Article

Rivers channelization and the (dis)continuos geomorphological effects on the fluvial system of the Macaé River - RJ

Retificação de canais fluviais e os efeitos geomorfológicos (des)continuos no sistema fluvial do rio Macaé - RJ

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Abstract: Hydraulic engineering works play a critical role in altering the natural behavior of a river landscape. One of the most common interventions is channelization, which directly entails the widening and deepening of the riverbed and modifying the channel's cross-sectional geometry. In Brazil, this type of work has often been conducted in floodplain areas and urban centers to ensure basic sanitation and promote economic activities. Despite its widespread use, there is a significant gap in research focused on the effects of these works on the evolution of river environments. From a geomorphological perspective, this intervention can trigger a series of changes in the pattern of hydrosedimentological processes in the river system, not limited to the altered segments. This study discusses the impacts of river channelization on the Macaé catchment, from a geomorphological approach and the recent trajectory of channel evolution. The results suggest that the intervention has intensified upstream erosion processes, characterized by rapid vertical incision of the riverbed, increased bank erosion with terrace exposure, and migration of meanders towards the channelized areas.

Keywords: Hydraulic Interventions; Base Level; Adjustment Zones; Meander Suppression.

Resumo: As intervenções hidráulicas desempenham papel crítico que podem mudar o comportamento natural de uma paisagem fluvial. Uma das intervenções mais comuns é a retificação de canais, que envolve diretamente o alargamento e aprofundamento do leito e na geometria transversal do canal. No Brasil, esse tipo de obra foi comumente realizada nos espaços das baixadas e em centros urbanos como forma de garantir saneamento básico e avanço das atividades econômicas. Apesar de sua ampla distribuição, há uma lacuna significativa de trabalhos preocupados com os efeitos dessas obras na evolução dos ambientes fluviais e suas implicações na evolução da paisagem fluvial. Do ponto de vista geomorfológico, essa intervenção pode desencadear uma série de mudanças no padrão dos processos hidrossedimentológicos no sistema fluvial que não se restringem somente aos segmentos alterados. Esse trabalho discute os efeitos da retificação de canais fluviais na bacia do rio Macaé, a partir de uma abordagem geomorfológica da trajetória recente de evolução dos canais. Os resultados indicaram que a intervenção intensificou os processos erosivos a montante, caracterizados pela rápida incisão vertical do leito, erosão marginal acentuada com afloramento de terraços e migração dos meandros em direção à retificação.

Palavras-chave: Intervenções Hidráulicas; Nível de Base; Zonas de Ajuste; Supressão de Meandros.

1. Introduction

The advancement of technology in fluvial environments marks a turning point in the restructuring of geomorphological thought, as new demands arise, aiming to understand the multiple facets of human interventions as key landscape controllers (Goudie, 1993; Szabó et al., 2010; Goudie; Viles, 2016).

The underlying premise is that human impacts, regardless of their form, can induce new processes as well as alter, intensify, or even disrupt those already in progress or "naturally" attributed to a given environment. Despite the growing interest in this topic (Kelly et al., 2018), the persistent questions highlight the main gaps in traditional models that seek to understand landscape process dynamics (Ghosh et al., 2022): What is natural? What is anthropogenic? At which scale do these processes occur? What changes occur? How do they occur?

Fluvial systems are key examples of how anthropogenic activities are significantly altering the dynamics of geomorphological processes (Gregory, 2006). While historical land-use changes have played a decisive role in modifying fluvial environments, it is hydraulic interventions that represent the most advanced degree of direct human influence on process dynamics and morphological changes in fluvial landscapes (Gregory, 2006).

In Brazil, although large-scale hydraulic engineering works date back to the mid-20th century, they came to national prominence in the 1930s with the creation of the National Department of Works and Sanitation (DNOS), an authority that worked in conjunction with the states to control and restructure the drainage network (Goes, 1942). The institution was responsible for works of great magnitude in all regions of the country, especially in the south and southeast and above all in the rivers of the northern region of the state of Rio de Janeiro, associated with the extensive floodplains of the region considered under the pretext of defense against floods and basic sanitation (Soffiati, 2005).

However, the main motivation for construction work in these lowland areas was more linked to the limitations imposed on the installation of agricultural and urban activities, motivated by the strength of the sugar and agricultural industries. The proximity to the sea and the abundance of river channels, the main means of accessing and transporting production, were the main motivations for occupying these areas since the European invasion in the 16th century.

Despite the diversity of interventions in the northern region of Rio de Janeiro, channelization is a common element in the main rivers throughout the state (Soffiati, 2021). This type of work took place, above all, in the areas of the wide fluvial and fluvial-marine plains of the rivers located on the Atlantic slope of the Serra do Mar, which was accompanied by the creation of artificial channels, in regions primarily close to the main cities that followed the premise of drainage control and sanitation.

The Macaé catchment, located in the northern region of the state of Rio de Janeiro, is one of the examples where part of its drainage network has been channelized, including both the main channel, its main tributary, and numerous tributary channels in the lowland areas (Assumpção; Marçal, 2012). Although the catchment has other direct hydraulic interventions such as dams and transposition in tributaries, sand extraction along the middle and lower reaches (Freitas et al., 2015), and dams and reservoirs in the catchment's hilly domain (Giesebart, 2022), the channelization of rivers stands out due to the extent and magnitude of this intervention in the drainage network.

The main challenge inherent in investigating impacts related to channelization is the question of what the channel's possible responses are and whether we can associate these responses with the changes brought about by the intervention. These questions are not just about understanding the direct impacts caused by channelization, but also about the distribution of its impact on the system, where these impacts are located and what the spatial dynamics associated with them might be.

Although important works have theorized about the expected effects of channelization of rivers (Brookes, 1988), it is necessary to seek to build models that incorporate, in the first instance, the local factors of a given space to the detriment of the use of global laws and models, given the imprecision and difficulty of reproducing analyses from one place to another, without making theoretical-methodological changes (Philips, 2007).

In this context, what is the starting point for studies in fluvial geomorphology? in cases where the channel is deepened due to channelization work, a significant unevenness can be created between the modified course and the original course, establishing a new local base level, or break in slope, which in the literature is also known as an artificially introduced Knickpoint (Bowman, 2023). The establishment of this local feature can condition a readjustment of the character of the longitudinal gradient of the main channel, in the process of migration to the remontant that begins to transmit the disturbance longitudinally (Brookes, 1988; Schumm, 1993; Charlton, 2007; Magalhães jr; Barros, 2020; Bowman, 2023).

Other effects may not be restricted to the main channel; the process of remontant migration can establish changes in the local gradient of the tributaries, causing a rejuvenation of the tributary channels, with an increase in water velocity and channel incision (Brookes, 1988; Charlton, 2007).

In addition to changes in longitudinal characteristics, transformations in the cross-sectional pattern of the channel alter the nature of geomorphological processes on a local scale, which in channelized segments intensify processes associated with longitudinal sediment transport (Brookes, 1988) to the detriment of the complex nature of hydro-sedimentary processes typical of winding stretches, generally attributed to the dynamics of sandy meanders (Hooke, 2013; 2022).

Although the subject is considered in some contexts to be "an impact of major proportions" (Freitas et al., 2015, p.20), what do we know about channelization in Brazil? There is a significant gap in studies concerned with the effects of these works on the evolution of river environments. Studies on rivers channelization are limited to an assessment of changes in the landscape and are restricted to a historical discussion of the context in which these works were conducted (Zanirato, 2011; Zola, 2018; Pessoa, 2019).

The aim of this work is to investigate the geomorphological effects triggered by channelization works in the Macaé catchments, in the areas dominated by the river and river-marine plains. The aim is to show how these works impact on the reorganization of geomorphological processes and their implications for the evolution of fluvial environments.

In view of the systematic alterations made by the now defunct DNOS and especially the channelization of channels, there is a primary need to gather information on the works carried out and to investigate what role they have played and may continue to play in the fluvial system of the Macaé catchment.

2. Study Area

The Macaé catchment (Figure 1) is located on the Atlantic slope of the Serra do Mar and is part of the Neoproterozoic Mobile Belt domain of southeastern Brazil, with the presence of Quaternary sedimentary deposits in the lower reaches of the catchment (IBGE, 2023). In the upper course, the organization of the drainage network is strongly influenced by the NW-SE, W-E and NE-SW regional structures (Dantas, 2000; Silva; Cunha, 2001) and by lithological variation (Almeida et al., 2012; Geraldes et al., 2012) which act on valley asymmetries and the establishment of local base levels (Cabral et al., 2023). The mid-course transition, represented by the compartment of hills and isolated hills, includes the transition from highly confined valleys and steep slopes towards the domain of river and river-marine plains (Dantas, 2000; Marçal et al., 2015).

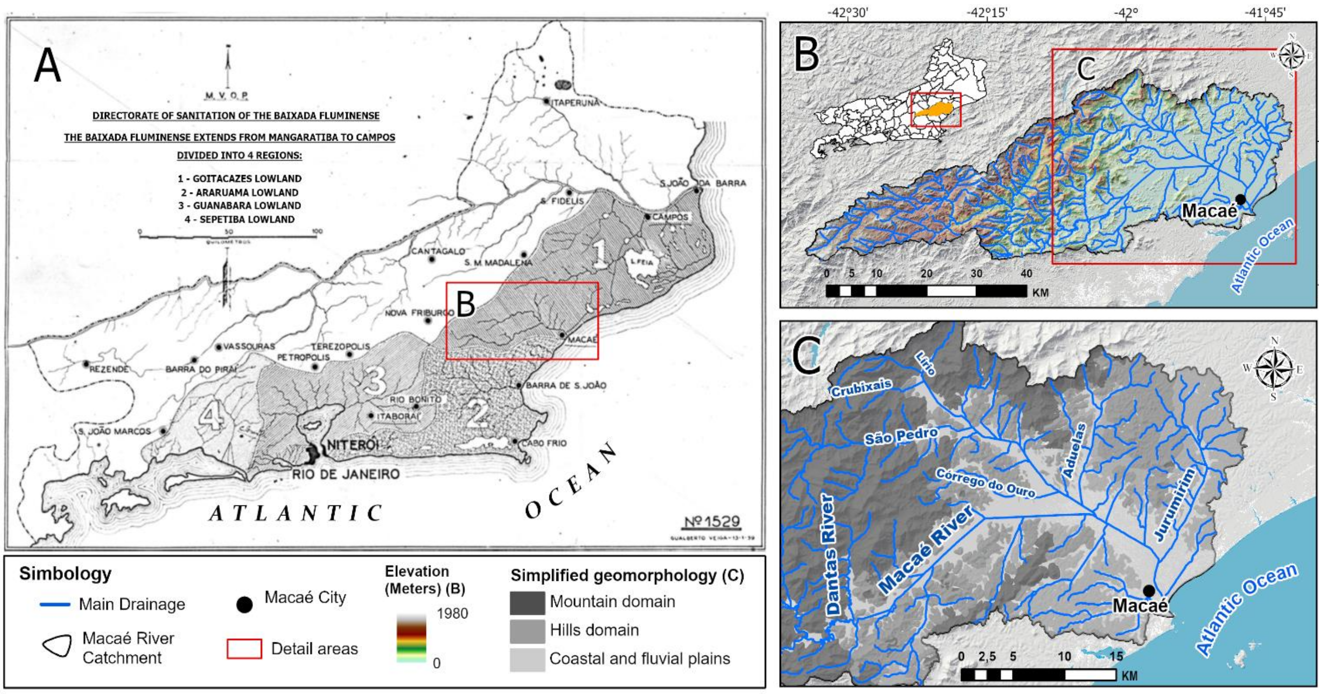

Figure 1. Location map of Macaé catchment with details of the lower reaches. In (A) Map of the National Department of Works and Sanitation highlighting the large lowland areas of the catchments on the Atlantic slope of Rio de Janeiro [n.d.]; In (B) the Macaé catchment; and in (C) highlighting the lower course with the simplified geomorphology and the main drainage adapted from IBGE (2018; 2023).

The local geology is mostly made up of Cambrian rocks with a large presence of the São Fidélis Unit (including kinzigites, quartzites and sillimanite-biotite gneisses) in the upper and middle reaches and Quaternary sediments in the lower reaches. This variation between segments with the presence of Cambrian rocks (São Fidélis Unit) with a transition to Quaternary deposits is seen in most of the catchment's main channels, especially the Macaé River and its main tributary, the São Pedro River. In the central domain of the catchment, it is worth highlighting the presence of the Sana Granite, a post-tectonic formation whose origin is associated with the Brasiliano cycle between 650 and 550 m.a. (Silva; Cunha, 2001), responsible for the highest slope values and associated with the segments of the upper course (Cabral et al., 2023).

The drainage network of catchment’s lower reaches has been completely de-characterized by the channelization works and the creation of artificial channels, which represent a drastic change in the environment. Assumpção and Marçal (2012) point out that a large part of the drainage network had already been channelized by 1968, while the main tributaries of the Macaé, São Pedro and Dantas rivers were channelized later. Naturally, the plains domain is described as an environment with a low associated topographic gradient with meandering channels of high sinuosity associated with marshy and swampy areas. Currently, this area has rectilinear channels, whose abrupt reduction in the natural sinuosity of the channel is one of the most important morphological changes in the drainage network of the lowland areas in the catchment (Assumpção; Marçal, 2012).

The urban development of the north of Rio de Janeiro, especially the area between the Macaé and Paraíba do Sul rivers, is marked by the context of the region's occupation, which dates to colonial times. Thus, the major impetus for occupying the region came from the insertion of the sugar economy throughout the 17th and 18th centuries, followed by the strengthening of the agricultural sector in later centuries (Lamego, 1946). The history of the region follows a path of “conquest of the rivers” marked by the appropriation of their courses to enable the expansion of the prevailing economic system (Chrysostomo, 2010), as well as by the deforestation of the Atlantic Forest progressively driven by the processes of occupation and exploitation that have intensified since the colonial period (Dean, 1996).

Although recent years have shown a retreat of pastoral areas and the advance of a natural vegetation domain (composed of “restinga,” mangrove and fragments of Atlantic Forest), since the 1980s the agropastoral field has been indicated as the biggest modifier of the landscape of the Macaé catchment (Guimarães, 2017). From this perspective, the current trends in land use and land cover changes indicate a tendency for economic development not to occur without a number of other serious socio-environmental problems, as seen from the 1980s to 2015 (Guimarães, 2017), which indicates the importance of management practices that discuss future scenarios for the functioning of the Macaé catchment in the short and long term (Marçal et al., 2017).

3. Materials and Methods

The first stage consisted of collecting two groups of data: (I) historical, documentary, and cartographic archives in collections such as the National Archives and the libraries of the Brazilian Institute of Geography and Statistics (IBGE); (II) remote sensing materials from 1969 to 2023.

The base data used topographic maps made available by the IBGE on a 1:50.000 scale topographic maps of Macaé (SF-24-M-I-3); Casemiro de Abreu (SF-23-Z-B-IN-4-MI2717-4); Trajano de Moraes (SF-23-Z-B-III-2) and Conceição de Macabu (SF-24-M-1-1); Landsat-5 images for the years 1984 and 1993; sequencing of Google Earth images between the years 2003, 2013 and 2023, corrected by means of manual adjustment; orthorectified images from the *Planet* platform for the year 2023. The images were georeferenced and manipulated in GIS environments using Arcgis Pro software.

The following mappings were then carried out: of the channelized segments, based on the integration of the cartographic documents of the National Department of Works and Sanitation (DNOS) retrieved from the National Archives, with the aid of the continuous cartographic base of the state of Rio de Janeiro, made available by IBGE (2018) at a scale of 1:25,000; delimitation of the segments of the sand meanders, with the aid of satellite images and based on previous work (Marçal et al., 2017; Brierley et al., 2019); of the river terraces based on the identification of probable points through image interpretation and field visits.

The next stage consisted of calculating indices and analyzing morphological changes according to the methodology proposed by Hooke (2013; 2022) and Fryirs and Brierley (2013). This stage included the following tasks: mapping the routes of each segment of the sandy meanders of the channels of interest for the years 1969 to 2023; calculating the Sinuosity Index (SI) for the 1969 to 2023 series and the maximum amplitude of the meander, covering 20 years of analysis in the 2003 to 2013 and 2013 to 2023 sections; characterizing the morphological adjustments according to the criteria of Hooke (2013; 2022) and individualizing and coding the meanders for spatial analysis of the adjustments.

To analyze the sinuosity of the data from 1969 to 2023, the correlation method was used, using the statistical significance test (P-value) and trend analysis using the Mann-Kendall test. The significance test was applied to verify the relationship between the variables, assessing whether the correlations observed were statistically significant, based on a pre-established significance level (95%). Trend analysis was conducted using the Mann-Kendall test, which makes it possible to identify and quantify the presence of monotonic trends in the data over the period analyzed (Kendall, 1975).

As a proposal for detailing on a local scale, codes were created to individualize each meander in the adjustment area according to the initials of each river and a number that varies according to its position in relation to the start of the channelization. Thus, as an example of the São Pedro River, the meanders were designated as SP and a digit. Code SP1 represents the meander closest to the channelization up to the last meander with the highest digit, which represents the meander furthest upstream of the system indicated.

The pattern of adjustments sought follows the types discussed in Hooke (2013; 2022). The identification of patterns of movement, such as the magnitude of events and distribution along the drainage can be important indicators in understanding the nature of the events in the segments analyzed. Figure 2 shows an illustrative table and elucidates the adjustment patterns found in the Macaé catchment, based on a comparison between the patterns for the years 2003 and 2023.

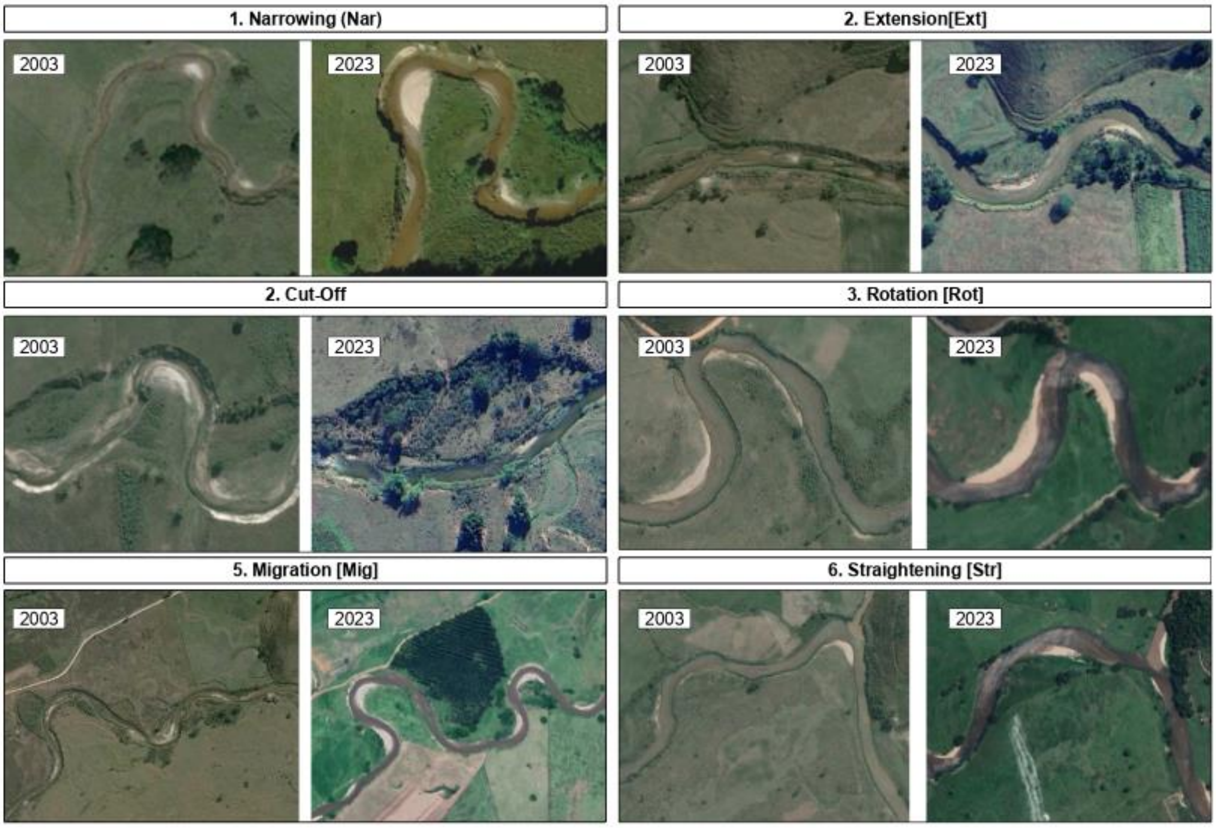

Figure 2. Synthetic picture frame of the adjustments identified in the sandy meanders for the Macaé catchment. Images taken from Google Earth from 2003 and 2023.

Based on the system of relative positions constructed, the main variable analyzed was the variation in the amplitude of the meanders in relation to their position. For this stage, statistical analyses were carried out to: (1) analyze possible non-linear correlations between the variables of interest and (2) verify the existence of groups of similar variables and their respective positions.

For correlation analysis, the Random Forest (RF) method was applied, which is a learning algorithm based on decision trees. Unlike traditional statistical decision models that are based on binary decisions (yes/no) in the predictor variables, RF is a method that combines multiple decision trees to improve the accuracy of the model, to minimize classification errors and accuracy in regression estimates (Liaw; Wiener, 2002; Genuer et al., 2010). In this study, the algorithm was used in the R software using the randomForest base package provided by the program.

The correlation graphs were presented together with Box-Plot graphs to identify and visually express the samples that could be considered “Outliers” in the data set. The graphs were constructed based on the amplitude variations for each position of the meanders established in the series from 2003 to 2013; and 2013 to 2023.

To group the data statistically, the K-means clustering algorithm was executed in the R software. The application consists of defining groups of data with statistically similar characteristics by establishing clusters, or K-groups (Bishop, 2006). The ideal number of clusters is defined by the algorithm, so that the product is a grouping of data in which the centroids that delimit these groupings do not change significantly with the addition of new groups (Steinley; Brusco, 2011).

The number of suitable clusters (K groups) was established using the elbow test. In this test, the Sum of Squares Error (SSE) between the points and the centroids of the clusters is calculated for different K values. The value of K is chosen at the point where the reduction in SSE occurs sharply. This point indicates the number of clusters that best represent the data, balancing the explained variability and the complexity of the model (Steinley; Brusco, 2011).

4.Results

4.1. Morphometric characteristics and morphological responses of the drainage network to channelization

The Macaé catchment has an extensive lowland domain, with various tributaries restricted to the low topographic control compartments that rise in the domain of isolated hills and hills and flow through the extensive river and plain domain. This context of low topographic control, together with the lithological characteristics of the lower course (Quaternary sediments) are features of the segment that have not limited the channelization of river channels and the creation of artificial channels. An analysis of the DNOS activities project for the lower reaches of the Macaé catchment shows that this domain has been systematically altered by the channelization of most of the rivers in the segment and by the creation of artificial channels (figure 3).

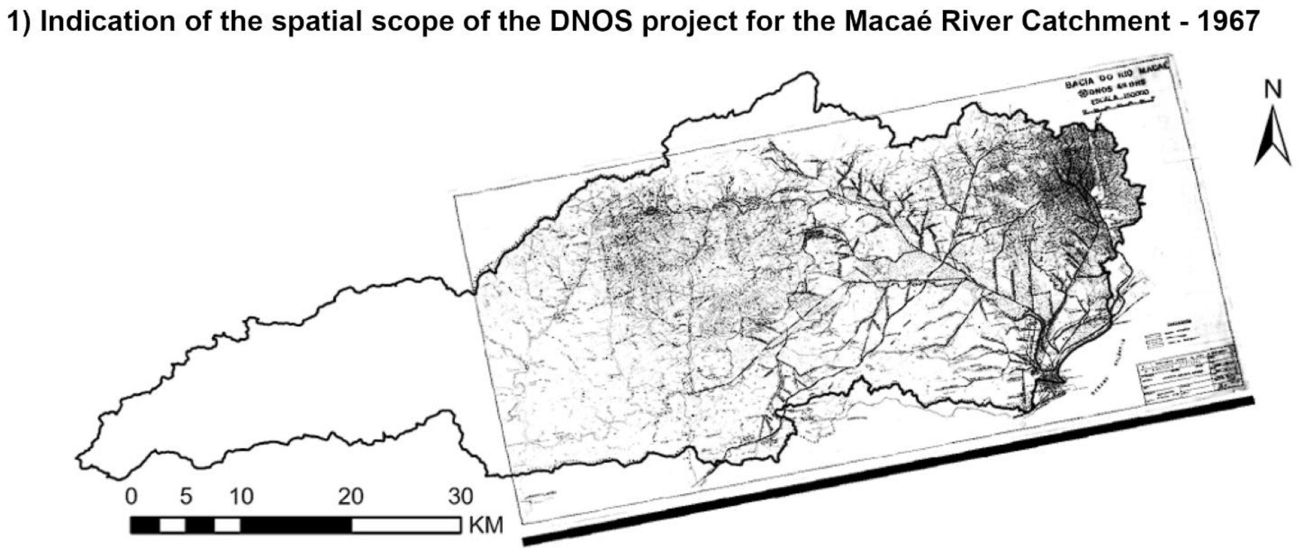

Figure 3. Map of the Macaé catchment, highlighting the 1967 DNOS activity project for the lower reaches of the catchment. Based on the project, the analysis and vectorization of the channelized segments from the DNOS activity project for the lower course of the Macaé River were conducted on a scale of 1:150,000, year 1967. Source: Department of Public Works and Urban Planning of Macaé municipality.

Table 1 presents information on the length and quantity of altered channels in the lower catchment, with a distinction by hierarchy and a characterization of the main channels that have undergone extensive channelization. These alterations are considered systematic because they are not restricted to isolated segments or the main rivers in the drainage network. In all, more than 370 km of canals of different hierarchies have had their morphology altered by the channelization works and represent approximately 50% of the anthropically modified morphology in relation to their natural condition (such as the São Pedro and do Lírio rivers and the Córrego do Ouro).

Table 1. morphometric data of the main channelized rivers

Data from the network drainage of the lower course					
Type of change			Extension (kilometers)		
Channelized rivers			375,26		
Artificial channels			505,23		
Numbers o Channelized rivers					
132					
Data from the main Channelized rivers					
Attributes	**Macaé**	**São Pedro**	**Rio Dantas**	**Lírio**	**Córrego do Ouro**
Channel Extension (km)	140	44	17	18	30
Channelized Extension (km)	44	20	2,4	9	15
Percentage channelization/extension (%)	30%	50%	15%	50%	50%
Fluvial Hierarchy	8ª	7ª	5ª	5ª	4ª
Final base-level	Atlantic Ocean	Macaé River	Macaé River	São Pedro River	São Pedro River

Channelization represents a common organization throughout the lower reaches of the catchment, ranging from artificial channels to those of greater hierarchy. In this context, there is a spatial configuration characterized by the interaction between different geomorphological compartments. One of these arrangements is the result of channels limited to the fluvial-marine plains, while the other occurs in a transition zone between segments of hills and hills towards the plains.

The channels restricted to the plains are characterized by their morphological adjustments, which are not significant given the low topographic gradient associated with it. However, the channelization of the meanders and the deepening of the channel alter the characteristics of that environment towards a more elevated energy flux system, given the changes in cross-section geometry of channelized channels.

Thus, we can delineate two general patterns regarding the occurrence of channelized channels and their interactions with the geomorphological compartments: (1) Those who retained segments of sandy meanders upstream of the channelization and accompany the transition between segments of hills and hills towards the plains; and 2) channelized channels restricted to the plains, characterized by a low topographic gradient.

The morphological responses identified in the field indicate that the segments of sandy meanders in the segments before the channelization, which accompany the transition from the middle course to the plains, present a common pattern of vertical incision and lateral expansion of the sandy meander channel (figure 4). The outcrops have shown similar patterns of height between 5 and 8 meters, distributed asymmetrically located on the left margin.

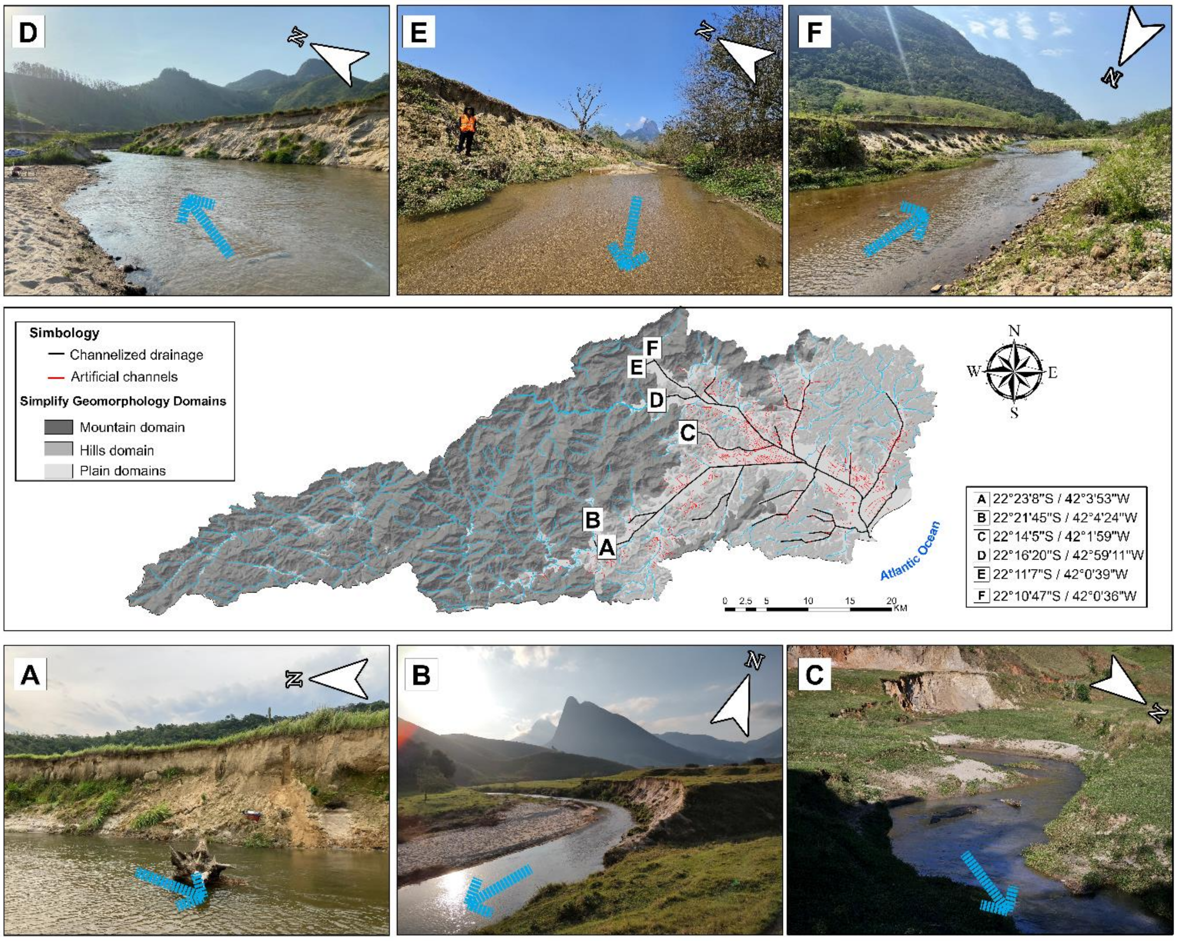

Figure 4. Map of the Macaé catchment showing examples of some outcrops of river terraces upstream of the channelization's: in the rivers (A) Macaé, (B) Dantas, (C) Córrego do Ouro, (D) São Pedro, (E) Rio Crubixais, (F) Lírio. Source: Data taken from IBGE (2018); Geomorphology adapted from IBGE (2023). In blue, the arrow indicates the direction of flow. Photographs taken in the field between 2022 and 2024.

Another common arrangement of morphological responses identified was the upward trend of the sinuosity of the main channels. Table 2 shows the sinuosity indices found for the sandy meanders segment in main channelized channels in the catchment, from 1969 to 2023. The analysis of tributaries was restricted to the series from the years 1969, 2003 and 2023, due to the resolution of the LANDSAT images used being incompatible with the average channel width.

Table 2. Variation of the Sinuosity Index (dimensionless) per year of the 1970 to 2023 series.

Sinuosity Index (SI)						
Rivers	**1969**	**1984**	**1993**	**2003**	**2013**	**2023**
Macaé	1,98	1,97	2,04	2,16	2,18	2,25
São Pedro	1,27	1,29	1,32	1,48	1,45	1,55
Dantas	1,22	1,28	1,34	1,29**	1,33	1,39

**** Channelization of a segment of the Dantas River between 1993-2003.**

Table 3 shows the results of the Mann-Kendall trend test applied to the sinuosity data of the Macaé, São Pedro and Dantas rivers, with emphasis on the interpretations of the Tau and P values. show increasing trends, which suggests that the sinuosity index of these rivers has been increasing consistently over time.

Table 3. Mann-Kendall Trend Test with Interpretation of Tau (τ) and P Values

Rivers	P*	(τ)**	Interpretation (τ)	Interpretation P
Macaé	0.02417	0.8666	increasing trend	significant
São Pedro	0.02413	0.8853	increasing trend	significant
Dantas	0.0628	0.7333	increasing trend	Not significant

***P < 0.05, reject the null hypothesis; P ≥ 0.05, accept the null hypothesis**

****(τ) = 1, increasing trend; (τ) = -1 decreasing trend**

Although the P-test values returned for the Dantas River (0.0628) do not provide sufficient evidence and confirm the null hypothesis, i.e. that is, the sinuosity index does not exhibit a significant trend over time, it is necessary to consider, within this context, the encroachments carried out on the Dantas River between the years 1993 and 2003, which drastically changed the morphology of the canal.

4.2. Meanders movements: tendencies and adjustments.

Analyses on the channel scale show important general trends for the organization of that segment in the series analyzed between 1968 and 2023, with significant variations on a local scale that may indicate segments of greater and lesser adjustment. Due to the complex nature of adjustments in sandy meanders, not necessarily the analyses at the drainage network scales express clear trends of adjustment (Hooke, 2013; 2022). A few mechanisms associated or not with the occurrence of adjustments in sand meanders are related to the elements in the local meander channel scale and need to be viewed in greater detail (Hooke, 2013; 2022). Between 2003 and 2023, 6 adjustment patterns were identified in 82 individualized meanders (Table 4). The pattern of extension (increase in amplitude) and migration (downstream or upstream movement) are the two predominant settings in sandy meanders.

Table 4. Codes and patterns of adjustments identified in main channelized rivers of Macaé catchment.

Adjustments identified and individualized by river and meander																				
Macaé River																				
COD	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20
Adjut 1	Ext	Mig	CS	Rot	Ext	Mig	Ext	-	Rot	Nar	-	-	Rot	-	-	Ext	Ext	-	Ext	Ext
Adjut 2	Mig			Mig			Nar		Ext				Trans					-		
São Pedro River																				
COD	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	SP9	SP10	SP11	SP12	SP13	SP14						
Adjut 1	Ext	Ext	Ext	-	Nar	Ext	Mig	CutOff	Nar	CutOff	Ext	Mig	Mig	Mig						
Adjut 2	Mig	Mig	Mig	Mig	Mig	Mig			Ext	Mig	Mig		Ext	Ext						
Dantas River																				
COD	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	
Adjut 1	-	Ext	Ext	Ext	Ext	Trans	Ext	Rot	Ext	Mig	Mig	Ext	Ext	Ext	Ext	Mig	Mig	Mig	Ext	
Adjut 2																Ext	Ext	Ext		
Lírio River																				
COD	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12								
Adjut 1	Ext	Ext	Ext	Ext	Est	MS	Ext	Ext	Ext	Ext	Nar	-								
Adjut 2	Mig	Mig	Mig	Mig	Mig	Est	-	-	Mig	Mig	Ext									
Corrego do Ouro River																				
COD	CO1	CO2	CO3	CO4	CO5	CO6	CO7	CO8	CO9	CO10	CO11	CO12	CO13	CO14	CO15	CO16	CO17			
Adjut 1	Ext	Ext	Nar	Ext	Ext	CutOff	Nar	Ext	Ext	Ext	Ext	CutOff	CutOff	Ext	Ext	Ext	Ext			
Adjut 2					Mig		Mig	Mig	Mig	Mig	Mig	Mig	Mig		Mig	Mig				

The two most commonly identified patterns of meander adjustment in the channels, both migration and extension can be attributed to natural adjustment mechanisms in sandy meander segments. Despite natural, the occurrence of these events may not necessarily occur in the same magnitudes over all the meander segments. Depending on local characteristics, which can be diverse, such as a greater valley confinement, the presence of hydraulic interventions, changes in local lithology, among others, some segments may present events of greater magnitude and others not necessarily some kind of adjustment.

Figure 5 shows the non-linear correlation analysis between the amplitude change variables and their relationship with the position of the meander. For the source condition of the displacement analysis, the following was defined 2003 as the reference year, or base year, for comparison in the series analyzed. The results include 20 years apart, considering two series 2003-2013 and 2013-2023 (figure 5).

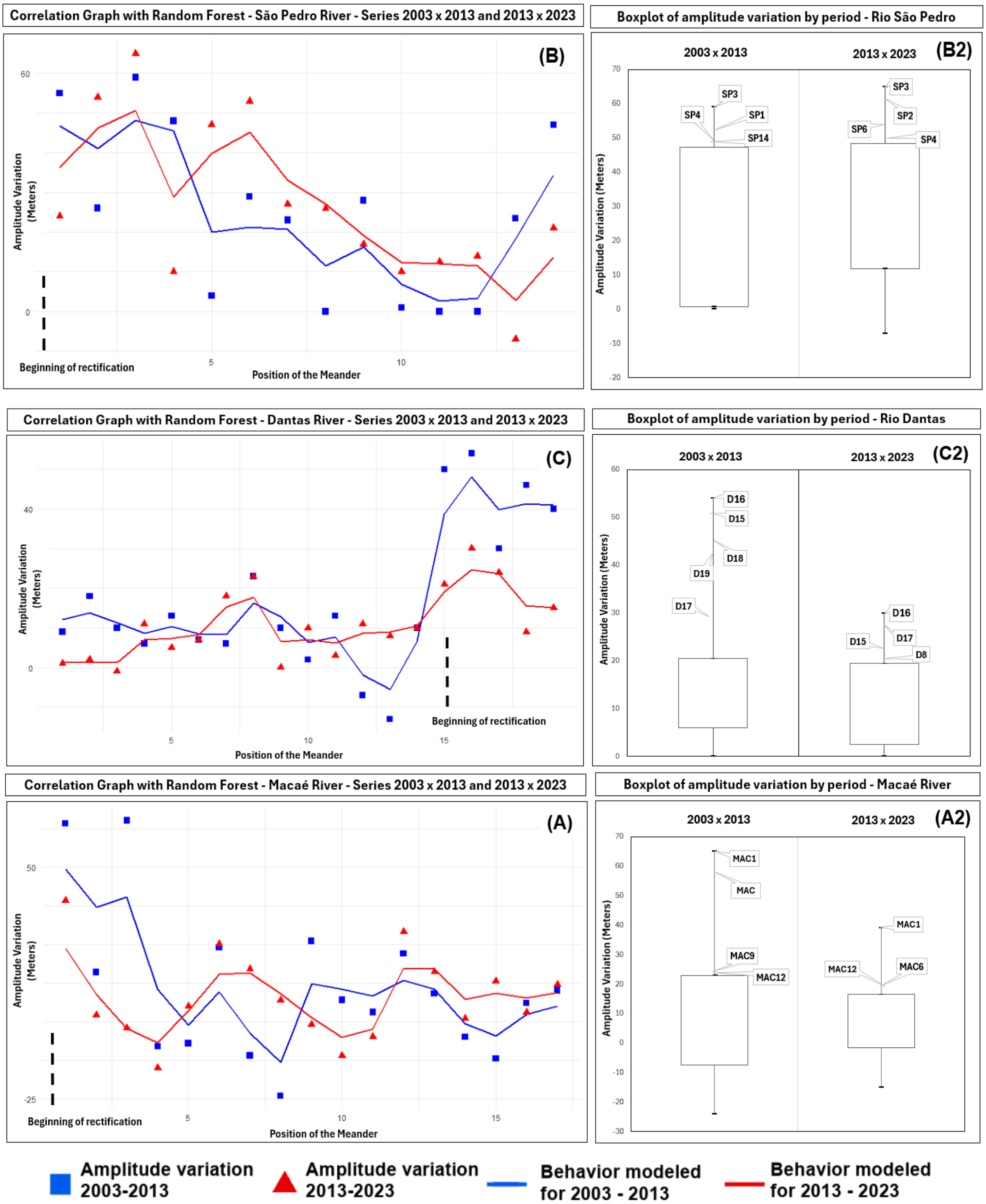

Figure 5: Relationship between amplitude variation (in meters) and meander position in the Macaé, São Pedro and Dantas River, calculated using the Random Forest non-linear correlation method. The blue squares and red triangles represent the amplitude values for the periods 2003-2013 and 2013-2023, respectively. The dotted line indicates the start of the channelization of the river. On the right, boxplots indicating the position codes.

In the general context of the main channels, there is significant variability in the relationship between amplitude and the position of the meanders over the years, indicating that factors other than simple location influence the river's morphology. Of all the rivers analyzed, the main channels of the Macaé and Dantas rivers were the ones with the most showed some more visible trend in behavior. Although the three behaviors are distinct, there is no evidence of more uniform trends, which indicates a non-linear response behavior, with more expressive stretches and others less expressive terms of the magnitude of the events.

Despite this, the behavior of the outliers is striking in the three main channels. Except for the São Pedro River, which showed a general trend of increasing amplitude in mostly the entire segment of sandy meanders, in the Macaé River and in the Dantas River, the main outliers are at the points close to the channelization, with significant adjustments both in the 2003 x 2013 series and in 2013 x 2023.

It is worth noting that the Dantas River has two stretches of channelization that are not contiguous, i.e., there are sand meanders between channelized sections. This particularity makes the interpretation of the results more complex and raises questions about the spatial distribution of effects of interventions, as well as the places where they may be inducing new adjustment dynamics. In both periods, channelization upstream of the channel indicates a point of significant disturbance, with the highest values of amplitude variation concentrated in this segment.

In the analysis of the general variation between the series (2003 and 2013; 2013 and 2023) the points close to channelization are similar from a statistical point of view and constitute clusters in the overall samples (figure 6). Except for the São Pedro River (figure 6B), which did not necessarily show a grouping close to channelization, although the highest values are concentrated in this segment, the Macaé River (Figure 6A) and the Dantas River (Figure 6C) are two examples of data clustering whose highest values in terms of amplitude variation are found in the meanders immediately next to the channelization.

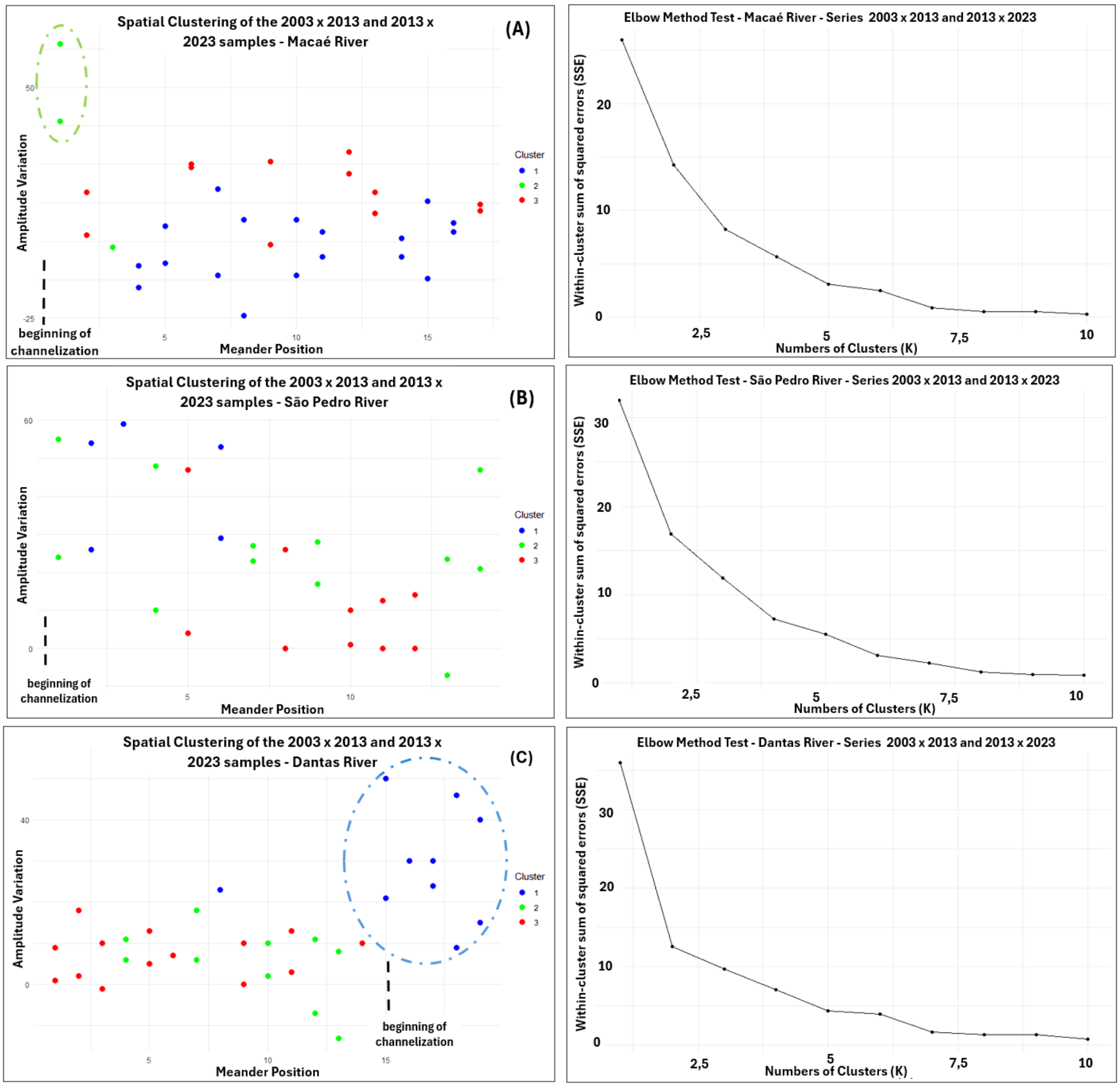

Figure 6. Spatial Cluster Analysis and Elbow Test for three rivers: Macaé River (A), São Pedro River (B) and Dantas River (C). The graphs on the left show the variation in amplitude as a function of the position of the meander for each river, with the colored dots representing different clusters (Cluster 1 in red, Cluster 2 in green, Cluster 3 in blue). The dotted lines indicate the beginning of the channelization of the rivers. The graphs on the right show the Elbow Test (Elbow Method) to determine the optimal number of clusters (K) based on the sum of squared errors within the clusters (SSE).

From a morphological point of view, the most significant changes in magnitude occur in some cases together with migration processes. Figure 7 shows the main morphological changes in the segments prior to channelization, considering the lines of the banks of the years 1969, 1984, 1993, 2003, 2013 and 2023.

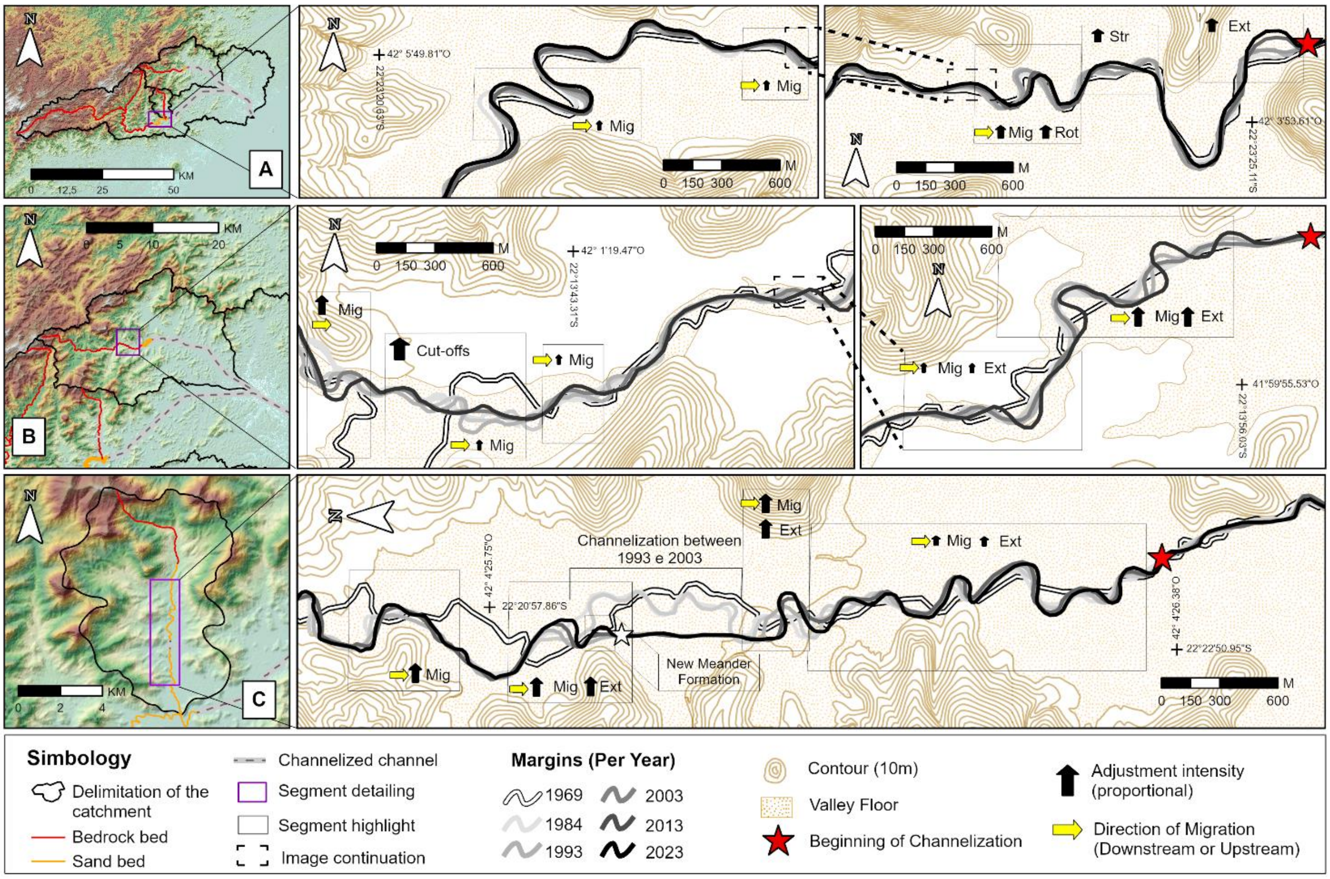

Figure 7. Analysis of morphological evolution in different years (1969, 1984, 1993 and 2023) and identification of adjustments in meanders for the Macaé (A), São Pedro (B) and Dantas (C) rivers. In detail, indication and location of the processes of migration (Mig), extension (Ext), Straightness (Str), Rotation (Rot) and the formation of new meanders, with analysis of intensity and direction of adjustment.

From the interpretation of the changes in drainage layout, it is possible to see that the points close to the channelization are also those with the greatest morphological changes in the channel (figures 7A, B and C). In this case, the São Pedro River (Figure 7B) and the Dantas River (Figure 7C) are noteworthy, as they both have greater changes in stretches close to the intervention. These changes are important evidence of processes reorganization of the drainage network that may have been induced or accelerated by the effects of the downstream channelization works.

5. Discussion

5.1 What do the adjustments tell us? Channelization, base level reduction and geomorphological implications

The results found for Macaé catchment indicate that the channelization of multiple channels similarly influences some aspects of the recent morphological adjustments identified. These aspects are represented by similar adjustment mechanisms, above all the downstream migration of meanders and the increase in the general and individual sinuosity of the meanders, which directs the discussion towards reducing the level changes in the transverse properties of the channel geometry and the effects generated on energy transfer longitudinal system.

The central issue centers on the understanding that all base levels, be they regional, local, or anthropically imposed, are primary controllers of the drainage network (Leopold; Bull, 1979; Schumm, 1993). The processes of falling or rising base level, in both cases, directly alter the longitudinal characteristics of the channel and consequently influence the dynamics of erosive energy. (Leopold; Bull, 1979; Schumm 1993; Charlton, 2007; Magalhães jr; Barros, 2020; Bowman, 2023).

When the river channel is affected by a rise or fall in the base level, the response in the expected system is an increase in the erosive or aggradation potential, as the fluvial adjustments occur in the direction of this drainage resumes its equilibrium profile, i.e. by adjusting towards a new gradient condition longitudinal, in which a balance is sought in the transfer of energy from upstream to downstream (Charlton, 2007; Bowman, 2023).

These adjustment processes can be understood as effects propagated longitudinally through a complex sequence of feedbacks (Charlton, 2007) that are not limited to the adjustment of the gradient, but also from the processes of erosion or deposition, as well as morphological changes in the channel, roughness of the bed and the shape of the drainage (Leopold; Bull, 1979; Schumm, 1993; 2005).

Two processes stand out in the Macaé catchment: (1) The extensive channelized segments of the canals (2) Several tributaries of different hierarchies channelized. Reducing the base level of the canal naturally affects its tributaries, since their final base level is the confluence itself with the main river, and this effect is expected to propagate upstream in the same mechanisms discussed above. Previously in the process of rejuvenation of the tributaries (Charlton, 2007), with a lesser magnitude of the depending on the characteristics of the segment and the event or disorder (Schumm, 1993).

The tributary channels are affected by the channelization of the main channel, as well as by its own channelization, so it can respond to two base level lowering events, which may imply more complex adjustments within variate magnitude over a brief period. Thus, this is one of the elements that can help explain why the lower-ranking tributaries show abrupt changes when compared to the main one's channels.

Lower hierarchy rivers naturally include areas of lower effective catchment, and it is expected that they have a lower volume of flow and associated energy. This may be one of the elements related to complex adjustment patterns identified in these channels. Despite this, it is important to emphasize the role of rainfall and mainly from extreme events that can alter, in a short period of time, the characteristics morphology of these stretches, making the nature of the adjustments close to a sporadic pattern and chaotic to the detriment of continuous adjustments.

Although the expected changes occur close to the point of disturbance (Schumm, 1993) in the face of the context of extensive flood plains with low topographic control and, due to the nature of the sediments Quaternary, the segments of sandy meanders are fully capable of adjusting both laterally and longitudinal, thus able to distribute any disturbances through various mechanisms.

These characteristics make these passages important trend indicators since: (1) they are the first areas in which the channel is able to adjust, as they lie between the segments morphologically controlled by the channelization downstream and upstream by the bedrock and valley confined segments; (2) they are segments subject to adjustments that can propagate more easily upstream and on a very short time scale, conditioned by mainly to local hydroclimatic dynamics and land use and cover; (3) the wide range of the nature of the possible adjustments, the changes in channel morphology have been significant and identifiable in the short term.

From this perspective, in the condition prior to channelization, the adjustments related to changes in the base level were attributed to variations in the precipitation regime and the sea level fluctuations themselves, as well as possible regional neotectonics events (Brêda 2018; West; Mello, 2020). With channelization, the current effects respond not only to these factors, but also to the changes in the transversal properties of the channel, above all by the lowering of bed, and by the change in its planform (figure 8).

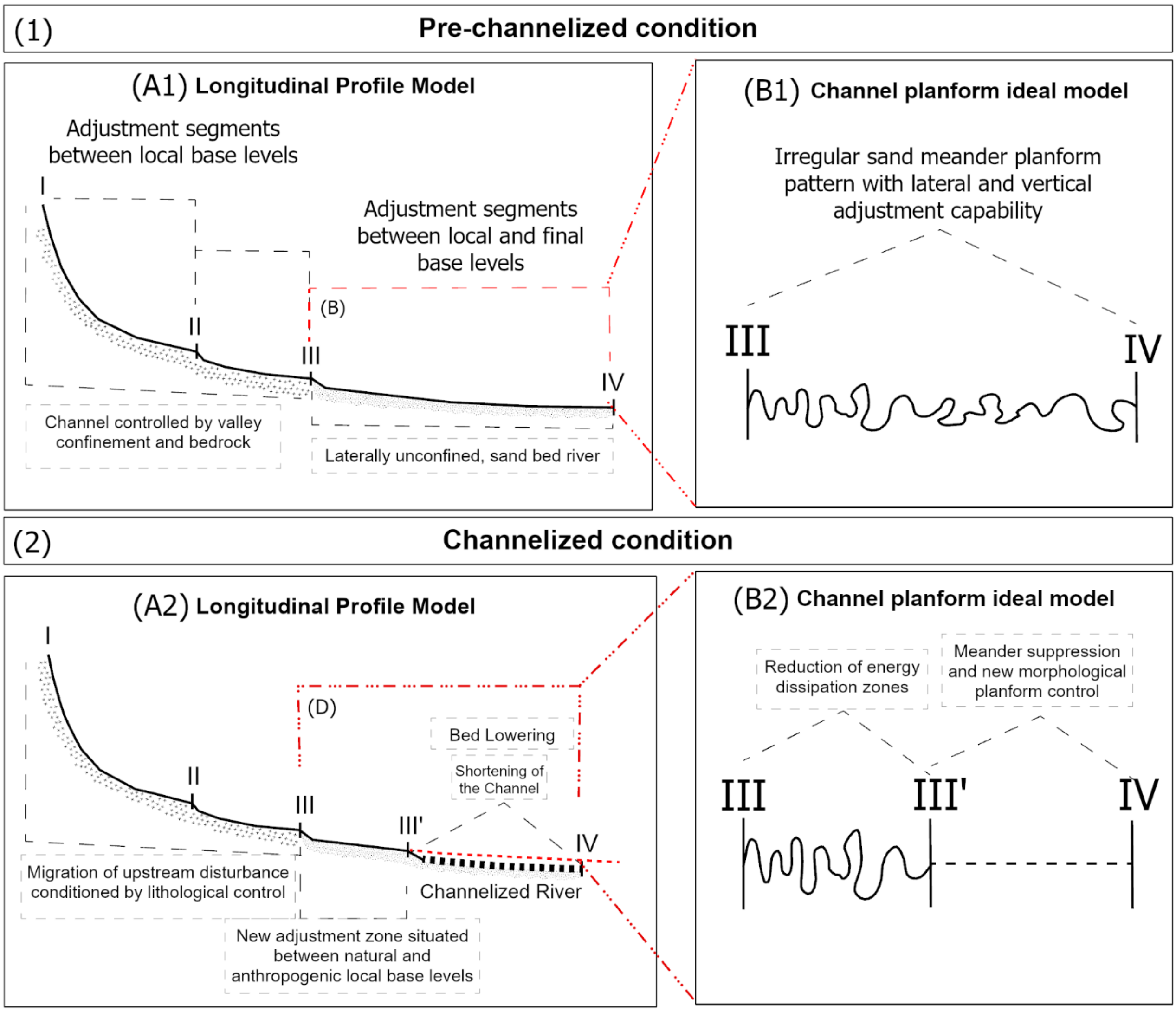

Figure 8. Theoretical model based on SCHUMM (1993) and BOWMAN (2023) showing the longitudinal profile idealized (A and C) and ideal representation of the channel's plan form (B and D) before channelization (1) and after channelization (2). In detail, points I, II, III, III' and IV represent theorical sections with changes in base level.

In the condition prior to channelization, ideal zones could be assigned longitudinally (Figure 8, A1). adjustments delimited between natural local base levels (Bowman, 2023) as a function of lithological variations (Cabral et al., 2023). In this condition, the pattern of the channels (Figure 8, B1) in the lower course was associated with sinuous and irregular meandering segments (Assumpção; Marçal, 2012), characteristic of the of rivers in extensive plains.

In the current condition (figure 8, Window 2), the lowering of the bed due to the channelization may have made a significant change to the characteristics of the longitudinal profile, with the insertion of a rupture anthropically introduced (Bowman, 2023) which now segments a new stretch of adjustment delimited between natural local base levels (figure 8, A2, points III to III') and anthropogenic levels (points III' to IV). From the point of view of morphology of the channel, the main alteration is represented by the suppression of an extensive segment of the lower course which was also associated with the shortening of the canal (Figure 8, B2).

In this way, we can think of the effects of channelization beyond a one-off pattern of change, but on continuous effects in the system. This can be understood through changes in the propagation of the downstream and upstream energy altered by the new morphological condition of the channel. These changes lead to two discussions:

(1) The direct morphological changes to the channel, especially the lowering of the bed, may have introduced a new adjustment zone delimited between local base levels. In the previous condition (Figures 8, A1 and B1), the

extensive The meander segment that followed the transition from the middle to the lower course and extended to the mouth was abruptly reduced to a small segment, delimited upstream by the beginning of the bedrock and confined river segment (Figure 8, A1, point III) and downstream by the start of the channelization (Figure 8, A2 point III'). Thus, a small segment of sandy meanders, which, due to their lithological characteristics and the condition of low confinement of valley, have different morphological adjustment mechanisms and may be representative areas of possible hydrosedimentological changes in the catchment; (2) the extermination of energy dissipation areas, a function exercised by the sandy meanders, may have altered the way energy has been propagated downstream in the river system (Figure 9).

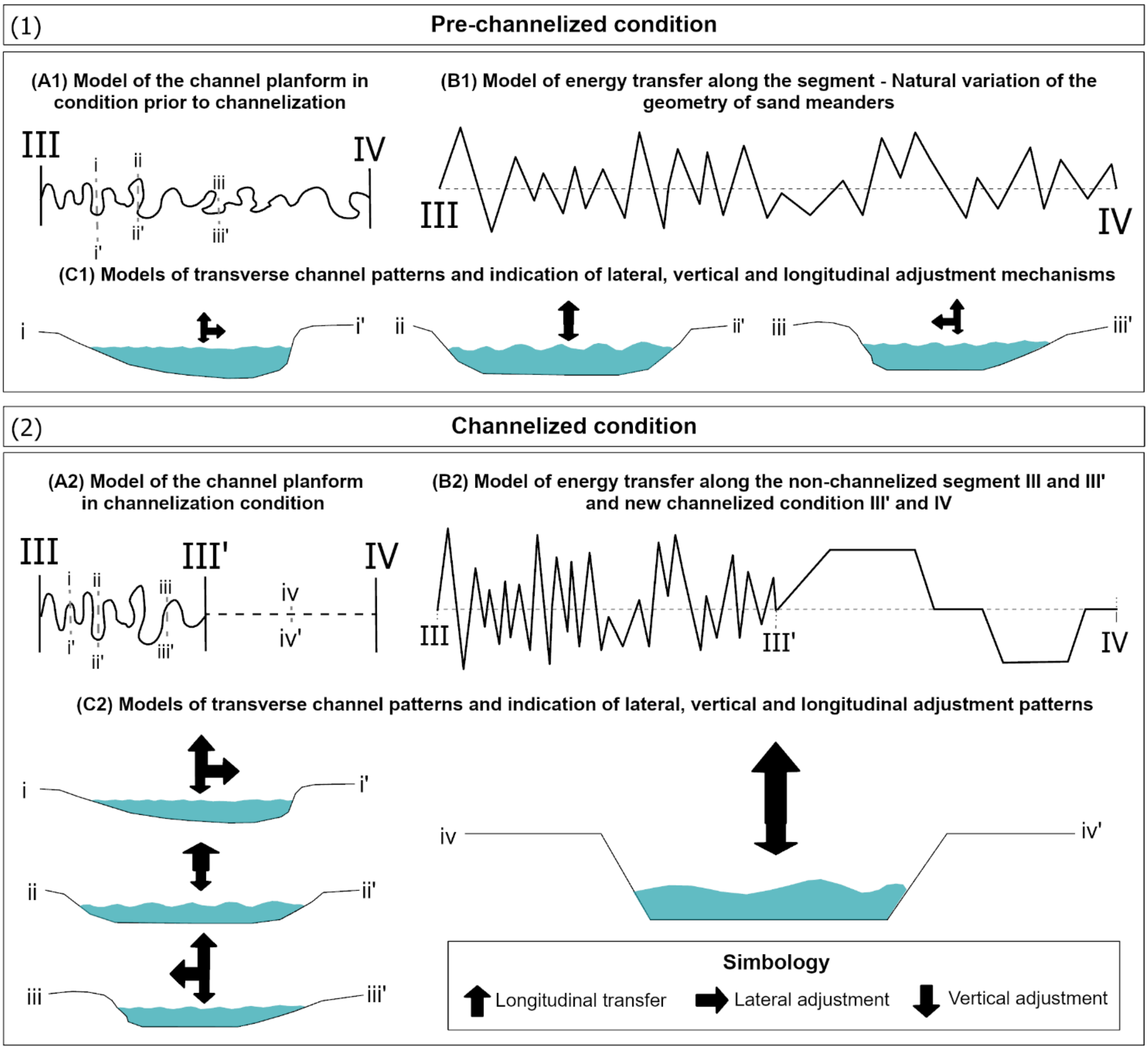

Figure 9. Schematic models of the cross-sectional channel patterns and adjustment mechanisms before and after channelization. Pre-channelization condition (1): (A1) Longitudinal profile of the channel, showing the variation in energy along the channel segment. (B1) Planform view of the channel before channelization, showing the natural meander geometry and (C1) Models of transverse patterns with indication of adjustment for the different geometries in meanders; (2) Channelized condition: (A2) Longitudinal profile, comparing the pre-channelization condition (III-IV) with the new condition after channelization (III-III'-IV). (B2) Planform view of the channel after channelization, showing the rectilinear geometry imposed and (C2) Cross-sectional pattern models with indication of adjustment for the different geometries in meanders after channelization. The schematic models of the patterns cross-sections the channel (i-i', ii-ii', iii-iii', iv-iv') indicate the lateral, vertical and longitudinal adjustment mechanisms, represented by the proportional symbols (black arrows).

The condition before channelization (figure 9, A1) represents the significant complexity attributed to the geomorphological processes in meander segments, represented by the diversity in terms of the dimensions of the processes (lateral, vertical and longitudinal) that accompany the different possible transversal geometries in these segments (figure 9, A1 and C1, points i-i', ii-ii', iii-iii'). Due to the diversity of processes attributed, the segments meanders are also marked by the natural alternation of intensity of the nature of the geomorphic processes (figures 9, B1).

With the channelization of a large part of the channel, there is a significant reduction in the number of meanders (Figure 9, A2) which today perform the function that every channelized river segment performed before the intervention. This change represents a linearization of channel's behavior (Figure 9, B2), since meandering environments with sandy channel beds have complex operating mechanisms, while channelized rivers, by the changes brought about by the intervention, do not share of the same dynamics (Figure 9, C2, points iv - iv').

Despite the significant immediate changes, the morphological adjustments related to the natural dynamics of the sinuosity, such as the increase in amplitude and the throttling of meanders until cut-off events are likely expected given the local topographic and climatic dynamics. However, the changes in the behavior of the entire meandering segment, due to the changes discussed above, may represent a new pattern of channel responses to higher and lower energy events.

Thus, the changes morphological as the own sinuosity of the segments do not necessarily represent gradual adjustment behavior. The very characteristics of the seasonal distribution of rainfall and the pattern of extreme events can drastically alter a specific segment or point of channel and meander, a process that may have has been intensified by the immediate and continuous changes imposed by the channelization.

Unlike the processes mentioned above, migration is a mostly directional adjustment. A indication of migration necessarily implies an understanding of the direction in which the adjustments are heading an attempt to establish new energy dissipation zones. Schumm (1987) points out that this mechanism adjustment is common in cases of rising or falling local base levels, the direction of migration of which will depend on whether the change occurred downstream or upstream, and the intensity according to the magnitude of the event.

From this perspective, the points close to the channelization, which had the highest variation values in their respective amplitudes, are also the points where the most expressive trends of migration are downstream of the meanders. This arrangement of more significant, spatially concentrated changes indicates that channelization is a point in the disturbance that has altered the magnitude of the process's upstream geomorphology.

It is important to note that channelization's took place in the mid-1960s, and that the universe of data more detailed images represents an absence of information with almost 40 years of adjustments without characterization. Even so, an analysis of recent adjustments indicates sections in which the responses to the channel channelization in the Macaé catchment may occur at a greater rate and magnitude and represent different with same mechanisms as the main channels.

6. Conclusions

The channelization of river channels in the Macaé catchment has altered important cross-sectional characteristics of a large part of the drainage network of the lower course, related to areas of large river plains. Despite these critical changes, the effects of the intervention were not restricted to the one-time or isolated changes that occurred over the course of the intervention of the work.

From a geomorphological point of view, the lowering of the bed of the main rivers and the main tributary rivers to the Macaé River may have induced a readjustment in the longitudinal character of the rivers that through the processes of upstream erosion may have established a new condition of longitudinal dynamics. Not restricted to longitudinal characteristics of the rivers, the change in the morphological pattern resulted in a significant loss of the complex nature of the adjustments associated with the old sandy meanders.

The condition prior to the rivers played a key role in dissipating energy along the entire length of the lower course, a pattern that was objectively contrary to the channelization. In the pre-channelization condition, it was a system closer to low-energy flux, likely swamps environments. In the current and recent condition, the magnitude of these adjustments is high, characterized by the rapid incision of the bed, the formation of new plains and the outcropping of river terraces.

The recent trajectory of morphological changes indicates that this area will continue to undergo significant changes, posing a few challenges for management and that they should seek to understand the relationship of channelization as a general modifier of the river landscape.

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