https://rbgeomorfologia.org.br/
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 25, nº 3 (2024)

http://dx.doi.org/10.20502/rbg.v25i3.2480

Research Article

Fluvial adjustments due to straightening and inadequate management of urban drainage: the Maringá Stream catchment, Southern Brazil

Ajustes fluviais da retificação e do manejo inadequado da drenagem urbana: a bacia hidrográfica do ribeirão Maringá, Sul do Brasil

Kenia Ketiri Beltramin[1] e Eduardo Souza de Morais[2]

[1] Multidisciplinary Studies Group of Environment, Department of Geography, State University of Maringá, Brazil. keniabeltramin20@gmail.com
ORCID: https://orcid.org/0009-0003-7272-9060

[2] Multidisciplinary Studies Group of Environment, Department of Geography, State University of Maringá, Brazil. esmorais2@uem.br
ORCID: https://orcid.org/0000-0003-0738-5532

Received: 28/09/2024; Accepted: 07/08/2024; Published: 15/09/2024

Abstract: The morphological channel changes can occur through direct interventions, such as engineering works, or indirectly due to alterations in the catchment runoff. This study conducted morphometric evaluations using geoprocessing techniques and fieldwork in fluvial reaches altered by straightening and influenced by urbanization in the Maringá Stream catchment, located in the northern state of Paraná, Brazil. The study analyzed the sinuosity index and the average width of three representative reaches between the years 1970 and 2017. The sinuous morphology of the reaches was straightened in the 1970s and 1980s and did not re-establish itself. Over the past two decades, these reaches exhibited a trend of increasing average width (~100%) due to urbanization in the drainage areas. However, intermittent periods of channel narrowing were also observed. This behavior is associated with bank erosion and failure, leading to the formation of benches. The morphogenesis of this relief unit in the channel results from inadequate management of stormwater runoff from urban areas. This scenario indicates the need for coordinated efforts between urban stormwater management and fluvial geomorphology to maintain the physical integrity of rivers.

Keywords: bench; urbanization; urban drainage; channel width; applied fluvial geomorphology.

Resumo: As mudanças na morfologia do canal fluvial podem ocorrer com intervenções diretas, como as obras, ou ainda indiretamente a partir das alterações no escoamento da bacia hidrográfica. Neste estudo foram realizadas avaliações morfométricas com emprego de geoprocessamento e trabalhos de campo em trechos fluviais alterados pela retificação e sobre influência da urbanização na bacia hidrográfica do ribeirão Maringá, norte do estado do Paraná. O estudo analisou entre os anos de 1970 e 2017 o índice de sinuosidade e a largura média de três trechos representativos. A morfologia sinuosa dos trechos foi retificada nas décadas de 1970 e 1980 e não se restabeleceu. Os trechos durante as últimas duas décadas apresentaram uma tendência de aumento na largura média (~100%), como resultado do aumento da impermeabilização da urbanização nas áreas de drenagem. No entanto, notou-se que houve períodos de estreitamento dos canais. Este comportamento é associado com a erosão e queda das margens, com consequente formação de patamares. A morfogênese desta unidade de relevo do canal é resultado do manejo inadequado do despejo de águas pluviais das áreas urbanas. Esta conjuntura indica a necessidade de esforços entre a gestão da drenagem de águas pluviais urbanas e a Geomorfologia Fluvial para a manutenção da integridade física dos rios.

Palavras-chave: patamares; urbanização; drenagem urbana; largura do canal; geomorfologia fluvial aplicada

1. Introduction

Rivers constantly change their morphological characteristics through bank erosion and deposition. Parameters such as width, depth, and sinuosity attest to morphological changes that may occur in the channel, in which natural events and human activities play a role in driving geomorphological processes. For example, flows of greater magnitude can culminate in bank erosion, causing strong variations in width (CHARLTON, 2007; WOHL, 2014), as well as a decrease in channel sinuosity (SCHUMM, 1977; HOOD, 2004). However, it is important to highlight that the intensity of the changes depends on the specific characteristics of the river and the magnitude of the triggering events.

Downs and Piégay (2019) investigated changes in channel width, depth, sinuosity, and pattern, finding that studies highlighting human impact primarily focused on changes in land use and cover, particularly due to agricultural activities and urban growth. Although urban areas represent a small part of land cover on a global scale, this type of land use and cover causes drastic changes to rivers (CHIN, 2020). Urban growth results in an increase in impervious areas, influencing the hydrological cycle of the catchment, leading to a reduction in water infiltration into the soil and an increase in runoff (ROSA, 2017). According to the hierarchy of fluvial processes during urbanization, evaluated by Montanher (2010), based on Wolman's model (1967), the river channel initially receives more sediment, increases in width, and decreases in depth with the beginning of urbanization. In later stages, the channel incises the bed, resulting in deepening and narrowing, and may even expose the bedrock. Furthermore, urbanization can also generate a drastic decrease in sinuosity (DENG et al., 2015; SILVA et al., 2017; ASHMORE et al., 2023).

With the development of urbanization, other types of changes frequently occur in rivers, such as direct changes in the channel morphology through straightening or channelization. The first type of direct intervention in the channel involves altering its original shape to make the morphology rectilinear and, in some cases, to create a wider and deeper channel (OLIVEIRA et al., 2006; ASSUMPÇÃO; MARÇAL, 2012). Channelization involves works that modify the channel using concrete and other materials in the river bed (ASSUMPÇÃO; MARÇAL, 2012). These interventions are generally carried out with the aim of containing the effects of floods so that the floodplain can be occupied or exploited (PONTINI, 2018). Evaluations of morphological changes in rivers under the influence of these interventions in Brazil, in the states of Rio Grande do Sul (RECKZIEGEL et al., 2005) and Rio de Janeiro (SANTOS; MARÇAL, 2021), showed an increase in erosion processes. However, there is also the case of the drastic alteration of the morphology of the Pinheiros River in São Paulo with the establishment of two channels, which accentuated the depositional processes (LUZ, 2015).

The morphological changes in river channels caused by urbanization also extend to ecological and social losses (CHIN et al., 2020). However, there is little scientific knowledge about how urbanization affects Brazilian rivers (MORAIS; MONTANHER, 2022). The impacts caused by this land use can generate results that differ from those found in places with different natural and historical characteristics (SANDER et al., 2012). Furthermore, impacts on rivers, as previously highlighted, can occur cumulatively with changes in the catchment or directly in the channel morphology (DOWNS; PIÉGAY, 2019). In this context, the hydrographic network of the municipality of Maringá, in the north of the state of Paraná, Brazil, stands out. Intense urbanization over the last few decades with the model of city occupation from the interfluve has enabled systemic investigations into the geomorphological disturbances of this type of land use (BAGGIO, 2014; PETSCH, 2014; SCHNEIDER et al., 2014; VIEIRA et al., 2021; SOUZA; MORAIS, 2023). In this study, we aimed to evaluate the morphometric and morphological changes of reaches altered by straightening and influenced by urbanization, using geoprocessing analyses and fieldwork. Understanding the river dynamics of the studied reaches allows us to assess how direct and indirect changes have affected the physical integrity of the river network.

2. Methodology

2.1. The study area

The three reaches are representative of the landscape dynamics of the Maringá catchment (Figure 1), which is the largest catchment in the municipality of Maringá, with an area of ~ 90km², located in the north of the state of Paraná, southern region of Brazil. R1 comprises the final length of 571m of the lower course of the Mandacaru Stream, while R2 and R3 have, respectively, lengths of 445m and 1,397m and are located in the middle and lower course of the Maringá Stream. It is important to note that R2 is located downstream of the confluence with the Mandacaru Stream, meaning that the R1 and R2 reaches are contiguous.

Figure 1. Location of the reaches in the Mandacaru (R1) and Maringá streams (R2 and R3) in the municipality of Maringá.

The lithology of the catchment area is dominated by basalts of the Paranapanema Formation, derived from the eruption of basic magmas during the Mesozoic Era (BRESSER et al., 2021). The basalts in this region have an aphanitic, porphyritic and amygdaloid texture in the upper part of the flow and are black and dark gray, greenish gray to dark brown, and when altered, rusty yellow (MINEROPAR, 2001). Close to the source of the Romeira Stream, in the southeast of the catchment, there is a layer of fine to very fine sandstones from the Goio Erê Formation with cross-stratigraphy and tabular facies of massive appearance, overlying on the basalt (BRESSER et al., 2021). These sandstones are of eolian origin and also date from the Mesozoic era (THOMAZ, 1984). In the lower course of the Maringá Stream, recent deposits of gravel, sand, silt, and clay have been observed in the floodplain.

The climate in the study area is classified by Koeppen (1948) as mesothermal humid subtropical (Cfa), with temperatures above 22° in the hottest month and below 18° in the coldest month, with a concentration of rain in the summer and the occurrence of night frosts in winter. The average annual precipitation corresponds to 1,706.08mm, with heaviest rainfall in the months of January, December and February (MONTANHER; MINAKI, 2020). Two additional factors that exert a significant influence on the climate are the location of the study area on the Tropic of Capricorn. These conditions increase temperatures during the summer, and the topographic characteristics of the northern region of Paraná, which facilitate the entry of tropical and extratropical atmospheric systems that accentuate the average values of the local climate (SALA, 2005).

The Maringá Stream catchment is situated within the Third Plateau of the Paraná region. The taxonomical subunit that encompasses this catchment, the Maringá Plateau, exhibits a relief characterized by low dissection and a predominant slope of less than 6%. The shape top is elongated and flattened, the slopes are convex, and the valleys have a "V" shape (MINEROPAR, 2006). In the drainage headwaters occupied by the urbanization of the Maringá Stream catchment, the relief is made up of subtly rounded tops and convex slopes with embedded valleys. In the middle segment of the Maringá Stream catchment, in the western part the relief is less dissected with less pronounced altitudes and slopes and more straight slopes with greater ramp lengths, in the eastern part, the slopes have a greater slope and shorter ramp lengths. In the lower segment, the slopes are more elongated, and the slopes are less steep (SALA, 2005).

2.2. History of land use and occupation

The colonization process of northern Paraná, promoted by the Companhia de Terras Norte do Paraná (CTNP) in partnership with the state government, began in the 1930s and was followed by intense changes in the landscape. To promote and encourage agriculture in the region, native vegetation was quickly replaced by coffee crops, which led to rapid demographic growth and urbanization of the area. The Companhia Melhoramentos Norte do Paraná (CMNP), which replaced the CTNP, formalized the urban nucleus of Maringá in 1947, located at the interfluve of the Ivaí and Pirapó catchment areas. As in the entire north of the state of Paraná, urban and agricultural development in Maringá involved intense deforestation of the original vegetation (SALA, 2005).

The decline of the coffee economy, intensified by the strong frosts that occurred in the region between the 1960s and 1970s, led to a gradual replacement of coffee monoculture with temporary crops such as soybeans and wheat. This change was accompanied by the mechanization of crops and the consequent increase in productivity, leading to the appreciation of small local properties (SAMPAIO, 2013; MORO, 1998). These changes in the countryside triggered a rural exodus in the region (MORO, 1998). Altogether, the municipality received a significant number of migrants. From 1950 to 1970, the total population increased from 38,588 to 121,374 inhabitants. Between 1970 and 1980, the urban population surpassed the rural population. Rapid demographic growth drove the increase in urban areas in the municipality (RUBIRA, 2016).

In this context, the Maringá Stream catchment has most of its area used for agricultural activity, mainly temporary crops such as soybeans. However, a considerable part has been altered by urban growth. In 2017, urbanized areas reached 38% of the Maringá Stream catchment and 87% of the Mandacaru Stream sub-catchment. In the latter, 32 neighborhoods were created between 1963 and 2006 (PETSCH, 2014).

2.3. Methodological procedures

The study of morphological and morphometric changes in the three fluvial reaches involved geoprocessing analyses and fieldwork. The aerial photographs and orbital images cover a 48-year period from 1970 to 2017 (Table 1). Aerial photographs from 1970, 1977, 1989 and 1995 were selected, the first two at scales of 1:8,000 and the last two at 1:20,000, acquired from the digital collection of the State University of Maringá. Images from the Quickbird satellite were also used using Google Earth Pro software from 2002, 2003, 2005, 2010, 2012 and 2014-

2017. The images were georeferenced, the sections vectorised and the cartographic products processed using the geographic information system QGIS Development Team (2020).

Table 1. Fluvial reaches and cartographic products used to analyse morphological changes.

Reach	Cartographic Product	
	Aerial photograph	Orbital Image
R1 –Mandacaru Stream	1977, 1989, 1995	2002, 2003, 2005, 2010, 2012, 2014, 2016 e 2017
R2 – Maringá Stream	1977, 1989, 1995	2002, 2003, 2005, 2010, 2012, 2014, 2015, 2016, 2017
R3 – Maringá Stream	1970, 1977	2003, 2005, 2011, 2012, 2014, 2015, 2016, 2017

The variations in width and sinuosity were assessed for each reach; however, there are cartographic products available to analyse the width prior to straightening in the R2. The average width of the channel was acquired using Eq. 1 described by Montanher (2019). To acquire the area of the channel reaches, the field calculator in the geographic information system QGIS Development Team (2020) was used.

$$W = \frac{A_t}{L_t} \quad (1)$$

where, W: average width of the reach; A_t: area of the reach; L_t: length of the reach.

The lengths of the reaches for calculating the sinuosity index were acquired using the measure tool also in the geographic information system QGIS Development Team, (2020). Eq. 2 was used to calculate the sinuosity index of the reaches:

$$S = \frac{L_t}{L_{tv}} \quad (2)$$

where, S: sinuosity of the stretch; L_t: length of the stretch; L_{tv}: length of the reach in the valley.

3. Results

3.1. Straightening

The straightening of reaches R1 (Mandacaru Stream) and R2 (middle Maringá Stream) took place between 1977 and 1989 (Figure 2), causing a decrease in sinuosity of 19% (from 1.27 to 1.03) and 17% (from 1.21 to 1.00), respectively. In R3 (lower Maringá Stream), straightening occurred between 1970 and 1977, with a decrease in sinuosity of 28.3% (from 1.48 to 1.06). Fieldwork showed that there was only excavation of the floodplain, as there is no evidence that the interventions included waterproofing the bed or constructing dykes. After the significant decrease in sinuosity in the three reaches due to straightening (Figure 4), this parameter remained relatively stable until 2017.

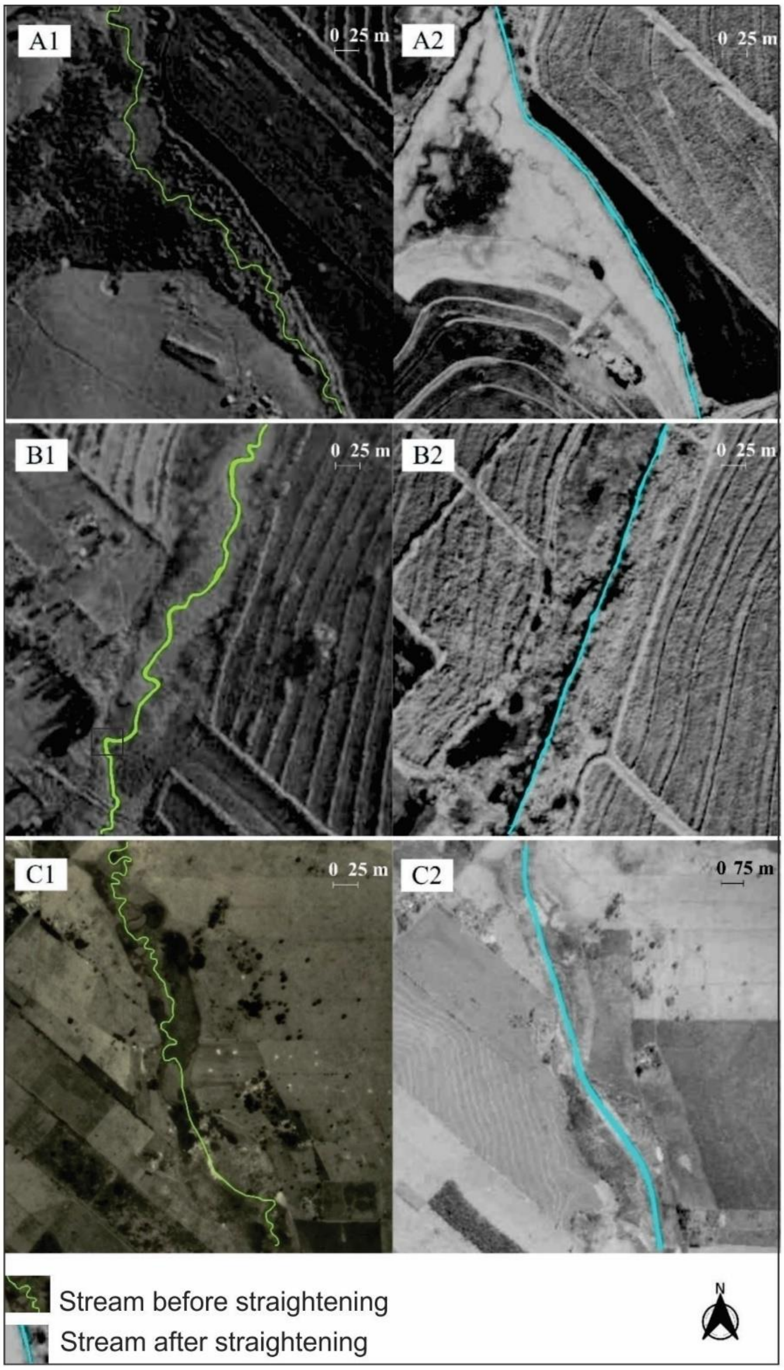

Figure 2. Pre and post straightening in R1 (A1 and A2) and R2 (B1 and B2) between 1977 and 1989 and in R3 (C1 and C2) between 1970 and 1977.

3.2. Temporal Analysis

The variations in the width of reaches (Figure 3) show the morphological changes over a 40-year period. Initially, it can be seen that straightening caused an 80% increase in the width of R2 between the years before (1977) and after (1995) the intervention. The other reaches do not have aerial photographs available to measure the width prior to straightening. Thus, it was observed that reaches R1 (1989-2002) and R3 (1977-2003) showed a decrease in width after straightening of 16% and 69%, respectively, indicating that the channels narrowed at intervals subsequent to this intervention.

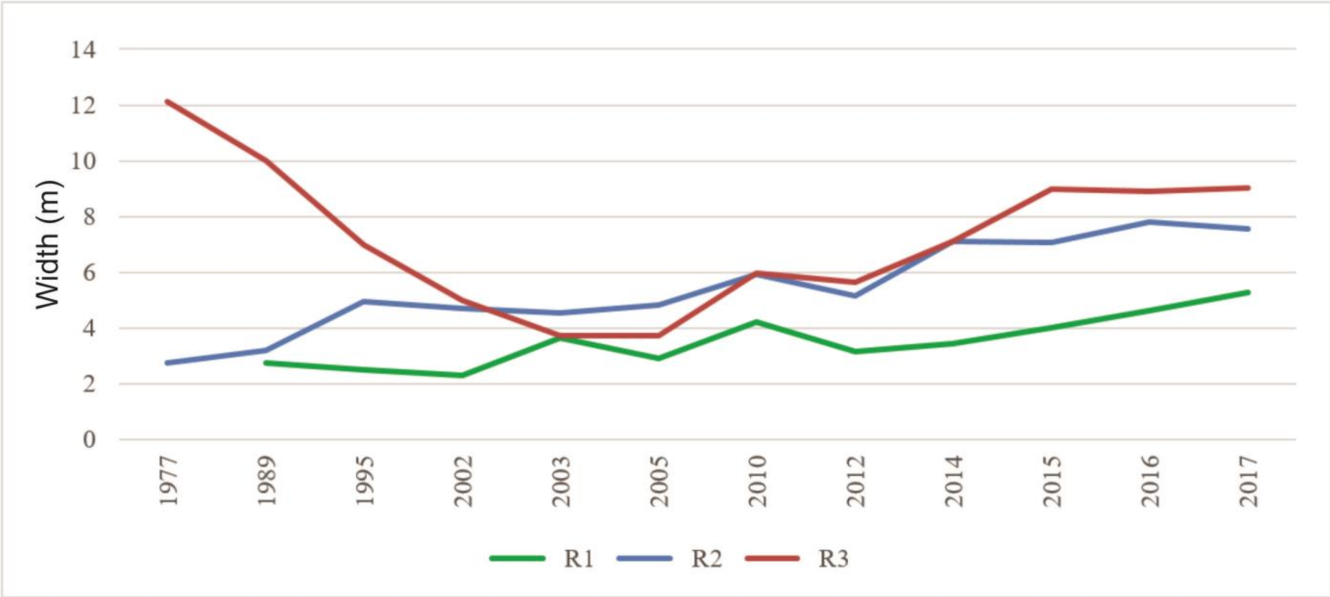

Figure 3. Width channel variations in the studied reaches.

Between 2003 and 2010, there was an increase in width of 29% and 60% in R2 and R3, respectively. This same behavior was also observed in R1 between 2002-2003 (59%) and 2005-2010 (46%); however, it was interrupted by a decrease in width (20%) between 2003 and 2005. Subsequently, there was a predominant decrease in width (6-25%) in the reaches during the short interval from 2010 to 2012. This was followed by the final interval from 2012 to 2017, during which the reaches showed a progressive increase in width (48% and 57%).

3.3. Spatial Analysis

Analyzing the R2 and R3 reaches makes it possible to assess the correspondence of channel changes between the middle and lower reaches of the Maringá Stream. In 1977, R2 had a width of 2.76 meters (pre-straightening), while R3 had a width of 12.14 meters (post-straightening), a difference of 341%. However, the average width of R2 (4.6 meters) became greater than that of R3 (3.7 meters) in 2003. These variations are due to the fact that R3 covers the final reach of the Maringá Stream, with a low gradient and relatively far from the urbanized area, which favored sedimentation and temporarily resulted in a channel width that was even lower than R2, which covers the middle course. Subsequently, as the hydrological regime continued to be influenced by urbanization, the R2 and R3 reaches were approximately the same width (7.1 meters) in 2014. From 2015 onwards, the lower reach (R3) became wider than the middle reach (R2). The increase in width has been progressive, but the process is more pronounced in R3 (9.00 meters) than in R2 (7.54 meters).

In addition, it is possible to assess the correspondence of the width variation between the contiguous reaches: the lower reaches of the Mandacaru Stream (R1) and the middle reaches of the Maringá Stream (R2). Both R1 (the lower reaches of the Mandacaru Stream) and R2 (the middle reaches of the Maringá Stream downstream of the confluence with the Mandacaru Stream) experienced an increase in average width between 2005 and 2010, a decrease in average width between 2010 and 2012, and a relatively progressive increase in width from 2012 onwards. This recent behavior indicates that, despite being different sub-catchments, the reaches exhibit similar processes resulting from increased urbanization in both drainage areas.

3.4. Morphological Analysis

The scenario of morphometric changes in the streams, with a low rate of lateral migration (sinuosity) but increasing width, reflects the effects of straightening and urbanization, resulting in flow characterized by erosive potential. The recent periods of narrowing identified in this study (Figure 4) are characterized by intense bank erosion. We observe that the recently eroded bank deposits are not entirely transported during floods, leading to a temporary reduction in width. Later, this material is reworked, forming benches (Figure 4).

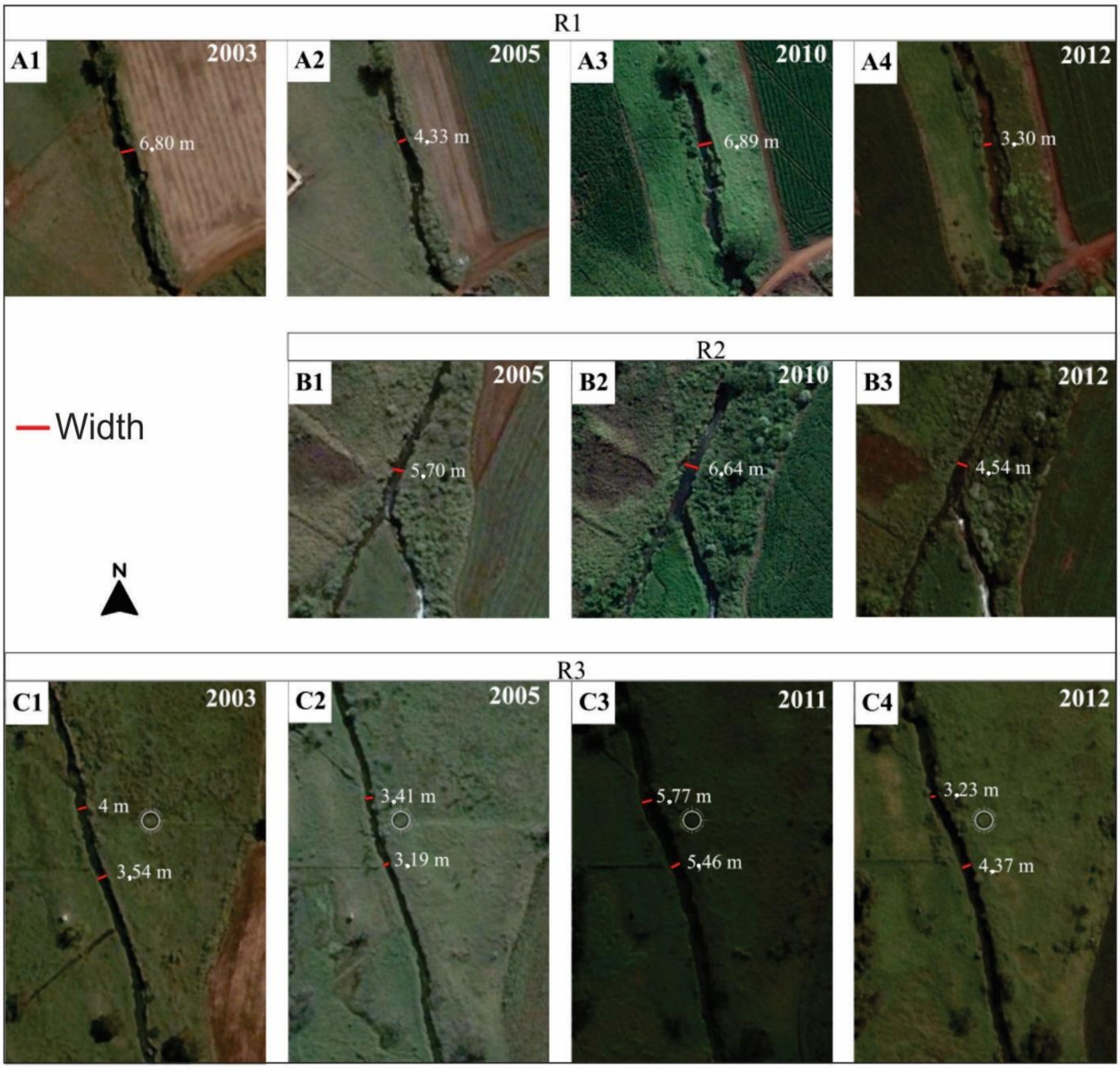

Figure 4. Variations in the average width of the three reaches, showing the increase in width permeated with periods of channel narrowing.

Benches in the Mandacaru Stream are relatively flat, discontinuous surfaces formed between the bed and the bank. There are alluvial benches covered by bank erosion deposits in reaches where there is insufficient capacity for sediment transport, and bedrock benches occur in reaches where there is capacity for sediment transport and the flow cause abrasion and detachment of the bedrock (Figure 5). Despite their similarity to bars, these geomorphological units are erosive relief units and are longer and more vegetated. Based on the analyses, we present below a model of the evolution of the reaches analyzed (Figure 5). Initially, the channel is at a preliminary stage of occupation of the catchment area (Figure 5.A). With the flow increase due to the urbanization in the catchment, erosive and incisive processes reshaped the channel (Figure 5. B). These processes favor erosion and bank failure, which results in the accumulation of sediment, generating periods of narrowing (Figure 5. C). These bank deposits encourage the formation of benches (Figure 5. D), which in some cases, with the intense erosion of the banks, make it possible to abrasion and detach the rock forming bedrock benches (Figure 5. E).

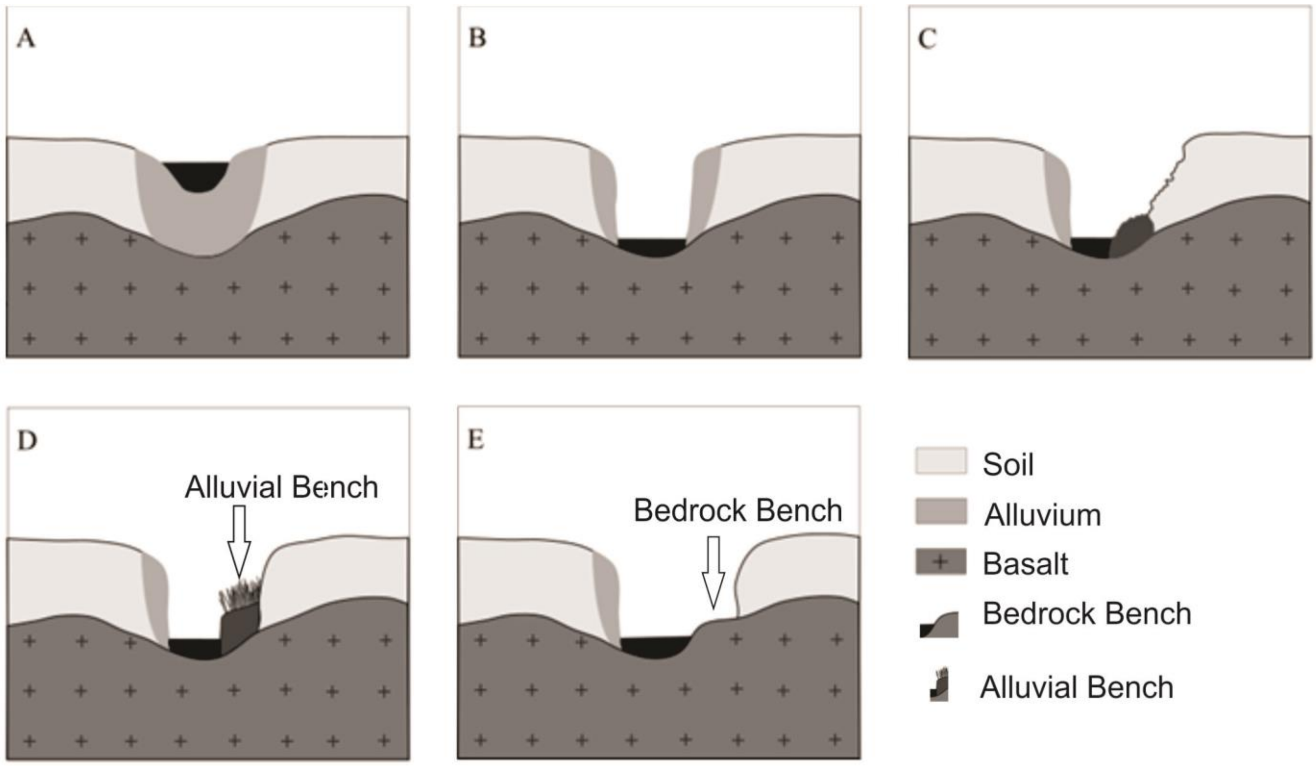

Figure 5. Model of bench formation. In (a) the channel before settlement of the catchment, in (b) the channel with erosion and incision of the bed due to impervious area by urbanization in the catchment. In (c) the banks have collapsed and been deposited in the channel. In (d) benches formed by bank deposits and in (e) bedrock benches.

4. Discussion

The reaches evaluated did not re-establish their sinuosity after the straightening that took place between 40 and 50 years ago, and the straightenings occurred at the intersection of the sinuous pattern of the channels. The deposits transported in the catchment come from basalt and this lithology gives rise to fine, cohesive sediments, creating conditions for bank stability (SANTOS et. al, 2008). In addition, the maintenance of straight morphology, as an effect of straightening in a meandering channel, has been reported on a time scale up to twice as long as that encompassed in this study (SALA; RHOADS, 2022).

The absence of sinuosity recovery may also be associated with urbanization in the catchment area (DENG et al., 2015), given that the increase in flow magnitude with drainage of impervious areas results in an increase in channel width (PARK, 1997; SANTOS; PINHEIRO, 2002; TANIGUCHI; BIGGS, 2015; MONTANHER, 2010; NAVRATIL et al., 2013). The urbanized areas in the upper reaches of the catchment under study have advanced intensively downstream, which has resulted in an increase in the magnitude of the flow (PETSCH, 2014). Additionally, bank erosion has been identified as the primary source of sediment in the Maringá Stream catchment (COELHO, 2007). This effect was first observed by Rigon (2010), who compared the bank erosion rates of 40.92 $cm \cdot month^{-1}$ and 0.25 $cm \cdot month^{-1}$, respectively, for the R1 drainage area (Mandacaru Stream catchment) and an adjacent rural catchment (Romeira Stream sub-catchment). Therefore, the changes imposed on the hydrological cycle as a result of urbanization and the expansion of impervious areas are associated with the observed increase in channel width over recent decades.

The oscillations in channel average width observed in reaches indicate the potential occurrence of micro-cycles in the channel change model influenced by urbanization, as proposed by Montanher (2013). This study emphasizes that the erosion and failure of banks during periods of high flows (RIGON, 2010; BAGGIO, 2014) enables the reworking of deposits and lateral sedimentation on the banks, which in turn gives rise to the formation of benches. Benches are defined as depositional surfaces of rivers, characterized by dissection processes (FERNANDEZ, 2003). In the studied reaches, these geomorphological units emerge as a fluvial response to the drainage flows of the urban area. These relief units exhibit morphogenesis similar to that described by Vietz et al. (2004), resulting from channel expansion followed by deposition. They are not necessarily formed by aggradation of flood flows (ERSKINE; SAYNOR, 1996; ERSKINE; LIVINGSTONE, 1999).

As the formation of benches is related to the contemporary hydrological regime, these relief units are bankfull stage indicators (FERNANDES, 2003). In the Mandacaru Stream (Figure 6), which is part of the study area (R1), benches have been investigated for the possibility of contaminant stocks (SOUZA; MORAIS, 2023). In this context, our study also contributes to the fact that there is a greater occurrence of benches in R1 and R2 compared to R3. In addition, the formation of bedrock benches (WOHL, 1992) was found in R1, as a response to the increase in the maximum stream power due to the greater urbanization of this drainage area.

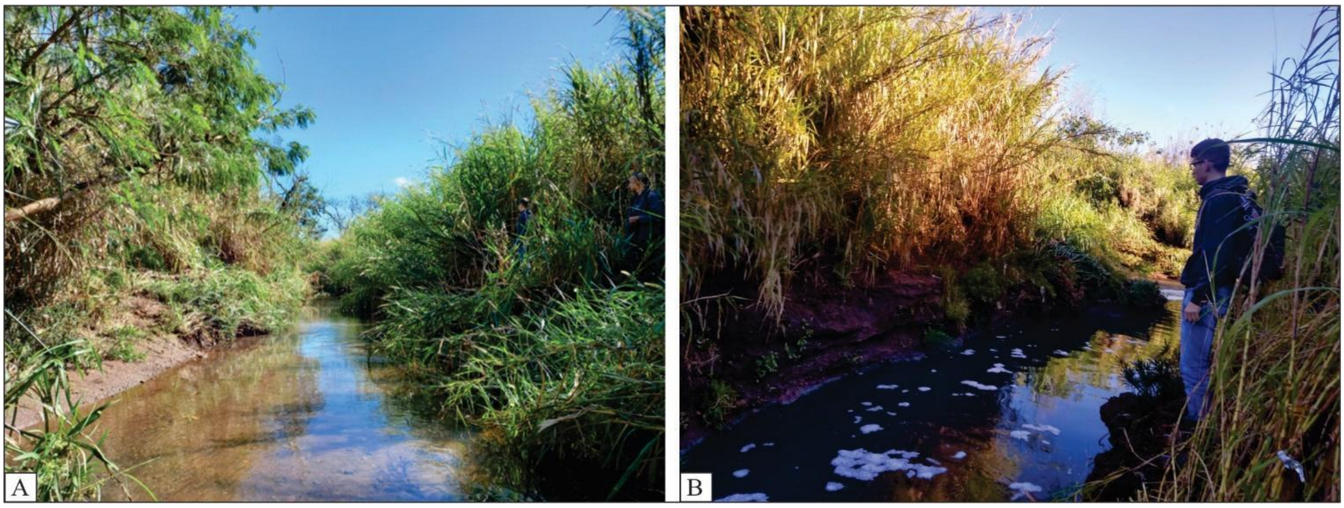

Figure 6. The alluvial (A) e bedrock (B) benches in right banks.

The study of morphological changes in channels under the influence of urbanization, but in catchments with sandy-textured soils in the northwest of the state of Paraná, revealed a high level of sedimentation in close proximity to the bank (MONTANHER, 2013). The formation of marginal levees as a result of these deposits leads to the accumulation of water on the sides of the floodplain, which in turn induces the formation of lakes. However, in the reaches assessed in this study, in a catchment area with clay-textured soils, there was no significant sedimentation, as observed in the channels analyzed by Montanher (op. cit.). Instead, there was an increase in width, maintenance of the sinuosity imposed by the straightening, and the formation of benches. In a study conducted in the municipality of Marechal Cândido Rondon with comparable lithological and topographical characteristics, but in smaller drainage areas and less dense urbanization, the assessment over a period of approximately ten years revealed a slight predominance of depositional processes in seven sections, compared to erosive processes in four sections (BORTOLUZZI; FERNANDEZ, 2010). The different adjustments of channels to the influence of urbanization highlight the importance of knowing the structure of the catchment, as well as integrating and expanding studies so that they involve comparing different urban landscapes.

The observed variations in channel width and the lack of re-establishment of sinuosity are, respectively, responses to urbanization and straightening. These responses have been identified as impacts on the physical integrity of rivers (GRAF, 2001). This hypothesis is corroborated by the assertion of Pelech and Peixoto (2020), who posit that there is a perception among Brazilian managers that rivers are merely conduits for water. It is imperative that efforts to manage catchments guarantee natural factors as imperatives for the processes and forms of the river system, in order to ensure the physical integrity of rivers. River restoration measures have resulted in the re-establishment of channel sinuosity (WOHL et al., 2015), thereby restoring river dynamics (e.g. migrations and floods). However, the challenge of making the flow of urbanization compatible with fluvial dynamics, as recognized in the fluvial geomorphology of urban rivers (CHIN et al., 2020), represents a more urgent issue for the sustainable management of the rivers.

5. Conclusion

The study facilitated an understanding of the morphological changes occurring in river reaches subjected to urbanization and straightening. The straightening occurred during the 1970s and 1980s, with the implementation of works that altered the morphology of the channels, transforming them from sinuous to straight. The reaches under analysis demonstrated no alterations in lateral mobility, thus preserving the straight morphology. However, during the period under analysis, there was a notable tendency for the average width increase, with intermittent periods of narrowing channel. It was observed that this latter process is associated with the formation of benches as a result of the bank erosion and failure and the reworking of marginal deposits in the channel bed, which can be considered a geomorphological response to urbanization. The loss of the physical integrity of rivers, as evidenced by alterations in morphology, is not inherently attributable to urbanization per se, but rather to the shortcomings of urban drainage systems, particularly with regard to their energy dissipators.

In this scenario, which is typical of Brazilian urbanization, fluvial geomorphology plays a pivotal role, with the challenge of contributing to territorial development. To address this issue, it is crucial to integrate knowledge in order to establish a sustainable relationship between urbanization and river dynamics. In the context of rainwater drainage, this necessitates a discussion on maintaining natural factors in river processes. Consequently, it is vital for fluvial geomorphology to play an effective role in urban drainage public policies, liaising with engineering to propose management strategies to secure the physical integrity of rivers.

Author's contributions: Conception, K.B. and E.M.; methodology, K.B. and E.M.; software, K.B.; validation, K.B. and E.M., formal analysis, K.B. and E.M.; data preparation, K.B.; article writing, E.M.; revision, E.M.; supervision, E.M. All authors have read and agreed with the published version of the manuscript.

Finding: This research has not received any external funding.

Acknowledgments: To Wilson Francisco de Oliveira and the Historical Documentation Center Program/CCH/UEM for their support with aerial photographs.

Conflict of Interest: The authors declare not having any conflict of interest.

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