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Natural and anthropogenic constraints of erosion processes in urban rivers

Condicionantes naturais e antrópicos de processos erosivos em rios urbanos. Condicionantes naturales y antrópicos de los procesos erosivos en ríos urbanos.

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ABSTRACT: Urban rivers are undergoing profound changes in their dynamics, with straightening, narrowing, widening, deepening of channels, channelling and pipes. They are often submerged, with cities and roads growing over them in favour of mobility and the solution of related problems such as flooding and erosion. In São Carlos, a city in the state of São Paulo, in the interior of Brazil, the extensive water network is not far from these degradations caused by urbanisation. This study assessed stretches of two watercourses (Monjolinho River and its tributary Gregório's Stream) that still have lateral permeable areas, but suffered with alterations over decades. We studied these stretches with erosion processes, interventions, engineering work in order to assess the natural and anthropogenic factors involved in modifications. The methodology consists of analysing process occurrence databases, historical and current cartographic documents and field surveys. Due to the worsening recurrence of these processes at many points, we believe that marginal alterations, land use in the surrounding area and rectifications are the cause and it is necessary to study them in depth in order to find a suitable corrective solution. The conditioning factors observed will make it possible for public authorities to take action that is more assertive.

KEYWORDS: Marginal erosion. Rectification of the watercourse. Anthropised Rivers. Geographic Information System.

1 INTRODUCTION

Urban settlements in Brazil, as in many other countries around the world, began and developed around watercourses that were the source of the sanitation needed by cities. Over time and with the growth of the urban population, there have been changes in forms of urbanisation and means of transport, leading to a consequent loss of water quality. Rivers lost their importance and cities suffocated them. These poorly planned urbanisation processes have led to many urban problems, one example being the disorganised occupation of floodplains.

As pointed out by Versaci *et al*. (2018) when addressing human intervention in rivers, exemplified in the context of Reggio Calabria, Italy, there is an increase in the effects of flooding, which can result in changes in river dynamics and increase the risk of flooding. Watercourses have submerged into channels, cities and roads have grown over them in favour of mobility and the solution of related problems such as pollution, flooding and erosion.

The main anthropogenic drivers of erosion are land use and climatic variations that generate a more intense hydrological cycle (O'Neal *et al*. 2005). Anthropogenic action, added to natural factors, contributes to the appearance of erosive features, which we can observe at various locations(Andrade *et al.* 2022).

Among the impacts of human activity on urban rivers, one of the most commonly observed is straightening works, which involve direct changes to the natural course of rivers.

Various studies have analysed morphological adjustments to watercourses due to anthropogenic action. Wolman (1967) analysed how human activity causes changes in runoff and sediment transport, pointing out that adjustments to the river channel have resulted from interventions such as dams and river regulation, changes in land use, canalisation, the effects of bridges and urbanisation.

In a Brazilian context, Assumpção (2009) observed that the morphological changes in the Macaé River (RJ) generated changes in the speed of flows, in the regions subject to erosion and deposition, in the pattern of discharges and in the granulometric composition of the sediments transported. In addition, the changes generated an increase in sediment load and flooding downstream of the rectification, as well as an increase in erosion along the banks.

Similarly, Ferreira *et al.* (2023) pointed out that research into the controversial process of channelling the Lenheiro Stream in São João Del Rei (MG), together with other changes to the local landscape, strengthens the argument that human beings play a significant role as geomorphological agents.

After the establishment of urbanised areas, erosion and channel widening can become more evident due to soil sealing. These changes are often one of the reasons for channelling and straightening urban rivers. The straightening of river channels is a widely used artificial alteration to the shape of rivers, involving the deepening and/or widening of the channel, as well as the removal of meanders (Assumpção & Marçal 2012). This process has a significant impact on the horizontal and vertical configuration of the channels, exerting a direct and indirect influence on the entire fluvial system of the basin.

The canals, among other works, become part of the urban landscape and denaturalise the dynamics of the river system (Rocha 2008).

In Brazil, the term canalisation refers to projects that include altering the course of the river channel followed by the application of concrete within it. Human interventions in river systems have resulted in changes to water flow characteristics, sediment transport and river bed morphology. These changes can bring benefits in certain cases, often short-lived, but can also have adverse impacts in other situations. Therefore, the effectiveness of channelling urban rivers can be temporary as the city develops. In addition, channelling can sometimes mitigate the problem of flooding in critical areas by transferring it downstream, generating more significant consequences than those previously observed (Miguez *et al.* 2015).

In the city of São Carlos, a municipality in the central region of the state of São Paulo, south-east region of Brazil, several urban streams and their watersheds have undergone rapid urbanisation processes, making them particularly vulnerable to environmental changes

In this specific study, we aimed to analyse stretches of two urban watercourses in São Carlos that still have lateral permeable areas, but suffered alterations over the last five decades. The first is a stretch of the Monjolinho River that includes the area around the Kartódromo and the outflow of the Santa Maria do Leme Stream, and the second is the final stretch of the Gregório Stream, before it flows into the Monjolinho River.

We assessed the process of urban occupation and its influence on the morphological behaviour of the channel, with the specific objectives: (I) carry out a historical analysis of watercourse rectifications; (II) to verify the influence of human occupation in the Santa Maria do Leme, Monjolinho and Gregório sub-basins on river dynamics and erosion processes.

2 METHODOLOGY

We selected stretches in the urbanised area of the Monjolinho River and the Gregório Stream, where there are or have been repetitive marginal erosion processes, to examine the correlation of these processes with the straightening of the watercourse and with anthropogenic occupation, through a space-time analysis.

The methodological approach adopted in this study consists of using geoprocessing tools, such as the QGIS software, to compare cartographic data, vertical aerial photographs and satellite images of different periods, from 1971 to 2023, to conduct a historical survey of anthropogenic pressure.

Satellite images are valuable resources for analysis, as they provide data on the location and characteristics of the drainage system at specific times, helping to reconstruct and interpret changes in a watercourse (Trimble 2008).

We also collected data in the field and from the literature on the condition of the channel, intervention works, rectification structures and interferences. We measured the width of the channel for each junction and the points where erosion occurs were studied using measurements and photographs.

Based on the collection of historical data on hazardous events of flooding and erosion organised by Eiras (2017), we made a compilation of data from 1993 to 2018 using local newspapers and websites, in order to spatialize the occurrences, observe recurrent points and observe possible correlations between them.

We processed the collected data and generated shapefiles in GIS to spatialise the anthropogenic pressure points surveyed and to allow an analysis of the concentration of current and historical erosion points, as well as flooding points.

3 STUDY AREA

The areas studied are located in São Carlos (SP), a medium-sized city with a population of 254,822 inhabitants and an urbanised area of 79.87 km² (IBGE, 2022). It is located between the parallels 21°57' and 22°06' south latitude, the meridians 47°50' and 48°05' west longitude (Figure 1).

The first section analysed comprises 865 metres of the Monjolinho riverbed, from upstream of the Kartódromo to the junction with the Santa Maria do Leme Stream. The second segment corresponds to the final 995 metres of the Gregório Stream to its junction with the Monjolinho River. Both represent two stretches of urban occupation and high anthropogenic pressure (Figure 1).

The Monjolinho River, with a length of 43.25 km, has its source near the urban area of São Carlos, crossing it and receiving several tributaries before following its course through the rural area of the municipality.

The Gregório Stream plays a significant role in the history and development of the city, as it was along this watercourse that the construction of the first streets and houses in São Carlos took place, emphasising its importance as a central element in the urban landscape of the time. Originating in the rural area near the Monjolinho springs, this stream crosses the urban area from east to west and today plays a crucial role in drainage, as it receives a large part of the rainfall runoff from the impermeable city.

Basalt outcrops of the Serra Geral Formation occur in the beds of these studied stretches (Pons 2006). The soils on the banks (Bartolomeu 2012) correspond to the young and mature residuals of the Serra Geral Formation (predominantly clayey in texture and purplish red in colour), alluvium (unconsolidated quartz sands, rarely clayey) and colluvium (talus material, influenced by sandy and basaltic material).

The climate in the Monjolinho basin region is tropical, with well-defined seasons: dry and cold between April and September, and wet and hot between December and February. From 1992 to 2010, the average annual rainfall was 1361.6 mm, with January being the wettest month (274.7 mm) and August the least rainy (22.8 mm), and regarding temperatures, the annual maximum was 27.1ºC and the annual minimum was 15.8ºC (Embrapa Meteorologia 2010).

The sites studied receive water flow from three different sub-basins, as shown in Figure 1. The first section is influenced by the High Monjolinho (36.0 km²) and Santa Maria do Leme (11.3 km²) sub-basins, while the second section corresponds to the area of influence of the Gregório sub-basin, with 19.1 km². It is important to note that this last sub-basin has most of its extension within the urban area of the municipality of São Carlos.

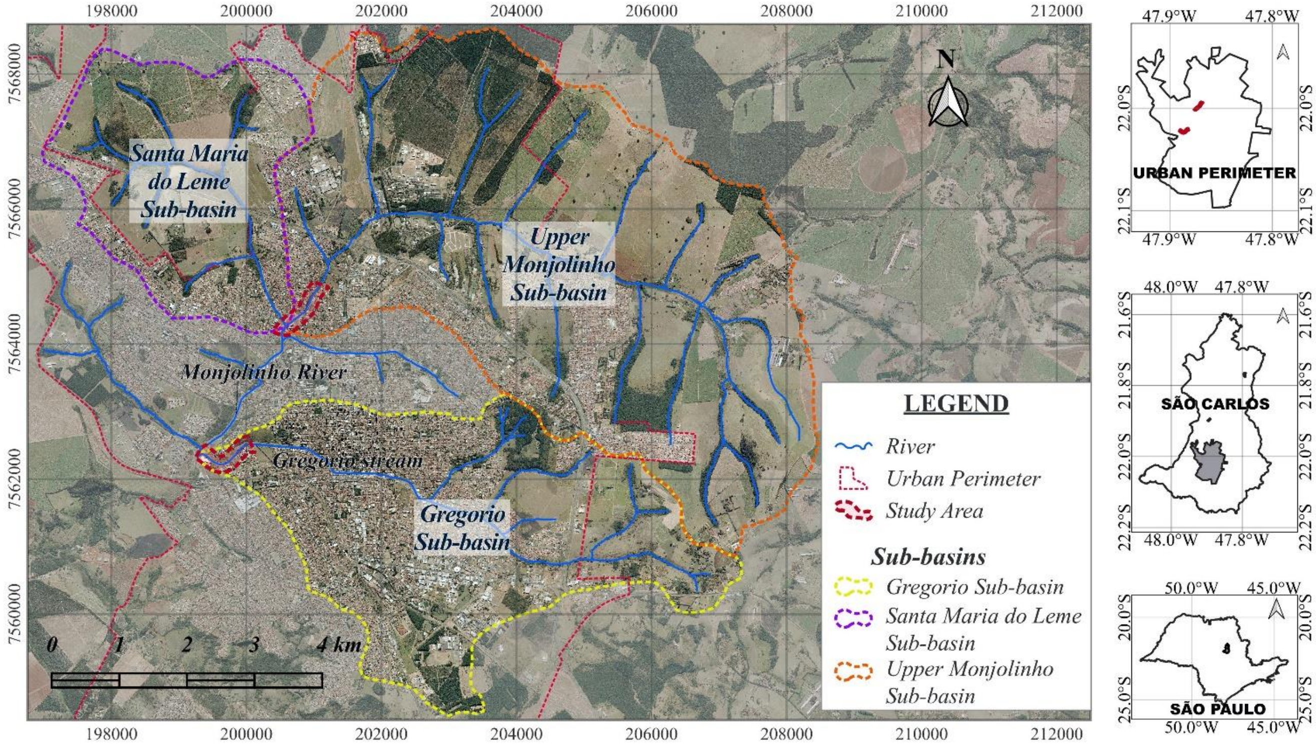

Figure 1. Location of the study area in the state of São Paulo, the municipality, in the urban area and with the sub-basins involved.

4 ANALYSIS OF ANTHROPISATION EFFECTS

By combining the cartographic data and the 1971 vertical aerial photograph, we drew up the 1971 land use and occupation map, which we compared with the 2023 map based on the 2023 satellite image (Figure 2).

We then analysed the erosion processes in order to correlate them with human activities through the mapped land use and occupation. Anthropogenic influence has an adverse impact on environmental changes due to a lack of planning, as is the case in the study region. It is therefore crucial to explore and understand the spatial distribution of land use, given its close relationship with marginal erosion processes.

In the time interval between 1971 and 2023, we observed that in addition to the urbanisation process, there was infrastructure construction, as well as the expropriation of areas near the banks of the Monjolinho River and the Santa Maria do Leme and Gregório streams, as shown in the highlighted sections.

In the region that corresponds to the sub-basins studied (Figure 2), we can see that in 1971 there was still little urban occupation, but there was a tendency towards growth highlighted by signs of new streets.

Figure 3 is a graphic representation of the historical comparison between 1971 and 2023, by land use type in percentages.

In 1971, pasture and undergrowth predominated (53.13%), followed by buildings (7.45%), green areas (0.46%), forest fragments (7.76%), streets (3.92%), agriculture (12.58%) and urban expansion or exposed soil (12.55%).

In 2023, there is a decrease in the area of pasture and undergrowth (35.26%), agriculture (6.80%) and area of urban expansion or exposed soil (5.18%), and an increase in the areas of buildings (29.10%), green areas (1.86%), forest fragments (12.20%) and streets (7.49%).

This analysis shows that urban occupation mainly affected areas previously used for pasture and agriculture, generating a 21.7 per cent increase in built-up areas between 1971 and 2023.

In the last 50 years occurs a constant removal of agropastoral vegetation in order to boost urbanisation. This practice resulted in a significant increase in impermeable urban areas, which in turn triggered substantial changes in the hydrological regime and behaviour of the watercourses within the sub-basins.

This clearly shows urbanisation without proper planning that takes into account the existing characteristics of the terrain, soils and watercourses.

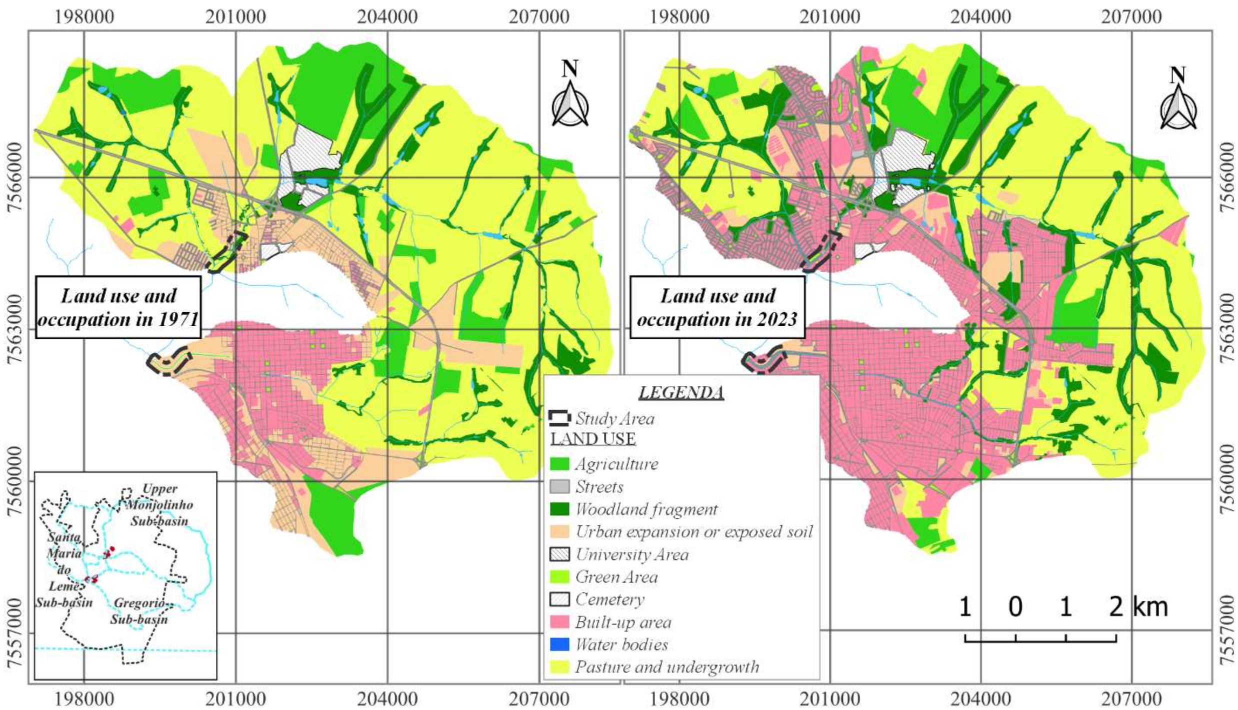

Figure 2. Land use classification maps for the years 1971 and 2023.

Land Use Types	1971	2023
Green Area	0.46%	1.86%
Woodland Fragment	7.76%	12.20%
Streets	3.92%	7.49%
Pasture and Undergrowth	53.13%	35.26%
Built-up Area	7.45%	29.10%
Cemetery	0.21%	0.21%
University Area	1.61%	1.61%
Agriculture	12.58%	6.80%
Urban expansion area or Exposed soil	12.55%	5.18%
Water Bodies	0.32%	0.29%

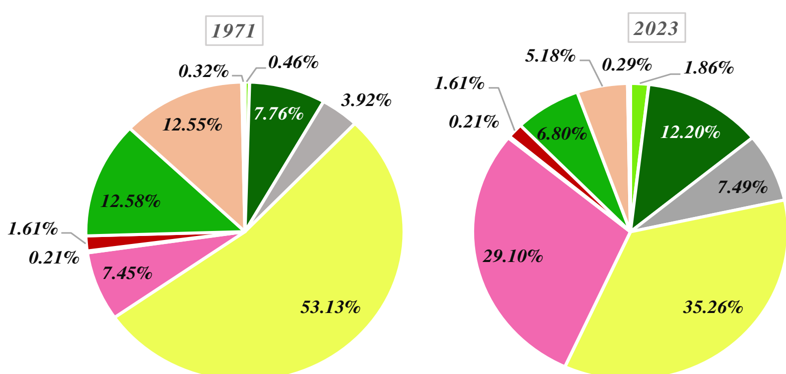

Figure 3. Graph of the percentages of and use and land cover classes in the sub-basins studied (Monjolinho, Santa Maria do Leme and Gregório) for the years 1971 and 2023.

We used vertical aerial photographs of São Carlos from 1971 and 1978 and satellite images obtained from Google Earth Pro from 2010 and 2023 to digitise the canals and observe the historical process of straightening off the watercourses.

Figure 4 shows the two studied areas. The historical images with suffix (a) corresponds to the surroundings of the Kartódromo at the mouth of the Santa Maria do Leme Stream on the Monjolinho River. The historical images with suffix (b) corresponds to the final portion of the Gregório Stream up to the point where it flows into the Monjolinho River at the place known as the Cristo rotatory.

By analysing the historical records of the 1971 and 1978 aerial photographs, we can see that the rectification work on the watercourses in the urban areas of the Monjolinho basin began in the mid-1970s, with most of the rectification works taking place after 1971, highlighted by the contrast with the rectification observed in 1978.

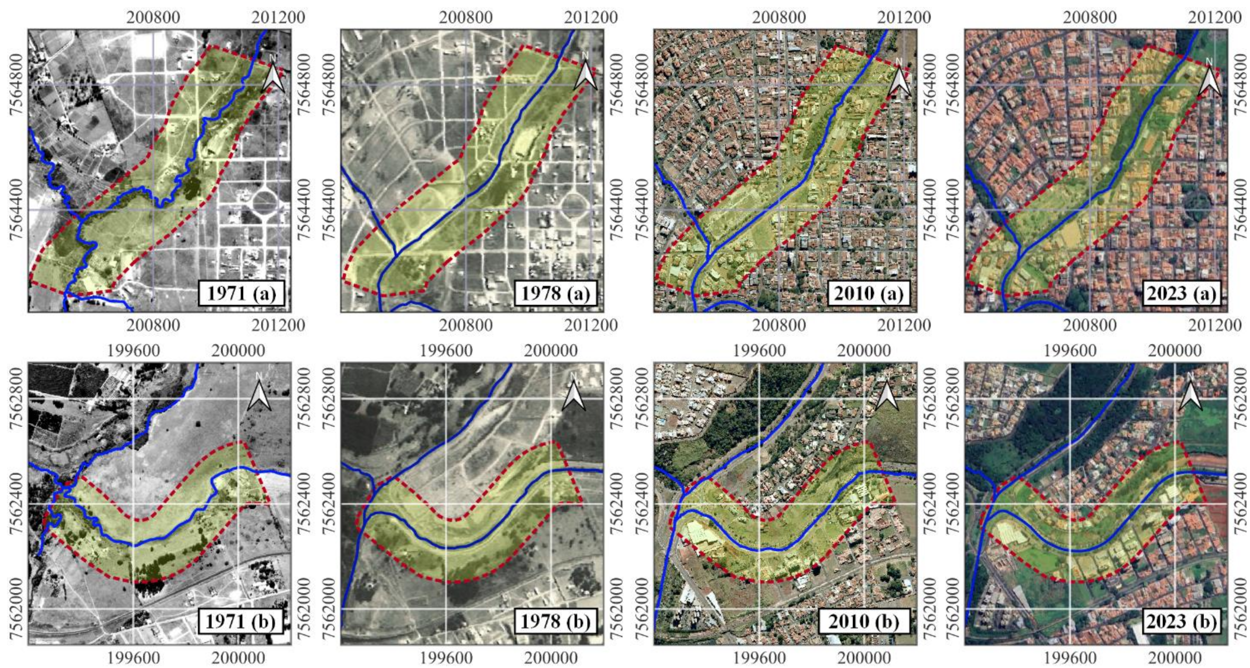

Figure 4. Historical aerial photographs from the years 1971 and 1978 (a) and (b), and Google Earth Pro satellite images from the years 2010 and 2023 (a) and (b). Suffix (a) correspond to the surroundings of the Kartódromo; suffix (b) correspond to the final portion of the Gregório stream.

These areas around the Kartódromo and the Cristo rotatory historically suffer from flooding and have an active process of urban occupation. Using the historical data on hazardous events collected, we spatialised and created a heat map referring to the distribution of floods in the studied areas (Figure 5) for further comparison to the distribution of historical and current erosion points. We observed a concentration of occurrences at the mouths of the Santa Maria do Leme (Figure 5 a) and Gregório (Figure 5 b) streams on the Monjolinho River.

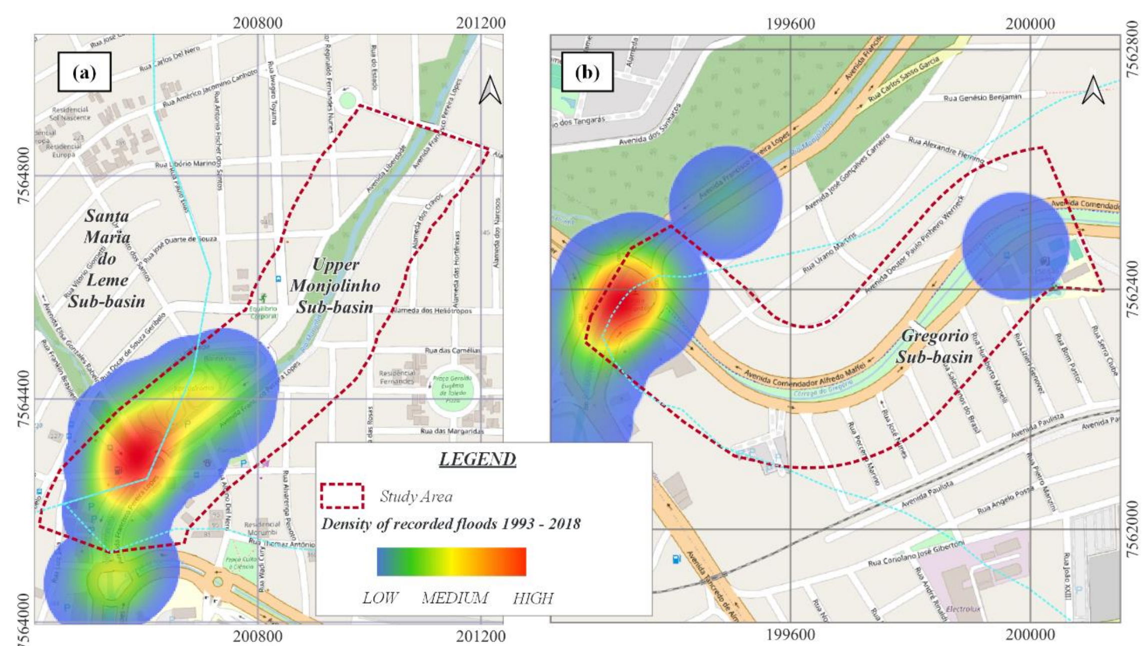

Figure 5. Heat Map of hazardous events of flooding recorded in the study area from 1993 to 2018. Suffix (a) correspond to Monjolinho River near the Kartódromo; suffix (b) correspond to the final portion of the Gregório Stream.

According to Freitas & Santos (2020), the construction of marginal avenues in the 1980s also contributed to urban growth in these sub-basins. According to the mapping carried out by the Institute for Technological Research (IPT 2015), the area in Figure 5 (a) has a medium risk classification for flooding. The flooding process affects roads, housing and the commercial area, with flood heights reaching up to 5.5 metres at some points, with a radius of 60 metres. Similarly, the area in Figure 5 (b) has a classification of high risk for flooding (IPT 2015).

Flooding occurs when the waters of rivers, streams and storm drains overflow due to the insufficient transport capacity of these systems, occupying areas that currently belong to housing, commerce, transport and recreation (Tucci 2007). These events occur because of the natural behaviour of rivers, aggravated by human intervention in urbanisation, or begin with anthropisation, including the sealing of surfaces and the channelling of rivers. Many of the impacts on river dynamics in the region studied are related to soil loss in areas with increased erosion and flooding.

4.1 *Evaluation of channel change*

To geospatialise the data recorded during the field study, we used a Garmin 76S GPS to record the points. The aim of this collection was to identify the main influences generated by human occupation that modify the natural flow of watercourses. We characterised straightening, channelling and interfering structures such as bridges and energy dissipation devices (Table 1). We also recorded erosion points, both current and historical.

Table 1. Rectification structures registered in the field and construction history of the study sections.

Rectification Structures	Sub-basins	Code	Construction Date
Bridge	Gregório	RGP-003	1978-1989
		RGP-002	1989-2004
	Monjolinho	RMP-010	1978-1989
		RMP-002	1971-1978
		RMP-001	jul/2019
	Santa Maria do Leme	RLP-001	1971-1978
Pedestrian bridge	Gregório	RGPP-002	2004-2010
Channelling	Monjolinho	RMC-003	mai/2016
	Gregório	RCG-006	2004-2010
		RCG-005	apr/2013
		RGC-004	apr/2013
		RGC-003	apr/2013

During the visit to the study site, we observed and documented stretches of the canal: siltation, with rubbish accumulating in the riverbed, as well as attempts to control marginal erosion that did not comply with the requirements for dealing with this type of process. It is important to emphasise that the straightening works require ongoing maintenance and care, including dredging the bed and adjusting the banks to prevent siltation and erosion.

Figure 6 shows the GIS overlay of the different studied watercourses layouts over time, as well as the characterised and geospatialised points.

In Figure 6(a), the transformation of the channel's layout over time is evident, reflecting the interaction between the banks of the Monjolinho and urban development. These changes driven by urbanisation needs are visible in the successive straightening of the canal. A notable example is the construction of the leisure infrastructure known as the Kartódromo, built on part of the original course of the Monjolinho River, which was meandering and now is straight. Today, the modifications to the channel result in banks that are susceptible to erosion and the deposition of sediment from the basin, affecting river processes.

As a result of the canalization and rectification work, the channel of the Monjolinho River lost its sinuosity, altering the course and shape of the drainage at the confluence of the Santa Maria do Leme Stream. This has an impact on the discharge regime, the patterns and speed of flows, and the occurrence of peak discharges at the mouth, as well as reducing the roughness of the bed. These factors contribute to the recurrence of erosive processes, triggering problems such as the destruction of natural habitats and riparian forest and wetlands, as well as soil subsidence and damage to infrastructure.

In the stretch corresponding to the Gregório Stream (Figure 6(b)), the rectified channel has concrete walls, with a straight and silted section. The stream has a maximum width of 8.5 metres and banks with a maximum height of 5 metres, with houses at a distance of 20 metres from the channel axis. We can see that the marginal slope has stretches with vegetation cover and others waterproofed.

The canalisation works at the junction of the Gregorio Stream and the Monjolinho River in its initial conception sought to solve the problem of flooding and possible disease outbreaks. According to Freitas & Santos (2020), between 1970 and 1974, the streambed lost its original layout to make way for the construction of streets, marginal avenues and residential and commercial neighbourhoods; the channelling of parts of the course allowed the sewage discharge to go directly into its waters and drain quickly out of the city.

To this day, flooding in this area is uncontrolled and the canalisation alters the continuity and flow of the watercourse, generating a turbulent flow due to the increase in speed, which leads to active marginal erosion. In the final stretch of this structure, there is an increase in the sediment load, and we see siltation.

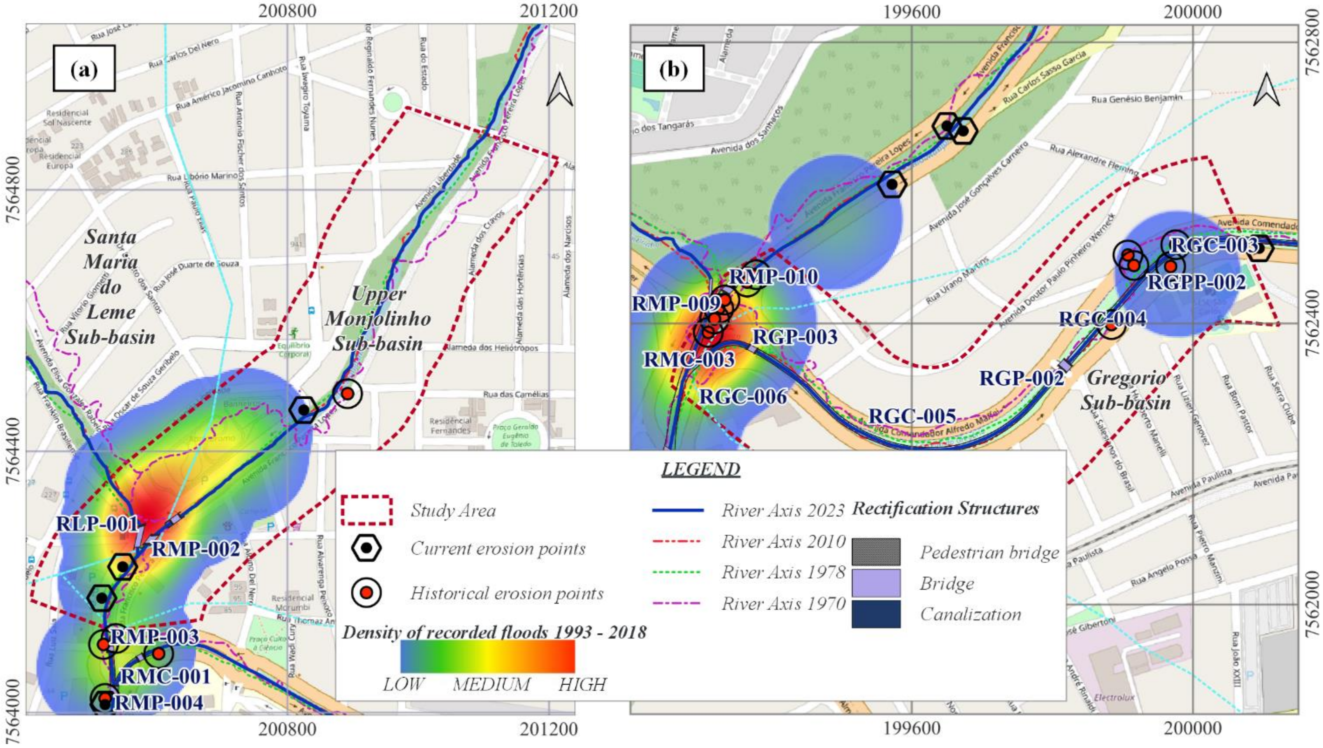

Figure 6. Visualisation of geospatialised erosion occurrences over the heat points of flood data, with overlay of watercourse trajectories over time.

We recorded the active and historical marginal erosion points (Figure 6) in the natural channel courses:

- Where there was an originally meandering course, according to the historical images;
- Downstream of a canalised stretch;
- Upstream of the rectification of the initial course of the watercourse (Kartódromo headland). In this stretch, the canal was winding and ran through the area where the Karting Track is now located;
- Upstream of the Cristo rotatory, in the stretch where the drainage water from the higher parts of the city reaches the Monjolinho River.

We observed frequent erosion points at the Cristo rotatory in the historical data collection, but this process is currently absent due to the existing channelisation; silting is evident in the concrete channel.

5 CONCLUSIONS

The frequent interventions in the watercourse, including straightening, construction of marginal roads, sealing of the soil, removal of vegetation, channelling, installation of drainage networks and construction of bridges, triggered a significant increase in flooding in the stretches studied, as well as contributing to marginal erosion and siltation of the Monjolinho River and Gregório Stream towards its mouth.

Based on the analysis of historical aerial photographs from 1971 and 1978, it is possible to infer that the rectification works on the watercourse surrounding the urban area of the Monjolinho basin began in the 1970s. This transformation had significant repercussions over time, especially with regard to the increased tendency for flooding in the Kartódromo and Cristo rotatory areas. Analyses of changes in land use and land cover in the basins between 1971 and 2023 show an increase in urbanised and impermeable areas, a significant reduction in areas of permeable soil, riparian forest, and undergrowth areas.

The alteration of the original course of the Monjolinho and Santa Maria do Leme watercourses during the 1970s emerges as one of the main causes of this phenomenon, helping to increase the likelihood of bank erosion downstream. This process, in turn, triggered a series of consequences that spread over time, manifesting themselves in a notable way over the last five decades.

The modification of the Monjolinho, Santa Maria do Leme and Gregório canals along the urban stretch over this 50-year period had a significant impact on their fluvial dynamics and on the areas within their catchments. These changes have not only altered the morphology of the watercourses, but have also directly influenced the interaction between the river system and the surrounding areas. It is necessary to make a careful assessment in order to adopt management strategies that take into account environmental dynamics and the resilience of local communities in the face of these transformations.

Given these scenarios, it is urgent for public authorities to adopt measures to preserve urban rivers, respecting their natural dynamics and avoiding interventions that could aggravate erosion and flooding problems.

It is therefore essential to review the intervention practices adopted in the watercourses of São Carlos, which often cause more damage than benefits. Instead of straightening and channelling watercourses, it is necessary to restore their morphology and riparian vegetation, ensuring their resilience and ability to regulate water flow.

6 ACKNOWLEDGEMENTS

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