Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 30, e22, 2025
Scientific/Technical Article

https://doi.org/10.1590/2318-0331.302520240123

The potential contribution of riparian vegetation in non-point source pollution control during rainfall events in a tropical urban watershed

Potencial contribuição da vegetação ripária no controle da poluição difusa durante eventos de precipitação em uma bacia hidrográfica urbana tropical

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Received: November 30, 2024 - Revised: March 13, 2025 - Accepted: March 15, 2025

ABSTRACT

The presence of riparian vegetation can reduce the transport of sediments into receiving water bodies from surface runoff during rainfall events. However, this process is still overlooked in tropical watersheds, limiting the capacity of managers and decision-makers to implement control measurements of non-point pollution sources. This study evaluated suspended solids concentrations in a predominantly urban tropical stream near its outlet during stormflow conditions. It also examined how the structure and conservation of riparian vegetation in the immediate surrounding of an urban stream reach likely influenced the patterns of inputs of such non-point source pollutants. Four rainfall events with distinct hydrological characteristics were studied. Event Mean Concentrations (EMCs) and Mass versus Volume [M(V)] curves were obtained for all the monitored events. Two Rapid Assessment Protocols (RAPs) were used to assess the structure and conservation status of riparian vegetation along the urban stream reach. The lack of an adequate riparian vegetation buffer was found to exacerbate soil loss due to erosion. Direct surface runoff generated within the watershed showed a high potential for pollution, with evidence of non-point source pollution and first-flush effects observed during rainfall events with lower intensity. These findings are expected to contribute to the ongoing discussion on urban forestry and riparian zone reforestation, supporting the development of strategies aimed at mitigating non-point source pollution.

Keywords: Event mean concentration; First flush; Stormwater runoff; Tropical stream.

RESUMO

A presença de vegetação ripária pode reduzir o transporte de sedimentos do escoamento superficial em corpos de água receptores durante eventos de precipitação. No entanto, esse processo ainda é negligenciado em bacias hidrográficas tropicais, limitando a capacidade de gestores e tomadores de decisão de implementar medidas de controle para fontes de poluição difusa. Este estudo avaliou as concentrações de sólidos suspensos em um riacho tropical predominantemente urbano em seu trecho próximo ao exutório durante regime de cheia. Também examinou como a estrutura e a conservação da vegetação ripária no entorno imediato de um trecho de riacho urbano provavelmente influenciaram os padrões de entrada de tais poluentes de fonte de poluição difusa. Quatro eventos chuvosos com distintas características hidrológicas foram estudados. As Concentrações Médias dos Eventos (CMEs) e as curvas Massa versus Volume [M(V)] foram obtidas para todos os eventos monitorados. Dois Protocolos de Avaliação Rápida (PARs) foram utilizados para avaliar a estrutura e o estado de conservação da vegetação ripária ao longo do trecho urbano do riacho. A ausência de uma faixa de vegetação ripária adequada foi um fator agravante para a perda de solo em razão da erosão. O escoamento superficial direto gerado na bacia apresentou um alto potencial poluidor, com evidências poluição difusa e efeitos de primeira carga de lavagem observados em eventos de precipitação menos intensos. As informações do estudo contribuem para o debate contínuo e essencial sobre arborização urbana e reflorestamento de zonas ripárias, apoiando o desenvolvimento de estratégias voltadas à mitigação da poluição difusa.

Palavras-chave: Concentração média do evento; Primeira carga de lavagem; Escoamento de águas pluviais; Riacho tropical.

INTRODUCTION

The rapid expansion of Brazilian cities during the second half of the last century led to a myriad of negative impacts on aquatic environments, primarily due to inefficient land use planning and high levels of wastewater not properly managed (Ribeiro et al., 2022). While these anthropogenic pressures affect all aquatic ecosystems, urban waterways are among the most severely impacted (Richardson & Soloviev, 2021; Szymańska et al., 2020). They often exhibit symptoms of the urban stream syndrome, such as higher peak flows, elevated concentrations of nutrients and contaminants, altered channel morphology, and reduced biodiversity (Praskievicz, 2022; Walsh et al., 2005). Urbanization and economic development are often prioritized over environmental preservation, which is frequently overlooked by both public authorities and society (Çarkoğlu & Kentmen-Çin, 2015; Sheykhi, 2022). In Brazil, for example, a recent federal law (14285/2021) has relaxed restrictions and penalties related to deforestation of natural areas and occupation of permanent preservation areas along urban riverbanks (Brasil, 2021).

Riparian vegetation (or riparian forest) refers to the permanently protected areas located along the banks of rivers and streams and around their springs (Brasil, 2012). Beyond their fundamental hydrological and ecological roles, such as flood mitigation and water filtration, these areas are essential for reducing the transport of sediments and other contaminants into rivers and streams during rainfall events by acting as natural barriers (Cicco & Arcova, 1999; González et al., 2017; Mello et al., 2020; Nunes & Rosa, 2020). Recent studies have shown that waterways with more extensive and preserved riparian vegetation generally have lower sediment inputs (Dufour et al., 2019; Martins et al., 2021). Understanding the interactions between rivers and streams and their riparian zones, particularly in terms of vegetation structure, is crucial for establishing and maintaining healthy urban environments (Prado et al., 2022). This is especially important in tropical regions, where high precipitation and temperature levels are common and, therefore, severe episodes of flooding and non-point source pollution are observed, increasingly exacerbated by climate change (Taniwaki et al., 2017).

Although sediment inputs into streams can occur even during baseflow conditions, the largest amounts are transported by stormwater runoff, along with other pollutants deposited through the ground that contribute to non-point source pollution (Xu et al., 2021). The most common methods to characterize water pollution originating from diffuse sources are Event Mean Concentration (EMC) and Mass versus Volume [M(V)] curves (Righetto et al., 2017). EMC estimates the mass of pollutants discharged per unit volume of runoff during a specific rainfall event (Ferreira, 2008; Perera et al., 2021). M(V) curves in turn describe pollutant flushes during an event by plotting the relative cumulative mass (M) of pollutants as a function of the relative cumulative volume (V) of runoff (Jensen et al., 2022). The M(V) curve approach enables the analysis of first flush (FF) phenomenon (Di Modugno et al., 2015). FF is observed when the initial part of the runoff carries the majority of the pollutant load in a given precipitation event (Gupta & Saul, 1996; Jensen et al., 2022; Lee et al., 2002). Identifying this phenomenon is essential for designing robust stormwater treatment systems that minimize the risk of discharging high pollutant loads into receiving water bodies (Perera et al., 2021; Walsh et al., 2015). In Brazil and other low- and middle-income countries (LMICs), the analysis of non-point source pollution is often constrained by high logistical costs and a lack of specialized professional training (Righetto et al., 2017). These challenges can hinder the assessment of pollutant loads, ultimately affecting the design and implementation of stormwater control measures (Tuomela et al., 2019).

In this context, the present study aimed to analyze suspended solids concentrations in a predominantly urban tropical stream near its outlet during rainfall events using EMCs and M(V) curves. The stream's watershed was considered urban because of its advanced urbanization in its lower elevations and accelerated development towards its higher elevations, with the conversion of agricultural and pasture lands into urban developments – reflecting a process observed in many watersheds in Brazil and other LMICs. Sediment transport is a key indicator in both urban and rural environments, as it reflects hydrological and environmental conditions that influence water quality, ecosystem health, and land-use sustainability. In urban areas, impervious surfaces accelerate runoff, increasing peak flows in watercourses and leading to excessive sediment mobilization from channel erosion. Also, sediment in urban waters often carries contaminants such as heavy metals, nutrients, and hydrocarbons, further degrading water quality. While nutrients could also serve as an important indicator in urban settings, the watershed in this study includes a rural portion, making suspended solids a more suitable indicator. In addition, we sought to examine how the structure and conservation of riparian vegetation, particularly in the mostly urban portion of the watershed, may influence non-point source pollution. We hypothesized that non-point source pollution and the FF phenomenon would be evident in the studied stream across all monitored rainfall events for suspended solids. We further hypothesized that the riparian vegetation status immediately around our urban stream reach would be indicative of unmanaged conservation practices, potentially contributing to increased suspended solids transport into the watercourse. By evaluating the role of riparian vegetation in non-point source pollution control, this research provides insights for improving urban planning, highlighting the importance of riparian recovery and conservation.

MATERIAL AND METHODS

Study area

The study was conducted in an urban stream located in São Carlos, a medium-sized city in the state of São Paulo, southeastern Brazil, with an estimated population of 254,857 inhabitants, according to the last census (Figure 1) (Instituto Brasileiro de Geografia e Estatística, 2022). The stream's watershed (11.18 km^2) comprises the monitored main stem (baseflow < 200 L s^{-1}) and six tributaries. The watershed perimeter was delineated using ArcGIS, leveraging its hydrology tools to process digital elevation model data. This involved performing flow direction and accumulation analyses, identifying pour points, and generating the watershed boundary to accurately define the drainage area of interest. Land use within the watershed is divided into urban areas (34%), pasture

Figure 1. Schematic map showing the location of the studied watershed and the analyzed sections. The sections are spaced approximately 100 m apart, with section 1 being the farthest from the watershed outlet, followed by sections 2, 3, 4, and 5, which is the closest.

and sugarcane cultivation zones (55%), and native vegetation (11%). The area is located within a region of secondary vegetation typical of the Cerrado and its transition to the Atlantic Forest. The total annual precipitation is approximately 1,500 mm, characterized by rainy summers (monthly average > 150 mm) and dry winters (< 70 mm) (Saltarelli et al., 2018). According to the Köppen-Geiger classification, the climate is humid subtropical with dry winters (Cwa), where the average monthly air temperature generally ranges from 17 to 23°C (Kottek et al., 2006).

Structure and conservation of the riparian vegetation

Rapid Assessment Protocol (RAP)

Two Rapid Assessment Protocols (RAPs) were used to assess the structure and conservation of the riparian vegetation in the urban portion of the studied stream: (1) Barbosa Neto et al. (2017), adapted from Callisto et al. (2002), and (2) Espíndola

(2022), adapted from Hannaford et al. (1997) and the U.S. Environmental Protection Agency (Environmental Protection Agency, 1987). Both protocols evaluate the riparian zone and the riverbed conditions. The first one uses eight indicators (type of land use along the waterbody margins, anthropogenic alterations, bank erosion, water odor, sediment deposits, presence of aquatic plants, riparian forest discontinuity, and riparian forest width), each with four possible scores: 0, 2, 3, or 5. The classification levels are as follows: "impacted section" (0 - 20), "altered section" (21 - 30), and "natural section" (31 - 40). The second protocol is divided into two groups. The first group allows the assessment of general characteristics of the watershed sections and the levels of environmental impacts resulting from human activities. The second group allows the evaluation of habitat conditions and the conservation status. This RAP also takes into consideration a set of indicators with evaluators. Scores for each evaluator in Group 1 (type of land use along the waterbody margins, erosion near and/or along the riverbanks and sediment accumulation in the riverbed, anthropogenic alterations, vegetation cover in the riverbed, water odor, water oiliness, water transparency, and substrate types) can be 0, 2, or 4, while in Group 2 (substrate types, rapids extent, rapids frequency, mud deposition, sediment deposits, alterations in the river channel, water flow characteristics, presence of riparian forest, bank stability, and riparian forest extent), scores can be 0, 2, 3, or 5. The final score, obtained by summing the values assigned to each indicator in both groups, reflects the level of ecological preservation of the studied sections, classifying them as "impacted" (0 - 40), "altered" (41 - 60), or "natural" (> 60). Using these RAPs enabled us to compare results across protocols, enhancing consistency and reliability in assessments while reducing the risk of bias or errors from a single method. Furthermore, the variation in their indicators highlights different aspects of riparian vegetation and riverbed conditions, providing a more comprehensive characterization (Masqueto et al., 2021; Cionek et al., 2024; Hurtado et al., 2024).

Riparian Vegetation (RV) and Riparian Forest Structure (RFS)

Two sets of variables proposed by Souza et al. (2013) were also analyzed: (1) Riparian Vegetation (RV), which includes tree density (number of trees per transect), basal area per hectare (sum of all cross-sectional areas per hectare), and average Diameter at Breast Height (DBH); and (2) Riparian Forest Structure (RFS), which includes the width of riparian vegetation, light availability, and the percentage of different vegetation types (trees, grasses, vines and bamboo, leaf litter, and exposed soil). All DBHs greater than 5 cm were measured at 1.3 m above ground level. The percentage of each vegetation type was determined through visual analysis and then calculated using a simple area percentage method. The percentage of trees was derived from the sum of the basal areas of the trees' DBHs. The width of the riparian vegetation was measured using a tape measure. Light availability along the stream, expressed as a percentage, was assessed using a spherical densiometer (Lemmon, 1956, 1957).

Sampling locations and frequency

The RAPs and the RV and RFS variables were assessed on both margins of five sections along the stream urban reach. Each section covered an area of approximately 100 m^2 and was spaced 100 m apart (Figure 1). Two sampling campaigns were conducted for the RAPs: one during the rainy season (February 2023) and another during the dry season (July 2023). The RV and RFS variables were analyzed only during the dry season, as seasonal changes in riparian vegetation composition in the study area were deemed negligible. Even though our focus was specifically on the most urbanized area of the watershed – near to its outlet and immediately surrounding the urban reach, where conditions likely exacerbate nonpoint source pollution inputs and are particularly relevant to this issue (Feijó-Lima et al., 2018) –, we recognize that analyzing additional sections along the entire main stem would provide a more comprehensive understanding of how vegetation structure and conservation influence sediment input into the watercourse system.

Characterization of non-point source pollution

Sampling and laboratory analysis

Samples to analyze the non-point source pollution influence on the urban stream were collected during stormflow conditions across four rainfall events (Table 3). To identify events likely to generate surface runoff, we used meteograms from the Center for Weather Prediction and Climate Studies (CPTEC) of the National Institute for Space Research (INPE) (www.inmet.gov.br/meteogramas), the Bauru Radar from São Paulo State University (Unesp) (www.ipmetradar.com.br), and Climatempo (www.climatempo.com.br/). Additionally, cloud formations were observed in the field to predict imminent precipitation. Rainfall indices [rainfall depth, rainfall duration, rainfall intensity, and previous days without precipitation (PDP)] were obtained from a weather station of the National Institute of Meteorology (INMET). Water levels in the stream during precipitation events were measured using a limnimeter that had already been installed at the watershed outlet prior to this study. Discharges were calculated with a rating curve (water level versus discharge) specific to the studied stream (Equation 1) (Fava, 2019).

$$Q = 24.191\, h^3 - 41.262\, h^2 + 33.249\, h - 5.951 \quad (1)$$

where Q is the discharge (m^3 s^{-1}) and h is the water level (m).

Stream water samples were collected manually. The number of samples per event (between 10 and 12) depended on the rainfall intensity and changes in water levels. For more intense events ($\geq$ 10 mm h^{-1}), a greater variation in water level was used for surface water sampling compared to less intense events. Sampling was conducted during both the rising and falling phases of the hydrograph and samples were collected at the beginning and end of the stormflow condition (base values) for all events. The samples were stored in 1-liter polyethylene bottles, kept cool, and sent to the Laboratory of Biotoxicology of Freshwater and Effluents

(BIOTACE) at the São Carlos School of Engineering (EESC) of the University of São Paulo (USP). The analyzed parameters included total suspended solids (TSS), fixed suspended solids (FSS), and volatile suspended solids (VSS). The analyses followed the protocols of the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 2017). EMCs were calculated and pollutographs and M(V) curves were elaborated for all parameters across all rainfall events.

Event Mean Concentration (EMC)

The EMC was calculated as the total mass of the pollutant divided by the total volume of runoff for an entire precipitation event (Equation 2) (Charbeneau & Barrett, 1998; Perera et al., 2021; Sansalone & Buchberger, 1997).

$$EMC = \frac{M}{V} = \frac{\int_0^{t_r} C_t Q_t dt}{\int_0^{t_r} Q_t dt} \cong \frac{\sum C_t Q_t \Delta t}{\sum Q_t \Delta t} \quad (2)$$

where M is the total mass of the pollutant over the entire event duration (g), V is the total volume of runoff over the entire event duration (m^3), t_r is the duration of the stormflow condition (min), C_t is the concentration of the variable over time (mg L^{-1}), Q_t is the discharge of the variable over time (m^3 min^{-1}), and Δt is the discrete time interval (min).

Mass versus Volume [M(V)] curves

The M(V) curve was generated by plotting the cumulative mass of pollutants as a function of the cumulative volume of runoff, based on discharge (Q_i) and concentration (C_i) values measured N times during the rainfall event at each interval Δt_i, assuming that Q_i and C_i vary linearly between two measurements (Equation 3) (Bertrand-Krajewski et al., 1998).

$$\frac{\sum_{i=1}^{j} C_i Q_i \Delta t_i}{\sum_{i=1}^{N} C_i Q_i \Delta t_i} = f\left(\frac{\sum_{i=1}^{j} Q_i \Delta t_i}{\sum_{i=1}^{N} Q_i \Delta t_i}\right) = f\left(\frac{\sum_{i=1}^{j} V_i}{\sum_{i=1}^{N} V_i}\right) \quad (3)$$

where N is the total number of measurements, j is the index from 1 to N, and V_i is the volume in the interval Δt_i.

The occurrence of the FF phenomenon was evaluated using the Geiger (1987) method through graphical analysis of the M(V) curve. FF is considered likely if the dimensionless cumulative mass of pollutants exceeds the dimensionless cumulative runoff volume at any point during the flow period. When plotting cumulative pollutant mass against cumulative runoff volume, a 45° line (the bisector) indicates uniform distribution of pollutants throughout the precipitation events. If the data for a specific event fall above the bisector, it suggests the presence of FF. Conversely, if the data fall below the bisector, it indicates that dilution is occurring.

Export of Total Suspended Solids (TSS)

The mass of suspended solids exported in the stream during stormflow conditions in each rainfall event was calculated according to Equation 4.

$$EM = EMC \cdot Q_{average} \cdot D \quad (4)$$

where EM is the exported mass of the pollutant (kg), EMC is the event mean concentration (kg L^{-1}), $Q_{average}$ is the average discharge (L d^{-1}), and D is the duration of the rainfall event (d).

RESULTS AND DISCUSSION

Structure and conservation of riparian vegetation in the urban stream reach

A general agreement between the protocols was observed. Average scores for the urban stream reach in the rainy and dry seasons were 17 and 18 in RAP 1 (Barbosa Neto et al., 2017) and 34 and 38 in RAP 2 (Espíndola, 2022), respectively (Table 1). For the left and right margins, the average scores were, respectively, 18 and 17 in RAP 1 (Barbosa Neto et al., 2017) and 39 and 34 in RAP 2 (Espíndola, 2022) (Table 1). These findings suggest that the dry season and the left margin displayed higher levels of environmental preservation. Overall, the average values for both margins classified the stream reach as "impacted" in both periods and no section was classified as "natural" according to the protocols considered.

The most significant changes observed between the seasons were primarily related to the degree of bank erosion and sediment deposition in the stream. During the dry season, some sections experienced increased bank erosion following intense rainfall events

Table 1. Scores from the rapid assessment protocols for the five sections (S) of the stream reach during the rainy and dry seasons.

Protocol	Left margin					Right margin				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Rainy season										
Barbosa Neto et al. (2017)	21*	21*	19	16	15	10	19	30*	8	15
Espíndola (2022)	41*	43*	39	33	32	32	33	43*	23	26
Dry season										
Barbosa Neto et al. (2017)	20	19	19	19	15	17	17	30*	11	15
Espíndola (2022)	39	47*	38	42	32	31	48*	42*	29	32

Sections classified as "altered" were highlighted with an asterisk (*), while those classified as "impacted" were left unmarked.

(Supplementary Material, Figures S1A and S1B). The capacity of rainfall to transport solid particles is a preponderant factor in water erosion (Machado et al., 2008). Regarding sediment deposition, more pronounced siltation was observed during the rainy season, with alluvial deposits and signs of undermining, particularly on the right margin (Supplementary Material, Figure S1C). The high level of sediment deposition on the right margin, especially during the rainy season, may be linked to the narrower riparian vegetation widths in the urban stream reach (Table 2). According to the Forest Code (Law No. 12.651; Brasil, 2012), a minimum strip of 30 m of riparian vegetation is required as a permanent preservation area along watercourses less than 10 m wide. The Urban Land Parceling Law (Law No. 6766; Brasil, 1979) prohibits construction within a 15-m strip around watercourses. However, in-situ measurements of the riparian vegetation along the stream reach revealed widths below the minimum required in all the monitored sections, highlighting the environmental degradation in this portion of our study area. This situation is very common in Brazil, so the results obtained here are representative of a large number of Brazilian urban rivers and streams (Bega et al., 2021; Martins et al., 2021; Mello et al., 2018; Miranda et al., 2021; Pimentel et al., 2021).

Regarding the RV variables, the highest tree density was observed on the left margin of S2 and S5 (Table 2). Although these sections had the same number of trees, their average DBH differed due to variations in basal area per hectare. The trees in S5 were shorter compared to those in S2, which explains the difference in DBH (Supplementary Material, Figures S1D and S1E). In the RFS assessment, the left margin of S2 was the most densely occupied by trees (18.1%) among all sections. However, leaf litter was predominant in this area (81.9%), similar to the left and right margins of S5. The left margin of S4 and the right margin of S1 were primarily covered with grasses (96.3% and 94.6%, respectively). The presence of bamboos on the right margin of S3 (47.0%) was also significant (Supplementary Material, Figure S1F). Another point of concern was the high percentage of exposed soil on the right margin of S4 (48.4%). This section was almost entirely cleared to construct a recreation area, leading to substantial irregularities in riparian zone occupation. Fernandes et al. (2011) found that proximal land use (30 m land use buffer) affects the structure of riparian vegetation more than distal land use (200 m land use buffer). Overall, the narrow riparian vegetation on both margins, along with low tree density and the dominance of grass and exposed soil in most sections, highlights the need for restoration efforts to increase vegetation cover, particularly in the most urbanized region of the watershed.

The association between vegetation types and light availability was evident across the evaluated sections. The right margin of S1, predominantly composed of grassland with sparse tree cover, exhibited the highest level of direct light availability (85.8%) compared to all the sections, followed by the right margin of S4 (51.5%), which was dominated by grass and exposed soil. The higher light availability suggests reduced canopy cover or gaps in vegetation, which raises concerns about increased potential erosion and non-point source pollution.

Characteristics of non-point source pollution in different rainfall events

This study encompassed rainfall events with varying hydrological characteristics, with rainfall intensities ranging from 4.2 to 19.0 mm h^{-1} and peak discharges between 1.9 and 10.2 $m^3 s^{-1}$ (Table 3). The peaks of pollutographs often coincided with those of the hydrographs, with increases in discharges generally followed by rises in suspended solids concentrations (Figure 2). This pattern was especially evident during rainfall events with the lowest intensities and durations (1 and 2), suggesting that sediments from the watershed were transported into the stream along with runoff. Moreover, contrary to our hypothesis, analysis of the M(V) curves revealed no evidence of non-point source pollution related to suspended solids in the study watershed during rainfall events with the highest intensities and durations (3 and 4) (Figure 3). This may be partially attributed to the high volume of water draining into the stream, which likely diluted the solids. These events were monitored in the months with the region's highest accumulated rainfall. During the rainy season, soil moisture levels are often elevated due to frequent precipitation events, which leads to increased surface runoff as a result of reduced infiltration rates (Breinl et al., 2021). On the other hand, non-point source pollution of suspended solids was observed during rainfall events

Table 2. Riparian Forest Structure (RFS) and Riparian Vegetation (RV) variables assessment for the five sections (S) in the urban stream reach margins.

Section		Left margin					Right margin				
		S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Riparian Vegetation											
Tree density (individuals m^{-2})		6.0	14.0	4.0	3.0	14.0	6.0	4.0	4.0	4.0	3.0
Basal area per hectare (m^2)		4.7	18.1	5.0	3.7	9.1	5.4	1.8	6.0	3.1	13.1
Diameter at breast height (m)		0.9	1.0	0.9	1.1	0.7	0.7	0.7	1.1	1.0	2.1
Riparian Forest Structure											
Vegetation type (%)	Trees	4.7	18.1	5.0	3.7	9.1	5.4	1.8	6.0	3.1	13.1
	Grasses	23.8	0.0	47.5	96.3	0.0	94.6	49.1	0.0	48.4	0.0
	Vines and bamboos	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.0	0.0	0.0
	Leaf litter	71.4	81.9	0.0	0.0	90.9	0.0	49.1	47.0	0.0	86.9
	Exposed soil	0.0	0.0	47.5	0.0	0.0	0.0	0.0	0.0	48.4	0.0
Width of riparian vegetation (m)		6.0	6.5	3.0	7.0	7.0	7.5	6.0	8.0	2.0	4.0
Light availability (%)		17.2	15.3	22.1	19.2	12.2	85.8	26.0	15.3	51.5	47.3

Table 3. Characteristics of the monitored rainfall events, along with the values for event mean concentrations (EMCs) and exported masses (EMs) of total suspended solids (TSS), fixed suspended solids (SSF), and volatile suspended solids (SSV).

Parameter		Unit	Rainfall 1	Rainfall 2	Rainfall 3	Rainfall 4
Rainfall duration		min	51	21	152	100
Rainfall height		mm	3.6	3.8	44.4	31.6
Rainfall intensity		mm h^{-1}	4.2	10.9	17.5	19.0
PDP		d	0.8	0.4	0.8	18.6
TPV		m^3	40,248	42,484	496,392	353,288
Basal water level		m	0.28	0.29	0.30	0.35
Average water flow		m^3 s^{-1}	1.4	1.8	4.2	3.3
Peak flow		m^3 s^{-1}	1.9	2.6	10.2	5.4
EMC	TSS	mg L^{-1}	74	103	205	131
	FSS	mg L^{-1}	58	76	164	87
	VSS	mg L^{-1}	17	27	40	44
EM	TSS	kg	317	234	7852	2594
	FSS	kg	249	172	6282	1723
	VSS	kg	73	61	1532	871

Abbreviations: PDP, previous days without precipitation; TPV, total precipitated volume.

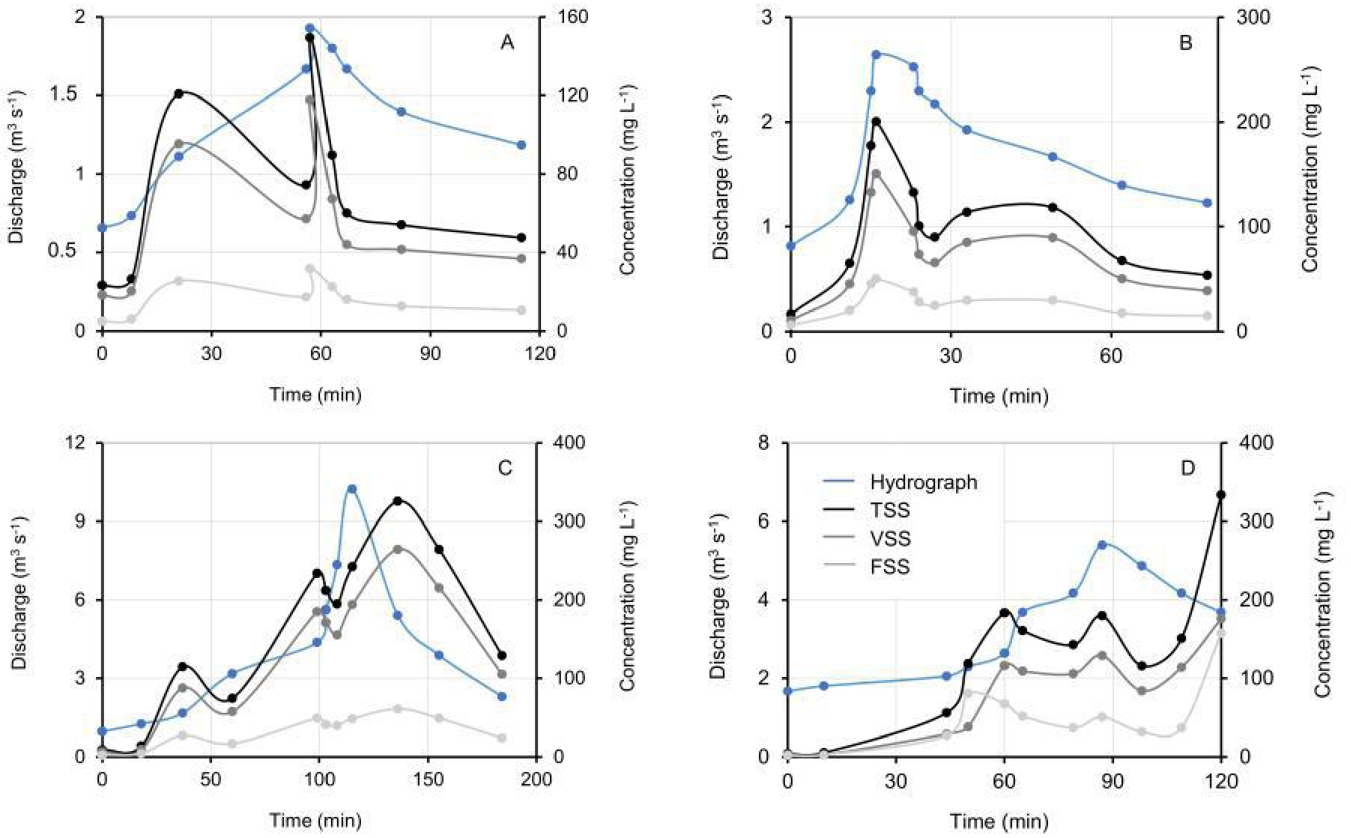

Figure 2. Hydrographs and pollutographs of total suspended solids (TSS), volatile suspended solids (VSS), and fixed suspended solids (FSS) obtained in the stream water for the monitored rainfall events (A) 1, (B) 2, (C) 3, and (D) 4.

characterized by the lowest intensities and durations (1 and 2). In these events, the runoff was not able to dilute the suspended solids and increased their in-stream concentrations.

Moreover, in cases of non-point source pollution involving suspended solids, the presence of FF was also observed (Figure 3). This phenomenon occurred after approximately 20% of the volume had drained for both TSS and their fractions, suggesting that runoff from the higher elevations of the watershed likely reached the outlet. Controlling FF is crucial in urban watersheds, especially in areas that are either highly urbanized or undergoing urbanization. This is particularly important in regions with degraded riparian vegetation, where surface runoff flows unimpeded, increasing the likelihood of water pollution. It has been demonstrated in numerous studies that a comprehensive understanding of the characteristics of the FF can inform the design of effective stormwater treatment systems (Maniquiz-Redillas et al., 2022). By targeting the removal of pollutants from the initial runoff before it reaches receiving bodies, these systems can significantly reduce water pollution (Di Modugno et al., 2015; Maniquiz-Redillas et al., 2022).

The highest EMCs of suspended solids were observed during the rainfall event with the greatest peak flow, rainfall depth, and duration, highlighting the substantial sediment-loading capacity of intense events (Table 3) (Rodríguez-Blanco et al., 2019). A comparison between the EMCs of FSS and VSS indicated that the suspended solids present in the stream water during rainfall events were primarily non-volatile (inorganic). It suggests a link to erosive processes in the watershed area, where minerals from the sandy soil of the region – exposed due to the absence or reduction of riparian vegetation – are transported to the receiving watercourse. This process contributes to siltation and increases the frequency of floods, a common occurrence in the study area (Fava et al., 2019; Peres & Schenk, 2021). In addition, the FSS and VSS displayed similar M(V) curves across all four events, indicating that both exhibited consistent transport and accumulation patterns across the different rainfall events (Figure 3).

Regarding the exported mass of suspended solids in the stream during each monitored event (Table 3), the highest values were associated with more intense rainfall (Beckers et al., 2024). Rainfall duration also seems to be directly related to sediment export (Haddadchi & Hicks, 2020). In the rainfall event with the longest duration and highest height, exported TSS reached 8 tons. In addition to significantly contribute to river silting, these solids may also act as mobile substrates, facilitating the transportation of additional pollutants, such as heavy metals and hydrocarbons (Settle et al., 2007). Given their substantial quantity, they should be considered into urban (and rural) runoff management.

The potential role of riparian vegetation in protecting stream water quality during rainfall events

As we hypothesized, the monitored sections were predominantly classified as "impacted" based on the RAPs, regardless of season and stream margin (Table 1). Visible erosion along the stream banks, siltation of the streambed, and the limited extent and fragmentation of riparian vegetation in the highly urbanized area are key factors likely contributing to non-point source pollution from suspended solids during the lower-intensity rainfall events, as well as the elevated EMCs. For example, Righetto et al. (2017) reported TSS EMCs ranging from 16 to 130 mg L^{-1} in a small Brazilian urban catchment with low permeability (n = 9) and an area of 0.14 km^2, whereas the present study presented higher EMCs, ranging from 74 to 205 mg L^{-1} (Table 3). Supporting these findings, Haddadchi & Hicks (2020) identified that watershed size and land use predominantly influence suspended sediment generation during smaller and more frequent rainfall events. It is important to note that while the five assessed sections near the watershed outlet provide a representative overview, they do not fully account for the spatial variability of riparian vegetation effects on sediment dynamics across the entire watershed, representing a limitation of the present study. Although rural areas at higher elevations may contribute to sediment inputs into the stream, their riparian buffers were better preserved. The average (± standard deviation) riparian vegetation width in the

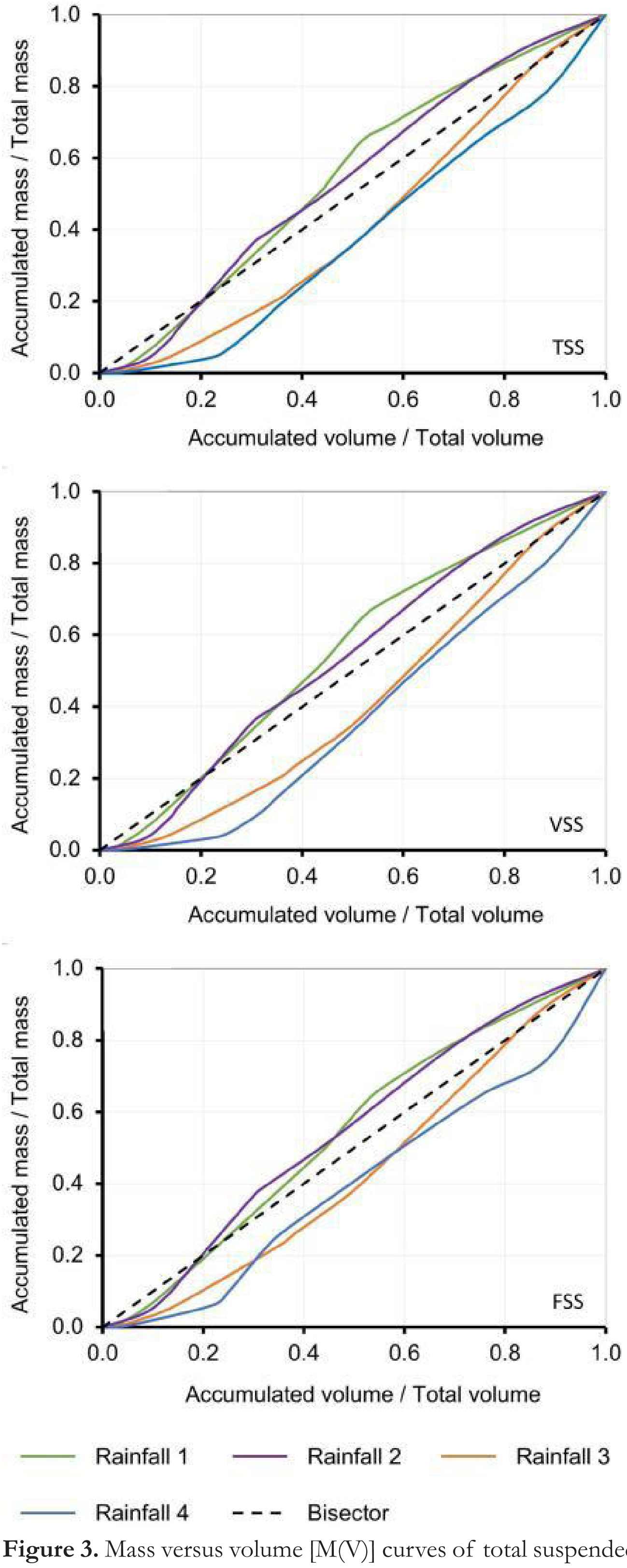

Figure 3. Mass versus volume [M(V)] curves of total suspended solids (TSS), volatile suspended solids (VSS), and fixed suspended solids (FSS) for the monitored rainfall events in the stream water.

studied urban stream reach was narrower than in the rural portion of the watershed (5.7 ± 2.0 m vs. 59.4 ± 32.9 m) (Supplementary Material, Figure S2). This contrast highlights the more degraded condition of riparian vegetation in the urban portion at lower watershed elevations. We acknowledge that a more comprehensive investigation across the watershed would be necessary to confirm the influence of degraded riparian vegetation in the predominantly urbanized portion of the watershed.

Riparian vegetation performs several critical environmental functions, such as stabilizing riverbanks through the development and maintenance of root networks that prevent erosion (Cicco & Arcova, 1999). Studies by Vigiak et al. (2016) and Martins et al. (2021) further emphasized the effectiveness of riparian vegetation in reducing sediment fluxes in river networks. Nevertheless, as also observed in our study, the absence of vegetation or insufficient width potentially increases soil loss due to water erosion, which can lead to reduced soil thickness, increased sediment deposition, diminished capacity to retain and redistribute water, and accelerated surface runoff (Santos et al., 2010). Moreover, the loss of important ecosystem services (e.g., flood buffering and the filtering of sediments and nutrients from the water) may occur in urban areas as a result of the riparian vegetation degradation (Giling et al., 2013; McTammany et al., 2007; Bega et al., 2024). If our studied urban stream reach had higher levels of riparian vegetation preservation, sediment inputs could be lower than obtained, particularly in lower intensity rainfall events and in the portion closer to the watershed outlet.

The erosion processes observed in the sections evaluated highlight the importance of riparian vegetation in protecting river water quality, especially during rainfall. In fact, the right bank of S3 exhibited no evidence of erosion in both periods. This section was composed primarily of bamboo (47.0%) and it had the second highest average DAP, indicating the presence of large trees (Table 2). In this context, the role of bamboo in mitigating erosion requires further discussion. *Bambusoideae* species are known for their adaptability to disturbed areas and, due to their rhizomes and underground stems, help contain slopes and reduce erosion. However, while the erosion control benefits of bamboo are well-documented, most of the identified species are non-native and largely of Asian origin. The introduction of invasive exotic species raises ecological concerns, as they can alter hydrological and nutrient cycles, outcompete native flora, and disrupt fauna-soil interactions by altering the composition and functioning of soil biota (Santos & Calafate, 2018; Silva et al., 2011). Indeed, there is a critical research gap regarding plant-soil interactions involving exotic *Bambusoideae* species (Calheiros et al., 2023). Understanding these interactions is important for assessing the long-term ecological consequences of using these species in restoration projects.

CONCLUSIONS

The absence of a proper riparian buffer near to the watershed outlet and within the urban area likely contributed to erosion, observed visually throughout the RAPs assessment, leading to sediment transport and deposition in the stream. Areas with grasses and exposed soil showed the most pronounced signs of erosion, while bamboo-dominated sections exhibited fewer signs of erosive processes, though its introduction requires further evaluation regarding potential ecological implications. Furthermore, non-point source pollution and the FF phenomenon occurred in half of the analyzed events, potentially highlighting the influence of fragmented riparian vegetation in exacerbating erosion and downstream siltation. Conservation measures are crucial to restoring riparian vegetation and mitigating these impacts.

Our research contributes to the ongoing and important debate on urban afforestation and the reforestation of riparian zones, supporting the development of strategies to mitigate non-point source pollution. Nevertheless, RAPs — being visual and qualitative in nature — are inherently subjective and results may vary depending on the observer's experience. Future research should incorporate advanced analytical tools and include paired watersheds studies in areas with varying riparian vegetation conditions, land use and land cover. At last, we reiterate that to gain a better understanding of the effects of riparian vegetation structure and conservation on sediment input to river systems during rainfall events, future studies should evaluate sections evenly distributed across the entire watershed.

ACKNOWLEDGEMENTS

Cecilia Loretti de Paiva thanks CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for the scientific initiation scholarship. João Miguel Merces Bega and Karen Tavares Zambrano are grateful to CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for their Ph.D. scholarships. Davi Gasparini Fernandes Cunha thanks FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) for financial support and CNPq for the research productivity grant.

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Authors contribution

Cecilia Loretti de Paiva: Study concept and design, acquisition of data, analysis and interpretation of data, and drafting of the manuscript.

João Miguel Merces Bega: Study concept and design, acquisition of data, analysis and interpretation of data, study supervision, and critical revision of the manuscript.

Karen Tavares Zambrano: Analysis and interpretation of data and critical revision of the manuscript.

Davi Gasparini Fernandes Cunha: Study concept and design, analysis and interpretation of data, study supervision, critical revision of the manuscript, and administrative, technical, and material support.

Editor-in-Chief: Adilson Pinheiro

Associated Editor: Mariana Madruga de Britor

SUPPLEMENTARY MATERIAL

Supplementary material accompanies this paper.

Supplemental Figure S1. Observations of significant erosion on the left bank of sections (A) 5 and (B) 2 (dry season) and on the right bank of section (C) 1 (rainy season), as well as the size of trees on the left bank of sections (D) 5 and (E) 2, and (F) the presence of bamboo on the right bank of section 3

Supplemental Figure S2. Delimitation of riparian vegetation throughout the entire drainage network of the studied watershed

This material is available as part of the online article from https://doi.org/10.1590/2318-0331.302520240123