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Research Article

River geometry responses resulting from hydrological changes in a partially urbanized watershed: an experimental study in Southern Brazil

Alterações na geometria fluvial decorrentes das mudanças hidrológicas em bacia hidrográfica parcialmente urbanizada: estudo experimental no Sul do Brasil

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Abstract: Impervious surfaces resulting from urbanization can increase peak flow magnitudes and affect the physical integrity of rivers, leading to alterations in channel morphometric parameters. This study investigates the relationship between cross-sectional morphometry and both drainage area size and the proportion of impervious surfaces. Ten cross-sections were analyzed within the Maringá Stream watershed, located in southern Brazil. This watershed, the largest in the municipality of Maringá (~90 km²), encompasses both urban and rural drainage areas. Morphometric parameters were obtained through field surveys, and geoprocessing techniques were employed to quantify drainage area size and impervious surface ratio. Significant univariate relationships were identified only between the width-to-depth ratio and depth, respectively, with drainage area size and impervious surface ratio. Multiple regression analysis demonstrated that width, channel capacity, and hydraulic radius had statistically significant coefficients with both explanatory variables. The findings suggest that the impervious surface ratio strongly influences fluvial morphometry, although hydraulic geometry is primarily governed by the combined effects of urbanization and drainage area size.

Keywords: Fluvial morphometry; Urban rivers; Impervious; Hydraulic geometry.

Resumo: A impermeabilização decorrente da urbanização pode aumentar a magnitude das vazões máximas e comprometer a integridade física dos rios, modificando os parâmetros morfométricos dos canais fluviais. Este estudo analisou a relação entre os parâmetros morfométricos de seções transversais, o tamanho das áreas de drenagem e a taxa de impermeabilização. Foram avaliadas 10 seções transversais da bacia hidrográfica do ribeirão Maringá, localizada no município de Maringá, sul do Brasil. Essa bacia é a maior do município (~90 km²) e abrange áreas de drenagem urbanas e rurais. Os parâmetros morfométricos foram obtidos por meio de levantamentos de campo, enquanto o tamanho e a taxa de impermeabilização das áreas de drenagem foram determinados com técnicas de geoprocessamento. Relações univariadas significativas foram identificadas entre a razão largura/profundidade e a profundidade, em função da área de drenagem e da taxa de impermeabilização. A análise de regressão múltipla indicou que a largura, a capacidade do canal e o raio hidráulico apresentaram coeficientes estatisticamente significativos com a área de drenagem e a taxa de impermeabilização. Os resultados indicam que a fração impermeável exerce influência relevante sobre a morfometria fluvial, embora a geometria hidráulica seja majoritariamente condicionada pela interação entre os efeitos da urbanização e o tamanho da área de drenagem.

Palavras-chave: Morfometria fluvial; Rios urbanos; Impermeabilização; Geometria Hidráulica.

1. Introduction

Materials commonly used in urban construction, such as building roofs, paved roads, and sidewalks, tend to render surfaces impermeable. Even some permeable surfaces in urban environments, such as exposed soils and lawns, may exhibit reduced infiltration capacity due to compaction of their upper soil layers. This condition significantly reduces infiltration at the watershed scale while increasing surface runoff (Tucci, 2001). These changes also alter hydrological processes, including reduced recharge of local unconfined aquifers and modifications to the hydrograph of the drainage system receiving the excess runoff, when compared to pre-urbanization conditions (Leopold, 1911; Chin, Gregory, and O'Dowd, 2020). Consequently, hydrographs tend to display flood peaks with higher magnitude and earlier occurrence (Stevaux and Latrubesse, 2017). For instance, Chin, Gregory, and O'Dowd (2020) report peak flows in urban areas that are two to four times greater, while Tucci (2001) indicates increases of up to six times relative to pre-urbanization levels. These processes intensify flood events, resulting in economic and social impacts.

Increased fluvial erosion is another process associated with urban expansion (Wolman, 1967; Hammer, 1972; Chin, 2006; Chin, Gregory, and O'Dowd, 2020). Channel dimensions and shape typically adjust to flow regimes (Fracassi, 2017; Stevaux and Latrubesse, 2017); therefore, significant changes in discharge tend to induce morphological adjustments in fluvial channels (Fracassi, 2017). One of the earliest studies to model the geomorphic response of fluvial channels to urbanization was conducted by Hammer (1972). Hydrological alterations caused by urbanization lead to geomorphological changes (Wolman, 1967; Gregory, 2006; Morais; Montanher, 2022), among which erosion is a predominant process (Fracassi, 2017). Erosion processes are generally concentrated in urbanized zones, while other forms of channel adjustment are more common downstream (Montanher, 2010; Montanher, 2013).

Hammer (1972) analyzed 78 watersheds near Philadelphia, USA, ranging in size from 2.6 to 15.5 km². For each watershed, a channel cross-section was surveyed, and drainage area, land use (including agricultural, forested, and both new and old residential areas), channel slope, watershed shape, and soil permeability were documented.

Hammer's (1972) empirical analysis applied a multiple regression model in which the response variable was channel capacity—defined as the cross-sectional area at bankfull stage (Stevaux; Latrubesse, 2017)—normalized by drainage area. Predictor variables included land use, slope, watershed shape, and soil permeability. The model explained 96.29% of the variation in cross-sectional geomorphology, with ten significant predictors, seven of which were related to land use.

The present study collected data from river channel cross-sections and land use and land cover across a watershed encompassing urban and rural areas in the municipality of Maringá, located in the northern region of Paraná State, in Southern Brazil. The objective was to assess the relationship between morphometric characteristics of the cross-sections and urbanization patterns within the watershed. The analysis draws on the conceptual framework established by Hammer (1972).

2. Study Area

The Maringá Stream watershed is located in the northern region of Maringá and is a tributary of the Pirapó River, which in turn flows into the Paranapanema River, a tributary of the Paraná River. Most headwater areas are situated in the urbanized portion, while the middle and lower reaches of the watershed are predominantly rural (Figure 1). Land use and land cover in the rural area consist primarily of temporary crops such as soybean and maize, with smaller proportions of forest and pasture. The climate in the region is transitional between subtropical and tropical, with average precipitation exceeding 150 mm·month^{-1} during December and February, and above 50 mm·month^{-1} in July and August (Montanher; Minaki, 2020).

The watershed is largely underlain by Mesozoic basaltic rock (Sala, 2005; Amaral, 2018), which supports convex and rectilinear slopes with low dissection, contributing to the development of V-shaped valleys. These features are classified within the morphostructural subunits of the Maringá and Campo Mourão plateaus (Santos et al., 2006). According to the digital landform classification for the state of Paraná, the relief within the Maringá watershed is predominantly characterized by hills, particularly gentle hills in the upper portion and a limited occurrence of undulating hills in the southern sector (Silveira et al., 2025). This variation in hill morphology reflects differences in slope steepness and local elevation range, which may influence erosional dynamics and the spatial distribution of urban expansion.

The dominant soil types are Red Latosols and Red Nitosols. Red Latosols are deep, porous soils well suited to mechanized agriculture, while Red Nitosols are clayey to very clayey. The latter, found in more dissected terrain, presents a higher susceptibility to erosion (Santos; Zaroni, 2021; Santos, Zaroni, and Almeida, 2021).

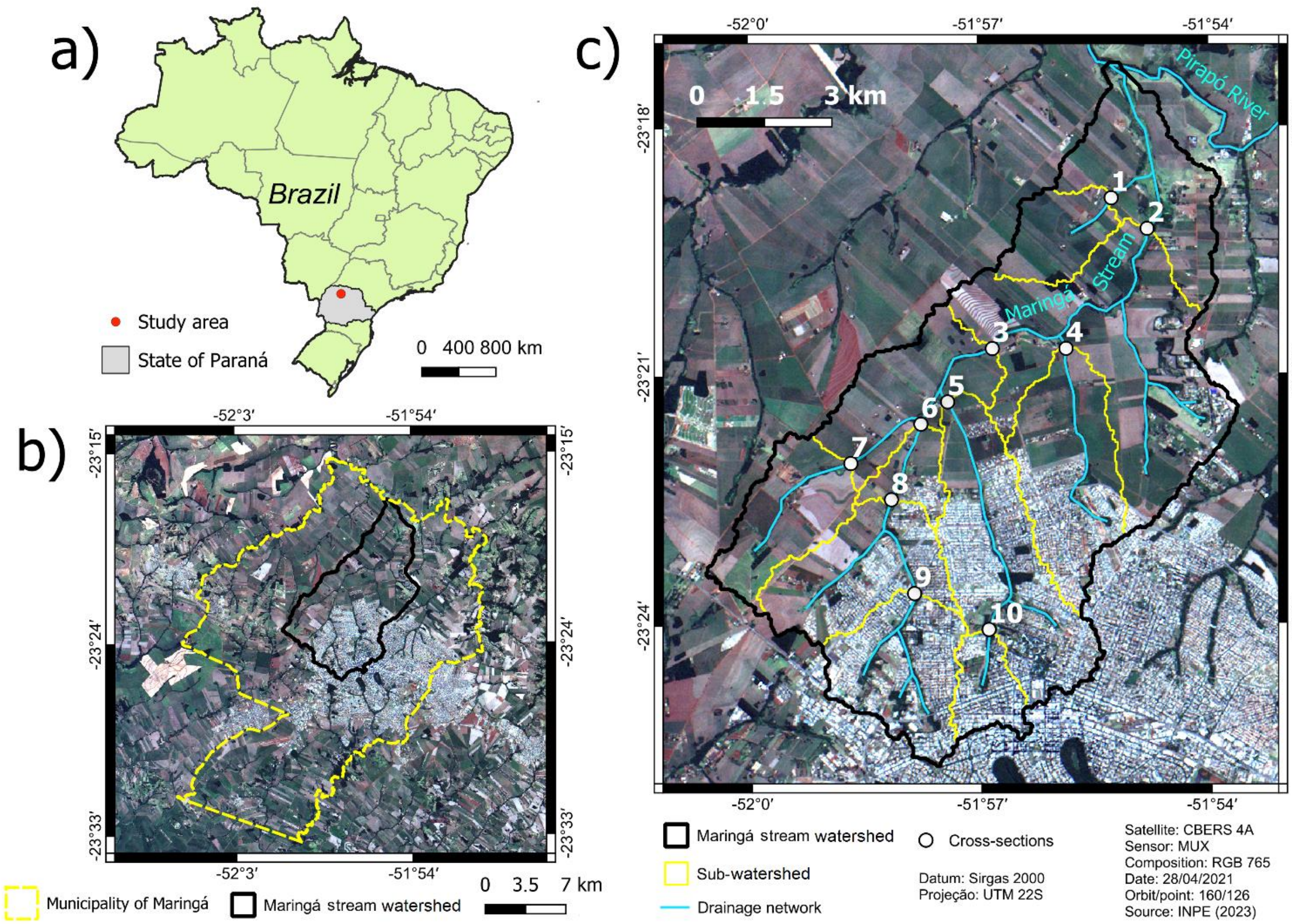

Figure 1. a) Location of the study area and the state of Paraná in the context of Brazil; b) Location of the Maringá stream watershed in the municipal context; c) Location of field data collection points and their drainage areas.

3. Materials and Methods

3.1. Definition of variables and field data collection

Ten locations were selected along the Maringá Stream watershed for cross-section surveys, and their respective drainage areas were delineated (Figure 1C). The distribution of these points was strategically planned to capture variations in drainage area size across the upper, middle, and lower sectors of the watershed, as well as differing degrees of urbanization (Figure 1).

In this study, in addition to channel capacity—as evaluated by Hammer (1972)—other morphometric variables were analyzed as potential response variables to two predictors: the drainage area associated with each cross-section and the proportion of impervious surface within those areas. Table 1 provides a summary of the variables analyzed.

Table 1. Summary of variables evaluated.

Variables	Unit	Nature
Width (W)	m	Response
Maximum depth (D_{max})	m	Response
Mean depth (D_{mean})	m	Response
Channel capacity (C)	m²	Response
Hydraulic radius (H_R)	m	Response
Ratio W/D_{max}	adm.	Response
Ratio W/D_{mean}	adm.	Response
Watershed area (A)	Km²	Predictor
Impervious ratio of the watershed (I)	%	Predictor

The field survey of morphometric variables was conducted through the following procedures: (1) placing stakes on both banks at each selected point, perpendicular to the longitudinal axis of the channel; (2) securing a rope between the stakes, marked at 50 cm intervals; and (3) measuring depth relative to the riverbed or banks using a leveling rod at 50 cm intervals. For each site, the positions of the left and right banks, as well as the date and time of the survey, were recorded.

It is important to note that the survey covered not only the wetted cross-section but the entire area defining channel capacity at the bankfull stage. Therefore, stake placement was guided by an interpretation of the geometric characteristics of each section, as illustrated in Figure 2.

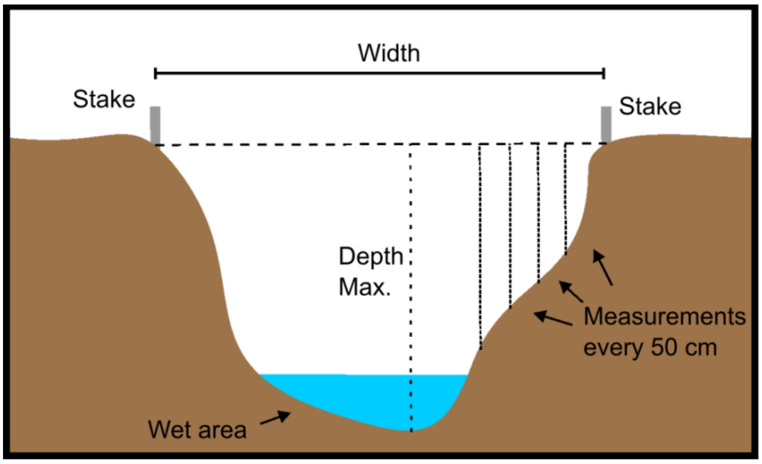

Figure 2. Illustrative representation of the cross-section survey.

Width (W) is defined as the linear distance between the stakes placed on both banks of the cross-section. Maximum depth (D_{max}) corresponds to the greatest vertical distance between the stretched rope and the channel bed or banks, including areas beyond the wetted section. Channel capacity refers to the total area of the polygon formed between the rope and the channel surface.

The hydraulic radius is calculated as the ratio between channel capacity and the wetted perimeter, the latter representing the length of the contact interface between the water and the channel surface. This parameter is essential for understanding fluvial dynamics, as it quantifies the relationship between the cross-sectional area and the wetted perimeter, thereby reflecting the frictional resistance affecting flow efficiency (Stevaux; Latrubesse, 2017).

The width-to-depth (W/D) ratio was calculated using both the mean depth (W/D_{mean}) and the maximum depth (W/D_{max}), with both values expressed as dimensionless quantities. This normalized variable was used to indicate the extent of bed lowering due to erosion at each section, relative to channels of varying sizes.

3.2 Mapping of sub-watershed and impervious areas

To delineate the drainage areas associated with each cross-section, or sub-watersheds, the SRTM DEM with 30 m spatial resolution (NASA, 2024) was used as the base dataset. This DEM was processed using the *r.watershed* algorithm (GRASS GIS, 2024a) to generate a raster file containing drainage directions. Subsequently, the *r.water.outlet* algorithm (GRASS GIS, 2024b) was applied to the drainage direction file, using field-collected coordinates for each point to delineate the corresponding drainage area.

To determine the proportion of impervious surfaces in each sub-watershed, a supervised classification using the maximum likelihood method was performed, with two defined classes: permeable and impervious areas. The term "urban area" was deliberately avoided as a synonym for "impervious area" due to its legal implications (e.g., urban perimeter) that do not necessarily reflect hydrological dynamics. For instance, urban zones may contain permeable features such as lawns, parks, and protected areas. During the classification training process, samples representing impervious areas included paved roads, residential buildings, structures of varying sizes, sheds, and similar features.

The imagery used for classification was acquired by the CBERS-4A satellite (WPM sensor) on 05/14/2023, orbit-point 210/142 (INPE, 2023). This sensor provides four multispectral bands at 8 m spatial resolution and one panchromatic band at 2 m resolution. A pansharpening procedure was conducted to generate a multispectral dataset with a modeled spatial resolution of 2 m. In the mapping of impervious areas, exposed soils were initially classified as impervious due to their spectral similarity—particularly in visible bands—to ceramic-tiled residential roofs. The sensor's limited spectral resolution limited the ability to address this issue automatically. However, manual corrections were applied, which was feasible given the relatively small extent of the study area.

3.3 Modeling

This study adopted a variation of Hammer's (1972) approach, which, as outlined in the introduction, demonstrated effectiveness in modeling the erosive response of river channels to urbanization. However, a known limitation of empirical modeling is its often-restricted generalizability, as models may only be applicable to landscapes similar to those in which they were developed (Bokulich; Oreskes, 2017). Consequently, Hammer's (1972) model would likely yield unreliable results for watersheds characterized by different climatic, geological, geomorphological, land use, and infrastructure conditions. For this reason, local data collection and context-specific statistical modeling were required for the present study.

Prior to modeling, an exploratory data analysis was conducted. Scatter plots were generated for each pair of predictor and response variables to evaluate the nature of potential relationships (linear or non-linear). Selected plots are presented and discussed in this article. Following the exploratory analysis, multiple regression analysis was performed (Rogerson, 2012), using watershed area and the proportion of impervious surfaces (Table 1) as predictor variables for seven cross-sectional parameters. Model performance was evaluated through the adjusted R^2, the overall model p-value, the statistical significance of each independent variable, and residual distribution.

4. Results and Discussion

A total of 25.34 km² of impervious surfaces were mapped on May 14, 2023, using the CBERS-4A image (Figure 3), representing 28.3% of the watershed. The urban area is primarily concentrated in the central-southern portion of the watershed, with some isolated developments in the eastern sector. As a result, certain delineated sub-watersheds exhibit high proportions of impervious surfaces (points 5, 6, 8, 9, and 10), while others, such as point 1, contain no impervious areas, and point 7 has very limited coverage (Table 2).

Regarding spatial extent, point 2 encompasses a substantial portion of the Maringá Stream watershed, whereas others, such as points 1, 7, and 10, include only first-order sub-watersheds.

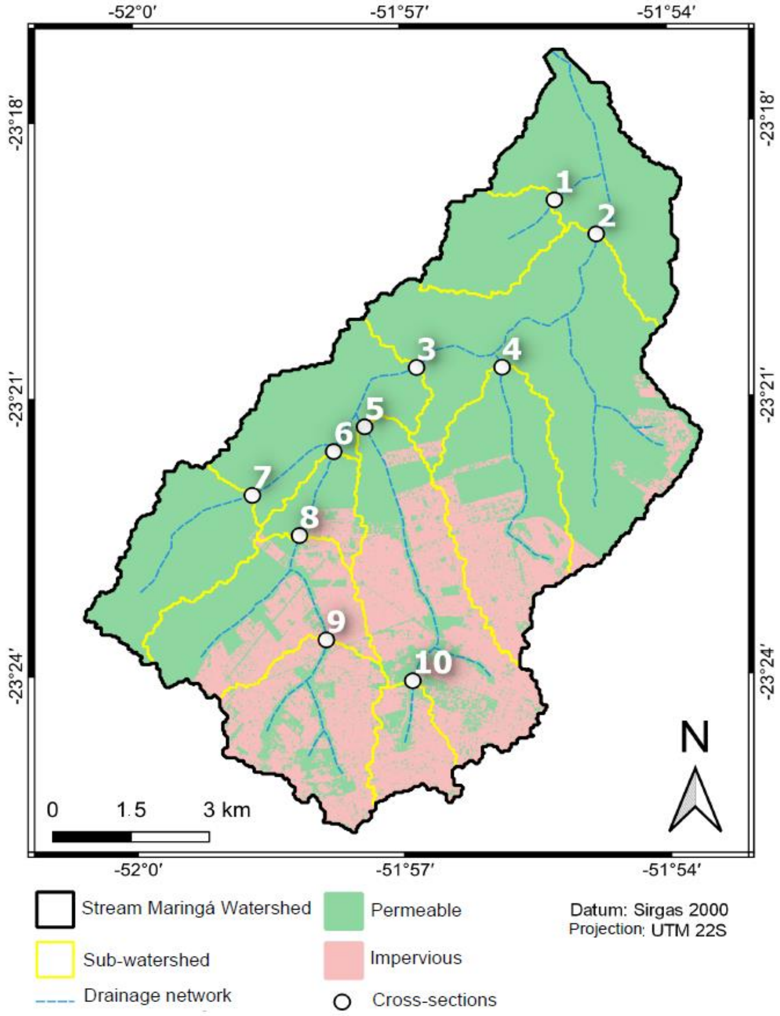

Figure 3. Permeable and impervious areas of the Maringá stream watershed, 2024.

Table 2. Morphometric and spatial data of all cross-sections, 2024.

Section	W(m)	D_{max} (m)	D_{mean} (m)	C (m^2)	H_R (m)	W/D_{mean}	W/D_{max}	A(km^2)	I (%)
1	5	1.4	1.08	5.40	0.84	4.63	3.57	3.96	0.00
2	15	2.5	1.98	29.65	1.67	7.59	6.00	76.76	33.02
3	16	3.59	2.60	41.58	2.16	6.16	4.46	47.85	42.00
4	10.08	3.3	2.19	22.09	1.66	4.60	3.05	9.65	42.62
5	10	3.5	2.20	22.00	1.65	4.55	2.86	15.39	66.41
6	13.5	2.53	2.05	27.70	1.73	6.58	5.34	18.45	53.48
7	3	1.05	0.82	2.47	0.60	3.64	2.86	6.44	0.19
8	14	3.15	2.15	30.08	1.79	6.52	4.44	16.05	57.75
9	11.1	2.92	1.99	22.11	1.60	5.57	3.80	7.88	70.77
10	12.5	3.94	2.34	29.26	1.81	5.34	3.17	2.87	77.45
Min.	3.00	1.05	0.82	2.47	0.60	3.64	2.86	2.87	0.00
Mean	11.02	2.79	1.94	23.23	1.55	5.52	3.96	20.53	44.37
Max.	16.00	3.94	2.60	41.58	2.16	7.59	6.00	76.76	77.45

The exploratory analysis of the relationship between sub-watersheds and morphometric variables (Figure 4) identified two sets of variables that appear to exhibit sensitivity to variations in drainage area. Width and channel capacity tend to increase non-linearly (logarithmically) with drainage area. As larger drainage areas generate greater channel flow, it is expected that channels adjust by expanding in both width and capacity. However, the R^2 values indicate limited explanatory power (R^2 = 0.36 and 0.42). This limitation may be associated with two outliers located in the lower-left region of the plots, corresponding to the rural sub-watersheds at points 1 and 7. These points form a distinct cluster in the graphs for mean and maximum depth, as well as hydraulic radius.

The width-to-depth ratio appears to be the only morphometric variable that responds directly to variations in drainage area, displaying a linear increase. This pattern reflects the tendency for greater fluvial incision in the upper course due to higher channel power. In contrast, in the lower course, although discharge is greater, reduced slope decreases longitudinal connectivity and promotes sediment deposition on the riverbed. Consequently, as transport capacity declines along the river network, the predominant incision process is gradually replaced by lateral erosion, which increases channel width in the downstream reaches.

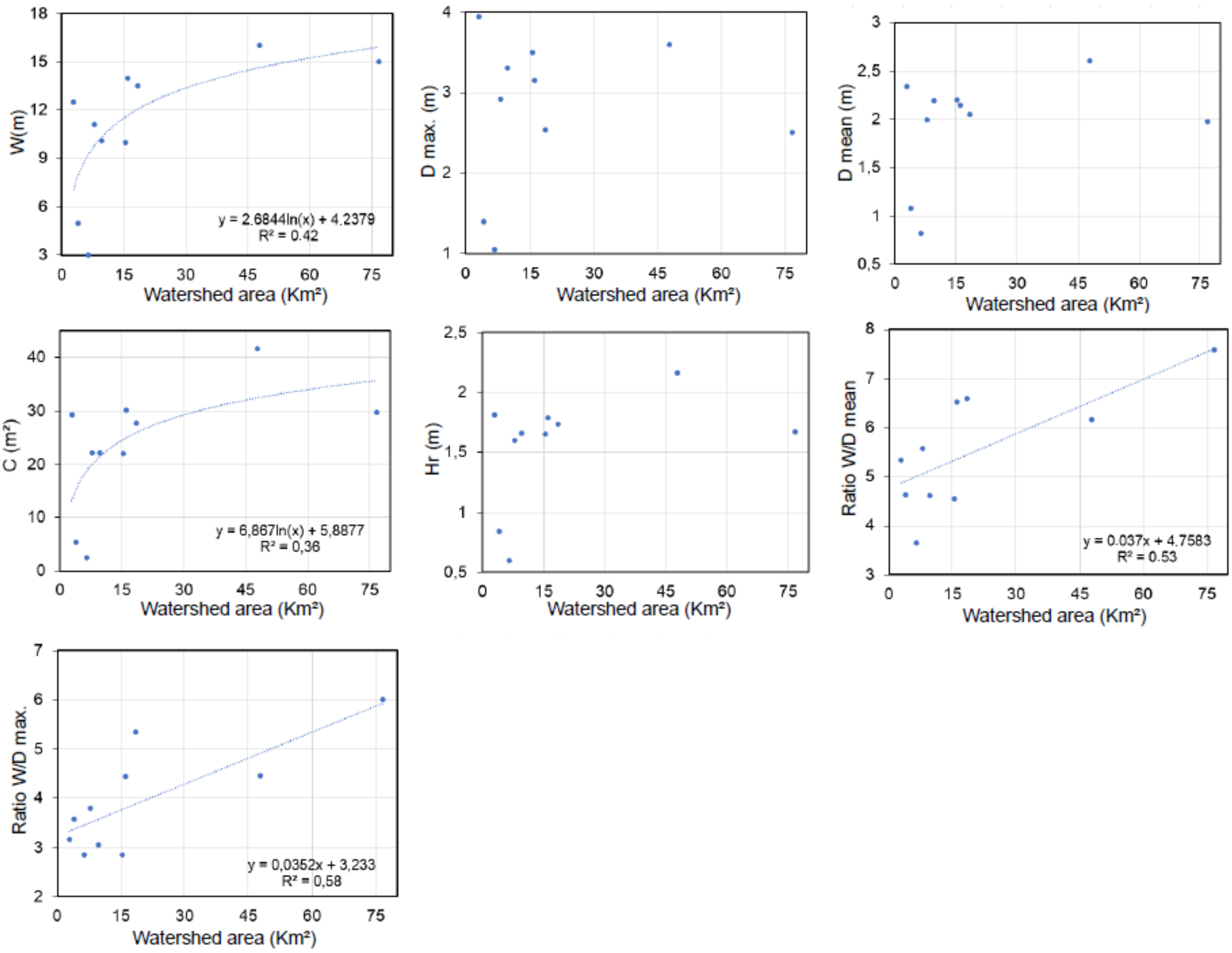

Figure 4. Scatter plots between the area of each sub-watershed and the morphometric variables of the cross-sections.

The exploratory analysis of the relationship between morphometric variables and the proportion of impervious surfaces in the sub-watersheds (Figure 5) revealed a potential linear relationship between section depth and impervious area, with maximum depth exhibiting the strongest response. As the proportion of impervious surfaces increases, stormwater concentration intensifies, thereby enhancing the potential for fluvial incision. Channel depth, as a response to impervious surface expansion, underscores the positive feedback associated with urbanization in the upper course, where incision is already expected and becomes further accentuated. This pattern is particularly evident in the absence of adequate stormwater retention and dissipation structures, which increases channel power.

However, studies on sandy and gravel-bed rivers in California have demonstrated a significant correlation between the percentage of impervious surfaces and both bankfull width and channel capacity, with the latter being especially predictable based on impervious surface coverage (Taniguchi; Biggs, 2015). In contrast, tropical rivers with steep gradients and gravel beds have shown resilience to changes in channel width and capacity in response to increasing imperviousness (Phillips; Scatena, 2013). Based on these findings, the authors argue that assessments of urbanization impacts in humid tropical regions should not rely on evidence from temperate climates.

Nevertheless, geomorphological and pedological characteristics of the watershed appear to exert a more significant influence on channel morphological changes than climatic conditions alone. This interpretation is supported by Jeje and Ikeazota (2002), who observed low rates of channel widening under urbanization in Nigeria, suggesting that fluvial responses are largely determined by local environmental factors rather than exhibiting uniform behavior across humid tropical rivers.

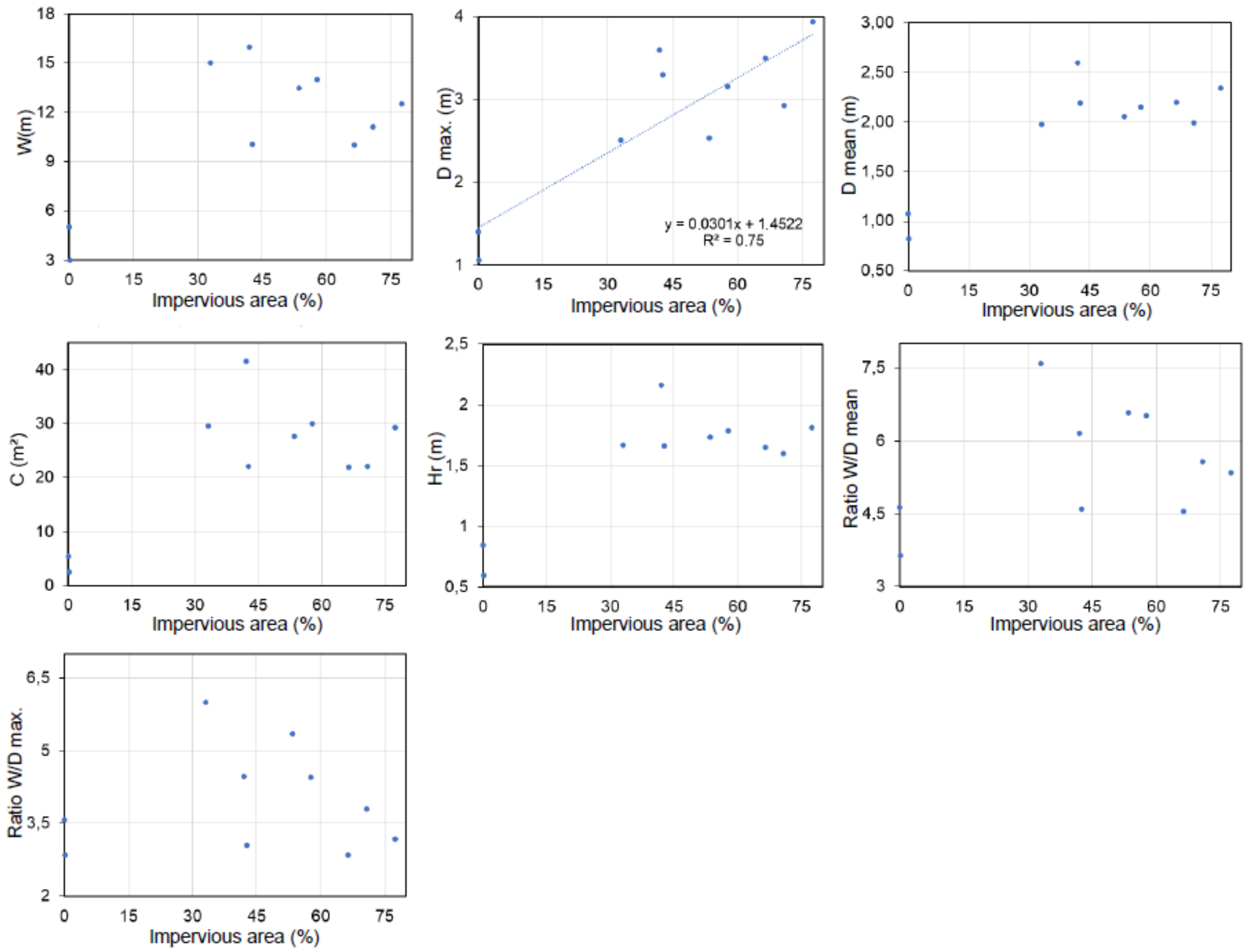

Figure 5. Scatter plots between the proportion of impervious areas in each sub-watershed and the morphometric variables of the cross-sections.

For the other variables, no direct relationship was identified with the proportion of impervious surfaces in the sub-watersheds. A comparison between the cross-sectional profiles of two first-order sub-watersheds (points 1 and 10), which have similar drainage areas (Figure 6), indicates that urban impermeability significantly increases channel width and capacity. By comparing sub-watersheds with similar drainage conditions—urban (points 9 and 10) and rural (points 1 and 7)—it was possible to evaluate differences in channel width. This analysis showed that channel width in urban drainage areas is, on average, 3.1 times greater than in rural areas—a ratio that exceeds the global average of 2.5 reported by Chin (2006).

However, it is important to emphasize that this average value is based on only two pairs of urban and rural sub-watersheds, with one pair matching the global mean. Additionally, channel cross-sectional area is expected to vary with drainage area due to increased discharge. Considering this context—in which both drainage area and impervious surface proportion may jointly explain variation in a single response variable—multiple regression analysis was applied. All previously described response variables were tested in relation to both predictor variables: drainage area and impervious surface proportion (Table 3).

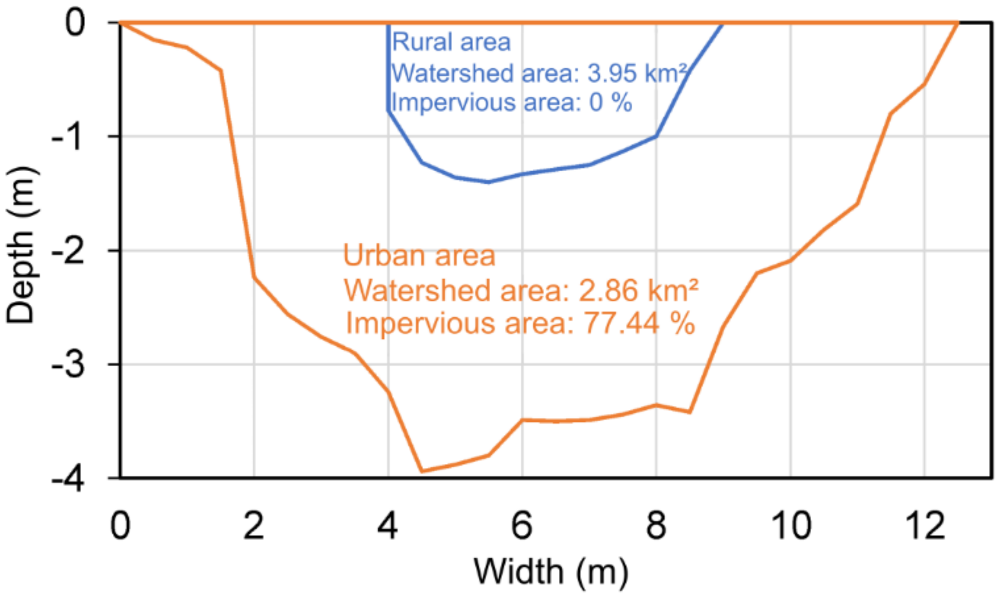

Figure 6. Cross-sections of drainage areas with rural occupation a point 1(blue) and urban occupation at point 10 (orange). Note that, despite having similar drainage areas, the channel capacity is 5.4 times larger in the urban area than in the rural area.

Table 3 presents only the results for which both predictor variables were statistically significant (p-value < 0.05). All slope coefficients were positive, indicating that section width, channel capacity, and hydraulic radius increase in proportion to both drainage area and the proportion of impervious surfaces in the sub-watershed. Notably, no clear univariate relationship was identified for these three response variables (Figures 4 and 5), suggesting that the interaction between the two predictors introduces additional complexity to the system's behavior.

Table 3. Multiple regression analysis results, 2024

Variable	Intercept	Watershed area		Impervious proport.		R^2	Adj. R^2	p-value (F)
		slope	p-value	slope	p-value			
W (m)	3.845	0.1173	0.0036	0.1073	0.0028	0.83	0.79	0.0017
C (m^2)	3.798	0.2924	0.0134	0.3026	0.0059	0.77	0.71	0.0053
H_R (m)	0.745	0.0092	0.0285	0.0138	0.0021	0.8	0.74	0.0035

Section width and channel capacity are correlated variables, and the finding that both vary proportionally with watershed area and the percentage of impervious surfaces is expected. A larger watershed area results in greater discharge, while impervious surfaces amplify flood peaks. Together, these factors drive channel adjustments, leading to increased width and cross-sectional area.

Of particular interest is the result concerning the hydraulic radius, which serves as an indicator of shear stress (Wei et al., 2023) and is more strongly associated with sediment transport than with flow velocity (Rocha, 2016). Variations observed in the analyzed sections suggest that channel morphology adjusts to improve flow efficiency as discharge and flood peaks increase due to urbanization.

A similar study conducted in a Nigerian city found no relationship between hydraulic radius and drainage area in urbanized regions (Jeje; Ikeazota, 2002). In contrast, the present study highlights that, through a bivariate analysis, the effects of urbanization—when considered jointly with drainage area—more explicitly influence channel geometry, indicating that such impacts extend throughout the drainage network and enhance flow efficiency.

5. Conclusions

This study evaluated the potential association between cross-sectional morphometric parameters, drainage area size, and the proportion of impervious surfaces in a watershed located in the municipality of Maringá, southern Brazil. The results indicated that: (i) the ratio of mean section width between urban and rural drainage areas exceeds the global average; (ii) a relationship exists between the width-to-depth ratio and drainage area, as well as between maximum depth and the proportion of impervious surfaces; and (iii) multiple regression analysis, using drainage area and impervious surface ratio as independent variables, revealed statistically significant relationships with section width, channel capacity, and, most notably, hydraulic radius. These findings demonstrate a strong influence of urbanization on hydraulic geometry, shaped by interactions between physical watershed characteristics and land-use changes along the channel network.

Author's Contributions: O.C.M.: Conceptualization, Data curation, Methodology, Formal analysis, Writing – original draft. E.S.M.: Writing – review & editing, Formal analysis, Investigation. B.C.S.M.: Writing – review & editing, Formal analysis.

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