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MORPHOMETRIC ANALYSIS OF THE CORUMBATAÍ RIVER BASIN - SP, BRAZIL: SUPPORTING ENVIRONMENTAL PLANNING

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Abstract: A detailed study of watersheds is essential for environmental and territorial planning, as well as for the sustainable management of water resources. In this context, morphometric analysis is an effective tool for identifying a basin's predisposition to erosion and flooding processes. This study presents a morphometric analysis of the Corumbataí River Basin, located in the center-east region of São Paulo State, Brazil. The basin supplies nine municipalities and holds strategic importance due to intensive agricultural, industrial, and urban activities. Dimensional parameters, drainage patterns, and relief characteristics were analyzed using SRTM data and Geographic Information Systems (GIS) tools. The results indicate a low propensity for flooding, moderately dissected relief, and low drainage density, which point to limited water availability. The roughness coefficient identified areas with high susceptibility to erosion, in contrast with the current land use, which is predominantly characterized by sugarcane cultivation and clay mining. Morphometric analysis proved to be effective in identifying environmental vulnerabilities and providing valuable support for the development of land-use and conservation policies that are more compatible with the basin's natural characteristics, reinforcing its potential as a tool for integrated environmental planning.

Keywords – morphometric analysis; Corumbataí River Basin; environmental planning

INTRODUCTION

Water is a fundamental resource for sustaining life and supporting human activities, with its global volume remaining virtually constant since the formation of the planet, changing only in its physical state through the hydrological cycle (Tundisi, 2009; Machado & Torres, 2012). However, water resource management has faced significant challenges, often marked by ineffective models disconnected from environmental preservation, leading to high social, economic, and ecological costs.

The intensification of the water crisis observed in recent decades is linked to population growth, urban concentration, and the intensive use of water across multiple sectors, resulting in reduced availability, especially in naturally scarce regions. In Brazil, the National Water Resources Policy defines water as a public good with economic value, prioritizing human consumption and animal watering in times of scarcity, thus reinforcing the importance of integrated and efficient water resource management.

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In this context, the watershed has become a key unit for environmental planning and management, as supported by various authors (Rodrigues & Adami, 2005; Coelho Netto, 2007; Silveira, 2009) and international frameworks such as the European Charter for Water (Council of Europe, 1968). Due to its physical characteristics, the watershed serves as a functional unit for analyzing hydrological dynamics and the impacts of land use and occupation.

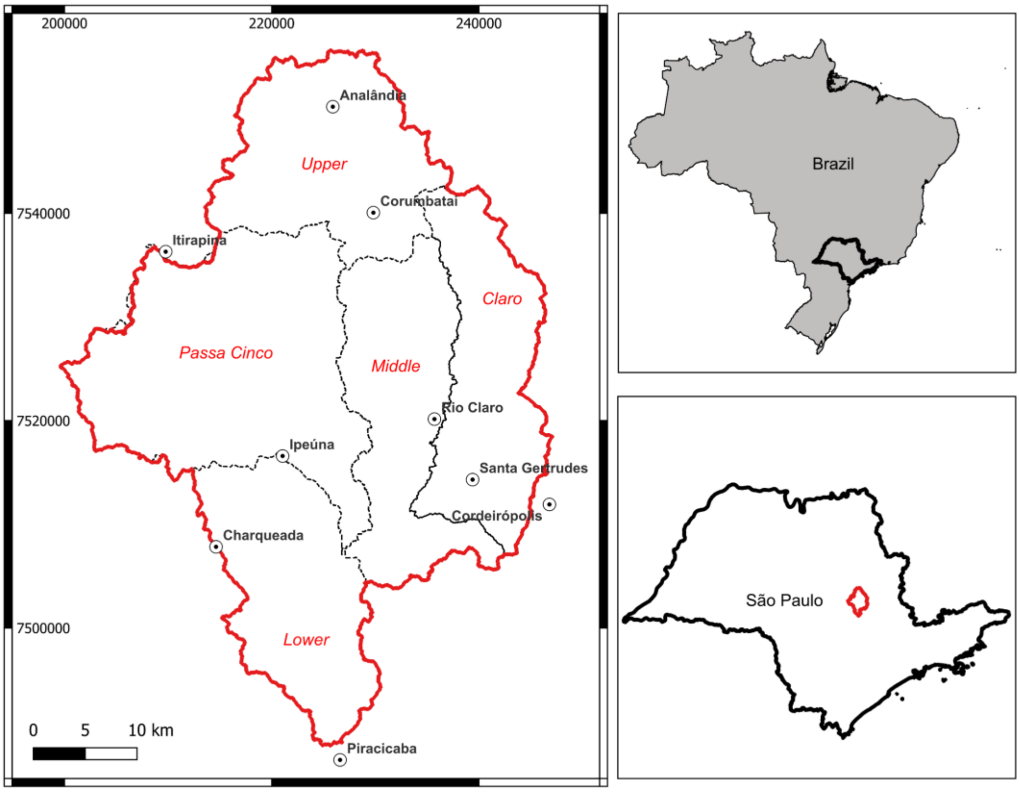
Morphometric analysis, by considering parameters such as relief, drainage patterns, and spatial dimensions, allows for the assessment of a basin's susceptibility to erosion, flooding, and environmental degradation, serving as a valuable tool to support territorial planning and water resource conservation (Christofoletti, 1980).

Given this context, the present study aims to perform a morphometric characterization of the Corumbataí River Basin and its sub-basins to understand their vulnerabilities and potentials within the scope of water resource management, especially considering the basin's strategic role in public water supply and productive activities in the center-east region of São Paulo State.

METODOLOGY

The Corumbataí River Basin was selected for this study due to its regional importance. It is in the center-east portion of São Paulo State and encompasses nine municipalities (Figure 1), forming one of the seven sub-basins that make up the Piracicaba, Capivari, and Jundiaí (PCJ) River Basins. Its main watercourse plays a vital role in supplying major urban centers such as Piracicaba and Rio Claro, highlighting its socioeconomic relevance in the context of regional agricultural and industrial development. According to IBGE (2022), the total population of the municipalities within the basin was 720,164 inhabitants. When considering only the area within the physical boundaries of the basin, the recalculated population is approximately 300,000, predominantly urban.

Figure 1 - Location of the Corumbataí River Basin and its sub-basins in the State of São Paulo, Brazil.



The main access to the region is via the Washington Luís (SP-310), which connects with the Anhanguera (SP-330) and Bandeirantes (SP-348) highways, providing direct access to São Paulo (the state capital). The basin is also served by a secondary road network consisting of state highways and rural roads that connect municipal centers. These roads are essential for transporting agricultural products and clay extracted for the Santa Gertrudes Ceramic Pole. However, most of these roads lack proper drainage infrastructure, which increases erosion along the road shoulders and contributes to the sedimentation of water bodies (Fundação Agência das Bacias PCJ, 2019).

The Corumbataí River Basin has a diversified economic history, initially influenced by the gold cycle and later boosted by the arrival of railways in the 19th century. Over time, the region consolidated key activities such as livestock farming, timber extraction, and the cultivation of coffee, oranges, and sugarcane, alongside growing industrial development. According to FUNDAÇÃO SEADE (2019), the basin's municipalities generated a GDP of R$ 45.4 billion, with Piracicaba contributing around 60%. The economy is mainly driven by the services sector (including public administration) and industry.

The region's predominant climate is humid subtropical, with an average annual precipitation of 1,400 mm and a dry season from April to September, according to the Köppen-Geiger (1930) classification. Altitudinal variation results in three distinct climate zones within the basin: subtropical without dry season and mild summer (Cfb); subtropical with dry winter and hot summer (Cwa); and subtropical with dry winter and mild summer (Cwb).

The Corumbataí River, the main tributary of the Piracicaba River, originates in the municipality of Analândia at an altitude of 1.058 m and flows into the Piracicaba River at the Santa Terezinha neighborhood at 470 m. Its main tributaries are the Passa Cinco River and the Claro Stream, the latter accounting for approximately 40% of Rio Claro's public water supply. The current division of the basin includes five sub-basins, as defined in the PCJ Basin Plan 2020–2030 (Figure 1).

Geologically, the area belongs to the Paraná Basin, which is characterized by sedimentary and volcanic formations. The Corumbataí and Pirambóia Formations account for more than 60% of the outcropping units and form the basis of the local relief, which includes hills, ridges, and alluvial plains, with elevations ranging from 460 to 1.070 meters and slopes below 2% in 40% of the basin area (Zaine, 2000).

Soil coverage is predominantly composed of Argisols, Latosols, and Neosols, with anthropogenic soils occurring in urban areas. The remaining native vegetation is limited, with only 22.7% of the basin area covered by fragments of Atlantic Forest (7.5%) and Cerrado (15.2%) biomes, concentrated in steep areas and riparian zones (Fundação Agência das Bacias PCJ, 2019).

Morphometric analysis is an essential tool for assessing the environmental vulnerability of watersheds and is widely used as an indicator of degradation and a support instrument for water resources management (Machado & Torres, 2012). In this study, the analysis was conducted using two complementary approaches: a segmented analysis, considering each sub-basin individually, and an integrated analysis encompassing the entire Corumbataí River Basin. This comparative approach allows for the evaluation of spatial heterogeneity related to land use and land cover across different sectors of the basin.

The adopted methodology follows the framework proposed by Christofoletti (1980), also supported by the foundational works of Horton (1945), Strahler (1957), and other classical authors. The analyzed parameters were grouped into three main categories: dimensional, drainage pattern, and relief metrics (Table 1). Initially, the drainage network hierarchy was established based on the

Strahler system (1957), in which first-order streams are those without tributaries, and the confluence of two streams of the same order generates a stream of the next higher order.

Table 1 - Morphometric parameters evaluated in the analysis of the Corumbataí River Basin and its sub-basins.

Aspects	Parameters	Methods and descriptions		References
Dimensional	Area (A)		Total area drained by the entire fluvial system, projected on a horizontal plane (km²).	Horton (1945)
	Perimeter (P)		The total length of the boundary line defines the outer limits of a drainage basin (km).	Schumm (1956)
	Basin length (L)		Longest straight-line distance from the outlet to a point along the perimeter (km).	
	Mean stream length (L_{sm})		Length of the main channel, measured using GIS software, accounting for meander sinuosity.	Christofoletti (1980)
	Stream lenght (L_u)		It is characterized by the sum of each stream segment in each successive order (km).	Christofoletti (1980)
	Circularity ratio (R_c)	$R_c = \left(\frac{4\pi A}{P^2}\right)$	Ratio between the catchment area and a circle with the same perimeter.	Miller (1953)
	Form factor (F)	$F = \frac{A}{L^2}$	Dimensionless ratio between the basin area and the square of its length.	Horton (1945)
	Compactness coefficient (C_c)	$C_c = \frac{P}{2.\sqrt{\pi.A}}$	Ratio between the basin area and the square of its length.	Horton (1945)
Drainage network	Stream frequency (F_s)	$F_s = \frac{N_u}{A}$	Ratio between the number of streams (N_u) and the area of the drainage basin.	Horton (1945) and Christofoletti (1980)
	Drainage density (D_d)	$D_d = \frac{L_u}{A}$	The total stream length across all orders per unit area.	Christofoletti (1980)
	Constant channel maintenance (C_{cm})	$C_{cm} = \frac{1}{D_d}$	The minimum area required to maintenance one meter of drainage channel.	Schumm (1956)
	Bifurcation ratio (R_b)	$R_b = \frac{N_u}{N_{u+1}}$	Relationship between the total number of segments of a given stream order (Nu) and the total number of segments of the next higher order (Nu+1).	Horton (1945)
	Length of overland flow (L_0)	$L_0 = \frac{1}{(2.D_d)}$	It represents the average distance traveled by surface runoff between the interfluve and the permanent stream channel.	Horton (1945) and Christofoletti (1980)
Relief	Relief (B_h)	$B_h = H - h$	Elevation difference between the altitude at the outlet and the highest point on the watershed divide.	Strahler (1952)
	Relief ratio (R_h)	$R_h = \frac{B_h}{L_{sm}}$	Ratio between the elevation range and the total length of the main channel	Schumm (1956)
	Ruggedness number (R_n)	$R_n = B_h.D_d$	Relationship between water runoff availability and erosive potential, expressed by the mean slope.	Melton (1957)

Physiographic data was extracted from satellite imagery provided by the Shuttle Radar Topography Mission (SRTM), carried out in 2000, which supplies global-scale stereoscopic elevation data. These images were accessed through the Earth Explorer platform of the United States Geological Survey (USGS).

To calculate the morphometric parameters, the drainage network data for the PCJ Basins was obtained from the metadata catalog of the National Water and Basic Sanitation Agency (ANA), structured at a 1:50.000 scale using vector data provided by the São Paulo State Water Agency (SP Águas). Data processing was performed using the open-source GIS software QGIS version 3.22.10. From the SRTM data, the Digital Terrain Model (DTM), basin and sub-basin delimitations, and main channel lengths were derived.

The delimitation procedures were carried out using the SAGA (System for Automated Geographical Analysis) extension, specifically the Terrain Analysis – Hydrology tool developed by Olaya (2007). This methodological framework enabled the generation of physical indicators that support the environmental diagnosis of the basin, aiming to inform territorial planning and the development of more effective and sustainable water management strategies.

ANALYSIS AND INTERPRETATION OF THE MORPHOMETRIC PARAMETERS

Tables 2 and 3 present the stream order hierarchy and total channel length in the Corumbataí River Basin and its sub-basins, showing a well-structured drainage network consistent with Strahler's model. Most streams are of 1st order, indicating a predominance of headwater channels and a fragmented network. As stream order increases, the number of channels decreases while their average length increases, reflecting natural drainage development.

The Upper Corumbataí sub-basin has the highest number of streams and the longest 1st order segments, highlighting its role in recharge. Passa Cinco and Claro sub-basins also stand out for their dense and extensive drainage networks. Notably, Passa Cinco contains the basin's only 6th order segment and the greatest total stream length, while Middle Corumbataí, with fewer channels, shows longer 5th order reaches, suggesting well-defined main channels in a sparser network. These results support the identification of hydrological patterns and guide sustainable watershed management.

Table 2 - Stream order hierarchy using the Strahler system for the Corumbataí River Basin and its sub-basins, including the count of stream segments.

Stream order	Corumbataí Basin	Sub-basin				
		Upper	Middle	Lower	Passa Cinco	Claro
1st	903	438	83	103	144	135
2nd	437	210	38	55	73	61
3rd	269	148	17	19	36	49
4th	110	43	5	5	32	25
5th	59	30	24	2	3	-
6th	22	-	-	22	-	-
Total	1800	869	167	206	288	270

Table 3 - Average channel length in km.

Stream order – length (km)	Corumbataí Basin	Sub-basin				
		Upper	Middle	Lower	Passa Cinco	Claro
1st	914,85	287,55	117,00	153,98	216,53	139,79
2nd	361,74	107,07	50,57	72,33	85,77	46,05
3rd	215,26	67,54	29,00	27,68	54,73	33,31
4th	173,20	23,28	7,85	9,86	87,22	44,99
5th	88,42	14,29	59,32	8,61	6,20	-
6th	38,42	-	-	38,42	-	-
Total	1791,89	499,68	263,74	310,88	420,45	264,14

Table 4 presents the morphometric parameters evaluated for the entire Corumbataí River Basin and its subdivisions. The total area of the Corumbataí Basin is 1.706 km², with the Claro sub-basin being the largest and the Middle Corumbataí sub-basin the smallest among the five sub-basins. The total length of drainage channels in the basin is 1.791.89 km, with the Passa Cinco Sub-basin standing out for having the longest drainage network, totaling 420,45 km, which indicates a well-distributed drainage pattern. The shortest average stream length is observed in the Upper Corumbataí Sub-basin, consistent with its role as a headwater region.

Table 4 - Dimensional morphometric analyses of the Corumbataí River Basin and its sub-basins.

Parameter	Corumbataí Basin	Sub-basin				
		Upper	Middle	Lower	Passa Cinco	Claro
Area (km^2)	1706,00	314,00	292,00	294,00	526,00	280,00
Perimeter (km)	339,00	134,00	164,00	123,00	185,00	149,00
Basin length (km)	67,01	22,91	31,68	29,44	34,34	31,90
Mean stream length (km)	139,51	33,63	57,67	38,33	62,75	44,92
Stream length (km)	1791,89	499,68	263,74	310,88	420,45	264,14
Circularity ratio	0,19	0,22	0,14	0,24	0,19	0,16
Form factor	0,38	0,60	0,29	0,34	0,45	0,28
Compactness coefficient	2,30	2,12	2,69	2,01	2,26	2,49

The circularity ratio is an important variable for understanding concentration time and the susceptibility of flooding in the central part of the basin. This ratio ranges from 0 to 1; the closer it is to 1, the greater the probability of sudden floods in the main channel during intense rainfall events affecting the entire basin. This is because tributary contributions tend to arrive at the main channel simultaneously, concentrating flow over a short period (Machado & Torres, 2012). In the case of the Corumbataí Basin and its sub-basins, the circularity values are generally low, indicating a lower tendency toward the type of flooding described above.

Basin shape, reflected by the form factor, is also directly related to concentration time. More circular basins tend to exhibit higher form factor values and are more susceptible to flooding. In contrast, elongated and narrow basins are less likely to be affected by widespread rainfall events, thereby reducing flood risk. The comparison between the study areas showed that the Upper Corumbataí sub-basin, due to its more circular shape, has a higher probability of flooding, whereas the Claro sub-basin, being narrower and more elongated, shows the lowest flood susceptibility.

The compactness coefficient is another indicator linked to flood susceptibility, particularly in the lower parts of the basin. This coefficient, always greater than 1, reflects the irregularity of the basin's shape, the higher the value, the more irregular the basin and the lower its flood risk. All analyzed sub-basins showed values above 2, with the Lower Corumbataí sub-basin presenting the lowest value.

Table 5 presents the parameters related to the drainage patterns of the Corumbataí River Basin and its sub-basins. The stream frequency, which expresses the ratio between the total number of watercourses and the basin area, is notably higher in the Upper Corumbataí sub-basin, reflecting the abundance of first-order streams and its location in the headwater region, characterized by steeper terrain.

Table 5 - Morphometric analysis of drainage patterns in the Corumbataí River Basin and its sub-basins.

Parameter	Corumbataí Basin	Sub-basin				
		Upper	Middle	Lower	Passa Cinco	Claro
Stream frequency (F_s)	0,72	1,85	0,42	0,51	0,38	0,65
Drainage density (D_d)	1,03	1,59	0,90	1,06	0,80	1,50
Constant channel maintenance (C_{cm})	975,36	628,40	1107,15	945,70	1251,04	665,95
Bifurcation ratio (R_b)	2,13	2,10	2,01	2,24	0,87	1,81
Length of overland flow (L_0)	0,49	0,31	0,55	0,47	0,63	0,33

The drainage density, as defined by Granell-Pérez (2001), represents the total length of drainage channels per unit area and indicates the availability of surface runoff. High values are associated with favorable hydrological conditions, such as low-resistance rock formations, poorly permeable soils, and scarce vegetation cover. Conversely, according to Rocha and Kurtz (2001), basins with denser vegetation tend to exhibit lower drainage density due to greater water infiltration and reduced erosion potential. Based on the classification proposed by Beltrame (1994), presented in Table 2, the Corumbataí Basin shows a medium drainage density, while the Middle Corumbataí and Passa Cinco sub-basins fall into the low-density category. The remaining sub-basins are also classified as the medium range.

The maintenance coefficient, which expresses the minimum area required to maintain 1 km of active stream channel (Machado & Torres, 2012), is highest in the Middle Corumbataí and Passa Cinco sub-basins, reflecting their lower drainage density, given the inverse relationship between these indicators.

The overland flow length refers to the average distance that surface runoff travels before reaching the nearest stream. According to the classification proposed by Sousa and Rodrigues (2012), the entire Corumbataí Basin was classified as having a moderate overland flow length, which aligns with the region’s gentle relief, where more than 40% of the area has slopes of less than 2%.

The mean bifurcation ratio (Rb), as described by Strahler (1952), is directly related to the degree of dissection of a basin. Values below 2 are typical of hilly terrains, while higher values may indicate basin elongation. The author also notes that bifurcation ratios below 2 may suggest tectonic or structural control over the fluvial network. In natural systems, values between 3 and 5 are considered normal. The Passa Cinco and Claro sub-basins presented values below this range, suggesting a lower degree of dissection and potentially reflecting the influence of more permeable substrates, typical of sedimentary formations and unconsolidated deposits — consistent with the presence of significant aquifers in the region.

To perform the morphometric relief analyses, a DTM was generated from the original SRTM data, followed by the development of a slope map classified according to the standards defined by EMBRAPA (1999) (Figure 2). These two products served as the basis for calculating the values presented in Table 6. Based on the slope map and elevation range, it is evident that the Passa Cinco sub-basin exhibits the greatest altitudinal variation and the steepest slopes, largely influenced by the presence of the Serra do Itaqueri in its western portion.

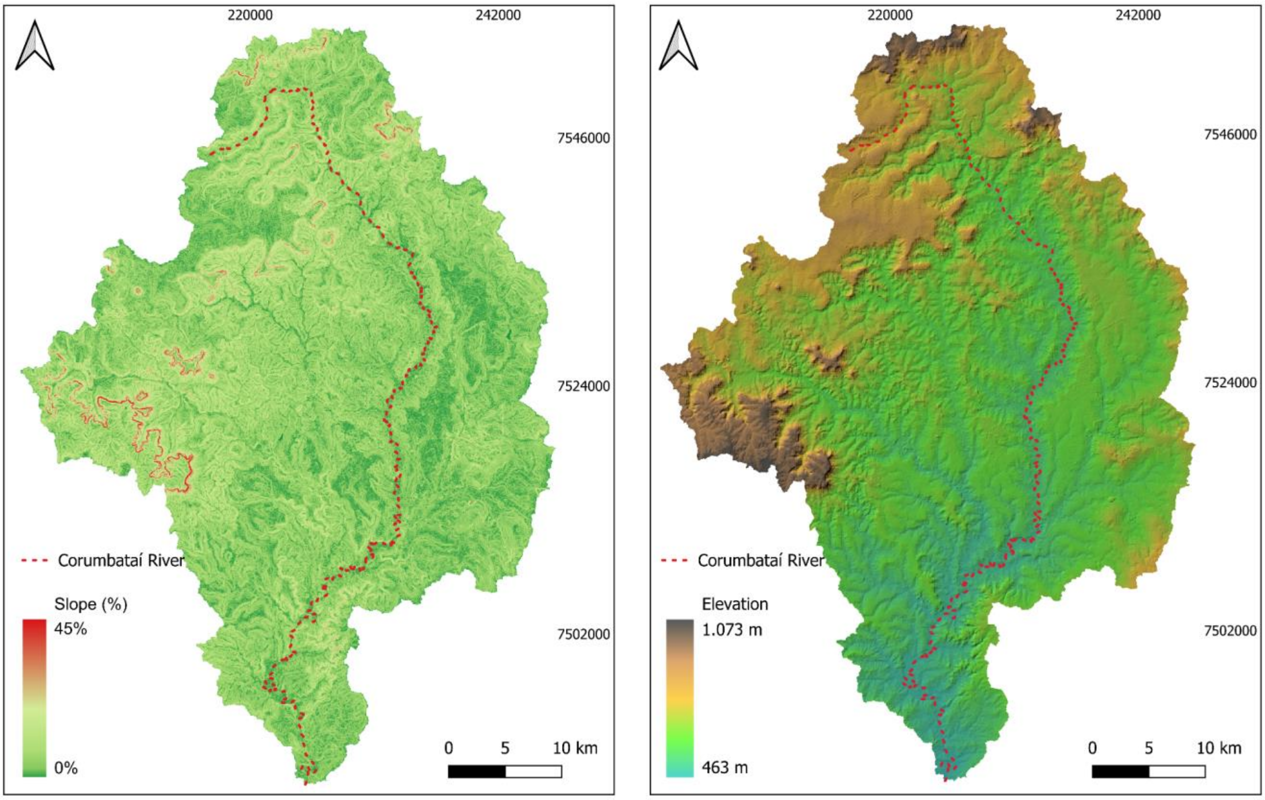
The relief ratio, as defined by Schumm (1956), expresses the relationship between the elevation range and the total channel length, serving as an indicator of the average slope of the basin. Higher values indicate steeper terrain between the headwaters and the outlet, as observed in the Upper

Corumbataí, Lower Corumbataí, and Passa Cinco sub-basins, which exhibit the highest slope gradients.

Table 6 - Relief-related morphometric parameters of the Corumbataí River Basin and its sub-basins.

Parameter	Corumbataí Basin	Sub-basin				
		Upper	Middle	Lower	Passa Cinco	Claro
Relief (Bh) (m)	610	469	272	487	572	251
Relief ratio (Rh) (%)	6,55	7,60	4,39	5,47	8,30	4,63
Ruggedness number (Rn)	4,37	13,95	4,72	12,71	9,11	5,59
Relief (Bh)	625,41	746,34	245,68	514,96	457,22	376,90

Figure 2- Slope and elevation maps of the Corumbataí River Basin.



The ruggedness number relates drainage density to average slope and is used to estimate the erosive potential of the watershed. According to Rocha and Kurtz (2001), basins with higher ruggedness values are generally more vulnerable to erosion processes caused by surface runoff. Rocha (1997) further suggests using this indicator to guide land use decisions, classifying values into four categories based on their distribution and range amplitude.

Based on this classification, the entire Corumbataí Basin is suitable for afforestation. The Middle Corumbataí sub-basin, with the lowest slope and the lowest ruggedness value, is better suited for agricultural activities. The Passa Cinco and Claro sub-basins present intermediate values, making them appropriate for pasture or agroforestry systems. In contrast, the Upper Corumbataí sub-basin, due to its steep slopes and high relief ratio, is most appropriate for forestation and conservation purposes.

However, land use in the basin does not align with these recommendations. In practice, the Passa Cinco and Lower Corumbataí sub-basins are characterized by intensive agricultural and livestock activities, particularly sugarcane cultivation to supply the sugar and ethanol industries located in the western part of the basin.

CONCLUSION

The morphometric analysis of the Corumbataí River Basin and its sub-basins proved to be a valuable tool for assessing the region's hydrological and environmental characteristics. The results revealed a predominance of headwater streams and a moderately dissected relief, with drainage and relief parameters indicating low flood susceptibility but heterogeneous susceptibility to erosive processes. Sub-basins such as Upper Corumbataí and Passa Cinco demonstrated greater altimetric variation and higher ruggedness, making them more prone to erosion and more suitable for conservation and forest restoration activities. In contrast, sub-basins with lower slope and ruggedness values, such as Middle Corumbataí, showed conditions more favorable for agricultural use.

However, the current land use, dominated by sugarcane, often contrasts with the environmental suitability suggested by the morphometric indicators, reinforcing the need for integrated watershed planning. The use of GIS tools and SRTM data allowed for a detailed and spatially disaggregated evaluation, supporting the development of targeted conservation strategies and the formulation of more compatible land-use policies.

These findings reaffirm the importance of morphometric studies as a technical and strategic foundation for sustainable watershed management, particularly in regions under intense anthropic pressure such as the Corumbataí Basin.

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