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Morphometry and urban floods in the Jaguaribe River basin, Salvador-BA

Morfometría e inundaciones urbanas en la cuenca del Río Jaguaribe, Salvador-BA

Morfometria e enchentes urbanas na bacia hidrográfica do Rio Jaguaribe, Salvador-BA

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Abstract

The aim of this research was to analyze the morphometric indices and their correlations with the episodes of floods in the Jaguaribe River basin. The landscape in the river basin is modified by the urbanization that resulted in the waterproofing of soils and the alteration of river channels. The use of geoprocessing techniques combined with the analysis of several technical works on the subject resulted in the Drainage Network Map. The studies in this map associated with the use of calculation methodologies indicated that morphometry would contribute to the rapid flow of water due to the elongated shape of the basin. However, with the intense anthropogenic changes, BHRJ currently has a strong propensity for urban floods.

Keywords: Morphometric Indices; Geoprocessing; Hydrographic Basin; Water flow; Urban Floods.

Resumen

El objetivo de esta investigación fue analizar los índices morfométricos y sus correlaciones con los episodios de inundaciones en la cuenca del río Jaguaribe. El paisaje en la cuenca del río se ve modificado por la urbanización que dio lugar a la impermeabilización de los suelos y la alteración de los cauces de los ríos. El uso de técnicas de geoprocesamiento combinado con el análisis de varios trabajos técnicos sobre el tema dio como resultado el Mapa de la Red de Drenaje. Los estudios en este mapa asociados con el uso de metodologías de cálculo indicaron que la morfometría contribuiria al rápido flujo de agua debido a la forma alargada de la cuenca. Sin embargo, con los intensos cambios antropogénicos, BHRJ actualmente tiene una fuerte propensión a las inundaciones urbanas.

Palabras clave: Índices morfométricos; Geoprocesamiento; Cuenca Hidrográfica; Flujo de agua; Inundaciones urbanas.

Resumo

O objetivo desta pesquisa foi analisar os índices morfométricos e suas correlações com os episódios de enchentes na bacia hidrográfica do Rio Jaguaribe. A paisagem na bacia hidrográfica encontra-se modificada pela urbanização que resultou na impermeabilização dos solos e na alteração dos canais fluviais. A utilização das técnicas de geoprocessamento aliadas à análise de diversos trabalhos técnicos sobre o tema resultaram no Mapa da Rede de Drenagem. Os estudos no referido mapa associado ao emprego de metodologias de cálculo, indicaram que a morfometria contribuiria para o rápido escoamento das águas devido o formato alongado da bacia. Porém, com as intensas modificações antropogênicas a BHRJ detém atualmente forte propensão às enchentes urbanas.

Palavras-chave: Índices Morfométricos; Geoprocessamento; Bacia Hidrográfica; Escoamento das Águas; Enchentes Urbanas.

Introduction

Considering the hydrographic basin as a strategic system for rural and urban planning. It is important to determine its morphometric parameters for the diagnosis of environmental potentials and its limitations of uses of its natural resources. This condition is essential for respecting the environmental requirements established in the Urban Development Master Plan regarding the conservation of water and vegetation resources in urban sites. In this context, this research has extreme importance for physiographic diagnosis and its impacts on the potential of urban floods in the Jaguaribe River hydrographic.

The main objective of this investigation was to analyze the morphometric parameters of BHRJ and establish correlations with its vulnerability to urban floods.

The morphometric indices studied corresponded to the geometric characteristics decomposed in the parameters of Area (A), Perimeter (P), Compactness Coefficient (Kc), Circularity Index (Ic), Shape Factor (Kf), Drainage Pattern (Pd).

The spatial characteristics of the drainage network were also analyzed, consisting of the main course length indexes (L), Total length of watercourses (Lt), Axis Length (Le), Sinuosity Index (Is), Drainage Density (Dd), Maintenance Coefficient (Cm), Basin Order (Ob).

Literature analysis: morphometric studies in watersheds

The essential concept of the river basin corresponds to an area drained by its main river and its tributaries. The volume of water entering the hydrographic system depends directly on the size of the drainage basin, total precipitation, its regime and losses by evapotranspiration and infiltration. In this context, the global flow of basins can be classified as exorreicas, arreicas and cryptorrhekas (CHRISTOFOLETTI, 1980, p. 102).

Venturi (2005, p. 147-148) defines the watershed as a system that encompasses a volume of solid and liquid materials with internal and external delimitation consisting of a set of processes through the entry of water from the atmosphere that affects the flow of matter and energy from its drainage systems.

Lima and Zakia (2000, p. 33-43), in addition to geomorphological concepts discuss the relevance of the hydrographic basin from an open system perspective, which receives energy from climatic agents and loses energy through deflúvio. The basins are described through interdependent variables that oscillate around a certain pattern, even when they suffer some kind of interference via anthropic actions, they are in dynamic equilibrium.

Lanna et al. (2001, p.121-126) emphasizes that drainage basins constitute the archives of the evolution of terrestrial relief. Thus, morphometric analyses were revealed through significant parameters to the study of geomorphological forms and processes.

Following this logic (Rodrigues e Adami, 2005, p.144-166) reinforce that morphometric indicators constitute excellent subsidies to understand geomorphological phenomena in the most diverse spatial and time scales. The calculation of the Circularity Index, Compactness Coefficient, Drainage Density and SL-Index make it possible to understand the erosive dynamics along the river channels of the river basins.

The Circularity Index corresponds to one of the morphometric parameters of the most relevant watershed. This index demonstrates how close a basin approaches the circular shape. The higher the circularity of the watershed, the greater the probability of flooding, due to the area being able to receive in its extension, the greater volume of precipitation, which would concentrate the greater volume of water in the main channel. This situation does not occur in elongated basins, which reduces the probability of flooding (CARDOSO et al. 2006, p. 241-248).

Castro and Alves (2003) in morphometric studies conducted in the Rio do Tanque (MG) hydrographic basin, obtained drainage density of 2.61 canals/km2. These results indicated that the basin had a wealth of river channels. While the maintenance coefficient of the basin indicated 406.5m^2.

In a study carried out in the watershed in the Ribeirão do Apertado (ES), the authors obtained a sinuosity index 1,28. This result demonstrated the tendency of the main channel to be rectilinear. Following the concepts of Lanna et al. (2001, p. 121-126), sinuousness index values close to 1.0 indicate rectilinear canals, while Is>2.0 points to tortuous rivers.

The calculations performed in Ribeirão do Arrependido (ES) by Calçavara et al. (2012, p.1788-1800), indicated the value of the drainage density that reulted at 2.46 Km/Km2. These researchers when confronting this data with the parameters established by Villela and Mattos (1975), which indicate variation from poor (0.50 Km/Km2) to well drained (>3.5 km/km2). They concluded that the sub-basin under study was included in the medium-drained basin class.

These authors associated this characteristic circularity index (Ic) calculation, which demonstrated that the basin has an elongated shape. It is a basin that facilitates the flow with the reduced possibility of flooding.

The orientation of the slopes indicates which segments will shelter during the year the highest incidence of solar radiation, higher humidity due to precipitation and according to the geographical characteristics of the area, and may also indicate the trends of the current atmospheric circulation in the basin.

The orientation of the slopes has a direct influence on the hydrological cycle of the hydrographic basin, considering that they influence the temperature of air, soil, evapotranspiration and the amount of radiation that has focused on the basin area (GUERRA; CUNHA, 2006, p.57).

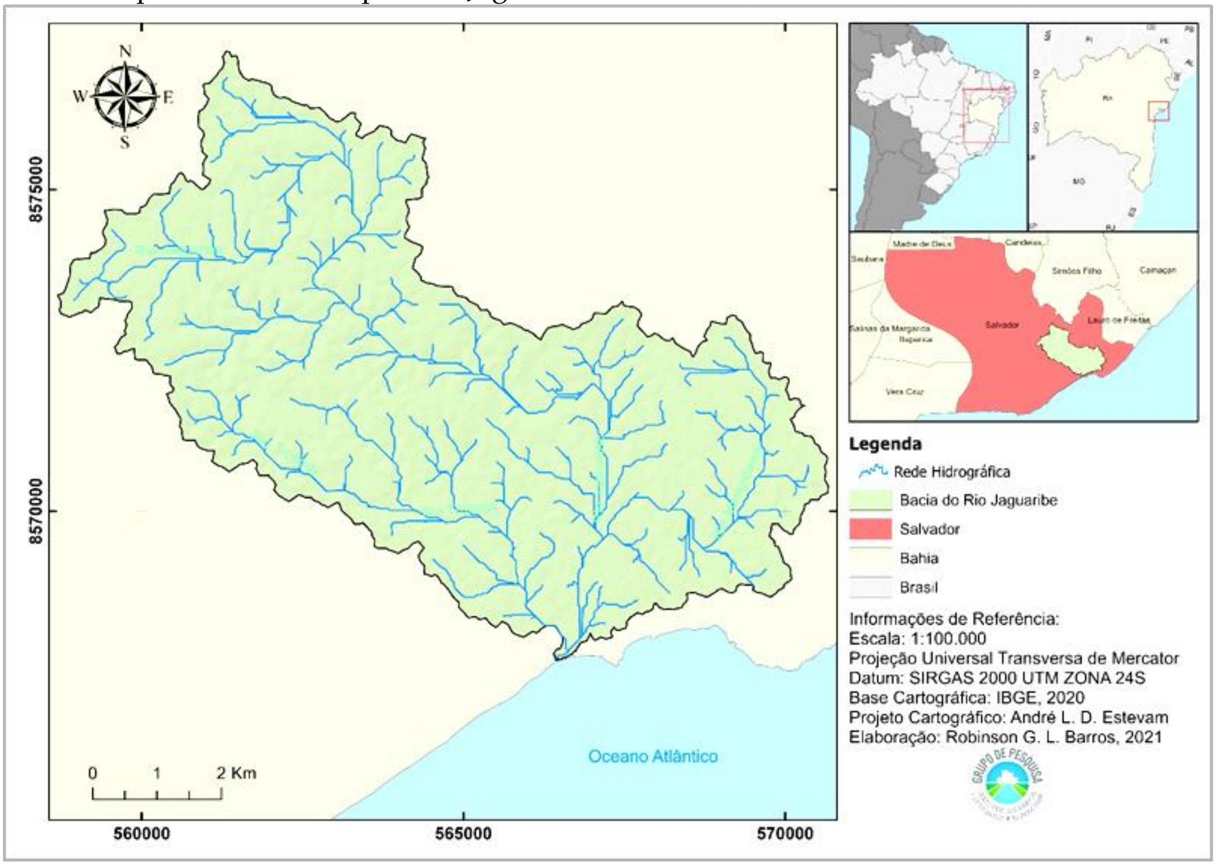
Geographical location and environmental characteristics of BHRJ

The Jaguaribe River basin is fully located in the urban area of Salvador, has its springs in the neighborhoods of Pirajá, Águas Claras, Valeria and Castelo Branco. It comprises an area of 51, 65 km2, draining 17% of the municipality. Receives the contribution of the sub-basins of the Trobogy and Mangabeira Rivers. The basin is located under the coordinates 12052’33’’ at 12057’49’’S and 38020’17’’ to 38025’14’’ W, according to map 1.

As for its geological aspects, BHRJ drains the sedimentary terrains of the Barreiras Group (sandy-claydeposits of Tércio-Quaternary age). The basin is also covered by the Salvador-Esplanada-Boquim Belt, which is composed of acid and intermediate granulolytic rocks and quaternary coastal marine deposits.

Bhrj river channels obey a branched dendritic or parallel drainage pattern and drain an area strongly controlled by geological fault structures with a strong structural component. The valleys were carved along the structural control, which generated the mouth of its main river in the Atlantic Ocean in a drowned valley with strong tidal penetration (SEI, 2003; SODRÉ, 2018).

Map 1 - Location map of the Jaguaribe River basin, Salvador



Source: Estevam and Barros. 2021.

The relief of the municipality of Salvador is characterized by hill seas and the Coastal Plateau that consists of reliefs with tabular tops capebed by sandy and sandy-clay sediments.

According to the studies by Gonçalves (2003, p. 71), the climate of Salvador is associated with atmospheric mechanisms that act on the eastern coast of the northeastern territory. This geographical position, according to the author, promotes concentrated rains in autumn-winter, under the action of more active frontal mechanisms and without the individualization of the dry season.

The climate of the municipality of Salvador is classified as Tropical Rainy Forest (Af), according to classification (Köeppen, 1936). Humid (B2rÁá). Second (Thornthwaite, 1948) Salvador has humid climate (B2rÁá). Rainfall data from the 4th

DISME (National Institute of Meteorology/Salvador/ Neighborhood of Ondina) indicates a water index of 48.4, with a surplus of 694.62 mm/year with evapotranspiration around 1,417 mm/year.

Regarding the main pedological aspects according to Radam Brazil (1981) the main soil classes present in BHRJ correspond to the following units:

a) TYPICAL DYSTROPHIC RED-YELLOW LATOSOL, medium texture and clayey Hz superficial A moderate, wavy relief and smooth wavy. Predominant soil class on the tops of the hills.
b) RED ARGISSOLO – TYPICAL DYSTROPHIC YELLOW, medium/clayey texture, superficial Hz A moderate, wavy relief and strong wavy. Predominant soil class on the slopes.
c) HYDROMORPHIC HUMILÚVIC ETENDUM, sandy texture, superficial HZ A moderate, smooth wavy and wavy relief. Predominant soil class in valley bottoms and alluvial plains.

The native vegetation cover is the Atlantic Forest biome composed of the Dense Ombrófila Forest, restinga and mangrove. Although intensely deforested, it saves important forest remnants around the Jaguaribe River and in the middle portion of the basin, in the middle and early stages of regeneration (SODRÉ, 2018).

Methodology and procedures

To analyze the susceptibility to the occurrence of bhrj floods, it was necessary to generate a map of the hydrographic basin using the radar image of the ALOS PALSAR-FBS sensor and the ArcGIS Geographic Information System program and its modules (spatial analyst tools) to process and map geographic data.

The delimitation of bhrj was performed using the MDE generated by the ALOS PALSAR-FBS image, the procedure used followed the conceptions indicated by Marques (2017). The radar image of the ALOS PALSAR-FBS sensor has a spatial resolution of 12.5 m used for the construction of the Terrain Elevation Model (MDE).

The same image guideed the production of the morphometric parameters range. This information was acquired in the Alaska Satellite Facility system operated and distributed by EarthData/National Aeronautics and Space Administration – NASA (ESA, 2020).

In this sense, morphometric information was generated for BHRJ from the propositions of Horton (1945), Strahler (1952), Shumm (1963) Vilela and Matos (1975), Christofoletti (1980) and Tonello (2005) as summarized in Frame 1. The determination of the parametric aspects associated with the analysis of structural interferences in the urban tissue allowed the investigation of susceptibility to urban floods.

Frame 1 - Morphometric parameters of a watershed

Morphometric Characteristics	**Parameters**	**Description**
Geometry	Area (A)	It comprises the topographic dividers and its interior plane, projected horizontally (TONELLO, 2005).
	Perimeter (P) Compactness	Length of waterchange line
	Coefficient (Kc)	Relationship of the perimeter of the studied basin and the circumference of a circle Kc=0.28(P/√A)
	Circularity Index (Ic)	Proportion of the area, with a relationship between the basin area and the perimeter squared CI=(12.57ª)P2
	Form Factor (Kf)	Ratio of the basin shape and the length of the Kf= A/L2 axis (VILELA and MATOS, 1975).
	Drainage Pattern	Analysis proposed by Christofoletti (1980)
Drainage Network	Length of main stroke (L)	Length of the main channel considering its symmetries (SHUMM, 1963).
	Total length of watercourses	Sum sums up the total lengths of the basin drains.
	Sinuosity Index (Is)	Proportion resulting from the relationship between the length of the channel and the vector distance between the two points.
	Drainage Density (Dd)	Relationship between the total length of the canals and the area of the dd= Lt/A basin (VILELA and MATOS, 1975).
	Maintenance Coefficient (Cm)	Minimum area required for the maintenance of one meter of flow channel, with the ratio of 1 and Dd multiplied by 1000 Cm=(1/Dd)1000
	Order of the Basin (Ob)	Method proposed by Strahler (1957).

Source. Estevam (2022).

Morphometric indicators of the Jaguaribe River basin

Morphometric indices are understood as interactive parameters that cannot be analyzed in a dissociated way in the process of understanding the hydrological dynamics of the hydrographic basin. Morphometric indices provide important information to environmental diagnosis and to understand anthropic or natural factors as can be seen in map 2, the Jaguaribe River basin is composed of the interconnected system of sub-basins of the Trobogy River, mangabeira river, cambunas river and the main river system.

The jaguaribe river hydrographic set comprises 160 courses of 1st order, 65 courses of 2nd order, 36 courses of 3rd order, 48 courses of 4th order, the course of the main river is of 5th order, (STRAHLER, p.913-920).

Geometry and drainage network

The Jaguaribe River basin has an Area (A) of 52.58 km2 and a perimeter of 88.07 km comprising 7.44% of the municipality. It constitutes a medium-sized basin with strong pressure from the urbanization process and total disconfiguration of its natural characteristics from the interventions of the state and municipal government.

The basin holds a total of 310 active and highly anthropized channels and transfigured to rectilinear channels due to the widespread channeling process. The 1st order channels have high potential for water production due to the spring points located in the lithological discontinuities and their interconnection with the lagoons in the fluviomarine plain and the high course of the basin.

The length of the main river is 19.2 km. The total length of all watercourses of the basin is 85.70 km The main river basin holds the largest amount of channels resulting in 35,331 meters. The Trobogy River sub-basin holds the largest number of first-order canals resulting in a total of 11,409 meters. The 5th order channel has a length of 2,234 meters and exhibits intense degree of waterproofing in its alluvial plains.

The lengths of all channels indicate a medium-sized basin with little long channels. The length of the canals are widely used in the formulas of hydrological models, especially the length of the main river (L). They directly influence the reduction or increase in concentration time (Tc) of a given basin.

The drainage pattern of the Jaguaribe River basin is predominantly dendritic. In some segments in the medium course both the Jaguaribe River and its tributaries exhibit rectangular drainage pattern due to the strong structural control of the granite rocks due to structural overimposition. This situation is observed in the BHRJ Map with the river hierarchy exposed in map 1.

The extensive channeling imposed by the interventions in the rivers courses of the Jaguaribe River and in its sub-basins of the Trobogy, Cambunas River and Mangabeira Rivers produced over time the retilinearization of significant stretches that connect the Atlantic waterfront to Avenida Luiz Viana Filho, following in parallel to the stretch of Avenida Orlando Gomes. The drainage channels with emphasis on the Jaguaribe, Trobogy and Mangabeira Rivers have long stretches in rectilinear pattern due to the channeling to contain the waters of the alluvial plains and feasibility of urbanization along the banks of the rivers.

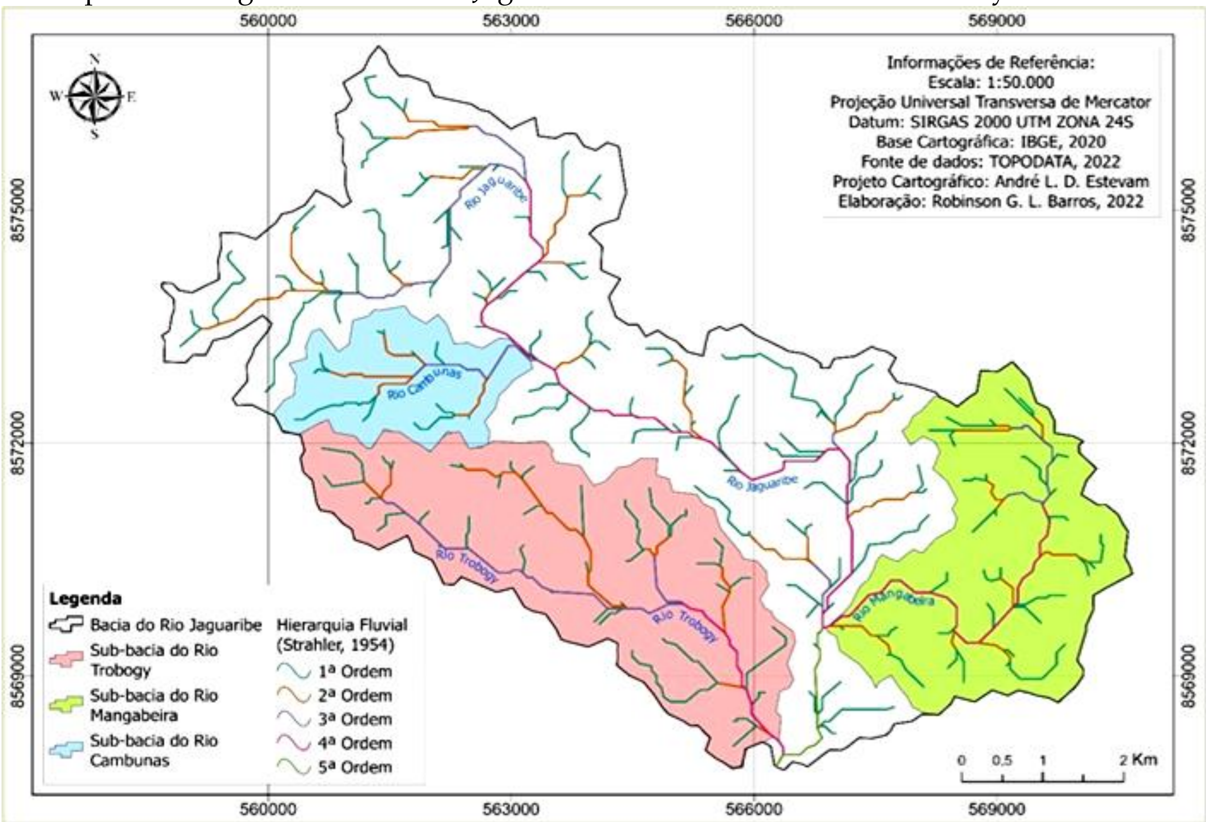
The screen basin has hierarchical ordering 5 according to Strahler's methodology (1957, p.913-920). The Jaguaribe River basin with its quantity of 1st order and 2nd order channels receive significant river discharges and transmits the flow of water to channels of 3rd, 4th and 5th highly channeled in a waterproofed area, raising the risk of flooding in the course of the rainy season especially in its low course where the piatã neighborhood is located.

The Circularity Index (Ic) is used as a way to eliminate subjectivity in the process of characterization of a basin. For the Jaguaribe River basin, the value of 0.30 was determined (values below 0.51 indicate elongated basins that favor runoff). The elongated shape is in line with the dive of fault structures from the continental interior to the east towards the Atlantic Ocean, which is indicative of the basin's strong structural control.

The Compactness Coefficient (Kc) or Gravelius index is used to determine the shape of the watersheds. It holds a minimum value of 1.0 which corresponds to perfectly circular basins. The closer to the unit, the greater the trend of the occurrence of floods. Represents the relationship between the perimeter and the basin area. The basin under study holds Kc = 1.79 m.m2. Fitting into a basin with a median tendency to floods (Chart 2).

As can be seen in Chart 2, Form Factor (Kf) according to Villela and Mattos (1975, 214p.) brings the relationship of the shape of the basin with a rectangle. In the Jaguaribe River basin, a value of 0.56 was found (values between 0.50 and 0.75 indicate a median trend in the occurrence of floods).

Map 2 - Drainage network of the Jaguaribe River basin and river hierarchy



Source. Estevam and Barros. 2022

The hydrographic frequency (Dh) represents the relationship between the number of river channels and the area of the watershed. This parameter is a strong indication of the ability of a basin to produce more or less water. Its purpose is to compare the frequency of the number of existing channels in a given area with standard size (HORTON, 1945). The basin under analysis presents Dh = 6.19 channels/Km². This data indicates low number of channels of the basin and its sub-basins.

According to Villela and Mattos (1975, 214p.) the drainage density varies inversely with the extent of surface runoff. Provides a good insight into the drainage of the basin. In this sense, the index can range from 0.5 km/km² for basins with drainages reduced to 3.5 or more, for exceptionally well drained basins. How can it be analyzed in Chart 2.

The drainage density of the Jaguaribe River basin presented an index of 2.67 km/km2, which characterizes this basin as exceptionally well drained, with a good disposition to originate new drainage channels. This result may be associated with impermeable soils and other aspects such as rainfall intensity, topography characteristics, water infiltration in soils.

This variable represents the degree of topographic dissection and/or the available amount of channels for flow. It is concluded that there is a high surface flow associated with high dissection due to the faster carving processes of talvegues especially in the high course of the hydrographic basin, as can be observed in Christofoletti (1981, 131p.). The canalization of the Jaguaribe and Trobogy Rivers implemented in 2019 by the Urban Development Company of the State of Bahia (CONDER) promoted the replacement of its natural intricacies by rectilinear and artificialized channels as can be observed in Photo 1 and Photo 2.

Photo 2 - Segment of the Jaguaribe River along Avenida Octavio Mangabeira. Salvador's Atlantic Waterfront.

Source. Field work. Phto Estevan 13.03.2022.

Photo 2 - Stretch of the Trobogy River, tributary of the Jaguaribe River. The bed is channeled and the absence of riparian forest and abandonment by the public authorities.

Source. Field work. Photo Estevam,13.03.2022.

As can be analyzed in Chart 2, the Index of Sinuosity (Is) presented a value of 2 Km.km-1 indicating that the Jaguaribe River and tributaries do not hold sinuosity in its low course of the basin; it is known that sinuosity is influenced by sediment load, lithological compartmentalization, geological structure and slope of canals (LANA et al., 2001, p.121-126).

Frame 2 - Results of morphometric parameters for BHRJ

Morphometric Characteristics	Parameters	Description
Geometry	Area (A)	52,58 km2
	Perimeter (P)	88,07 km
	Compactness Coefficient (Kc)	1,79 m.m²
	Circularity Index (Ic)	0,56
	Form Factor (Kf)	Predominante dendrítico
Drainage Network	Length of main stroke (L)	19,2 Km
	Length of main stroke (L)	85.704 metros
	Circularity index (Ic)	0,30
	Hydrographic Frequency (Dh)	6,19 canais/Km²
	Sinuosity Index (Is)	2 Km.km-1
	Drainage Density (Dd)	2,67 km/km2
	Maintenance Coefficient (Cm)	373,16 km2/km
	Order of the Basin (Ob)	5

Source. Estevam (2022)

The maintenance coefficient corroborates the above discussion indicating that the area essential for perennial maintenance of the drainage channels of the Jaguaribe River basin is 373.16 km2/km (Chart 2). In the watershed on screen this flow is intensified by the strong urbanization process that interferes in the water production capacity of the basin with the release of sewage and the macro and micro drainage channels of the avenues.

Final Considerations

The jaguaribe river urban watershed covers a total area of 52.58 km2 with a perimeter of 88.07 km and comprises 7.44% of the municipality of Salvador. It is the second largest area size of the total of 15 watersheds that drain the urban site of the metropolis. BHRJ consists of the sub-basins of the Trobogy, Mangabeira and Cambunas rivers. According to morphometric studies and river hierarchy is identified as order 5 basin and has elongated shape.

The rivers that drain the BHRJ flow over several geoenvironmental units rich in biodiversity. They circulate on land covered by important remnants of the dense, high- and medium-sized anthropophilic forest. They drain the fluviomarine plains of the pre-coastal façade of Salvador and encompass relevant heritage of geodiversity such as the Parque das Dunas e Lagoas do Abaeté with its internal and external dunes.

The morphometric characterization and its hierarchy associated with studies on physiographic aspects as shape and length of channels provided information that defines it as an elongated basin of low potential to the occurrence of urban floods, considering the scenario of its natural landscape conditions. The various interferences in its drainage systems and throughout the bathed area resulted in an artificialized landscape.

The channeling of segments of the main course Rio Jaguaribe from Avenida Luís Viana Filho to the Atlantic waterfront promoted its retilinearization. That is, the rivers have lost their natural configuration of the meandric drainage pattern along the plain. This new configuration of the canals interfered in their natural ability to attenuate the flow rate that would occur naturally due to the roughness of the bed and the natural impediments that the concave and convex curves of the intricacies originally offered to river flow.

The basin subject to this investigation had favorable conditions for the flow. However, with the various changes it was developed into a system highly favorable to floods. In this sense, structural hydrological measures are necessary that favor the infiltration of water into the soil and allow the reduction of flow peaks. These conditions would minimize the occurrence of flood episodes, giving communities in the basin-bathed neighborhoods the safety and urban comfort necessary for quality of life.

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