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Physical characterization of fourteen Brazilian hydrographic basins: proposition of the indicator of the average slope of the rivers and the coefficient of susceptibility to floods

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Abstract: Morphometric parameters are highly relevant information for the physical characterization of river basins. This study physically characterized 14 southern Brazilian basins according to 10 morphometric parameters related to the order, shape, characteristics of the drainage system and slope of the basins, in addition to developing an analysis of their correlations. The methodology consisted of processing the digital elevation model, made available by the TOPODATA project of the National Institute for Space Research (2008), with a spatial resolution of 30 meters, complemented with information from the Google Earth GIS. As a result, in addition to the characterization and classification of the basins, two new morphometric parameters were proposed. The first, called the indicator of the average slope of the rivers, demonstrated good performance in simultaneously representing the slope of the basin and the sinuosity coefficient of the rivers, synthetically equivalent to the average slope of all the rivers in the basin. The second was the flood susceptibility coefficient, which represents the set of all the spatial characteristics of the basin and its rivers. The results suggest that the latter is an excellent indicator for analyzing flood risk in small and medium-sized basins. Classification criteria were also proposed for the parameters runoff length, roughness coefficient, axial slope and indicator of the average slope of rivers and flood susceptibility coefficient.

Key words: morphometry; hydrographic basin; flood

1 Introduction

The flow characteristics of a river basin are controlled by its geomorphological structure (EZE; JOEL, 2010), which can be represented by a set of morphometric factors. According to Strahler (1964), morphometric factors provide a quantitative description of the basin geometry. Their knowledge significantly helps in understanding the hydrological behavior of river basins, providing information about their formation and development (BISHT et al., 2018; DAR; CHANDRA; ROMSHOO, 2013; IFABIYI, 2004; JAIN; SINHA, 2003; OKOKO; OLUJJINMI, 2003; PARETA; PARETA, 2012; ROMSHOO; BHAT; RASHID, 2012; SONI, 2017; VANDANA, 2013). Proper management of the river basin also depends on knowledge of its physical characteristics, facilitating the understanding of issues related to its environmental dynamics (RAWAT; MISHRA, 2016).

Several researches and studies have been carried out with the aim of improving morphometric characterization techniques and tools or, simply, providing indicators that can be applied in regionalization studies (MAGESH; CHANDRASEKAR, 2012; MAGESH; CHANDRASEKAR; KALIRAJ, 2012).

Among the main physical characteristics of hydrographic basins, the following can be highlighted as having the greatest influence on hydrological behavior: shape, relief, area, geology, drainage network, soil and type of vegetation cover (SANTOS; HERNANDEZ, 2013; SANTOS et al., 2018).

Obtaining morphometric parameters is generally based on the collection of physiographic data, which, by definition, are measurable physical characteristics of river basins (SANTOS et al., 2018). These data, in turn, can be divided into three dimensional categories: linear (one dimension), flat (two dimensions) and spatial (three dimensions) (KALIRAJ; CHANDRASEKAR; MAGESH, 2015). Therefore, morphometric analysis involves performing linear, area and gradient measurements, with the aim of obtaining a quantitative description of the drainage system and surroundings (BISHT et al., 2018; NAUTIYA, 1994; SONI; TRIPATHI; MAURYA, 2013; SONI, 2017; STRAHLER, 1964; TRIPATHI; SONI; MAURYA, 2013).

For this purpose, geospatial information on the river basin is used, which can be obtained through topographic maps or satellite images. Initial conceptual efforts were limited by data availability, with studies generally associated with low-resolution maps and long periods between updates. With the modernization of data acquisition methods, including terrestrial topographic techniques, aerial and satellite acquisition methods, and the development of information technology, physiographic studies have become faster and more assertive. The development of remote sensing (RS), geographic information systems (GIS), and global positioning systems (GPS) has significantly aided hydrological science, enabling greater availability of geographic information, as well as faster processing (HAMDAN; KHOZYEM, 2018).

Such data and tools have been used in the analysis, manipulation and extraction of geospatial information from river basins, favoring the development of knowledge. Examples include: Agarwal (1998), Al Saud (2010), Al-Ghamdi et al. (2012), Basihy et al. (2017), Bisht et al. (2018), Chavan and Gadge (2013), Chopra, Dhiman and Sharma (2005), Dawod et al. (2011), Geena and Ballukraya (2011), Kouli et al. (2007), Kumar et al. (2000), Moussa (2003), Nag (1998), Narendra and Nageswara (2006), Obi Reddy, Maji and Gajbhiye (2002), Soni, Tripathi and Maurya (2013), Soni (2017), Tripathi, Soni and Maurya (2013) and Vittala, Govindaiah and Honne Gowda (2004). According to Hamdan and Khozyem (2018), SR and GIS have proven to be adequate and efficient tools for the quantitative description of the morphometric characteristics of river basins, in addition to enabling low operational costs (GROHMANN; RICCOMINI; ALVES, 2007; RAWAT; MISHRA, 2016; RAWAT; MISHRA; TRIPATHI, 2012).

In this context, the digital elevation model (DEM) is the central basis for studies on the physical characterization of basins, allowing the storage of geospatial information in grid format and ensuring the automation of the geographic information analysis process (SAHOO; JAIN, 2018). The DEM's spatial matrix is based on a pre-established graphic and analytical resolution, which is a function, among other factors, of the data acquisition technology.

Currently, the new generation of photosensors can provide data acquisition with spatial resolutions of less than 2 meters, according to Bajracharya and Jain (2020). This evolution has the potential to transform the analysis and modeling of hydrological processes, especially in the delineation of channel networks (SAHOO; JAIN, 2018) and wetlands (WU; LANE, 2017), helping to understand runoff generation processes (DEGETTO GREGORETTI; BERNARD, 2015) and their analytical modeling, as cited by Biron et al. (2013), Liu and Zhang (2011), Rigon et al. (2016) and Yang et al. (2014).

Despite technological advances in the field, most studies carried out in the last ten years have been based on geospatial geospatial data with resolutions of around 30 meters. In favor of this, according to Bajracharya and Jain (2020) and Sahoo and Jain (2018), hydrological models have little sensitivity to the DEM resolution, and different resolutions provide results with no statistically significant difference when applied in morphometric analyses. Another relevant aspect to be considered is that increasing the resolution of the geospatial database leads to a significant increase in the need for storage and processing. Therefore, the cost-benefit ratio of increasing the DEM resolution is still debatable (BAJRACHARYA; JAIN, 2020).

Satellite images and aerial photographs are also important sources of information, helping in the analysis of the characteristics and geometry of channels, roughness and use of the basin. Their application can be done through visual, graphical or photometric analysis (KALIRAJ; CHANDRASEKAR; MAGESH, 2015; KALIRAJ; MEENAKSHI; MALAR, 2012; MESA, 2006).

The first morphometric studies date back to the 1940s, and their evolution has been based on the proposal of new methods that sought to relate the hydrological behavior of river basins to their physical characteristics. The scientific and technical efforts expended in defining the characteristic parameters of river basins also deserve equal attention, with notable interest for engineering and society in general.

Thus, this work, in addition to contributing to the physical characterization of 14 Brazilian river basins, focusing on the Southern Region of Brazil, also presents a correlation analysis between the morphometric parameters studied, with the aim of collaborating with the classification of the potential for occurrence of extreme maximum flow events in the river basins, proposing a method indicative of the susceptibility of flooding in the river basins, based on their physical characteristics.

2 Methodology

Fourteen river basins were selected, with predominantly rural areas, located in southern Brazil, with availability of raster data and variability of morphometric characteristics. The location of the selected river basins is shown in Table 1, with the geographic reference being the fluviometric station at their mouths.

Initially, the raster data were processed in geoprocessing software, using the "Archydro" routine to delimit the sub-basins, and the "Slope" tool of the software itself to obtain the slopes. The DEM was made available by the TOPODATA project of the National Institute for Space Research (2008), which performed successive refinements and corrections of errors in the Shuttle Radar Topography Mission (SRTM) data, provided by the U.S. Geological Survey. The resolution of the geospatial data matrix used was 30 meters. Some additional information, such as the axial length of the basin, the highest order river slope and the maximum slope of the basin, were obtained from the DEM of the Google Earth GIS.

Watercourses were classified according to the methodology of Horton (1945), modified by Strahler (1952; 1957; 1964). Briefly, the method consists of assigning an integer order number to each section of watercourse delimited between a source and a bifurcation or between two consecutive bifurcations. The channels represented by the segments that begin their flow trajectory from a source are defined as first order. The other segments formed by the junction of two sections of the watercourse with the same order (ω) are classified by the first integer immediately higher than that of the confluent sections ($\omega + 1$). When segments of the watercourse of different orders join, the segment formed downstream corresponds to the one of the highest order between them. Finally, the order of the basin (Ω) is given by the river of highest order.

Figure 1 illustrates the graphical results obtained for the Parque Tingui station.

Based on the geospatial information obtained for the river basins, the parameters listed in Table 2 were estimated, as proposed by Horton (1933; 1945), Miller (1953), Schumm (1956) and Strahler (1952; 1964; 1968) and used by Kaliraj, Chandrasekar and Magesh (2015).

All basins were classified considering the criteria presented in Tables 3 and 4.

Next, a correlation analysis was performed between the morphometric factors, with the aim of identifying their relationship patterns, with special attention to the parameter called basin roughness coefficient, as it allows for the synthetic representation of the three-dimensional spatial geometry of the river basin. The method used for this was the Spearman coefficient, which according to Bauer (2007) is indicated for samples whose hypothesis of bivariate normality is not confirmed, requiring only that the variables be measured on an ordinal scale. To classify the results, the following intervals were used:

- $0 \leq \rho \leq 0.30$: weak correlation;
- $0.30 < \rho \leq 0.50$: moderate correlation;
- $0.50 < \rho \leq 1$: strong correlation.

The normality of the data was verified by the Shapiro-Wilk test, adopting $\alpha = 5\%$. The Shapiro-Wilk test is apparently the best test of adherence to normality, according to Mesquita, Castelo Branco and Soares (2013). Shapiro and Wilk (1965) developed this test and showed that it is efficient for different distributions and sample sizes, when compared to the results of other tests.

Finally, based on the results of the correlation analysis, two new indicators representing the physical characteristics of the basins were proposed, called the average river slope indicator and the flood susceptibility coefficient, obtained by the conceptual adaptation of the bibliographic parameters shown in Table 2.

3 Results and discussion

According to Table 3, the basins studied have drainage areas of approximately 4 to 850 km^2 and orders according to the Strahler classification (1964) from 3 to 6, being considered small to medium-sized. Table 4 presents the classifications of each hydrographic basin, according to the classification criteria existing or proposed in this study.

Table 1. Basins analyzed and their location

Basin name- station code	River name and location
UFSC	Rio do Meio - Florianópolis (SC)
Piteu - 58217500	Ribeirão Palmital - Cachoeira Paulista (SP)
Itariri - 81580000	Rio do Azeite - Itariri (SP)
Vargem Grande - 65006055	Rio Palmital - Pinhais (PR)
Parque Tingui - 65019640	Rio Barigui - Curitiba (PR)
CGH Caju - 73331850	Rio Xanxerê - Xanxerê (SC)
Salto das Flores - 74400000	Rio das Flores – Paraí'so (SC)
Mirim Doce - 83040000	Rio Taió - Mirim Doce (SC)
PCH José Barasuol - 75188000	Rio Conceição - Ijuí (RS)
Guatapará Baixo - 74300000	Rio das Antas - Anchieta (SC)
PCH Fazenda Velha - 60710800	Rio Ariranha - Jataí (GO)
PCH Angelina - 84022000	Rio Tijucas - Angelina (SC)
Itapocu - 82350000	Rio Itoupava – Jaraguá do Sul (SC)
Ermo - 84949800	Rio Itoupava - Ermo (SC)

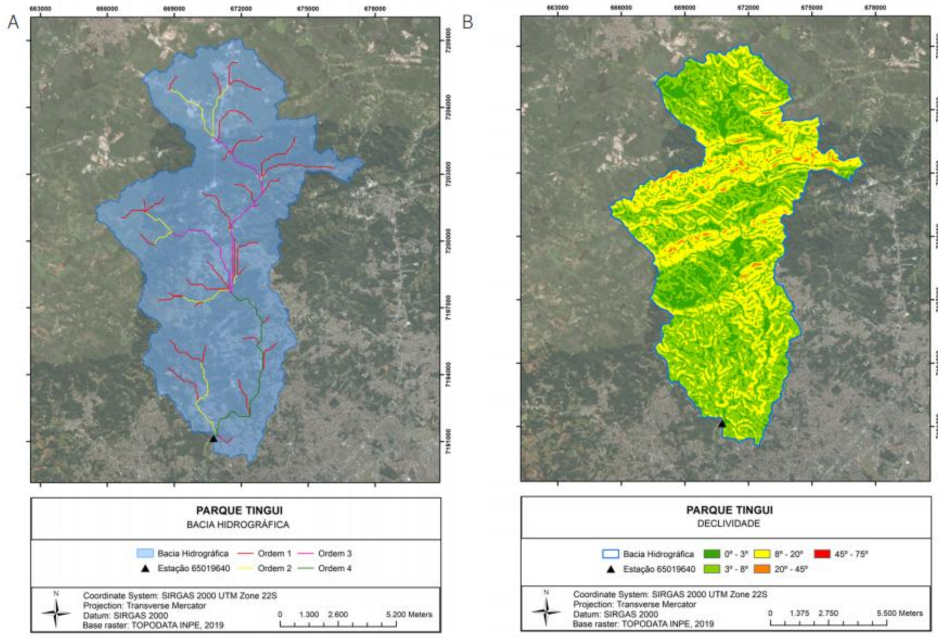


Figure 1. Processing of geospatial information of basins

Table 2. Summary of morphometric parameters

Name / Equation	Description
Drainage density $D_D = \frac{\sum L_C}{A}$	It is the ratio between the total length of the channels (ΣL_C) and the area of the watershed (A). Vilella and Mattos (1975) state that the expected values range from 0.5 km/km^2 for poor drainage basins to 3.5 km/km^2 or more for exceptionally well-drained basins. This parameter is directly linked to the topography and reflects the relationship between the shape of the basin and the infiltration processes and the response time to precipitation (KALIRAJ; CHANDRASEKAR; MAGESH, 2015). The lower the drainage density of the basin, the higher the infiltration rate, which, in turn, increases groundwater recharge (KRISHNAMURTHY et al., 2000). The opposite is true with regard to the direct runoff response.
Hydrographic density $D_H = \frac{N}{A}$	It represents the ratio between the number of channels (N) per unit area of the hydrographic basin (A), according to Christofoletti (1974). It is related to the branching capacity of watercourses.
Confluence density $D_C = \frac{N_C}{A}$	It is the ratio between the number of confluences or bifurcations (N_C) and the area of the river basin (A). Low confluence densities indicate alluvial basins, while high density values mean hill structures (HORTON, 1933). There is also a direct relationship between drainage density and confluence density (KALIRAJ; CHANDRASEKAR; MAGESH, 2015)
Compactness coefficient $K_C = \frac{P_B}{P_C}$	It consists of the relationship between the perimeter of the basin (P_B) and the perimeter of a circle ($P_C = 2\sqrt{\pi A}$) of the same area as the hydrographic basin. According to Carvalho and Silva (2006), its value is always greater than 1, and the lower its value, the shorter the concentration time.
Form factor $K_F = \frac{\bar{L}}{L}$	It is the ratio between the average width of the basin $(\bar{L} = \frac{A}{L})$ and the length of the basin axis or axial length (L) (from the mouth to the most distant point of the area). Carvalho and Silva (2006) highlight that the lower its value, the less susceptible the basin will be to flooding.
Surface runoff length $L_G = \frac{1}{2D_D}$	It is defined as the distance of surface runoff of water until it reaches a given channel (HORTON, 1945). It can be estimated as half the inverse of the drainage density (DD). The shorter the surface runoff length, the shorter the concentration time of the river basin (IFABIYI, 2004).

Basin slope $D_B = \frac{\sum D_P}{n}$	It is the arithmetic mean of the slopes between each pixel $(D_P = \frac{\Delta Z_i}{L_P})$ of the digital elevation model, estimated by the ratio between the unevenness of adjacent pixels (ΔZi) and their spatial resolution (L_P). This characteristic represents the average slope of the drainage surface of the basin up to its outlet. The slope of the basin is one of the effective aspects for assessing floods, and the speed of surface runoff increases as the slope increases (KALIRAJ; CHANDRASEKAR; MAGESH, 2015).
Axial slope $D_A = \frac{\Delta z}{L}$	It consists of the relationship between the maximum difference in altitude of the basin (Δz) and the length of the basin axis or axial length (L) (from the mouth to the most distant point of the area).
Coefficient of sinuosity of watercourses $K_S = \frac{L_R}{L_T}$	It is the relationship between the length of the main river (LR) and the length of the main river thalweg (LT) measured in a straight line from the source to the outlet. It is related to the velocity control in the basin and the time of concentration. Leopold and Wolman (1957) recommend that basins with a K_S value lower than 1.5 be considered to have low sinuosity and those above this value to have high sinuosity.
Coefficient of roughness of the watershed $K_R = D_D \cdot \Delta_Z$	It is the product of the maximum difference in altitude of the basin (Δz) by its drainage density (DD), and is related to the average slope of the watercourses. High roughness values indicate steeper slope basins, while low roughness values indicate less steep basins that are less influenced by geological structures (KALIRAJ; CHANDRASEKAR; MAGESH, 2015).

Table 3. Physiographic and morphometric data of the basins studied

Parameters and units			UFSC	Piteu	Itariri	Vargem Grande	Parque Tingui	CGH Caju	Salto das Flores	Mirim Doce	PCH José Barasuol	PCH Fazenda Velha	Ita- pocu	PCH Angelina	Guatapará Baixo	Ermo
Physiographic characteristics																
Basin area	A	km2	4,31	39,11	72,89	88,05	107,15	112,73	255,51	280,87	505,30	560,92	762,20	784,30	813,17	855,78
Perimeter	P_B	km	16,01	50,58	66,29	80,04	86,1	73,26	152,94	141,12	156,84	209,52	201,96	411,87	195,48	256,56
Length of rivers	L_R	km	15,75	34,59	52,14	73,38	87,84	77,49	189,00	206,84	373,83	371,87	415,49	556,88	600,18	679,66
Axial length	L	km	3,05	13,90	9,15	20,14	18,39	16,46	43,70	31,29	31,30	36,99	40,57	37,83	40,87	43,35
Number of confluences	N_C	un	40	9	16	29	37	33	79	78	158	55	112	215	238	225
Channel numbers	N	un	56	14	26	33	51	41	100	105	209	210	153	279	304	300
Maximum slope	Δ_Z	m	381	410	943	215	101	393	352	580	125	65	831	862	188	1210
Thaleg of the river of order Ω	L_T	km	0,30	9,84	4,25	11,91	6,80	7,67	15,90	24,30	7,98	7,75	15,75	3,52	14,76	4,88
Order river length Ω	L_M	km	0,30	10,74	4,81	15,54	9,49	8,57	28,71	30,35	14,23	9,04	27,34	5,78	36,69	8,98
Highest order	Ω	-	4	3	4	3	4	4	4	4	5	5	5	5	5	6
Morphometric parameters																
Drainage density	D_D	km/km²	3,65	0,88	0,72	0,83	0,82	0,69	0,74	0,74	0,74	0,66	0,55	0,71	0,74	0,79
Hydrographic density	D_H	N/km²	12,99	0,36	0,36	0,37	0,48	0,36	0,39	0,37	0,41	0,37	0,20	0,36	0,37	0,35
Confluence density	D_C	NC/km²	9,28	0,23	0,22	0,33	0,35	0,29	0,31	0,28	0,31	0,10	0,15	0,27	0,29	0,26
Compactness coefficient	K_C	-	2,16	2,26	2,17	2,39	2,33	1,93	2,68	2,36	1,95	2,48	2,05	4,12	1,92	2,46
Deformation factor	K_F	-	0,46	0,20	0,86	0,22	0,32	0,42	0,13	0,29	0,52	0,41	0,46	0,55	0,49	0,46
Surface runoff length	L_G	km	0,14	0,57	0,69	0,60	0,61	0,72	0,68	0,68	0,68	0,76	0,91	0,70	0,68	0,63
Basin slope	D_B	%	23,6	18,0	32,9	8,0	12,8	13,5	13,2	24,7	7,0	3,8	24,0	24,7	21,1	32,9
Axial slope	D_A	%	12,5	2,9	10,3	1,1	0,5	2,4	0,8	1,9	0,4	0,2	2,0	2,3	0,5	2,8
Coefficient of disinclination	K_S	-	1,03	1,09	1,13	1,30	1,40	1,12	1,81	1,25	1,78	1,17	1,74	1,64	2,49	1,84
Roughness coefficient	K_R	m.km/km²	1392	363	674	179	83	270	260	427	92	43	453	612	139	961
Application of the proposed methods in river basins																
Parameters and units			UFSC	Piteu	Itariri	Vargem Grande	Parque Tingui	CGH Caju	Salto das Flores	Mirim Doce	PCH José Barasuol	PCH Fazenda Velha	Ita- pocu	PCH Angelina	Guatapará Baixo	Ermo
Indicator of average river slope	D_R	%	12,5	2,7	9,1	0,8	0,4	2,1	0,4	1,5	0,2	0,2	1,2	1,4	0,2	1,5
Flood susceptibility coefficient	K_{SE}	%.km/km²	45,6	2,6	7,4	0,9	0,5	1,7	0,6	1,4	0,3	0,1	1,1	0,3	1,6	2,2

Table 4. Morphometric classification of the basins studied

Parameters and criteria		UFSC	Piteu	Itariri	Vargem Grande	Parque Tingui	CGH Caju	Salto das Flores	Mirim Doce	PCH José Barasuol	PCH Fazenda Velha	Itapocu	PCH Angelina	Guatapará Baixo	Ermo
D_D	Low– $D_D < 0{,}50$ km/km^2 Regular-$0{,}5 \leq D_D < 2$ km/km^2 High– $2 \leq D_D < 3{,}5$ km/km^2 Very High -$D_D \geq 3{,}5$ km/km^2	Very high	Regular	Regular	Regular	Regular	Regular	Regular	Regular	Regular	Regular	Regular	Regular	Regular	Regular
D_H	Low-$D_H < 3$ N/km^2 Average-$3 \leq D_H < 7$ N/km^2 High-$7 \leq D_H < 15$ N/km^2 Very High-$D_H \geq 15$ N/km2	High	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
D_C	Low -$D_C < 3$ N_C/km^2 Average-$3 \leq D_C < 7$ N_C/km^2 High-$7 \leq D_C < 15$ NC/km^2 Very High-$D_C \geq 15$ NC/km^2	High	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
K_C	High– $K_C \leq 1{,}25$ Average-$1{,}25 < K_C < 1{,}5$ Low $K_C \geq 1{,}5$	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
K_F	High– $K_F \geq 0{,}75$ Average-$0{,}75 < K_F < 0{,}50$ Low – $K_F \leq 0{,}5$	Low	Low	High	Low	Low	Low	Low	Low	Average	Low	Low	Average	Low	Low
L_G	Poorly Drained $L_G \geq 1$ km Medium Drained -0,33 km $\leq$ LG < 1 km Well Drained -0,15 km $\leq L_G <$ 0,33 km Very well drained– $L_G <$ 0,15 km	Very well drained	Medium drained	Mediamente drenada	Medium drained	Medium drained	Medium drained	Medium drained	Medium drained	Medium drained	Medium drained	Medium drained	Medium drained	Medium drained	Medium drained
D_B	Flat-$D_B < 3\%$ Softly wavy-$3 \leq D_B < 8\%$ Wavy-$8 \leq D_B < 20\%$ Strongly wavy -$20 \leq D_B < 45\%$ Mountainous -$45 \leq D_B < 75\%$ Greater Cliff– $D_B \geq 75\%$	Strongly wavy	Wavy	Strongly wavy	Wavy	Wavy	Wavy	Wavy	Strongly wavy	Softly wavy	Softly wavy	Strongly wavy	Strongly wavy	Strongly wavy	Strongly wavy

D_A	Flat-$D_A < 0{,}4\%$ Gently sloping - $0{,}4\% \leq D_A < 1\%$ Inclined-$1\% \leq D_A < 2\%$ Moderately inclined-$2\% \leq D_A < 3\%$ Strongly inclined -$3\% \leq D_A < 9\%$ Mountainous– $D_A \geq 9\%$	Mountai -nous	Moderately inclined	Mountainous	Inclined	Gently sloping	Moderately inclined	Gently sloping	inclined	Flat	Flat	Moderately inclined	Moderately inclined	Gently sloping	Moderately inclined
K_S	Rectilinear-$K_S \leq 1{,}2$ Average sinuosity - $1{,}2 < K_S < 2$ High sinuosity -$K_S \geq 2$	Rectiline -ar	Rectilinear	Rectilinear	Average sinuosity	Average sinuosity	Rectilinear	Average sinuosity	Average sinuosity	Average sinuosity	Rectilinear	Average sinuosity	Average sinuosity	High sinuosity	Average sinuosity
K_R	Little susceptible -$K_R < 300$ m.km/km2 Regular – $300 \leq K_R < 750$ m.km/km2 Susceptible-$750 \leq K_R < 1.000$ m.km/km2 Very susceptible-$K_R \geq 1.000$ m.km/km2	Very suscepti-ble	Regular	Regular	Little susceptible	Little susceptible	Little susceptible	Little susceptible	Regular	Little susceptiblel	Little susceptible	Regular	Regular	Little susceptiblel	Suscetível
D_R	Slightly inclined – $D_R < 0{,}5\%$ Gently sloping - $0{,}5\% \leq D_R < 1\%$ Inclined-$1\% \leq D_R < 2{,}5\%$ Moderately inclined - $2{,}5\% \leq D_R < 5\%$ Strongly inclined - $D_R \geq 5\%$	Strongly inclined	Moderately inclined	Strongly inclined	Gently sloping	Slightly inclined	Inclined	Slightly inclined	Inclined	Slightly inclined	Slightly inclined	Inclined	Inclined	Slightly inclined	Inclined
K_{SE}	Low- $K_{SE} < 1$ %.km/km^2 Regular -$1 \leq K_{SE} < 2$ %.km/km^2 High-$2 \leq K_{SE} < 10$ %.km/km^2 Very tall– $K_{SE} \geq 10$ %.km/km^2	Very high	High	High	Low	Low	Regular	Low	Regular	Low	Low	Regular	Low	Regular	High

The drainage density varied between 0.5 and 0.9 km/km^2, and the basins were considered to have regular drainage, according to Beltrame (1994). The exception was the basin of the Federal University of Santa Catarina (UFSC), presenting a very high drainage density, which may increase the chance of flood peaks and reduce the concentration time. A similar behavior was observed for the hydrographic density, so that, according to the scale proposed by Lollo (1995), all basins are classified as having low hydrographic density, with the exception of the UFSC basin, classified as having high hydrographic density. Naturally, this confirms the expectation of the occurrence of extreme flood events in the UFSC basin.

A significant difference was also found between the results of the confluence density for the UFSC basin in relation to the others. It was observed that the greater the number of confluences per drainage area is the better drained the hydrographic basin is, which is justified by the greater fragmentation of the drainage area of the various watercourses, thus aiding the process of surface water runoff in the basin.

Figure 2 shows a strong positive correlation between the parameters drainage density (DD), hydrographic density (DH) and confluence density (DC), since they represent the same physiographic characteristics of the basin. Based on this and since there is no reference classification scale for confluence density, the same classification scale used for hydrographic density, proposed by Lollo (1995), was adopted.

Analyzing the shape of the river basins, one can find homogeneity in the compactness factor (K_C) of the studied basins, except for the Angelina PCH, which presented a compactness coefficient twice as high as the others. According to the Gravélius criteria, no basin presents a risk of sudden floods, since the spatial distributions of their drainage areas are not very concentrated. For Singh, Cui and Byrd (2014), basins with irregular geometry allow greater distribution of the runoff, resulting in an increase in the concentration time, which suggests a lower concentration of direct surface runoff flows. Therefore, this index helps to describe the space-time relationship of the direct surface runoff of the basin, and the surface runoff of the river basin is relevant in the description of the hydraulic process.

The shape factor is conceptually directly related to the occurrence of heavy rainfall throughout the basin, with this phenomenon being less likely the more elongated the river basins are (LORENZON; DIAS; TONELLO, 2015). The results found for the shape factor (KF) indicate that all the basins studied have a predominance of elongated shape, with the basins most susceptible to flooding, according to this criterion, being Itariri, PCH José Barasuol and PCH Angelina. The shape coefficient, despite also presenting a moderate correlation with the other parameters, proved to be more significant than the compactness coefficient for the physical description of the basin.

The runoff length (LG) is directly related to the concentration time of the watershed and, when associated with the average velocity of direct runoff, can help in its estimation. The runoff length showed a strong inverse correlation with drainage density and confluence density and a moderate correlation with hydrographic density. It also showed a moderate positive correlation with the shape coefficient. Therefore, it has good potential to synthetically represent the flat characteristics and drainage capacity of the watershed. For its classification, a proposal is presented in Table 4, prepared based on the compactness of the watershed.

Based on the principle that surface runoff occurs in two very distinct ways (on the basin surfaces or slopes and in watercourses), it is necessary to know the average slope behavior for both hydraulic trajectories. The slope of the basin can be easily estimated by the geospatial data processing processes, using routines already widespread in most GIS software. Therefore, according to the criteria of the Brazilian Agricultural Research Corporation (Embrapa, 1979), the basins were classified from gently to strongly undulating, with a predominance of basins with undulating to strongly undulating relief. The basin slope (D_B) showed a strong and moderate positive correlation with axial slope, basin roughness coefficient and shape factor, and strong and moderate negative correlations with hydrological density and confluence density.

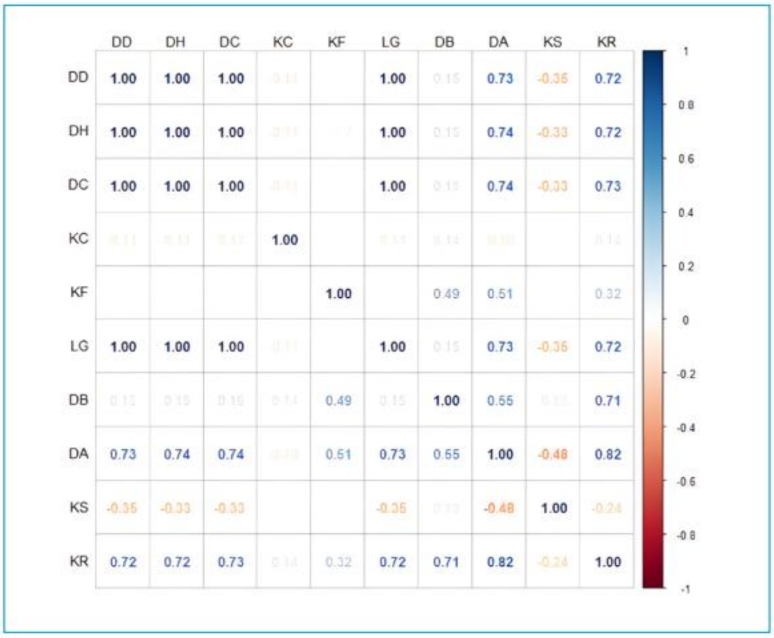


Figure 2. Spearman's correction coefficient

Estimating the average slope of rivers using DEM in GIS software still presents some operational difficulties, requiring several routines, which result in estimates with a high degree of uncertainty. Therefore, its estimation is generally based on manual graphical measurement methods, which, in addition to demanding high operational effort, represent sources of errors and uncertainties, mainly related to the reproducibility of the process.

In order to corroborate this, it was proposed to use an indirect indicator to characterize the global average slope of the rivers in the basin. By combining the morphometric parameters axial slope (DA) and sinuosity coefficient (KS), according to Equation 1, the indicator of the average slope of the rivers (DR) was obtained, later classified by the criteria shown in Table 4.

$$D_R = \frac{D_A}{K_S} \quad (1)$$

Where:

D_R: indicator of average river slope (%);

D_A: axial slope (%);

K_S: sinuosity coefficient (dimensionless).

The axial slope of the basin can be stated as the relationship between the difference in altitude of the basin and the length of its predominant axis, being strongly correlated with the three-dimensional geometric parameters and with the slope of the basin. It was also identified that the axial slope presented values in the order of 20% of the slope of the studied basins. The axial slope (AD) had a strong negative correlation with the sinuosity coefficient of the watercourses and a moderate correlation with the hydrographic density. Furthermore, it presented a strong positive correlation with the roughness coefficient of the basin.

According to Souza et al. (2017), the sinuosity coefficient (KS) varies between 1 and 2, with 1 indicating straight channels, while values close to 2 indicate high channel sinuosity. The UFSC and Piteu river basins were those with the greatest straightness in the channels, while the basins with the most sinuous watercourses were Salto das Flores, PCH José Barasuol, Itapocu, PCH Angelina and Ermo. The Guatapará Baixo river basin has the greatest sinuosity.

The correlation coefficient between the axial slope (D_A) and the river slope indicator (D_R) was $\rho = 0.96$, corroborating the hypothesis that the axial slope associated with the sinuosity coefficient can satisfactorily represent the global average slope of the rivers in the hydrographic basin.

The results applied to the basins studied are shown in Table 4. The UFSC and Itariri basins can thus be classified as strongly sloping, with low sinuosity and high slope. On the other hand, the basins of Parque Tingui, Salto das Flores, PCH José Barasuol, PCH Fazenda Velha and Guatapará Baixo have very sinuous watercourses and low axial declivity, and are classified as slightly sloping. The other basins have an average slope of around 2%. In summary, it can be seen that the space-time relationship of direct runoff in the basin can be described by four main characteristics, described in Table 5, and the combination of the first three characteristics makes it possible to indirectly describe the three-dimensional shape of the basin.

Therefore, the basin roughness coefficient is a three-dimensional representation parameter of the river basin, allowing the association of various information governing the behavior of direct flow. According to Figure 2, this coefficient presented moderate and strong correlation with several parameters, except for drainage density, confluence density, compactness coefficient, surface runoff length and sinuosity coefficient. It is worth noting that the association of the sinuosity coefficient with the axial slope, according to Equation 1, presents a strong compound correlation with the basin roughness coefficient ($\rho = 0.83$).

In general, the higher the basin's roughness coefficient, the greater its slope and the better its drainage conditions. It is also more susceptible to simultaneous precipitation events in the basin, i.e., the greater the potential for extreme maximum flow events. In this logic, by crossing the classification criteria of the parameters, it was possible to propose the classification ranges indicated in Table 4. Therefore, the UFSC basin is considered very susceptible, and the Ermo basin, susceptible to flood events. The other basins are considered regular and not very susceptible to this type of event.

By evaluating the formulation of the basin roughness coefficient, it was possible to propose the refinement of its representation, by replacing the maximum altimetric slope parameter with the basin axial slope. In Figure 3, the existence of a geometric relationship between the axial slope and the basin roughness coefficient can be seen, with $R^2 = 0.80$, adjusted to a nonlinear regression model.

Based on this behavior, it was possible to propose the flood susceptibility coefficient, estimated by Equation 2, with the classification shown in Table 4, thus refining the description of the three-dimensional geometry of the basin.

$$K_{SE} = D_D . D_A = \frac{\Sigma L_C}{A} . \frac{\Delta z}{L} .100 \quad (2)$$

Where:

K_{SE}: flood susceptibility coefficient (%.km/km^2);

D_D: drainage density (km/km^2);

D_A: axial slope (%);

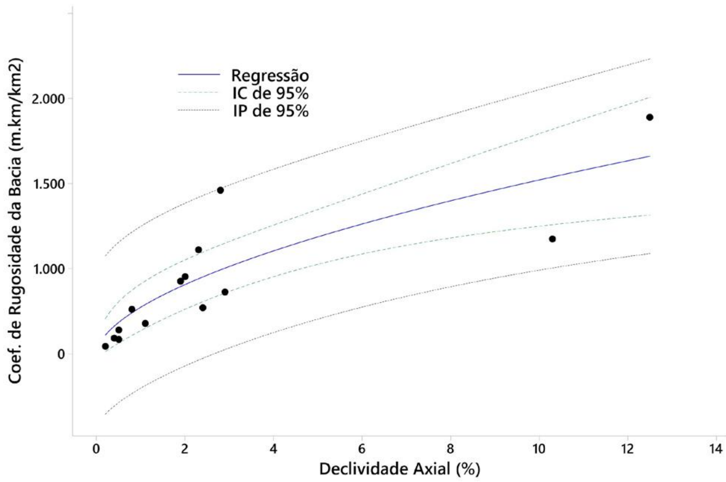
A: drainage area (km^2);

ΣL_C: length of rivers in the basin (km);

L: axial length (m);

Δz: maximum elevation difference (m).

The proposed coefficient is related to the shape of the basin (A and L), providing an indication of the sinuosity of its watercourses, the basin's compactness and drainage potential (ΣL_C, L and A), as well as its slope (Δz, L).



IC:confidence interval IP: prediction interval

Figure 3. Relationship between axial slope and roughness coefficient

It is worth highlighting the importance of the axial length in the proposed method, as it is the scale parameter. Analyzing the results of the correlation analysis in Figure 2, it is clear that the flood susceptibility coefficient satisfactorily represents the physical characteristics of the basin, as it does not present a correlation with only two parameters (shape coefficient and confluence density).

Physically, the susceptibility coefficient also represents the magnitude of the basin's concentration time. The higher the coefficient, the shorter the expected concentration time for basins with similar physical characteristics. Analyzing the results obtained by applying the proposed method, according to Table 4, it was found that they were consistent with the other morphometric parameters, although with a degree of refinement in the risk classification. It was found that the UFSC basin is still considered to be at very high risk for flooding. On the other hand, a more refined analysis of the slope conditions of the basins leads to the classification of three basins as high risk, specifically the Piteu, Itariri and Ermo basins. The Vargem Grande, CGH Caju, Mirim Doce and Guatapará Baixo basins were also included in the list of regular risk.

In practice, the results express a prediction of the behavior of the flood hydrograph (its shape and scale), and the frequency of occurrence of extreme events is a function of the probabilistic behavior of the hydrological precipitation events.

4 Conclusion

Despite the complexity of hydrological processes in river basins, predicting the behavior of direct runoff involves, among other factors, the geometric characterization of the basins. The interaction between their various physical characteristics and these with direct surface runoff is the subject of several studies, with different approaches.

However, it is clear that the uncertainties associated with the model parameter estimation processes can be very relevant to the quality of the results. Based on this, it is understood that the search for more parsimonious methods, with fewer and more representative input parameters, can enable, for practical application purposes, satisfactory results with greater applicability.

Regarding the basins studied, the most significant variations in shape and drainage conditions were identified for the UFSC basin; from a morphometric point of view, this is the most susceptible to flooding. The Itariri, Piteu and Ermo basins also deserve to be highlighted, as they present a high risk, related to their slope and the dendritic structure of their drainage system. Therefore, a significant relationship was identified between the morphological factors of the basins and their possible behavior when faced with extreme flows.

In the correlation analysis between the morphometric factors, it was possible to identify a strong relationship between the shape factor and the parameters related to the characteristics of the basin's drainage network (drainage density, hydrographic density, confluence density and surface runoff length). Because of the possibilities presented by geoprocessing software, it is understood that the application of the drainage density parameter is more favorable to represent this class of two-dimensional characteristics.

The compactness coefficient did not present a significant correlation with any of the morphometric parameters studied, being little representative to describe the physical characteristics of the hydrographic basin.

Evaluating the behavior of the morphometric parameters in the altimetric dimension, it was possible to see that the axial slope is related to the parameters of the three-dimensional shape and the channel network of the basin.

The sinuosity coefficient of the watercourses in the basin showed low correlation with the other parameters, however, when associated with the axial slope, it began to show significant correlation with the average slope of the watercourses. The axial slope alone showed good correlation with the average slope of the basin. In this study, it was possible to propose criteria to classify it, adapted according to the Embrapa method (1979).

Of all the morphometric parameters studied, the basin roughness coefficient can be highlighted as the most representative of the physical characteristics of the basins, since it is correlated with all the other parameters, except for the sinuosity and compactness coefficients. Based on this, it was possible to propose a classification method.

In addition, this study presents a contribution to the basin roughness coefficient method, incorporating the axial slope in its formulation. As a result, it was possible to propose an indicator that indirectly represents the shape and slope of the basin, as well as the sinuosity of the watercourses. The results found for the basins studied were satisfactory and can assist in disaster risk classification methodologies.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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