https://rbgeomorfologia.org.br/
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 25, nº 3 (2024)

http://dx.doi.org/10.20502/rbg.v25i3.2547

Research Article

Assessment of the morphometric characteristics of the sub-basins of the Grijalva-Villahermosa Hydrological Region in southeastern Mexico

Avaliação das características morfométricas das sub-bacias da Região Hidrológica Grijalva-Villahermosa no sudeste do México

Ojilve Ramón Medrano-Pérez[1,2], Lucia Sanaphre-Villanueva[2,3,*], María José Juárez-Rodríguez[4]

[1] CONAHCyT-Tecnológico Nacional de México/Instituto Tecnológico Superior de Misantla (ITSM), Misantla, Veracruz, Mexico. E-mail. omedrano@conahcyt.mx. ORCID: https://orcid.org/0000-0002-5445-1136

[2] Centro del Cambio Global y la Sustentabilidad, A.C. (CCGS), Villahermosa, Centro, Tabasco, México.

[3] CONAHCYT - Universidad Autónoma de Querétaro, Facultad de Ciencias Naturales. Carretera San Juan del Río - Jalpan km 119, Camargo, Peñamiller, Querétaro, México. E-mail. lucia.sanaphre@conahcyt.mx. ORCID: https://orcid.org/0000-0001-5566-7230

[4] División Académica de Ciencias Básicas (DACB), Universidad Juárez Autónoma de Tabasco (UJAT), Cunduacán, Tabasco, México. E-mail: mariajosejuarezrodriguez5@gmail.com. ORCID: https://orcid.org/0000-0003-1157-4168

Received: 07/02/2024; Accepted: 28/05/2024; Published: 09/07/2024

Abstract: Morphometric analysis of watersheds is key to identifying and establishing comparisons between geomorphological, topographical, morphodynamical, and hydrological characteristics in watersheds with limited climatic information. Recurrent flood events and vulnerability to related adverse effects have characterized southeastern Mexico. The main goal of the research is to evaluate the statistical relationships of 12 morphometric parameters and examine their significance for grouping sub-basins with similar morphometric characteristics, to analyze the homogeneity in morphodynamical and hydrologic behavior of the 26 sub-basins of the Grijalva-Villahermosa Hydrological Region (RH30D), in southeastern Mexico. The results revealed four distinct sub-basin groups. Group 1 showed positive correlations with efficient drainage patterns, while group 4 was associated with heavy floods and large flows. Although groups 2 and 3 presented values close to the mean for most parameters, differences were observed in having inverse values for Bifurcation ratio (Br) and Stream Frequency (Fs). Furthermore, group 3 presented drainage patterns controlled by geological structures (high Br values), while group 2 showed a high number of streams per unit area, from which faster hydrological responses are inferred. This study seeks to contribute to knowledge, research, and decision-making on related topics.

Keywords: geomorphology; basins; morphometric; statistical analysis; clustering.

Resumo: A análise morfométrica de bacias hidrográficas é fundamental para identificar e estabelecer comparações entre diferentes características geomorfológicas, topográficas, morfodinâmicas e hidrológicas em bacias hidrográficas com informações climáticas limitadas. O sudeste do México tem sido caracterizado por inundações recorrentes e vulnerabilidade aos efeitos adversos associados. O principal objetivo da pesquisa é avaliar as relações estatísticas de 12 parâmetros morfométricos e examinar sua significância para agrupar sub-bacias com características morfométricas semelhantes e assim analisar a homogeneidade no comportamento morfodinâmico e hidrológico nas 26 sub-bacias do Grijalva-Villahermosa Região Hidrológica (RH30D) do sudeste do México. Os resultados revelaram quatro grupos distintos de sub-bacias. O Grupo 1 apresentou correlações positivas com padrões de drenagem eficientes, enquanto o grupo 4 foi associado a tendências de inundação devido a cheias fortes e grandes fluxos. Embora os grupos 2 e 3 tenham apresentado valores próximos à média para a maioria dos parâmetros, observam-se diferenças em possuir valores inversos para Razão de Bifurcação (Br) e

Frequência de Fluxo (Fs). Por um lado, o grupo 3 apresenta padrões de drenagem controlados por estruturas geológicas (altos valores de Br), e o grupo 2 apresenta um elevado número de riachos por unidade de área, a partir dos quais se inferem respostas hidrológicas mais rápidas. Busca contribuir para o conhecimento, pesquisa e tomada de decisões sobre temas relacionados.

Palavras-chave: Geomorfologia; bacias; morfométrico; análise estatística; agrupamento.

1. Introduction

Geomorphology considers morphometry as the quantification of morphology (Sukristiyanti et al., 2018); that is, the shape and magnitude of the land surface (Shekar & Mathew, 2022). The morphometric analysis of watersheds is a crucial method for identifying relationships and establishing comparisons between various geomorphological and topographic aspects and conditions in an area (Shekar & Mathew, 2024; 2022); and it is considered a prerequisite for a hydrological study (Bharath et al., 2023). It is key to understanding the morphodynamical and hydrological functioning in basins with scarce data availability (Castillo-Cruz & Medrano-Pérez, 2023; López-Ramos et al., 2022; Del Águila & Mejía, 2021), being a key determinant in planning and prioritizing basins, hydrological modeling, and natural resource conservation, allowing inferences about aspects related to relief, soil condition, drainage characteristics, surface runoff, and the potential associated with surface and groundwater, the erosive and infiltration capacity of the basin, as well as sediment transport (Bharath et al., 2023; Shekar & Mathew, 2024; 2022; Sukristiyanti et al., 2018).

The watershed is a hydrological analysis unit where surface water flows from high points through drains, channels, streams, and rivers towards a defined water body (Bharath et al., 2023; Sukristiyanti et al., 2018), integrating a series of environmental processes and characteristics expressed in the morphometry of the drainage networks (Bharath et al., 2023; Castillo-Cruz & Medrano-Pérez, 2023). Territory management based on the study of basin dynamics is key, among other things, to preventing soil erosion, conserving water, protecting biodiversity, and ensuring primary activities and long-term growth (Shekar & Mathew, 2022). In general, although a complete classification of all parameters is not available (Sukristiyanti et al., 2018), when carrying out the systematic analysis of the morphometric characteristics of basins, authors such as Castillo-Cruz and Medrano-Pérez (2023), Medrano-Pérez et al. (2021), Del Águila and Mejía (2021), Álvarez-Soberano and Medrano-Pérez (2020), and Romero et al. (2019) consider certain parameters grouped as a) general (area, perimeter, maximum and minimum elevation, among others); b) basin shape (form factor, Gravelius compactness factor, and circularity, among others); c) relief shape (mean basin elevation, mean main channel elevation, average channel slope, among others); and d) drainage network (drainage density, concentration time, among others).

The massification of access to Geographic Information Systems (GIS), remote sensing techniques, and Digital Elevation Models (DEMs) have enhanced watershed morphometry studies around the world (Castillo-Cruz & Medrano-Pérez, 2023; Shekar & Mathew, 2022; López-Ramos et al., 2022) with various applications and scopes. For example, they have been used for morphometric analysis per se (Del Águila & Mejía, 2021; Reis et al., 2023), for prioritizing areas for intervention or management (López-Ramos et al., 2022), geohydrological modeling (Vargas et al., 2020; Volonté & Gil, 2023), or determining flood susceptibility (Portuguez-Maurtu et al., 2023; Servidoni et al., 2023), among others. Likewise, there are local approaches and regional ones that comprise groups of basins or sub-basins (Doffo & González-Bonorino, 2005; Matovelle & Heras 2020; Yunus et al., 2014). Such regional studies provide the necessary information, for example, for spatially differentiated management (Obeidat et al., 2021) or to understand the variation in the supply of certain environmental services (Burbano-Girón et al., 2016). Given the quantitative nature and the enormous amount of data generated in morphometric analyses, problems have arisen in their management and interpretation because often due attention is not paid to data processing and statistical analysis (Różycka & Migoń, 2021).

In the case of Mexico, there are some antecedents of basin analysis with a morphometric approach (Velázquez-Sánchez et al., 2024; Méndez-Gutiérrez et al., 2021; Guevara-Gutiérrez et al., 2019; Mendoza et al., 2019; Romero et al., 2019); their combination with geomorphological aspects (Castillo-Cruz & Medrano-Pérez, 2023; Muñoz-Salinas et al., 2023; Álvarez-Soberano & Medrano-Pérez, 2020; Bocco & Prieto, 2014), and their combination with vegetation (López-Pérez et al., 2015). Given the potential of morphometric studies in understanding hydrological dynamics, their implementation is highly relevant in a Mexican region that has historically been affected by severe flood events: the Mexican southeast, particularly the state of Tabasco, where these events recurrently cause significant economic, material, and human losses (Arreguín-Cortés et al., 2014). Although floods represent one of the relevant problems in this region, the quality of climate information is a significant limitation in their prevention and management (Andrade-Velázquez & Medrano-Pérez, 2020), so the use of morphological parameters for hydrological characterization can solve these limitations.

In this context, morphometric analysis is key not only for the precise quantification of the shape and magnitude of the terrain but also for determining the statistical relationships between the different morphometric parameters, which contributes to the identification of patterns and relevant conclusions about the hydro-geomorphological functioning of watersheds. However, there are limitations regarding data processing and statistical analysis in morphometric studies, highlighting the importance of approaches that consider the systematic and rigorous integration of statistical analysis for understanding the morphometric dynamics of basins.

The present research describes the hydrological dynamics of 26 sub-basins of the Grijalva-Villahermosa Hydrological Region (RH30D) according to morphometrics parameters. This is one of the most important regions in the country in terms of flow, hydroelectric production, oil generation, and biological and socio-cultural richness. The objective was to group sub-basins according to their morphodynamical and hydrological similarity, using multivariate methods, to provide useful input for prevention, management, and control of flood risk.2.

2. Study Area

The Grijalva-Villahermosa Hydrological Region (RH-30D) is one of six hydrological sub-regions within the Grijalva-Usumacinta Hydrological Region (RH-30). It is situated between the parallels 17°0' and 18°30' north latitude and the meridians 91°30' and 93°15' west longitude. It is bounded by the Gulf of Mexico to the north, the state of Tabasco and a small portion of Veracruz to the west, Tabasco and Chiapas to the east, and Chiapas to the south. RH-30D covers an area of approximately 22,806 km2, with Tabasco accounting for 47.5% and Chiapas for 52.5% of its territory. It fully encompasses seven municipalities in Tabasco and 32 in Chiapas, as well as having partial territorial jurisdiction over another 26 municipalities spanning both states. The region is inhabited by 2,955,967 people, with 62.2% residing in Tabasco and 37.8% in Chiapas, primarily concentrated in the municipal capitals (Figure 1).

In terms of physiographic provinces and morphological landscapes, the area in Tabasco state is characterized by plains and terraces with elevations reaching up to 70 meters above sea level (m a.s.l.). Additionally, there are intermontane valleys, hills, and mountains, along with alluvial and diluvial plain reliefs. Slopes on detrital and limestone rocks dominate, where erosive processes shape the terrain, ranging in elevation from approximately 40 m a.s.l. to 1,020 m a.s.l. (Velázquez-Sánchez et al., 2024; Zavala-Cruz et al., 2016).

In Chiapas, a portion of the study area lies within the Gulf Coastal Plain (LCG), characterized by typical alluvial plains and hills. The Sierra Norte de Chiapas (SNC) encompasses the Northern Mountains (MN) and the Highlands of Chiapas (AC). Within the MN and AC systems, various relief forms are recognized, delineated by a series of mountain ranges separated by elongated valleys (Rubio & Triana, 2006). The altitude of the LCG and SNC physiographic provinces varies between -12 m a.s.l. to 929 m a.s.l. and -1 m a.s.l. to 2,903 m a.s.l., respectively. (Figures 1 and 2; JAXA/METI ALOS PALSAR L, 2011).

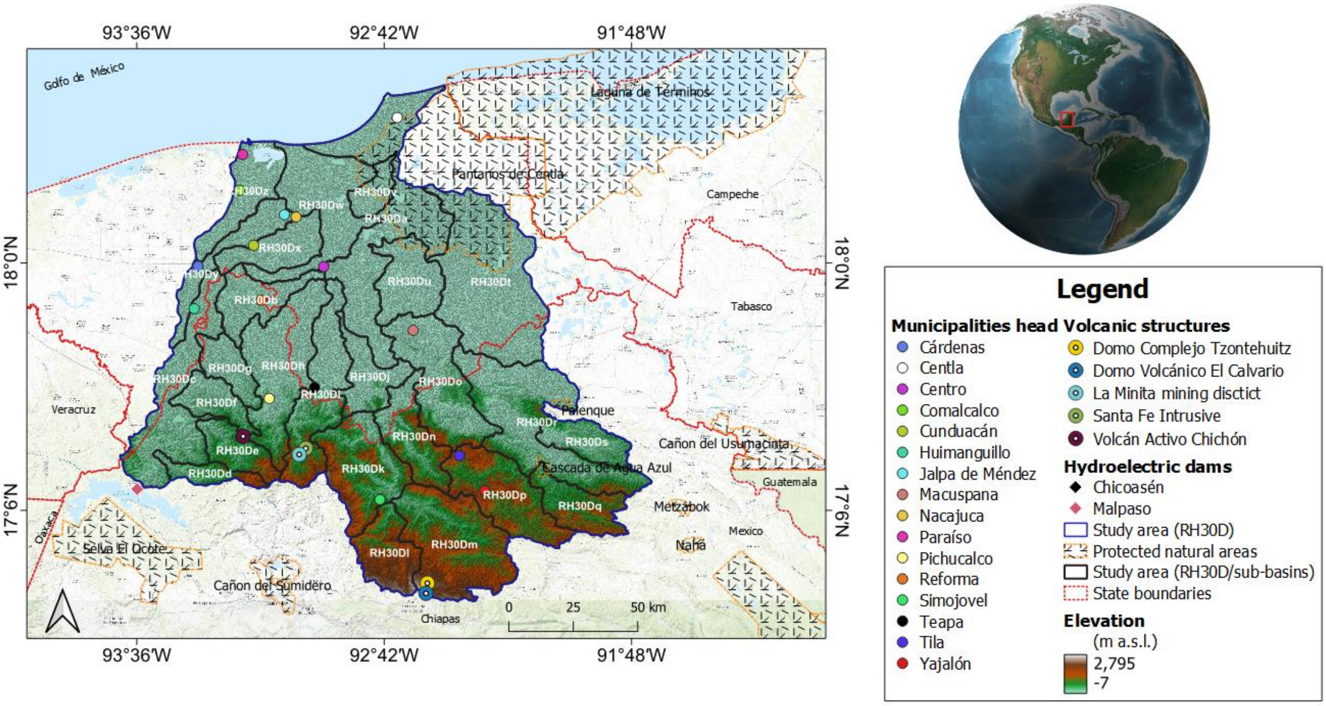

Figure 1. Location of the study area and characteristics of elevation, volcanic structures, hydroelectric dams and municipalities. Source. Own elaboration based on spatial information from Bustamante-Orozco et al. (2023); SINA (2023); INEGI (2023), and CGIAR-CSI (2022).

In terms of the geological context of the study area (see Figure 2), marine, fluvial, and lacustrine sediments, comprising clays, silts, and sandstones, among others, predominate. The water table depth is 3.5 meters. Additionally, notable volcanic structures such as the Chichón/Chichonal volcano, the Santa Fe Intrusive, and the La Minita, El Calvario, and Tzontehuitz domes are present (see Figure S1; Bustamante-Orozco et al., 2023).

Concerning soil composition, according to INIFAP and CONABIO (1995), the RH-30D comprises soils such as Alisols, Arenosols, Cambisols, Fluvisols, Gleysols, Leptosols, Vertisols, among others (see Figure S1). These soils are predominantly of alluvial and organic origin with low drainage capacity (Pérez-Falls et al., 2022), which contributes to the formation of lakes and lagoons (Medrano-Pérez et al., 2023; Marín & Torres-Ruata, 1990).

Biodiversity within the region is characterized by various ecosystems, including grasslands, marshes, reed beds, rainforests, poplar forests, mangroves, and a small portion of forests and high evergreen rainforest (DOF, 2010). Additionally, the area encompasses three protected natural areas with different management categories: part of the Pantanos de Centla, designated as a Biosphere Reserve; the Cascadas de Agua Azul, categorized as a Wildlife Protection Area, and Palenque, designated as a National Park.

The R H-30D receives an average annual precipitation of 2,461 mm, with seasonal variations; the wettest month (October) averages 390 mm, while the driest month (April) averages 63 mm (Fick & Hijmans, 2017). According to García and CONABIO (1998), in the region predominates two climate types with year-round rains, semi-humid warm [(A)C(fm)] and humid warm [Am(f)]. However, the semi-humid warm climate is only found in the southern part of the Grijalva-Villahermosa Region (Figure S2), over the Sierra Madre de Chiapas, with elevations that range from 1,000 to 1,500 m a. s. l. The mean annual temperature exceeds 18°C, dropping below 18°C in the coldest month, and surpassing 22°C in the warmest month. In the area with the humid warm climate, the mean annual temperature is above 22°C, and in the coldest month, it remains above 18°C.

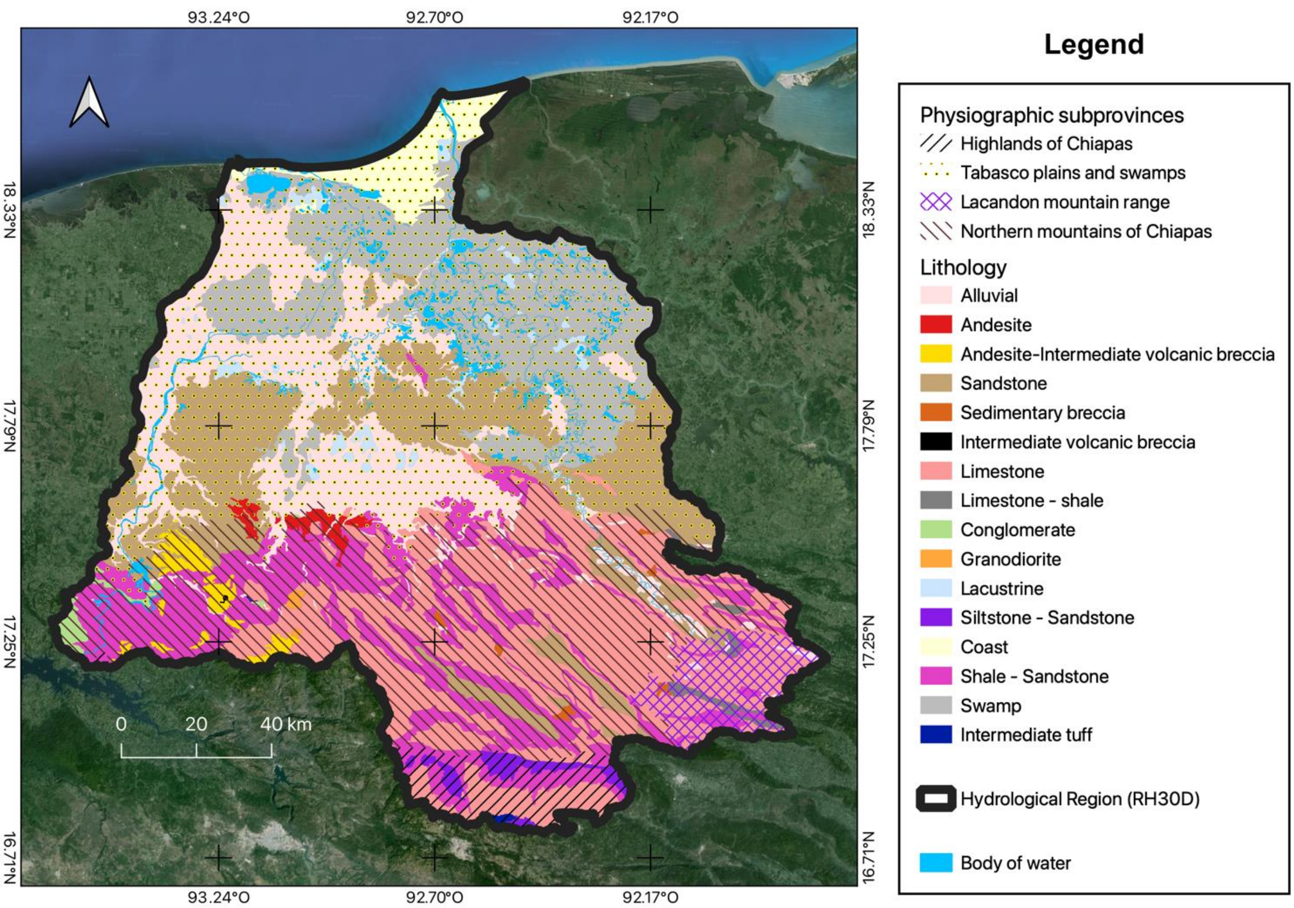

Figure 2. Physiographic provinces and lithology of RH30D. **Source**. Own elaboration based on: INEGI 2001, conjunto de datos vectoriales fisiográficos. Continuo Nacional. Escala 1:1 000 000. Serie I (Subprovincias fisiográficas); INEGI (1977 - 1989). Conjunto de Datos Geológicos Vectoriales escala 1:250,000.

The RH-30D region is notable for its abundant water resources, receiving waters from the Highlands of Chiapas and Guatemala, with rivers such as the Grijalva-Mezcalapa, Samaría, El Carrizal, Tacotalpa, Chacté, Tulijá, Pichucalco, and de la Sierra, among others. Additionally, there are lagoon systems including Laguna de las Ilusiones, Mechoacán, Maluco, La Ceiba, Ismate, and Chilapilla, among others. The Nezahualcóyotl (Malpaso) and Ángel Albino Corzo (Peñitas) dams also influence the hydrological and socio-ecosystem dynamics of the Tabasco's plain (Figure S3). The Grijalva River has been shaped by anthropogenic factors (such as flood control works and pollution) and historical channel bifurcations that have occurred multiple times (Mendoza et al., 2019). Furthermore, Bustamante-Orozco et al. (2023) and Medrano-Pérez et al. (2023) report significant groundwater dynamics in this area. The predominant activities in the RH-30D region are agriculture, livestock farming, and energy production (hydroelectric and oil).

3. Materials and Methods

We selected 12 morphometric parameters (MP) considered in previous studies (Castillo-Cruz & Medrano-Pérez, 2023; Medrano-Pérez et al., 2021; Álvarez-Soberano & Medrano-Pérez, 2020), and others deemed relevant due to the hydrological conditions present in the study area, which comprises 26 sub-basins. These parameters are: Form Factor (Ff), Elongation Ratio (Er), Circularity Ratio (Cr), Compactness Coefficient (Cc), Lemniscate Ratio (K), Relief Ratio (Rh), Drainage Density (Dd), Ruggedness Number (Rn), Bifurcation Ratio (Br), Texture ratio (Tr), Stream Frequency (Fs), and Length of Overland Flow (Lg). A simplified chart of the methodology is shown in Figure 2.1, and the definitions and meanings of the MPs are shown in Table 1.

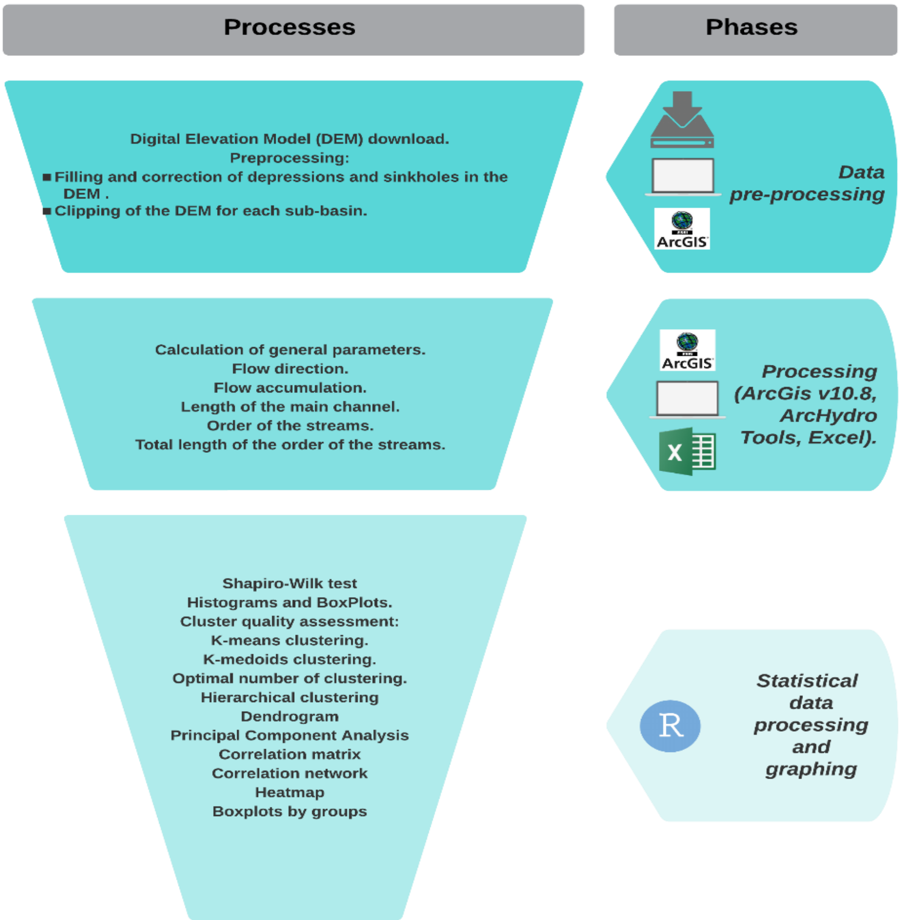

Figure 2.1. Methodological scheme of the research.

3.1 Obtaining Base Data

The first step to calculate the MPs was to obtain the delimitation of the 26 sub-basins corresponding to the Grijalva-Villahermosa Hydrological Region (RH30D). This was downloaded from the National Water Information System (SINA) of the National Water Commission (CONAGUA) (SINA, 2023). Subsequently, the Digital Elevation Model of the area (DEM) was obtained from the Alaska Satellite Facility (ALOS PALSAR), with a horizontal resolution of 12.5 x 12.5 m (JAXA/METI ALOS PALSAR L, 2011), providing suitable accessibility and global coverage characteristics for the regional of basin analysis, yielding consistent results and acceptable precision for the scope of the study. The DEM was then corrected to fill existing depressions or sinks using the ArcHydro Tools in the ArcMap v. 10.8 software (ESRI, 2011), as a preliminary step to calculating the MPs. ArcHydro Tools employs a rational, efficient, and consistent algorithm for extracting the drainage network, as detailed by Rather et al. (2017). A threshold of 2000 was used in this study to produce a well-defined drainage network corresponding to the characteristics of the analyzed area.

3.2 Obtaining Morphometric Parameters (MPs)

First, we calculated the general parameters of the sub-basins (such as area, perimeter, etc.), and then, from the DEM, we obtained the drainage network (see Table S1) using the Strahler method (Strahler, 1964) with ArcHydroTools (ESRI, 2011). This analysis provided for each sub-basin the stream order, the total stream length, and the length of the main channel. Using these inputs, the MPs were calculated according to the formulas shown in Table 1.

3.3 Statistical Processing

Statistical processing was performed in R v.4.2.2. and its graphical interface RStudio v.4.2.2. (R Core Team, 2022). The normality of the parameter distributions was analyzed using the Shapiro-Wilk test (1965). Once the non-normal morphometric parameters were identified, a Johnson transformation was performed with the R package of the same name (Santos-Fernández, 2014). Since the resulting values of the transformation are Z-values, the untransformed parameters were also converted to Z-values to make them comparable.

In order to observe the relationships between the MPs, Pearson correlations were obtained between all MPs using the Performance Analytics package (Peterson & Carl, 2020), and a correlation network was created to visually identify the grouping of MPs using the R package corrr (Kuhn, Simon, & Cimentada, 2022). To identify the sub-basins with similar hydrological behavior according to the multivariate relationships of the MPs, a clustering was performed using the K-medoids method, which aims to maximize the similarity of elements within each cluster and maximize the difference between observations in different clusters. The first step was to define the appropriate number of clusters or groups, which was done through an elbow analysis using the K-means as the partition function with the R package NbClust (Charrad et al., 2014). Once the number of groups was defined, they were obtained by K-medoids using the R package cluster (Maechler, Rousseeuw, Struyf, Hubert, & Hornik, 2022). For the visualization of the groups and the understanding of the multivariate relationships of the morphometric parameters, the medoids were represented in a biplot of a principal component analysis (PCA), using the first three axes, with the R package FactoExtra (Kassambara & Mundt, 2020). Finally, to visualize the sub-basins with similar variations in the MPs and better interpret the results about the obtained medoids, a heatmap (base R Heatmap function) was created for each MP. To characterize the obtained groups, their mean, standard deviation, and coefficient of variation were calculated, and to determine in which MPs there were significant differences between the group means, a Kruskal-Wallis analysis with a Dunn post hoc analysis was performed. By analyzing the characteristics of the identified sub-basin groups, a flood risk level was assigned to each sub-basin according to the information provided by the MPs.

Table 1. Morphometric parameters (MP) calculated for each sub-basin.

Parameter	Type	Definition	Formula	Meaning of PM
Drainage Density (Dd)	Drainage	Ratio of the total length of the drainage network of a basin to the area of the basin.	$Dd = \frac{Lu}{A}$ (km/km^2)	The higher the drainage density, the faster the response of the watershed to a storm, evacuating the water in less time, since a drop of water must travel a shorter length of slope, with a higher runoff velocity. tendency to runoff and erosion (Horton, 1932).
Texture ratio (Tr)	Drainage	Ratio between the total number of first order streams and the perimeter.	$Tr = \frac{Nu}{P}$	Values > 8 are associated with a high risk of soil erosion (Horton, 1945).
Form Factor (Ff)	Form	Ratio of the length to the width of the watershed. It is measured as the area of the basin divided by its length squared.	$Ff = \frac{A}{L^2}$	Indicative of the discharge regime: the lower the value, the faster the response in elongated basins in valleys. For irregular basins with permeable soil, it is not a sensitive indicator (Horton, 1932).
Stream Frequency (Fs)	Drainage	Ratio between the total number of streams and the area.	$Fs = \frac{Nu}{A}$	The higher the frequency of streams, the faster the response of the watershed (Horton, 1945).
Lemniscate Ratio (K)	Form	Ratio through a Lemniscata equivalent to the same length and area of the basin.	$K = \frac{\pi L^2}{4A}$	The shape index k, through a lemniscate equivalent to the same length and area of the basin, classifies the hydrological capacity of the basin in a better way than a circle, which may underestimate its drainage capacity. Low values are associated with a catchment with a more rounded shape, which would consequently have strong floods, large peak flow value, high flow velocity, erosion processes and high suspended sediment rates. High values are associated with elongated basins with slower hydrologic responses (Chorley, Donald, & Pogrzelsk, 1957).
Compactness Coefficient (Cc)	Form	Ratio between the perimeter of the basin and the perimeter of a	$Cc = 0.28\ \frac{P}{\sqrt{A}}$	Low values are associated with a round-shaped basin, and high values are associated with elongated basins (Gravellius, 1914).

Parameter	Type	Definition	Formula	Meaning of PM
		circumference with the same area as the basin.		
Length of Overland Flow (Lg)	Drainage	Ratio of the inverse of 2 times the drainage density.	$Lo = \frac{1}{(2 * Dd)}$ (m)	It is the distance water must travel before concentrating into streams. A low value of Lg (< 0.2) indicates high relief, short flow distances, more runoff and less infiltration, leading to increased vulnerability to flash floods. A high value (> 0.3) means gentle slopes and long flow paths, allowing more infiltration and reduced runoff (Horton, 1945).
Bifurcation Ratio (Br)	Drainage	Ratio between the number of segments of a given order and those of immediately higher order.	$Rb = \frac{Lu}{Lu + 1}$	Low values mean that the drainage pattern is independent of geology, while high values are associated with drainage patterns controlled by geologic structures (Horton, 1945).
Circularity Ratio (Cr)	Form	Ratio between the area of the basin and the area of a circle of equal perimeter.	$Cr = \frac{4\pi A}{P^2}$	High values are associated with a more circular basin shape, and low values with elongated basins (Miller, 1953).
Elongation Ratio (Er)	Form	Ratio between the diameter of a circle with the same area as that of the basin and the length of the main channel.	$Er = 1.128 \frac{\sqrt{A}}{L}$	Generally, this index is classified into low and high values. Low values are associated with elongated basins, and high values with circular basins (Schumm, 1956).
Relief Ratio (Rh)	Relief	Ratio between the slope and the length of the basin.	$Rh = \frac{R}{L}$	Low values mean low slope and low relief, and high values mean steep relief and high slope (Schumm, 1956).
Ruggedness Number (Rn)	Relief	Ratio of slope to drainage density.	$Rn = R * Dd$	High values correspond to basins with relief possibly affected by tectonic uplift, while low values are associated with tectonic stability or slow uplift rates (Melton, 1957).

4. Results

The present study addresses 12 morphometric parameters (MPs) in the 26 sub-basins composing the Grijalva-Villahermosa Hydrological Region (RH30D), grouped and analyzed according to their similarity. Table S1 show sub-basins' general parameters, while Table S2 shows their MPs values. Figure 3 shows the geographic variation of MPs. According to the Shapiro-Wilk normality test, only 3 of the 12 parameters follow a normal distribution: Ff, Er, and Cr. With the Johnson transformation applied to the remaining variables, a normal distribution was achieved for all MPs (Table 2).

Table 2. Shapiro-Wilks test(1965)

Morphometric parameters	Before data transformation		After data transformation	
	W	**p-value**	**W**	**p-value**
Ff	0.954	0.291	Not transformed	-
Er	0.980	0.877		
Cr	0.970	0.626		
Cc	0.900	0.016	0.992	0.999
K	0.843	0.001	0.979	0.854
Rh	0.887	0.008	0.935	0.103
Dd	0.848	0.001	0.964	0.467
Rn	0.839	0.001	0.961	0.413
Br	0.837	0.001	0.972	0.688
Tr	0.894	0.011	0.982	0.911
Fs	0.656	0.000	0.978	0.823
Lg	0.718	0.000	0.940	0.140

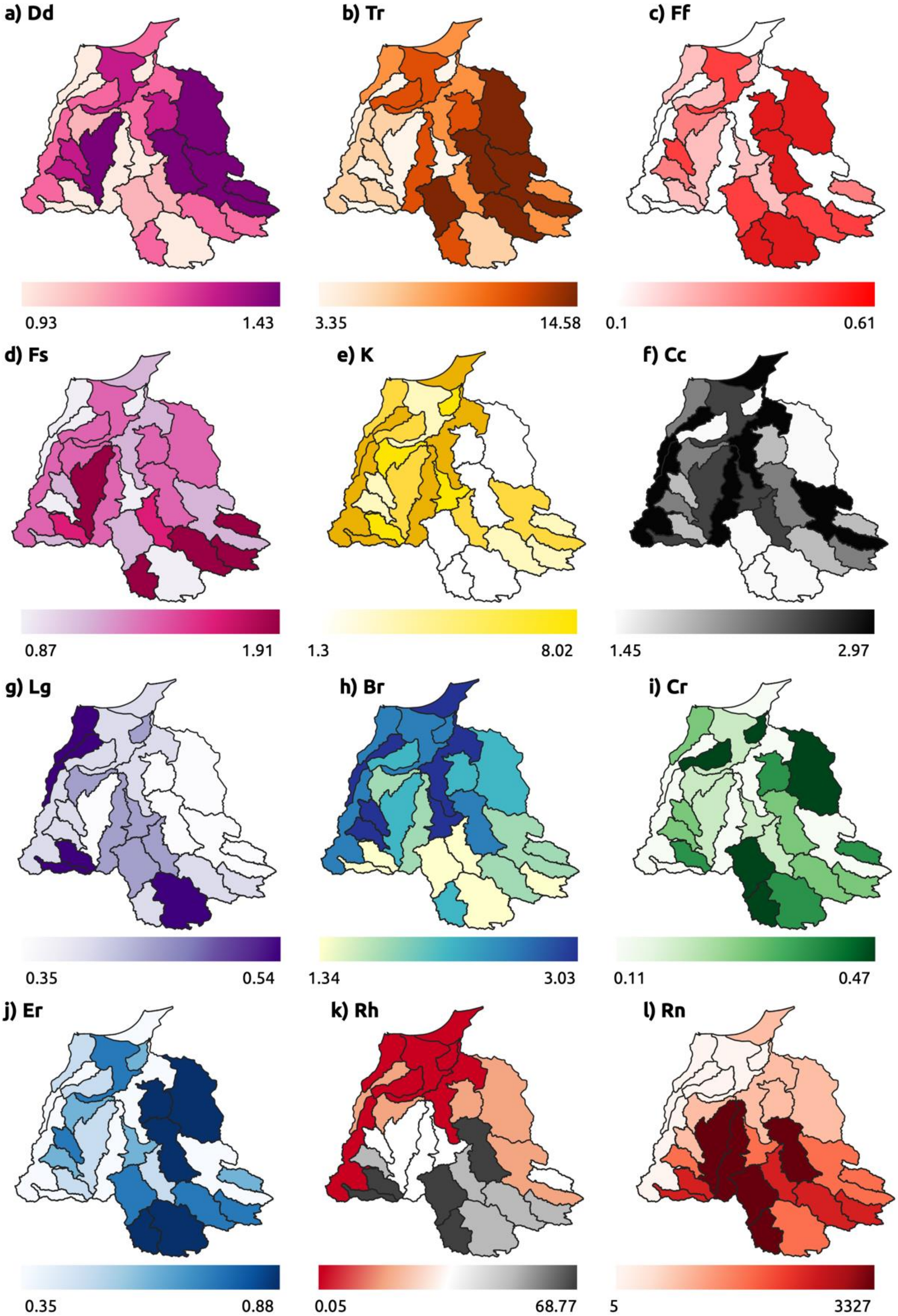

Figure 3. Morphometric parameters of RH30D by sub-basin: a) Drainage density; b) Texture ratio; c) Form factor; d) Stream frequency; e) Leminiscata ratio; f) Compactness factor; g) Surface flow length; h) Bifurcation ratio; i) Circularity ratio; j) Elongation ratio; k) Relief ratio; and l) Roughness number.

The variation of the data in the MPs presents a homogeneous behavior (Figure 4). The length of overland flow (Lg) is displayed as the parameter with the lowest data variability concerning the mean. The pairwise correlations of the MPs shown in Figure 5 revealed that the strongest associations occur between MPs of the same type (i.e., between parameters that measure shape, drainage, or relief). On the other hand, the correlation network between the MPs shows certain groupings (Figure 6): a) parameters associated with the shape of the sub-basin (Ff, Er, Cr, Cc, K); b) Length of Overland Flow and Drainage Density (Lg, Dd), and c) Relief and Ruggedness (Rh, Rn). Additionally, one of the drainage parameters, Tr, is associated with the shape parameters Ff, Er, and K.

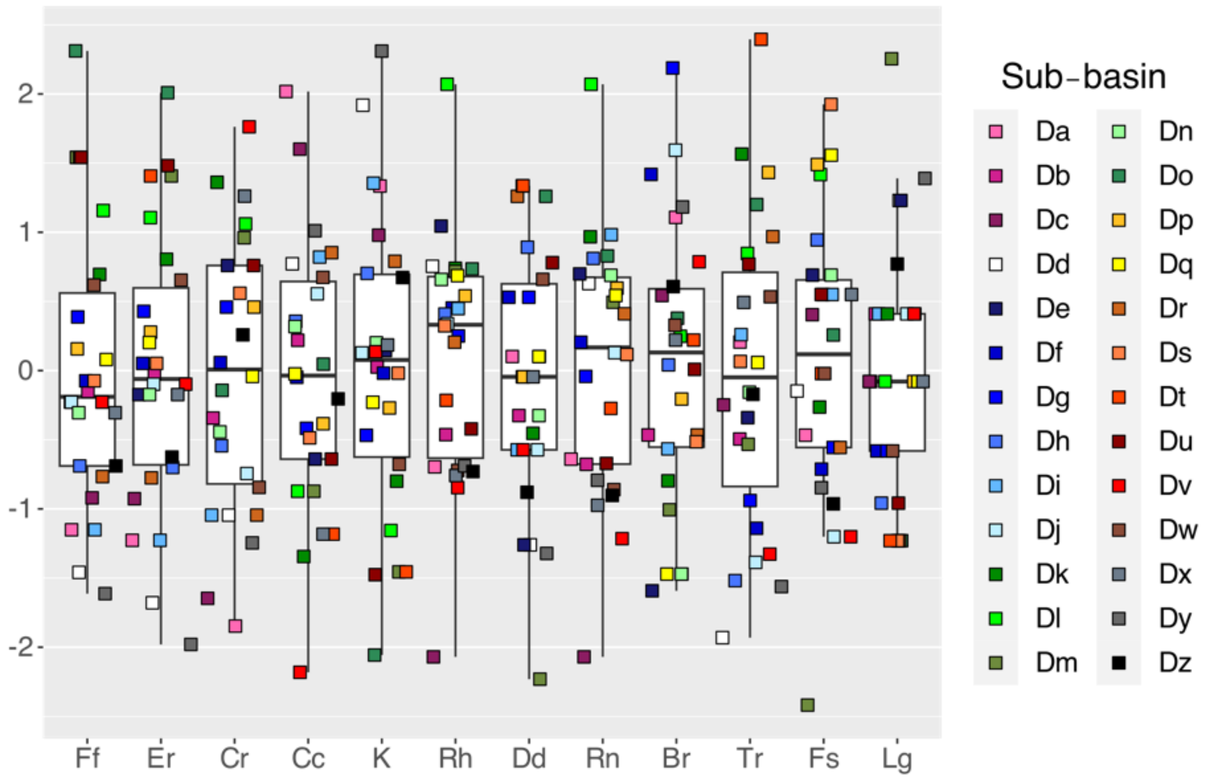

Figure 4. Morphometric parameter's boxplots.

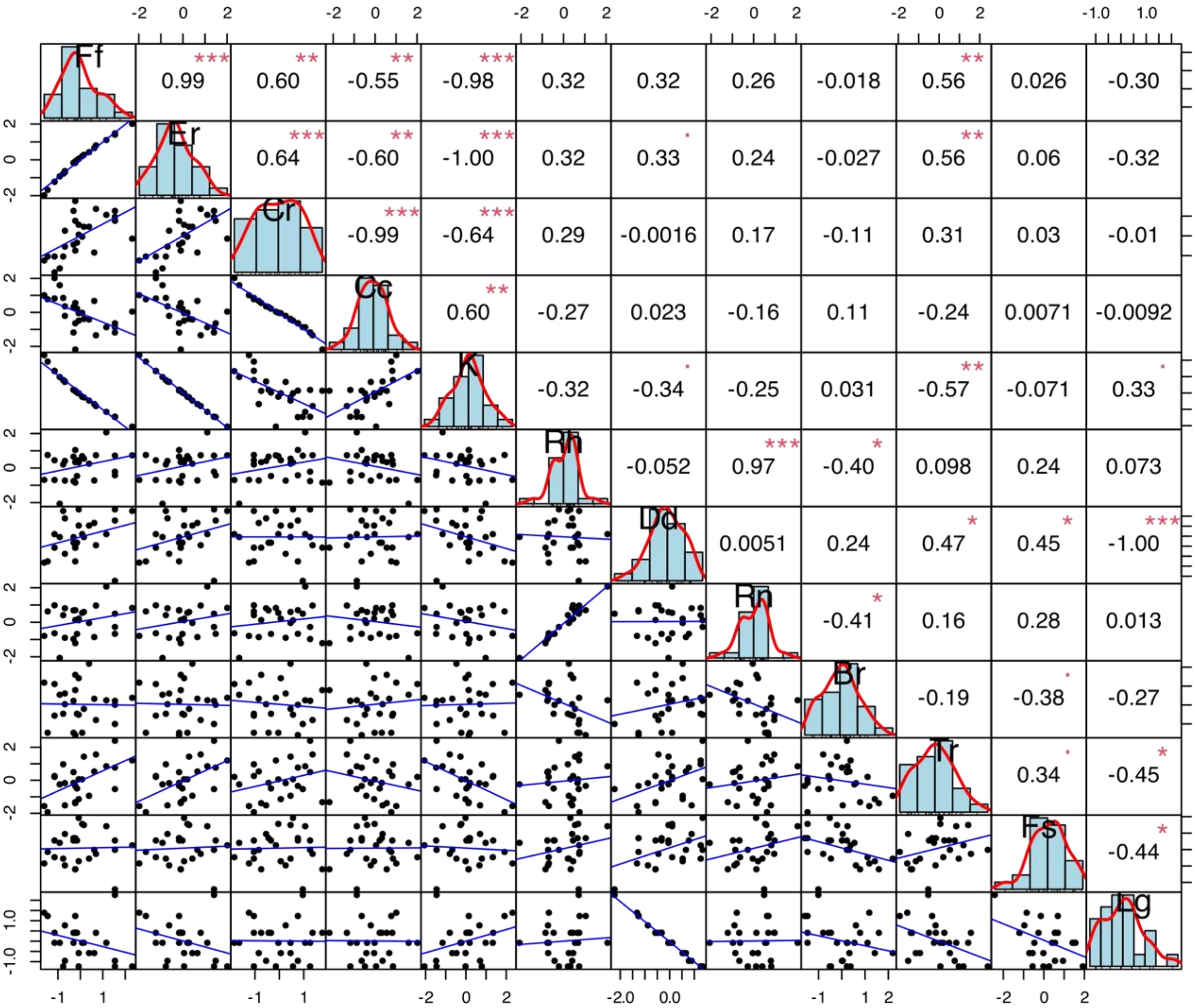

Figure 5. Pearson correlations of the morphometric parameters. The diagonal of the matrix shows the histograms of each morphometric parameter (MP). The upper triangle displays the correlation coefficients (r) with their p-significance ("***" = 0; "**" = 0.001, "*" = 0.01, "." = 0.05), and the lower part shows the scatter plots of each correlation.

The medoid clustering analysis classified the sub-basins into 4 groups (Figures 7 and 8). Group 2 stands out with the highest number of sub-basins, 9, followed by Group 4 with 7 sub-basins, Group 3 with 6, and Group 1 with 4. Additionally, Figure 7b shows the spatial distribution of this clustering, indicating that Groups 2 and 3 have sub-basins mainly distributed in mountainous areas (compare Figures 1 and 7), while in Group 4, lowland areas predominate. Clearly, the sub-basins of Group 1 stand out for their very elongated shape, while those of Group 4 are characterized by a shape that tends to be more rounded.

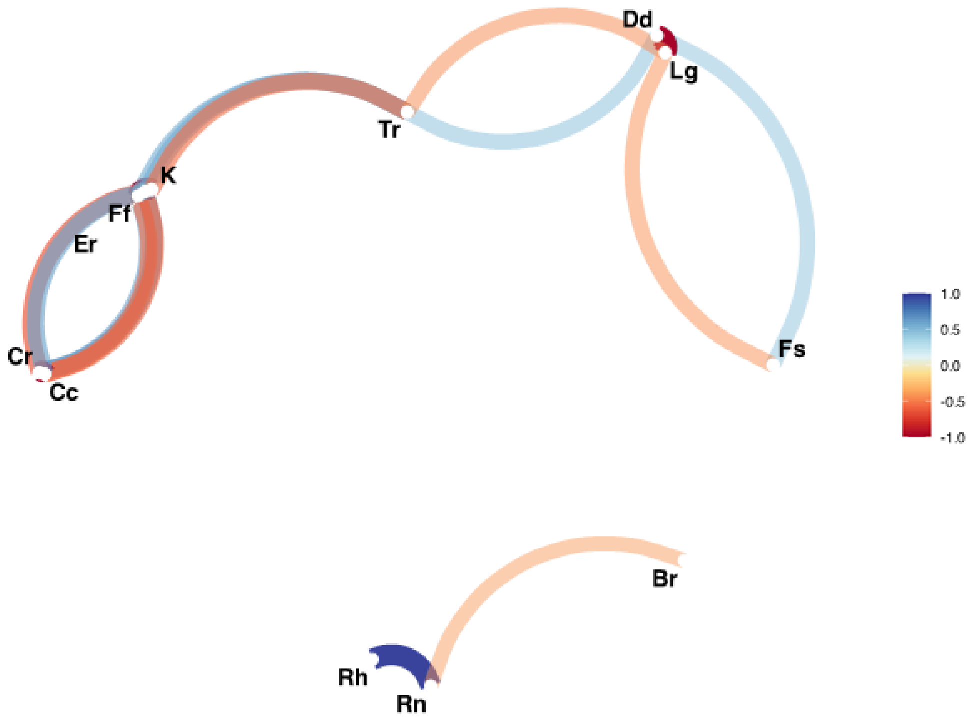

Figure 6. Pearson correlation network between morphometric parameters (r ≥ 0.4).

Regarding the Principal Component Analysis (PCA, Figures 7a and c), the first two axes explain 61.9% of the variation in the MPs, and the third axis explains an additional 17.2% (Figure 7c). In the supplementary information (Tables S3, S4, and S5), the percentages of accumulated variance and the influence and contribution of the variables in each of the obtained dimensions can be observed in detail.

The PCA analysis reveals that the primary component, explaining 40.9% of the variance of the MPs, distinctly separates the sub-basins from groups 1 and 4 (Figure 7a). Group 1 exhibits the highest values in the lemniscate ratio (K) and the compactness coefficient (Cc), characteristics associated with elongated basins. Conversely, Group 4 showcases maximum values of elongation ratio (Er), form factor (Ff), Texture ratio (Tr), and circularity ratio (Cr), indicative of more rounded basins. Meanwhile, Group 3 sub-basins are positioned at the center of the PCA's axes 1 and 2 biplot, indicating intermediate values for all MPs. Similarly, Group 4 appears centrally on the biplot of PCA's axes 2 and 3. Group 2 tends to occupy the central part of axis 1 but is distinguished from other groups along component 2 due to a greater length of overland flow (Lg). Additionally, Group 2 stands out on the third PCA axis, exhibiting high values of relief ratio (Rh) and ruggedness number (Rn). Conversely, Group 3 exhibits maximum differentiation from Group 2 with high values of bifurcation ratio (Br) (Figure 7b).

The heatmap representing the different MPs across the 26 analyzed sub-basins and the boxplots for each MP facilitate comparison of their values between groups. The most notable differences are observed between the MPs of Groups 1 and 4, which show opposite trends in K and Cc compared to Ff and Er. Conversely, Groups 2 and 3 exhibit opposing behaviors in parameters such as bifurcation ratio (Br) and stream frequency (Fs). Table S6 provides the mean, standard deviation, and coefficient of variation of the MP values for each identified group.

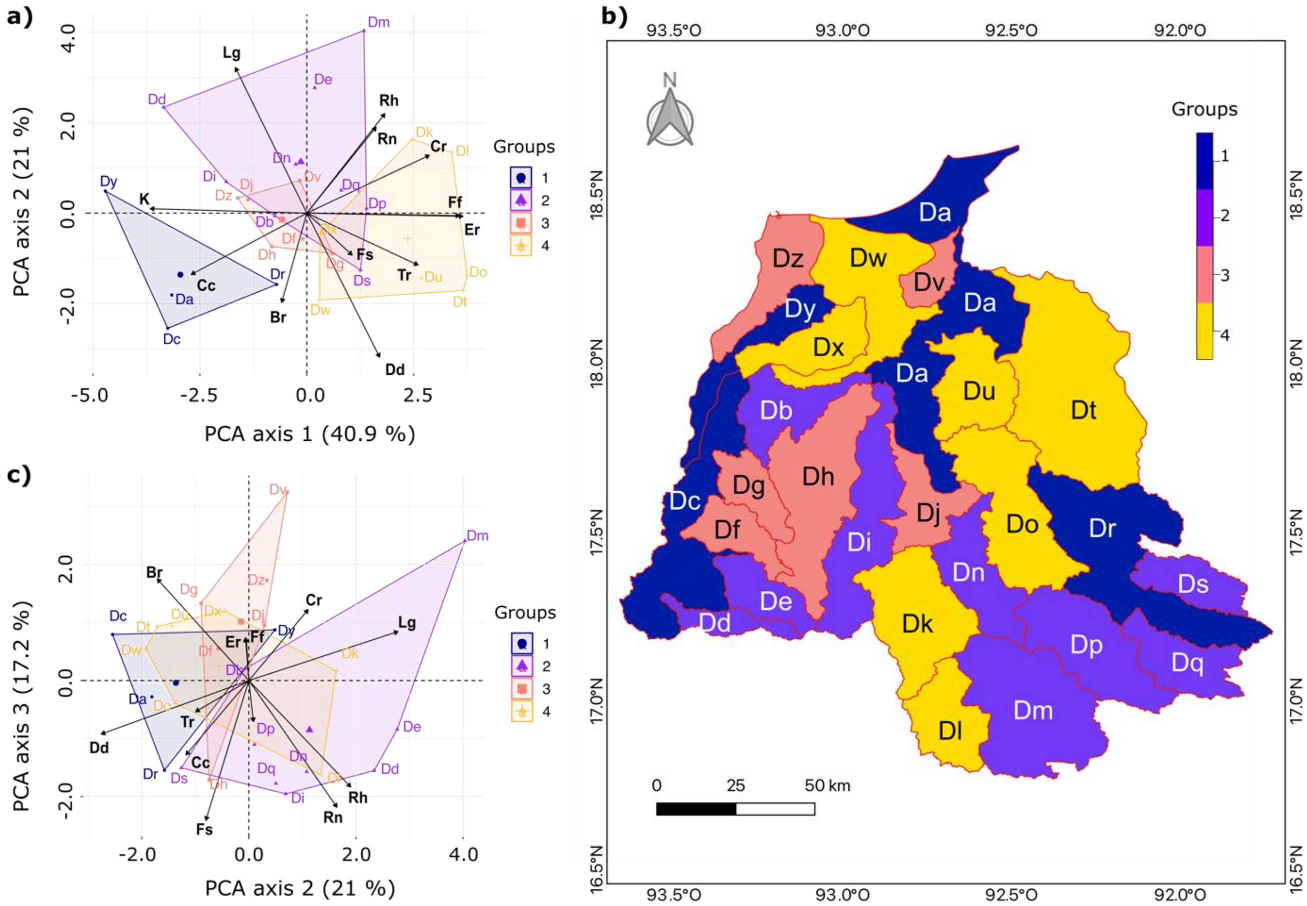

Figure 7. Clustering of sub-basins by medoids. The biplots of the first three principal components of the PCA are shown, where the relationship between the sub-basin groups and the morphometric parameters (MPs) is observed in sections a and c, and the map with the spatial distribution of the groups (section b). The biplots display the MPs as arrows and black letters, and the sub-basins are indicated with colored letters according to their group.

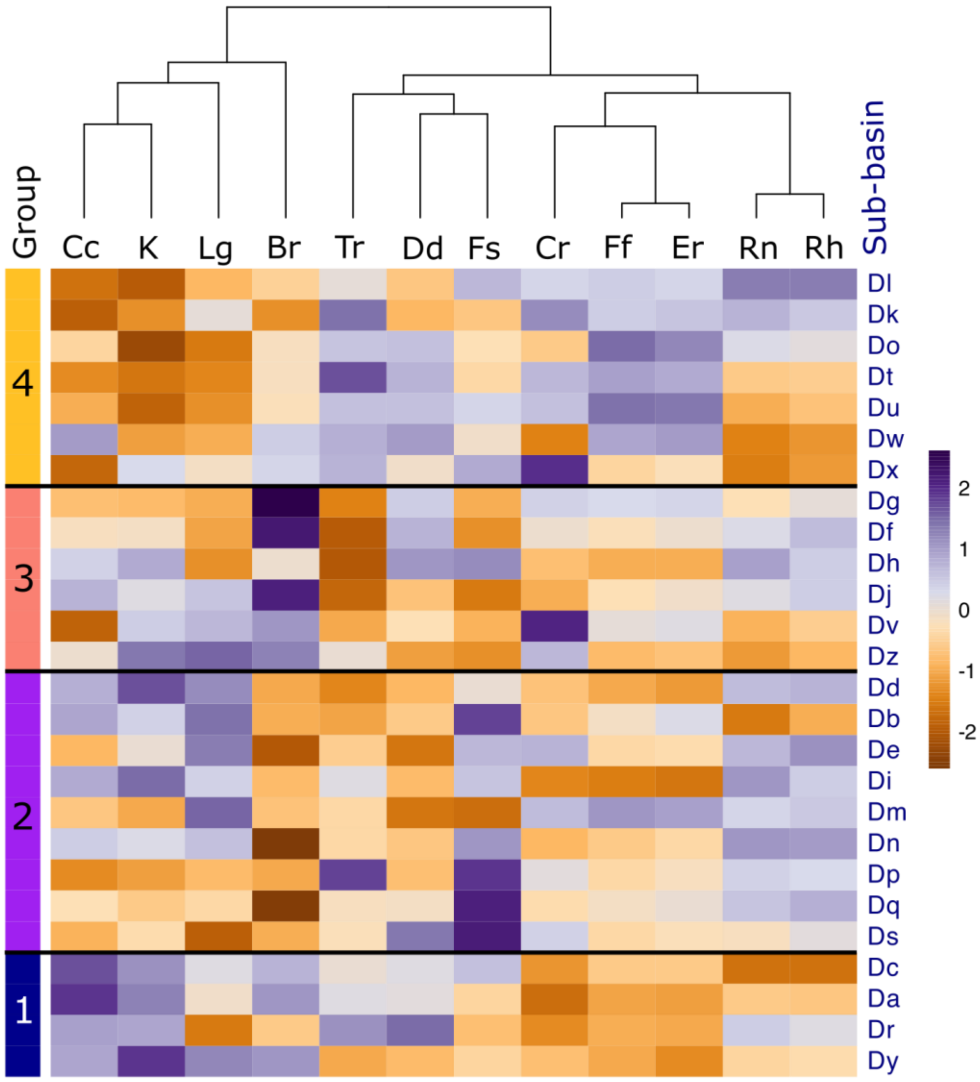

Figure 8. Heatmap showing for each column how the values of the morphometric parameters (MPs) of the sub-basins vary with respect to the rest (purple cells, values above the mean; orange cells below the mean, in standard deviations). The cluster above the matrix shows a hierarchical grouping between MPs, while the colors on the left show the groups of sub-basins obtained with the medoids.

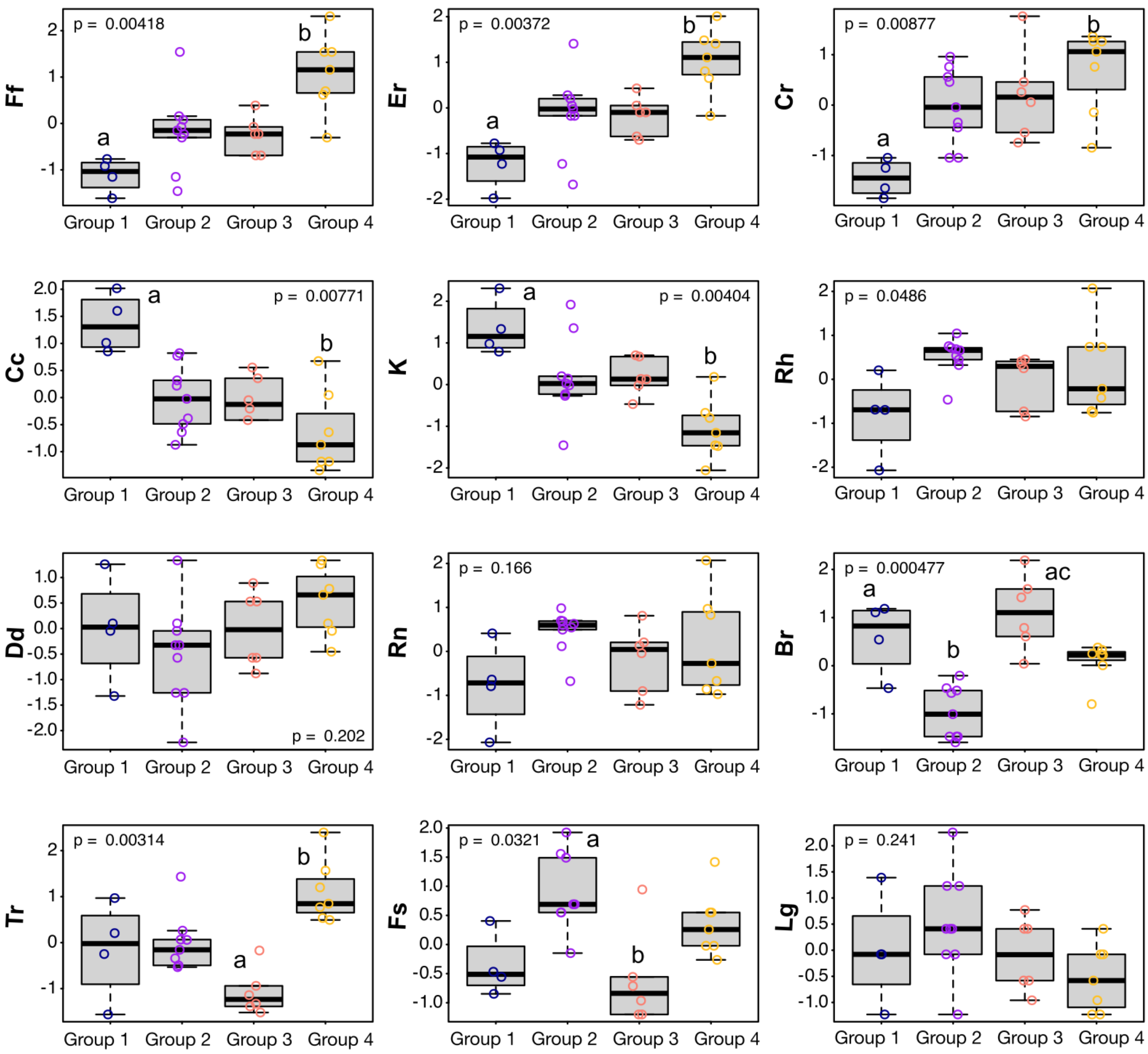

Figure 9. Boxplots of the morphometric parameters by groups of sub-basins obtained with the medoids. Significant differences between groups are shown with different letters. Groups without letters did not show significant differences (Dunn's test).

5. Discussion

We analyzed the relationships between 12 morphometric parameters (MP) in the 26 sub-basins that make up the Grijalva-Villahermosa Hydrological Region (RH30D), intending to identify clusters with similar hydrological behavior and identify those exposed to higher flood risks.

5.1 Relations among sub-basins morphometric parameters

The RH30D is a region with significant morphometric variation, featuring a mountain range in the southern watershed, which is part of the Chiapas highlands. This area transitions into lower elevations towards the middle part and ends in the Tabasco plain to the north, where runoff, flow rates, and sediments concentrate before flowing into the Gulf of Mexico. These relief characteristics influence temperature and precipitation variability, ecosystem diversity (INE, 2004), and the configuration of the hydrographic network, impacting the region's geomorphology (Sang et al., 2022; Jin et al., 2021; Wu et al., 2020; Ghomash et al., 2019). The drainage network for all sub-basins is of 4th, 5th, and 6th orders, showing clear patterns in river channel arrangements and a high-energy drainage network (Castillo-Cruz & Medrano-Pérez, 2023). This indicates the presence of structural relief controls (such as faults, fractures, folds, dikes) and erosion processes (INE, 2004).

Pearson correlations (Figure 5) revealed the strongest associations between MPs that measure similar aspects of the basin: shape, drainage, or relief, as illustrated in Figure 6. Shape parameters provide indirect information, and changes in these parameters could impact water flow, sediment accumulation, and precipitation distribution (Garg et al., 2017). The highest positive correlation was found between the form factor and the elongation ratio (Ff and Er, $r = 0.99$), as both parameters measure how elongated a sub-basin is using its area and length (Matovelle & Heras, 2020). The circularity ratio (Cr) also positively correlated with these parameters ($r = 0.60$ and 0.64, respectively, $p < 0.01$). Additionally, there is a positive correlation of 0.6 ($p < 0.01$) between Cc and K, as both have high values for elongated basins and low values for more rounded basins, indicating their association with the runoff concentration capacity.

Regarding topography, the relationship between MPs associated with relief, specifically Rh (relief ratio), Rn (ruggedness number), and Br (bifurcation radio), is noteworthy. The highest correlation occurs between Rh and Rn ($r = 0.97$, $p < 0.001$). Since both are ratios of elevation relative to the length of the basin and the drainage density, respectively, it can be inferred that basin length varies directly with drainage density in the study area (Doffo & González-Bonorino, 2005). This suggests that topographic characteristics affect water flow resistance and spatial precipitation distribution, influencing runoff and erosion (Meshkat et al., 2019; Idowu et al., 2002). There is also a low association between MPs related to the efficiency of a basin's drainage system, specifically Dd (drainage density) and Tr (texture ratio,0.47, $p < 0.1$). This low relationship is partly because Tr is associated with basin shape (elongated basins tend to have a low number of streams per unit perimeter), while channel length per unit area depends more on lithological and permeability properties. This influence of lithology and permeability on the morphological configuration of the drainage network is reported by Castillo-Cruz & Medrano-Pérez (2023) for the Grijalva and Usumacinta sub-basins within the study area and its influence zones. Similarly, the positive connection between Br and Dd suggests that greater bifurcation is linked to higher drainage channel density, significantly impacting drainage system efficiency and runoff capacity (Di Lazzaro et al., 2015). Furthermore, the positive correlation observed between Fs and Dd implies that a higher frequency of streams is related to a higher drainage channel density (Marani et al., 2003), which could have implications for runoff management and hydrological efficiency. Finally, there is an association between a drainage MP and several shape MPs: Tr correlated with Ff, Er, and lemniscate ratio (K) ($r = 0.56$ for the first two, and $r = 0.57$ for the last one, $p < 0.01$). These correlations result from a higher number of streams per unit perimeter in rounded basins compared to elongated basins, as the area per unit perimeter is greater in the former, leading to more streams.

5.2 Grouping of sub-basins according to their morphometric parameters

Figures 8 and 9 (and Table S6) illustrate how sub-basin groups differ based on certain patterns of morphometric parameter (MP) variation using medoid grouping. For instance, in group 1, the circularity ratio (Cc) and compactness coefficient (K) have high values, while Ff and Er have low values, indicating very elongated basins. Conversely, group 4 has inverse values for these parameters, indicating rounder basins. Groups 2 and 3 show values close to the mean in almost all parameters, translating into different hydrological behaviors. However, they differ particularly in their Br and Fs values: group 3 has drainage patterns likely controlled by geological structures (high Br values), whereas group 2 has low Br values and a high number of streams per unit area (high Fs), indicating faster hydrological responses compared to group 3.

5.3 Multivariate relationships of morphometric parameters and flood risk

Morphometric parameters associated with high flood susceptibility include those related to basin shape (K, Ff, Cc, Cr, Er) and the number and length of streams (Dd, Tr, Fs, Lg). Multiple studies (e.g., Kadam et al., 2016; Cerignoni & Rodríguez, 2015; Sólyom & Tucker, 2007) have shown that round-shaped basins are more prone to flooding because water accumulates in the channels at similar distances from the main order channel, leading to strong streams and large flow rates that can cause prolonged floods and high erosion and sedimentation rates (Chen et al., 2019; Palla et al., 2018; Marra et al., 2014). Elongated basins typically do not flood as easily due to their rapid hydrological response (Reis et al., 2023; Galbiati & Savi, 1995). The water immediately begins to leave the basin through the channels closest to the outlet point, and gradually adds the flow of the furthest channels, which removes the water accumulated in the basin with a gradually increasing flow rate (Chorley, Donald, & Pogrzelsk, 1957; Horton 1932, 1945; Miller, 1953; Schum, 1956).Drainage density and texture are also crucial in flood risk (Pallard et al., 2009; Dingman, 1978), as higher channel density allows for faster water evacuation at higher flow rates (Horton 1932, 1945).

Principal component analysis (PCA) and grouping by medoids indicate that the primary axes (1 and 2) are associated with the shape and drainage of sub-basins, essential for identifying flood-prone sub-basins. MPs like K, Ff, Cc, Tr, Cr, and Er correlate with axis 1, while Dd and Lg correlate with axis 2 (Table S5). Group 4, with the highest drainage density and roundest shape, has the highest flood susceptibility, whereas group 1, with very elongated basins, has the lowest flood risk. However, the geographical position of sub-basins must also be considered. Sub-basins Dk and Dl, despite being in group 4, start in the southern watershed in the mountain range, minimizing their flood risk. In contrast, the remaining sub-basins of group 4 are in the lower part of RH30D, where flood events have been recorded (Arreguín-Cortés et al., 2014). Thus, sub-basins Dw, Dx, Du, Tr, and Do are considered high-risk for flooding. Sub-basin Da, despite being in the low-risk group 1, is located in the Tabasco plain and receives flows from several upstream sub-basins, making it highly susceptible to flooding.

The relationships between shape parameters, elongation, and compactness of the basin are relevant for hydrological response and runoff distribution (Sólyom & Tucker, 2007). Drainage density and texture ratio indicate the efficiency of the drainage system, which is key in understanding runoff capacity (Rodríguez-Iturbe et al., 1992). Roughness number and bifurcation ratio characterize the hierarchy of the drainage system and impact hydrological response (Bogale, 2021; Kumar et al., 2018; Sreedevi et al., 2013). The altitude differences between the Tabasco plain and Chiapas mountain range influence erosion and channel formation, affecting runoff and geomorphology (Brown & Pasternack, 2014). Likewise, it should be mentioned that between the sub-basins of the Tabasco plain and the Chiapas Mountain range there are marked altitude differences, with this variability in relief being an important determinant in key processes such as erosion and channel formation, mainly in mountain rivers (Brown & Pasternack, 2014). Consequently, altitude is considered an important trigger in the complex interactions between precipitation, runoff, and geomorphology; in addition to an important constraint in the characterization of the hydrology of a region (Sang et al., 2022; Jin et al., 2021; Wu et al., 2020; Ghomash et al., 2019).

In turn, parameters such as drainage density, stream frequency, and surface flow length are key indicators of flood risk, according to the basin-level analysis conducted by Flores et al. (2020) in urban and peri-urban areas. Also, Zúñiga et al. (2020) demonstrated that the form factor, elongation ratio, and circularity ratio are fundamental to determine flood potential, particularly in basins affected by urban development. On the other hand, Graziano et al. (2021) proposed a conceptual model that integrates multiple stressors, highlighting the importance of parameters such as relief ratio, roughness number, and Texture ratio in flood risk analysis in Pampean streams. Additionally, Rai et al. (2017) found that the bifurcation ratio is a fundamental parameter for assessing flood susceptibility in a hydrographic basin. Therefore, these results highlight the importance of geomorphometric parameters analysis and integration in flood risk assessment in hydrographic basins.

In this context, basin prioritization is presented as a key tool for intervention and analysis regarding the flooding problem in the RH30D for future research. Our results contribute to understanding the complex relationships between morphometric parameters and their implications for the hydrological response of the analyzed sub-basins. However, as mentioned earlier, it is essential to carry out additional validations and contextualize these findings within the specific geographical and hydrological environment of the study area, integrating aspects such as field measurements, expert consultation, and literature.

6. Conclusions

The Grijalva-Villahermosa Hydrological Region (RH30D) presents significant hydrological complexity with a network characterized by topographic features typical of the Chiapas mountains and the Tabasco plain. Analysis of 12 morphometric parameters across 26 sub-basins reveals groupings and hydrogeomorphic behaviors. Group 1 has efficient drainage patterns, while group 4 is prone to flooding due to strong streams and large flow rates. Groups 2 and 3 show average values in most parameters but differ in Br and Fs values, with group 3 potentially controlled by geological structures and group 2 having faster hydrological responses due to a high number of streams per unit area.

This geomorphological analysis provides a comprehensive view of RH30D's hydrological complexity. The identified correlations can inform future water management strategies, such as controlling stream frequency in high drainage density areas or implementing flood control measures in flood-prone basins. However, these findings need additional validation considering local factors (e.g., previous studies, field measurements, geographic, climatic, geolitological, soil, and hydrological factors). Integrating morphometric and hydrological data is essential for future research and water management strategies.

Author's contributions: Medrano-Pérez, O.R.: conceptualization, methodological-technical development and editing, writing the original manuscript, correcting and editing, interpretation, obtaining and editing results; **Sanaphre-Villanueva L.**: script writing, editing and obtaining results, writing the original manuscript, correcting and editing, interpretation; **Juárez-Rodríguez, M.J.**: data acquisition, obtaining morphometric parameters and writing the original manuscript.

Funding: The research was not funded.

Acknowledgments: The authors thank the anonymous reviewers for their comments and recommendations in improving this research. ORMP is grateful to the Investigadores por México program (CONAHCYT) and to the Cátedras-CCGS project no. 963 entitled "Towards sustainable water management in southeastern Mexico and adjacent areas of Central America".

Conflict of Interest: The authors declare not having any conflict of interest.

Supplementary materials: Supplementary material associated with this article can be found, in the online version, at doi:[http://dx.doi.org/10.20502/*rbg.v25i3.2547*]. This includes the tables and figures that are referred to in the main text of the article.

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