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Morphometric Characterization of the Watersheds of the Main Water Bodies in the Peri-Urban Area of Dakar Using GIS and Remote Sensing: The Case of the Mbao Stream, Lake Mbeubeuss, and Lake Rose

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Abstract

The watersheds of Dakar's peri-urban water bodies are undergoing significant urban transformation, yet their morphometric characteristics remain poorly documented. To address this, this study provides a detailed morphometric characterization of the watersheds of the Mbao backwater, Lac Rose, and Lac de Mbeubeuss, using advanced Geographic Information System (GIS) tools. The delineation of the watersheds and the extraction of the hydrographic network were performed using the 30-meter SRTMGL1 v003 dataset processed in ArcGIS 10.7. After hydrological conditioning of the elevation model, selection of outflow points, and extraction of the network at a threshold of 500 cells (0.45 km^2), the linear, shape, relief, and hypsometric parameters were calculated. The extracted networks are of order 3 to 5, and their drainage densities range from 1.02 to 1.22 km/km^2. Shape factors ranging from 0.29 to 0.51 and Gravelius compactness coefficients ranging from 1.44 to 1.69 indicate generally elongated basins. The Lake Rose basin has the largest surface area and the most developed drainage network, while Lake Mbeubeuss has the flattest topography. These results indicate low channelization at the selected threshold and provide a morphometric basis for hydrological analysis and water body management. However, their interpretation remains limited by the SRTM's resolution, sensitivity to the threshold, low relief, and incomplete representation of urban drainage.

Keywords

Watershed, Morphometry, GIS, Prioritization, Drainage Density, Hypsometry, Urban Hydrology, Hydrological Vulnerability, Dakar

1. Introduction

Water bodies are essential ecosystems that provide numerous hydrological, ecological, and socio-economic functions. They play a major role in regulating the water cycle, maintaining biodiversity, storing surface water, and offering a variety of ecosystem services. However, these environments are now under increasing pressure from urbanization, changes in land use, and the effects of climate change, which could alter their hydrological functioning and ecological balance [1] [2].

In this context, the watershed is the key hydrological unit for understanding the processes that govern how water bodies function. Indeed, it controls the collection, transfer, and distribution of runoff, as well as the movement of sediments, nutrients, and pollutants to aquatic environments [3]. Therefore, understanding the hydrogeomorphological properties of watersheds is an essential step to analyze the factors that can influence the functioning of aquatic ecosystems. In this regard, morphometric analysis stands out as a particularly useful tool because it allows us to quantify the geometric, topographic, and structural characteristics of watersheds [4] [5]. However, while morphometric analyses have been widely applied in different hydrological contexts around the world, the watersheds of the main peri-urban water bodies in Dakar are still relatively under-documented. This lack of knowledge limits our understanding of their hydrological functioning and reduces the scientific basis needed to assess their sensitivity to environmental and climate pressures.

This study fits into that perspective. It aims to analyze the morphometric characteristics of the watersheds of three main peri-urban water bodies in Dakar, namely Lake Mbeubeuss, Lake Rose, and the Mbao Marsh, using Geographic Information Systems (GIS) and remote sensing. The goal is to identify morphometric parameters that could influence their hydrological functioning and to provide a scientific basis for future studies focused on assessing the vulnerability of water bodies in the peri-urban area of Dakar.

2. Materials and Methods

2.1. Study Area

The three water bodies studied are located in the suburban area of Dakar, at the heart of the Niayes region. Lake Rose (Lake Retba), located northeast of Dakar, sits in a coastal depression separated from the ocean by a sand dune ridge. Lake Mbeubeuss is located in the Malika area, in the Keur Massar department, while the Mbao stream is situated on the southern coast of the Cape Verde Peninsula, in the Mbao municipality. These environments are characterized by low elevations, interdunal depressions, and high urban pressure [6]. **Figure 1** shows the location of the study area and the water bodies.

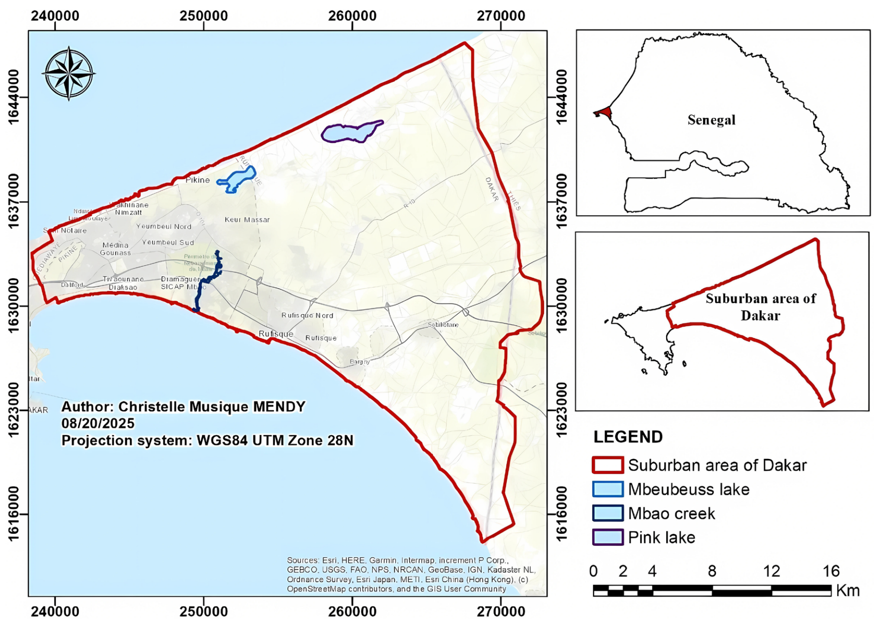

Figure 1. Madman geographic location of the study area.

2.2. Data and Tools

This study is based on the use of a set of spatial data, particularly the Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM 1 Arc-Second Global) with a 30 m resolution provided by the United States Geological Survey (USGS). Spatial analysis and watershed delineation were carried out using ArcGIS 10.7, which allows for the processing of geospatial data and the extraction of key morphometric parameters.

2.3. Delimitation of Basins and Extraction of the Hydrographic Network

The process consisted primarily of two steps: delineating watersheds and prioritizing hydrographic networks. First, the digital elevation model (DEM) from the NASA Shuttle Radar Topography Mission Global 1-arcsecond, Version 003 (SRTMGL1.003) was reprojected into the WGS 84 coordinate system. Tile N14W018, identified in USGS EarthExplorer by the scene number SRTM1N14W018V3, was downloaded in GeoTIFF format. It covers approximately the area between 14˚ and 15˚N and between 18˚ and 17˚W. The product is distributed with a grid resolution of 1 arcsecond, or approximately 30 m. The reprojection process was performed while maintaining a spatial resolution compatible with the original DTM and by applying a resampling method suitable for elevation data. To ensure the model's hydrological continuity, artificial depressions in the DTM were then corrected using the "Fill" tool. The flow direction and flow accumulation were calculated using the "Flow Direction" and "Flow Accumulation" tools, respectively. For each of the three water bodies studied, the outflow point was defined at the location where the hydrographic network extracted from the DTM converges toward and reaches the water body in question. Next, the hydrographic network was extracted using a threshold of at least 500 cells—corresponding to a drained area of 0.45 km^2—in order to retain only the major watercourses. The choice of this threshold was evaluated through a sensitivity analysis involving several accumulation thresholds (250, 500, 700, and 1000 cells) to examine their influence on the structure of the hydrographic network. For each threshold, the order of the watersheds, the total length of the channels, and the drainage density were compared. This choice is consistent with Ludat and Kübler, who used an identical threshold for a 30-meter GLO-30 DEM and verified the extracted network by comparing it with high-resolution ESRI World Imagery [7]. A threshold of 500 cells was also used in a morphometric analysis conducted in Ghana based on a 30-meter DEM [8]. Finally, the hydrographic networks were ranked according to the Strahler classification, where first-order streams are the segments that receive no tributaries, and when they join, they form a second-order stream. Similarly, two second-order streams merge to form a third-order segment, and so on up to the main river [9]-[11].

Figure 2 shows the different steps in delineating the watersheds.

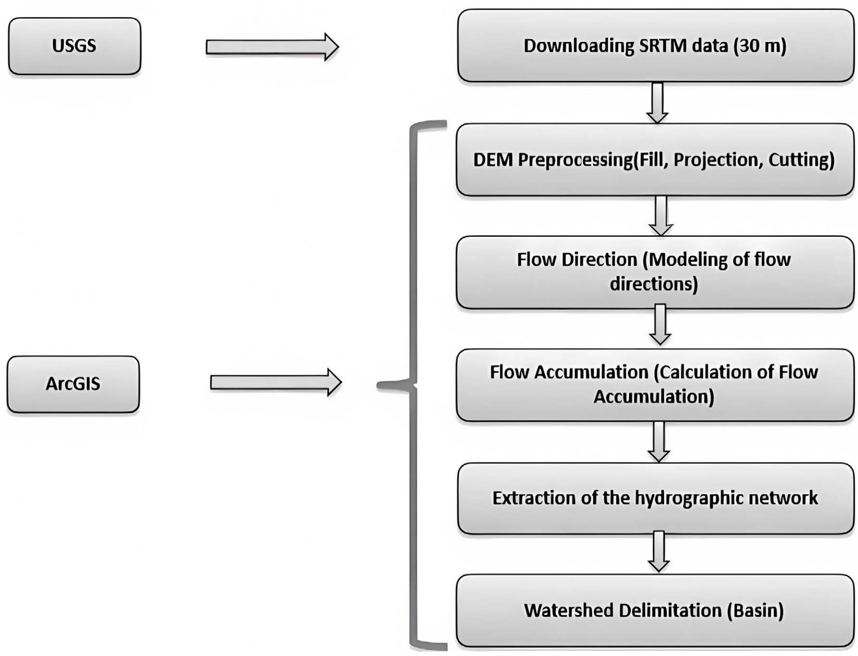

Figure 2. Methodology for defining watersheds.

2.4. Morphometric Settings

Morphometric evaluation is based on a set of classic indices that characterize the physical structure of each watershed while taking into account three groups of parameters (linear, shape, and relief) [12]. Linear parameters describe the hierarchy and branching of the network: stream order (U), number of segments (Nu), cumulative length (Lu), average length (Lum), length ratio (RLu), bifurcation ratio (Rb), drainage density (Dd), segment frequency (Fs), drainage texture (T), and surface flow length (Lo) [13]. Shape parameters include area (A), perimeter (P), form factor (Ff), Gravelius compactness coefficient (KG), circularity ratio (Rc), elongation ratio (Ra), and stream maintenance constant (C) [14]. Relief parameters include altitude range, relief ratio, relative relief, ruggedness index, and hypsometric information [15].

Table 1 describes the different parameters used for the morphometric analysis of the various watersheds studied.

Table 1. The morphometric parameters.

Morphometric Settings	Formulas	Description	References
		Linear settings	
Flow order (U)	-	Hierarchical order of the flow	[16]
Flow number (Nu)	Nu = N1 + N2 + …Nn	where N1 = first-order stream, N2 = second-order stream, and Nn = number of streams	[16]
Flow length (Lu)	Lu = L1 + L2 + …Ln	where Lu = Length of the watercourse, L1 = Length of the first-order watercourse, L2 = Length of the second-order watercourse, and Ln = Length of the stream of order "n"	[16]
Average stream length (Lum)	Lum = Lu/Nu	where Lu = Length of rivers of a given order (km), Nu = Number of river segments	[16]
Flow Length Ratio (FLR)	RLu = Lu/Lu − 1	where Lu = Total length of rivers of order u, Lu-1 = Total length of rivers of the next lower order	[16]
Bifurcation Report (Rb)	Rb = Nu/Nu + 1	where Nu = Number of river segments present in the given order, Nu + 1 = Number of segments in the next higher order	[17]
Drainage density (Dd)	Dd = L/A	where Lu = Total length of the watercourse, A = Area of the watershed	[16]
Flow frequency (Fs)	Fs = N/A	where N = Total number of waterways, A = Watershed area	[16]
Drainage texture (T)	T = Dd * Nj/A	where Nj = Number of streams of order j, A = Watershed area, and Dd = Drainage density (km/km^2)	[16]
		Shape settings	
Area (A)	-	Watershed area in km^2	-
Perimeter (P)	-	Watershed perimeter in km	-
Form factor (Ff)	Ff = A/(Lb)^2	where, A = watershed area, Lb = length of the watershed	[16]
Gravelius compactness coefficient (KG)	KG = 0.28P√A	where, P = Perimeter of the watershed, A = Area of the watershed	[18]
Circularity ratio (Rc)	Rc = 4πA/P^2	where, A=Area of the watershed, P=Perimeter of the watershed	[19]

Continued

Elongation ratio (Ra)	Ra = √(A/π)/Lb	where, A = watershed area, Lb = length of the watershed	[17]
Constant channel maintenance (C)	C = 1/Dd	where, Dd = Drainage density	[16]
		Relief settings	
Watershed relief (Rb)	Rb = hmax − hmin	Vertical distance between the highest point and the lowest point of the watershed	[17]
Relief report (Re)	Re = Rb/Lb	where, Rb = Watershed relief, Lb = Watershed length	[17]
Relative relief (Rr)	Rr = Rb * 100/P	where, Rb = Watershed relief, P = Watershed perimeter	[20]
Robustness number (Rn)	Rn = Re * Dd	where, Rb = Watershed relief, Dd = Drainage density	[17]
Hypsometry	-	Represented by the hypsometric curve	-

3. Results and Discussion

3.1. General Organization of the Basins

The delineation and extraction of the hydrographic networks of the watersheds of the Mbao Creek, Lake Rose, and Lake Mbeubeuss are shown in Figures 3-5, respectively. This illustration shows that the three watersheds have dense, branched hydrographic networks and dendritic (tree-like) drainage systems, similar to the hydrographic profile of the Dakar region [6].

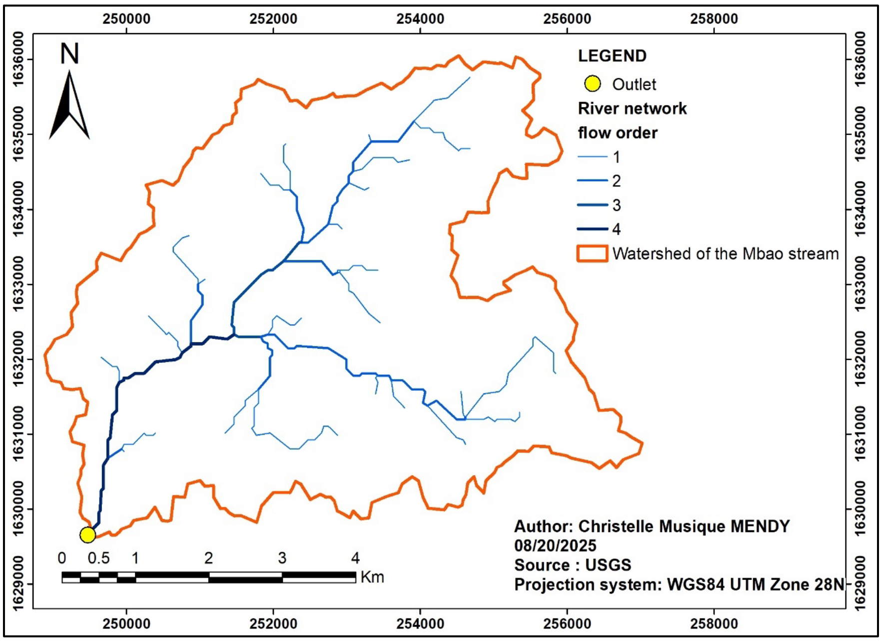

Figure 3. Map of the Mbao Creek watershed.

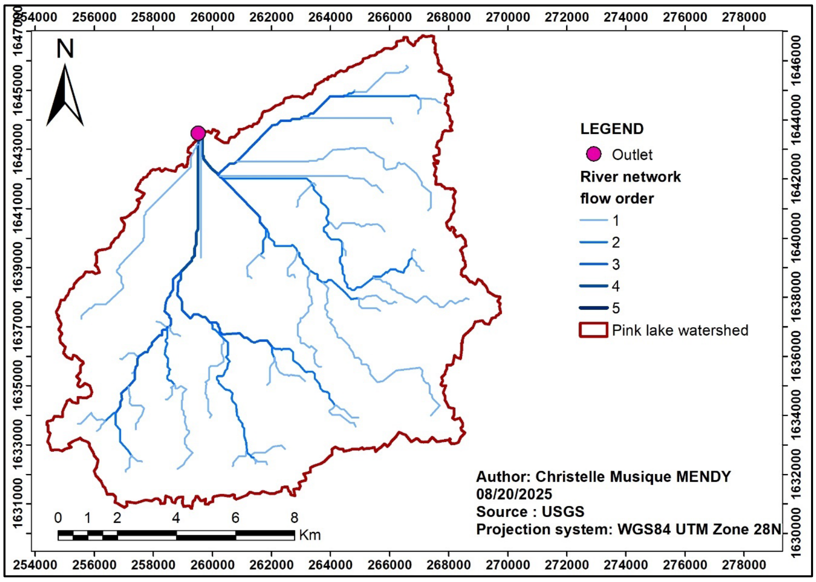

Figure 4. Map of the Pink Lake watershed.

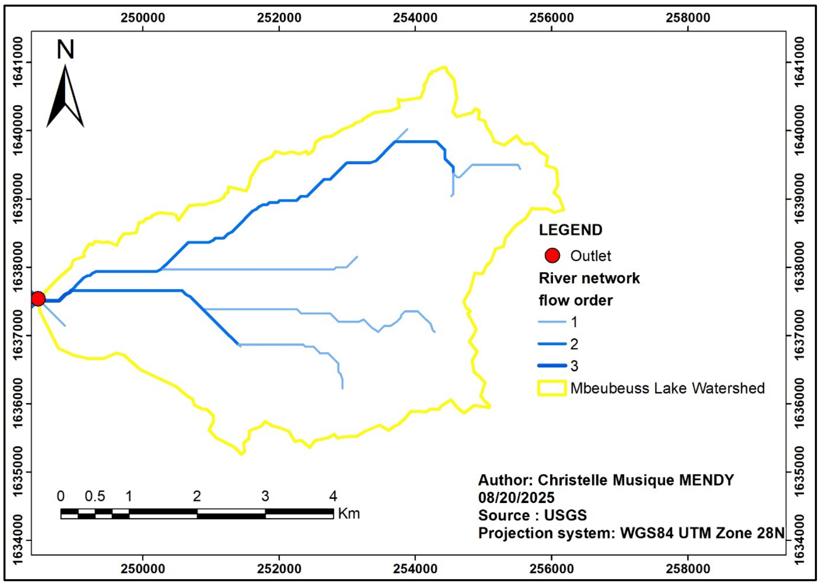

Figure 5. Map of the Mbeubeuss lake watershed.

3.2. Structure of the River Network

The main calculated linear parameters help to describe the structure of the river network in the studied watersheds. Their values are shown in **Tables 2-3**. Using the Strahler method, the Lac Rose watershed has 346 segments, mostly made up of first-order streams (221 segments), and its network totals 188.26 km. The Mbao marsh watershed has 54 segments with a combined length of 33.02 km. The Mbeubeuss watershed has 19 segments and a total length of 23.69 km.

The basins of Lake Mbeubeuss, the Mbao stream, and Lake Retba are respectively identified as third-, fourth-, and fifth-order basins, thus featuring dendritic drainage networks. This branching setup shows limited structural control, meaning the water networks aren't strongly influenced by the geology [21] [22]. The geological characterization of the Mbao stream, Lake Retba, and Lake Mbeubeuss basins is confirmed by the average values of their bifurcation ratio, which is an important parameter derived from the ratio between the number of stream segments of a given order "Nu" and the number of streams of the next higher order (Nu + 1). In fact, the average bifurcation ratio values of the different basins are below 6.

Table 2. Calculated linear settings.

Flow order (U)	Flow number (Nu)	Flow length (Lu)	Average stream length (Lum)	Flow Length Ratio (FLR)	Bifurcation Report (BR)
Watershed (Mbao Creek)					
1	29	17.39	0.60	-	1.81
2	16	9.57	0.60	0.55	5.33
3	3	2.06	0.69	0.22	0.50
4	6	4.00	0.67	1.94	-
Total/Average	54	33.02	0.61	0.38	2.55
Watershed (Pink lake)					
1	221	87.51	0.40	-	3.56
2	62	57.47	0.93	0.66	1.32
3	47	33.77	0.72	0.59	3.13
4	15	9.43	0.63	0.28	15.00
5	1	0.09	0.09	0.01	-
Total/Average	346	188.26	2.76	0.38	5.75
Watershed (Mbeubeuss lake)					
1	10	12.01	1.20	-	1.43
2	7	11.14	1.59	0.93	3.50
3	2	0.55	0.27	0.05	-
Total/Average	19	23.69	1.25	0.49	2.46

The stream frequency introduced by Horton corresponds to the stream frequency (or channel frequency) Fs, expressed as the number of stream segments per unit area [3]. In this study, the stream frequencies of the watersheds are low and range between 0.82 and 2.24. This low variation indicates significant runoff in the watersheds.

Drainage density is the ratio of the length of a watercourse to the area of its watershed. It is a morphometric indicator that allows for an indirect assessment of runoff and infiltration conditions within a watershed. Low values of this indicator may be associated with relatively permeable soils and favorable infiltration, while high values may reflect conditions more conducive to runoff concentration, particularly in contexts of low permeability. In our case study, the drainage densities obtained for the watersheds of the Mbao backwater (1.03 km/km^2), Lake Rose (1.22 km/km^2), and Lake Mbeubeuss (1.02 km/km^2) are relatively low. From a morphometric perspective, these values suggest conditions that are potentially favorable for infiltration and a moderate propensity for runoff concentration.

The drainage texture, which reflects the spacing of the flow lines, mainly depends on the lithology, infiltration, and relief. According to Horton, it corresponds to the total number of stream segments relative to the perimeter of the basin. Smith identifies five texture classes: very coarse (<2), coarse (2 - 4), medium (4 - 6), fine (6 - 8), and very fine (>8) [23].

In this study, the textures of the drainage networks of the watersheds are below 2. This indicates that this group has a very coarse texture.

Table 3. Calculated linear settings (continued).

Settings	Mbao Creek watershed	Lake Rose Watershed	Mbeubeuss Lake Watershed
Drainage density (Dd)	1.03	1.22	1.02
Flow frequency (Fs)	1.68	2.24	0.82
Drainage texture (T)	0.93	1.74	0.44

Linear parameters are important indicators of the soil erosion process in a watershed because of the role rivers play in transporting and removing sediments from soil erosion. In fact, high values of these parameters can indicate more intense erosive activity and an increased sensitivity of the watershed to erosion [5].

3.3. Basin Morphology and Potential Concentration Time

Determining areas and perimeters is important because they form the basis for calculating other shape factors. The basin of Lac Rose is the largest (154.58 km^2), followed by that of the Mbao creek (32.12 km^2) and then Mbeubeuss (23.14 km^2). The perimeters range from 24.70 km (Mbeubeuss) to 71.23 km (Lac Rose).

Shape factors (Ff) below 0.52, elongation ratios (Ra) between 0.30 and 0.40, and Gravelius coefficients (KG) above 1.4 indicate non-circular, generally elongated basins. An elongated shape usually tends to reduce the immediate synchronization of inflows from different parts of the basin and produces a more spread-out hydrograph compared to a circular basin of similar size [24].

The channel maintenance constant (C), defined as the inverse of drainage density, represents the basin area (in km^2) needed to maintain one kilometer of watercourse. Its value gives an idea of the relative size of landforms and their evolution. The maintenance constant for the watersheds studied ranges from 0.88 to 1.01, which indicates low erodibility of the watersheds [25].

The different shape parameters that were calculated and analyzed are shown in **Table 4**.

Table 4. Calculated shape settings.

Settings	Mbao Creek Watershed	Lake Rose Watershed	Mbeubeuss Lake Watershed
Area (A)	32.12	154.58	23.14
Perimeter (P)	34.29	71.23	24.70

Continued

Minimum altitude (Zmin)	1.00	2.00	8.00
Maximum altitude (Zmax)	46.00	55.00	22.00
Basin length Lb (km)	10.58	17.46	7.77
Form factor (Ff)	0.29	0.51	0.38
Gravelius compactness coefficient (KG)	1.69	1.60	1.44
Circularity ratio (CR)	0.34	0.38	0.48
Elongation ratio (Ra)	0.30	0.40	0.35
Constant channel maintenance (C)	0.97	0.82	0.98

3.4. Relief and Hypsometry

The relief of a basin (Rb) is the difference in elevation between the highest point (the ridge line) and the lowest point (the outlet) of a basin. It's a key factor to understand how the terrain evolves, how the river network forms, and how water flows [14]. The reliefs of the watersheds range between 46 and 1 m (Mbao Marigot basin), between 55 and 2 m (Pink Lake basin), and between 22 and 8 m (Mbeubeuss Lake basin) (**Table 5**).

Table 5. Calculated relief settings.

Settings	Mbao Creek watershed	Lake Rose Watershed	Mbeubeuss Lake Watershed
Pelvic relief (Rb)	45	53	14
Relief report (Re)	4.25	3.04	1.80
Relative relief (Rr)	131.24	74.41	56.67
Robustness number (Rn)	0.004	0.004	0.002

The relief ratio (Re) comes from the ratio between the basin relief (Rb) and the maximum length of the basin. The relief coefficient is an important factor because it gives information about the overall slope and thus the intensity of erosion processes in the watershed [26]. For the basins studied, the Re values range from 1.80 to 4.25.

Relative relief (Rr), also called relative elevation, is the ratio between the maximum relief of a watershed and its perimeter. It helps in assessing the general morphological characteristics of the watershed. A high relief index indicates a high runoff potential [27]. The watersheds of the Mbao creek, Lake Rose, and Lake Mbeubeuss have very high relief index values, and therefore significant surface runoff.

The roughness index, defined by Strahler, corresponds to the product of the basin's relief and the density of its river network. This indicator thus incorporates both the slope and the length of the slopes [4] [12]. Applied to the studied basins, its calculation shows very low values, around 0.002 to 0.004 (see **Table 5**). This confirms that the catchment areas of the Mbao marsh, the Pink Lake, and Lake Mbeubeuss are not very sensitive to soil erosion.

Table 5 shows the calculated relief parameters.

The elevation maps of the three watersheds (**Figures 5-7**) show differences in the amplitude of the relief. The Lake Rose watershed has the highest maximum elevation (55 m), followed by the Mbao backwater (46 m), while Lake Mbeubeuss is characterized by gentler topography, with elevations ranging from 8 to 22 m. Despite these differences, all three watersheds generally have low elevations and topographically low areas surrounding the bodies of water. The spatial distribution of elevations allows for the identification of topographic gradients and the main potential flow directions. This information thus provides an essential basis for delineating watersheds and analyzing flow dynamics, complementing the morphometric parameters studied.

The hypsometric curve is a summarized representation of the distribution of land areas according to elevation [28]. It is a standard tool for morphometric analysis used to characterize the shape of the landscape and assess the extent of its geomorphological evolution [29]-[31].

The interpretation can be based, in particular, on the overall shape of the curve, as well as on the hypsometric integral, which reflects the relative proportion of the basin's volume located above different elevations [29].

In this study, the classification of the watersheds of the Mbao backwater, Lake Mbeubeuss, and Lake Rose is based primarily on the general shape of their hypsometric curves, rather than on a threshold value for a hypsometric index. The resulting curves (**Figures 6-8**) reflect an advanced stage of morphological evolution of the terrain, allowing these watersheds to be associated with an early or highly evolved stage of their geomorphological development. This interpretation aligns with Strahler's classical approach, according to which the morphology of hypsometric curves can be correlated with the various stages of watershed evolution. However, this classification should be considered a relative morphometric interpretation of the degree of landform evolution, rather than a determination of the absolute age of the watersheds. Indeed, the shape of hypsometric curves can also be influenced by lithology, geological structure, erosion processes, and tectonic conditions [29].

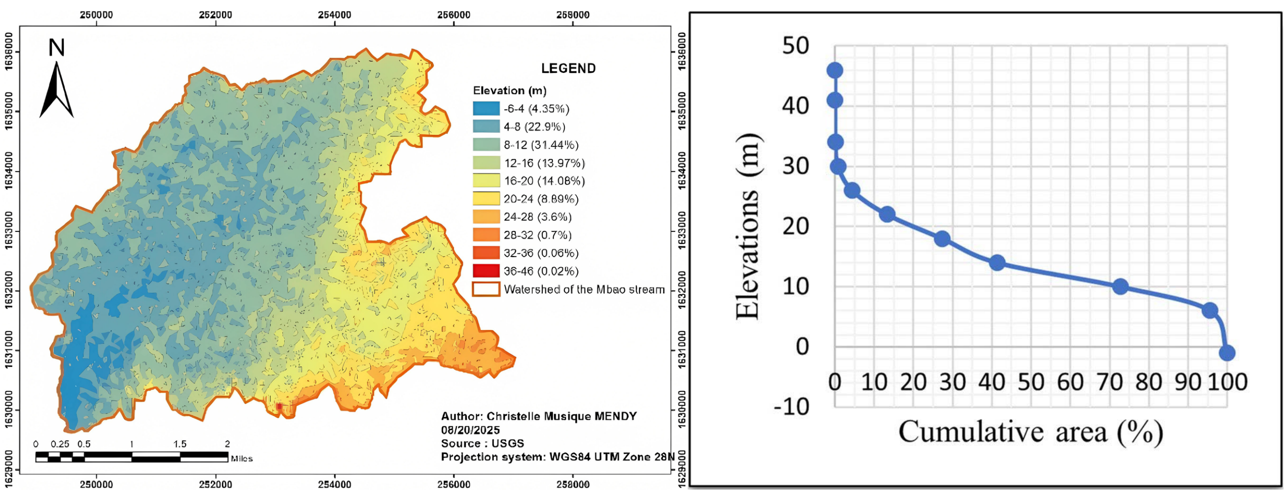

Figure 6. Elevation map of the Mbao Creek watershed.

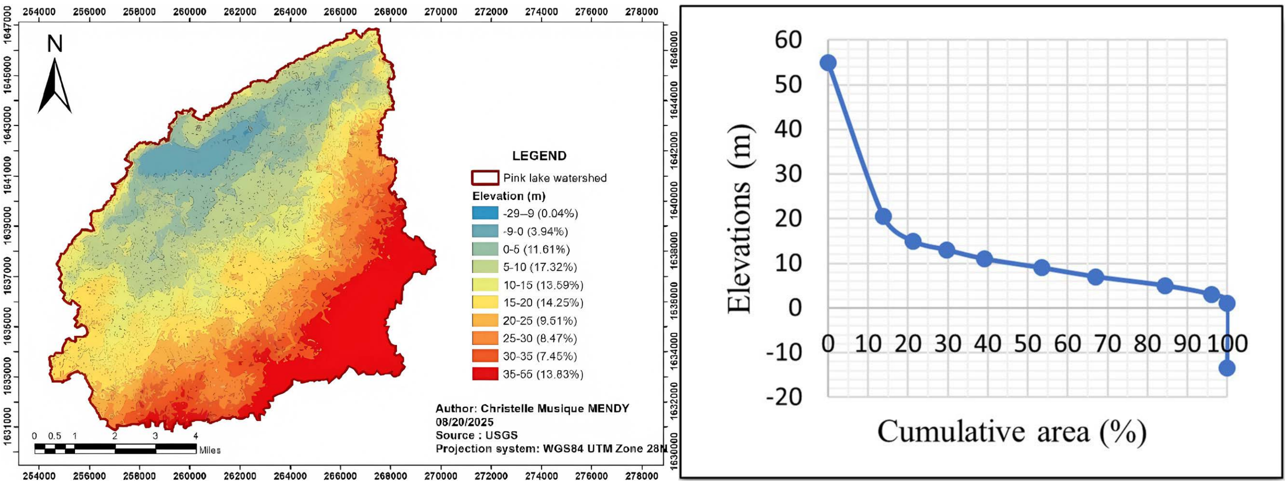

Figure 7. Elevation map of the Pink Lake watershed.

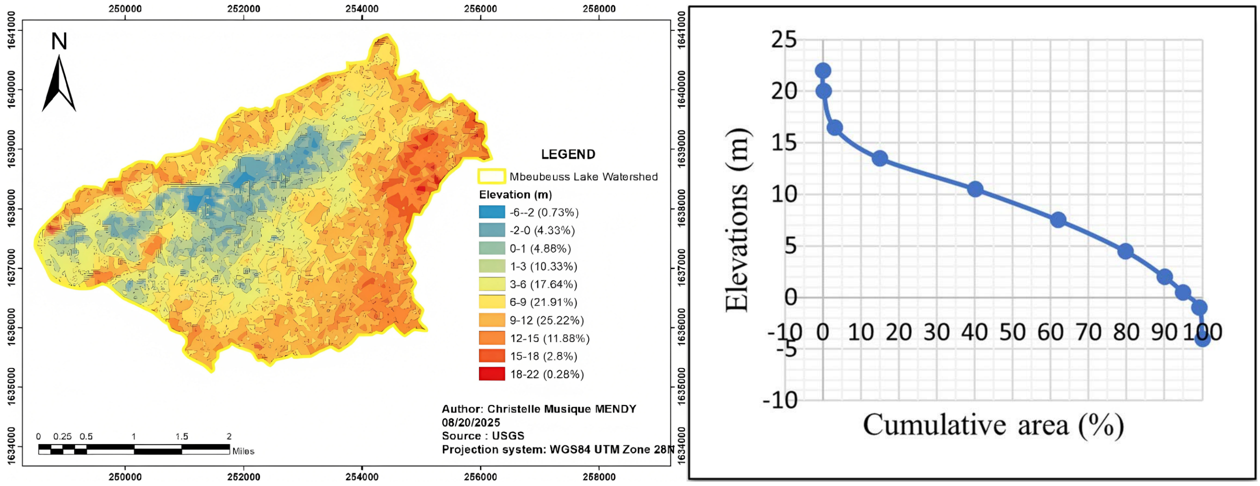

Figure 8. Elevation map of the Mbeubeuss lake watershed.

4. Conclusion and Outlook

The morphometric study of watersheds is an essential step in understanding their hydrological dynamics and preventing water-related risks, such as floods, drying, and erosion. It was carried out using remote sensing and GIS data, analyzing linear, shape, and relief parameters. The watersheds of Marigot de Mbao, Lac Rose, and Lac Mbeubeuss mainly have a dendritic drainage network, with streams ranging from 3rd to 5th order. The low values of the number of segments (Nu) and cumulative lengths (Lu) indicate relatively low-hierarchy and temporary networks. Low values of the robustness number (Rn) indicate a limited influence of geological and tectonic structures on the drainage layout. The low drainage densities (Dd) observed suggest the presence of relatively permeable materials, significant vegetation cover, and gently sloping terrain. The circularity and elongation indices show that the basins generally have an elongated shape. This analysis provides a basis for understanding flow processes and future hydrological studies. However, the results can be affected by land use and the limitations of the 30 m DEM in urban areas.

Author Contributions

Conceptualization: C. M. Mendy, L. V. Sambou and S. Ndao. Methodology: C. M. Mendy and L. V. Sambou. Software: C. M. Mendy. Formal analysis: C. M. Mendy and L. V. Sambou. Investigation: C. M. Mendy, C. Ndiaye and E. M. Pignandi. Data curation: C. M. Mendy. Validation: C. M. Mendy, L. V. Sambou, S. Ndao, C. Ndiaye and E. M. Pignandi. Visualization: C. M. Mendy. Writing—original draft preparation: C. M. Mendy. Writing—review and editing: L. V. Sambou, S. Ndao, C. Ndiaye and E. M. Pignandi. Supervision: L. V. Sambou, S. Ndao, C. Ndiaye and E. M. Pignandi. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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