Geotechnology Applied to Morphometric Characterization of the Lucite River Sub-Watershed, Mozambique

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***Abstract*—The morphometric characterization of river watersheds is of great importance and is used to predict extreme hydro-meteorological phenomena (floods). The aim of this work was to morphometrically characterize the Lucite River sub-watershed using geotechnologies. Based on the Digital Elevation Model, using SRTM (Shuttle Radar Topography Mission) data, the following watershed morphometrics were determined: Drainage area, Watershed perimeter, Coefficient of compactness, Form factor, Circularity index, Declivity, Altitude, Maintenance coefficient, Drainage density, Hydrographic density, Torrential coefficient and Watershed order. All procedures were processed in ArcGIS 10.5 software. The results suggest that the Lucite River sub-watershed is not very susceptible to flooding under normal rainfall conditions, due to the low values of Drainage Density 0.021, Hydrological Density 0.028, Compactness Coefficient 1.92 and Form factor 0.43, presenting an elongated and irregular shape. Although these values do not indicate the need for flood prevention strategies, however in situations of abnormal rainfall, the sub-watershed could be susceptible to flooding, as some values are close to the threshold.**

***Keywords*—watershed, morphometric characterization, geoprocessing**

I. Introduction

The hydrographic watershed stands out as an integrating environmental unit, which allows the analysis of its various components and processes within a systemic approach. This can be recognized as a spatial reference unit for studies of various phenomena, with emphasis on geomorphological and hydrological ones [1].

According to Cunha and Bacani [2], the physical characteristics of a watershed are elements of great importance in its hydrological behavior due to the close relationship between the hydrological cycle and these elements. From the knowledge of these watershed data, it is possible to indirectly infer hydrological values for places where hydrological information is scarce.

Morphometric characterization is still one of the first and most common procedures for understanding the hydrological and environmental dynamics within a watershed [3]. Knowledge of morphometric characteristics is a tool for diagnosing natural physiographic conditions, its natural picture can conform to susceptibility to floods [3, 4].

Morphometric parameters, Form factor, Drainage density, and Land slope are indicators of susceptibility to environmental degradation [5]. The morphometric characteristics also reflect some land properties, such as infiltration and runoff of rainwater, and express a close correlation with the lithology, geological structure, and surface formation of the elements that make up the earth's surface [6].

The Geographic Information System (GIS) has proven to be an efficient tool for water studies and management of hydrographic watersheds. In this sense, the images of the Digital Elevation Model are indispensable sources of data, as they enable lower costs and time reduction in field work for studies of water resources. Several studies have shown the potential of applying the Digital Elevation Model for the morphometric characterization of watersheds [7–9].

The study of watershed morphometry has been extensively studied since the 1950s by [10–13], among others. Currently, the study of morphometric parameters has been applied to flood risk assessment and watershed behavior. In the absence of observed hydrological data, morphometry can provide timely information on the watershed's hydrological characteristics and physiographic data [14].

The morphometric characterization of a watershed is the starting point for studies related to environmental dynamics, enabling better management and use of its natural resources [15–17].

The sub-watershed of the Lucite River is part of the Buzi Watershed, this is one of the largest watersheds in central Mozambique, and cyclically several extreme hydrometeorological events have been recorded, with emphasis on floods. From this perspective, the main objective of this work was to morphometrically characterize the Lucite sub-watershed, to subsidize the management of extreme hydrometeorological events.

II. Materials and Methods

A. Study Area

The study area is the Lucite River sub-watershed, which is part of the Buzi Watershed, which is located east of Manica Province, in the Sussundenga district, Mozambique, Fig. 1.

The climate of the sub-watershed is predominantly of the Tropical Rainy Savannah-AW type (*Köeppen classification*), with two distinct seasons, the rainy season, and the dry season. The average annual precipitation at the nearest station (Massambuzi) is around 1171 mm, while the average annual potential evapotranspiration is in the order of 1271 mm. The highest rainfall occurs in the period between November and March of the following year. The dry season starts from May to September when rainfall does not exceed 20mm. The water balance shows that the period of greatest water volume occurs from November to March, in which precipitation is greater concerning the amount of evapotranspiration.

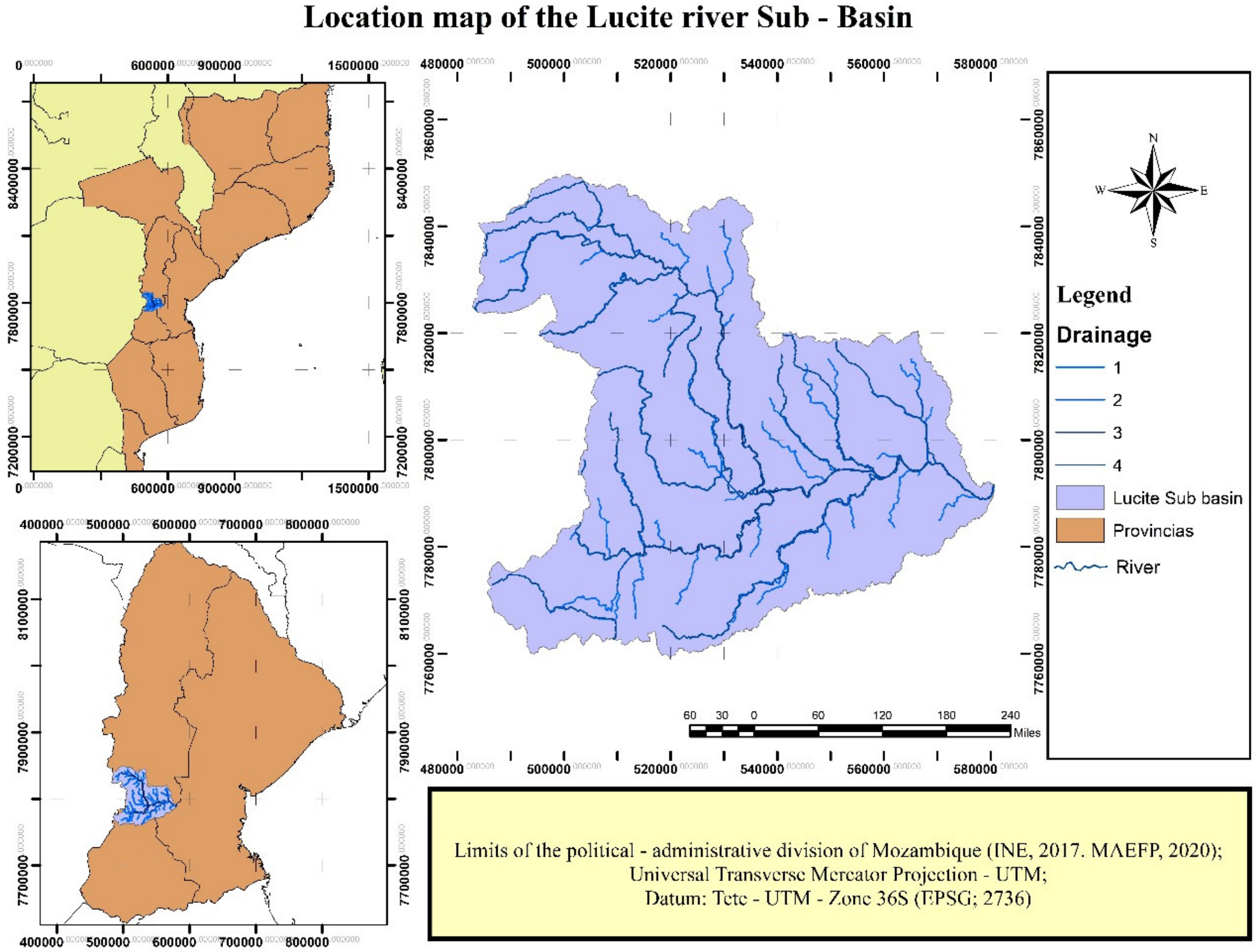

Fig. 1. Geographic location map.

Regarding the relief, the study area is characterized by the predominance of mountain ranges in a strip bordering Zimbabwe, called "Zimbabwe Craton". This formation comprises basalts, rhyolites, and alkaline larvae. To the west of the sub-watershed, along the border with Zimbabwe, is the mountain massif of Chimanimani, with peaks that rise above 1,500 meters and cover an area of about 1,050 km², and It is in this area that the highest point is Mount Binga, with 2,436 meters of altitude. well-scripted methods section lays the foundation for your research by outlining the different methods you used to derive your results.

B. Data Acquisition

For this study, the Digital Elevation Model (DEM) was used, referring to SRTM data (Shuttle Radar Topographic Mission 3), with 90 m of spatial resolution (http://srtm.csi.cgiar.org/). Initially, depressions were filled, and relief flaws (MDE) were corrected using the ArcGIS Fill algorithm. After correcting the DEM to remove the pixels that could compromise the flow of water, the preferred direction of the flow on the surface was determined using the Flow Direction tool, which defines the flow for each pixel in only one direction, within eight related possible paths for nearby pixels. The acquisition of the flow accumulated on the surface was defined with the Flow Accumulation algorithm, which consists of representing the flow segments by pixels selected in the previous step. At this stage, it was possible to define the mouth of the watersheds, thus obtaining the contribution area upstream of that point. For the automatic delimitation of the watersheds, the Watershed algorithm was used and at this stage, it was also possible to extract the drainage network for the study areas. With the watershed obtained and delimited in a Raster file (Pixel), it was necessary to convert them to vector format, and the area and perimeter were calculated.

C. Determination of Morphometric Parameters

Based on the delimited watershed and information on the area and perimeter, the different morphometric characteristics were obtained: Drainage area (A), Watershed perimeter (P), Compactness coefficient (Kc), Form factor (Ff), Index of Circularity (IC), Slope, Altitude, Maintenance Coefficient (Cm), Drainage Density (Dd), Hydrographic Density (Dh), Torrentiality Coefficient (Ct) and Watershed order.

The form factor was determined by relating the shape of the watershed to that of a rectangle, corresponding to the ratio between the average width and the axial length of the watershed. This factor was determined using the methodology proposed by Mosca [18]. According to Maidment *et al*. [19], watersheds susceptible to flooding have form factor values equal to or greater than 0.5. A watershed with a low form factor is less subject to flooding than another of the same size but with a higher form factor.

The compactness coefficient was determined through the correspondence between the perimeter of the watershed and the perimeter of the circumference of a circle with the same area as the watershed. The methodology of [20], is to determine the compactness coefficient. The Kc is a dimensionless value that does not depend on the area, but on the shape of the watershed, being greater the more that shape moves away from the circular. The greater the Kc, the less compact the watershed is [21].

According to Guidolini [14], the minimum value of Kc is equal to 1, which indicates a circular watershed, and the higher the compactness coefficient, the more irregular the watershed becomes. According to Schmitt and Moreira [22], Kc values between 1 and 1.25 indicate a watershed with a high propensity for flooding, values between 1.25 and 1.5 are a watershed with an average tendency to large floods, and values above 1.5 are a watershed not subject to major flooding.

The Circularity Index (CI) is a shape index that assesses the degree of elongation of the watershed, tends towards unity as the watershed approaches a circular shape, and decreases as the shape becomes elongated [23]. Methodology was used to determine this parameter [24].

Drainage density relates the total length of all channels present in the watershed (perennial, intermittent, and ephemeral) and the total area of the watershed. The drainage density (Dd) indicates the level of development of the drainage system of a watershed [15]. This parameter indicates the greater or lesser speed with which the water leaves the hydrographic watershed. high Dd values indicate areas with little infiltration and better channel structuring [25].

From the drainage density, it was possible to calculate the Maintenance Coefficient (Cm), which represents the necessary area that the watershed must have to keep each meter of drainage channel perennial.

This coefficient represents the necessary drainage area in square kilometers, to sustain a linear kilometer of channel [19], indicating an estimate of the minimum area that is required for the drainage channel to be implemented and developed.

The Maintenance coefficient is the inverse of the drainage density. While a low Dd is an indicator of good capacity for water infiltration into the soil and vegetation cover, a low Cm means that the channel is unable to keep a kilometer of fluvial channel active. The higher the Cm class, the better the channel's ability to stay active. This is one of the most important indices for the characterization of the drainage system [26].

Hydrographic density (Dh) relates the number of rivers or canals to the watershed area. This index expresses the magnitude of the watershed's hydrographic network, indicating the capacity to generate new watercourses [27].

However, the Torrentiality Coefficient (Ct) allows quantifying the tendency of a hydrographic watershed about the occurrence of floods, by multiplying the hydrographic density by the drainage density. This tendency will be greater the greater the value of Ct, this parameter having great importance in small watersheds, due to the shorter torrentiality time.

The ordering of the watercourses was carried out considering the fluvial hierarchization methodology established by [10–12].

To characterize the relief of the sub-watersheds, the maximum and minimum altitudes and the altimetric amplitude were determined. Altimetric Amplitude is the difference between the highest and lowest altitudes of the watershed area.

The altitudes and slopes of the watershed were classified. It should be noted that the variation in altitude is a very important factor, as temperature and precipitation are related to altitude. Temperature variations influence water losses that occur in the form of evaporation and transpiration, whereas variations in precipitation will act directly on surface runoff and infiltration [14].

The slope of the watershed is a feature of great hydrological interest, especially for small watersheds, in which the surface runoff will determine the shape of the hydrograph [28]. This occurs because the slope is one of the factors that regulate the speed of this flow. Furthermore, the slope will have a great influence on the erosion process [17]. The steeper the terrain, the faster the surface runoff, the shorter the concentration time, and the higher the flood peaks. Table 1 summarizes the main indices, formula, and methodology used.

Table 1. Morphometric parameters and their mathematical expressions

Index	Eq.	Ref.
Compactness coefficient	$K_c = 0{,}28 * \frac{P}{\sqrt{A}}$	Cardoso *et al*. (2006)
Form factor	$K_f = \frac{A}{L^2_{axial}}$	Horton (1932)
Circularity Index	$I_c = \frac{12{,}57 * A}{P^2}$	Borsato e Martoni (2004)
Watershed Order	Ord	Strahler (1988)
Maintenance Coefficient (Cm)	$\mathrm{Cm}\left(\frac{1}{Dd}\right) * 1000$	Schumm, S.A. (1956)
Torrentiality coefficient	$Ct = Dd * Dh$	
Densidade de drenagem (Dd)	$D_d = \frac{L_t}{A}$	Horton (1932, 1945)
Hydrographic Density (Dh)	$\mathrm{Dh} = \frac{\mathrm{N}}{\mathrm{A}}$	Christofoletti (1980).
Altimetric amplitude (Hm)	$Hm = Hmax - Hmin$	Schumm, S.A. (1956)

P - Watershed perimeter (m), A - drainage area (m²), Laxial - watershed axial length (m), Lt - total length of all channels (km), Δaltimetric - Altimetric amplitude, Hmax- Maximum Altitude,

Hmin-Minimum Altitude; Ord= Watershed Order. N - Number of rivers or channels of the first order.

III. Result and Discussion

In terms of geometric characterization (Table 2), the Lucite River sub-watershed has a drainage area of 5,125.85 km² and a perimeter equal to 493.18 km. The compactness coefficient (Kc) found was 1.92, associated with the respective form factors of 0.43, indicating that these sub-watershed, under normal precipitation conditions, are little susceptible to flooding, since such values found indicate that this sub-watershed has an elongated and irregular shape. According to Schmitt and Moreira (2015), Kc values between 1 and 1.25 indicate a watershed with a high propensity for flooding, values between 1.25 and 1.5 are a watershed with an average tendency to large floods, and values above 1.5 are a watershed not subject to major flooding.

The result of these indices is reinforced by the circularity index (CI) found, (CI = 0.26), since the distance from the unit indicates that the sub-watersheds do not tend towards a circular shape, that is, they have a more elongated shape and, therefore, have lower runoff concentration, due the, Circularity Index (CI) values greater than 0.51 show that the watershed tends to be more circular, being more prone to flooding, and, on the other hand, CI values smaller than 0.51 suggest that the watershed tends to be more elongated contributing to the surface runoff process [29].

Table 2. Morphometric characteristics of the Lucite River sub-watershed

	Morphometric characteristics	Units	Results
Geometric characteristics	Total Area	Km²	5,125.85 Km²
	Perimeter	Km	493.18 Km
	Form factor (Kf)	-	0.43
	Compaction coefficient (Kc)	-	1.92
	Axial length	km	108,71 Km
	Circularity Index (Ic)	-	0.26
Relief features	Maximum altitude	m	2,385.00
	Minimum altitude	m	49.00
	Altimetric amplitude (Hm)	m	2,336.00
Features of the drainage network	Main channel length	km	129.8 Km
	Drainage density (Dd)	km/km²	0.021
	Torrentiality coefficient (Ct)	m² m-1	0.000588
	Hydrographic Density (Dh)	channels/km²	0.028
	Maintenance Coefficient (Cm)	m²/m	47.61
	Number of 1st order channels	-	38
	Watershed order	-	4

In this sense, the elongated shape of the sub-watershed denotes less possibility of intense precipitation simultaneously covering its entire extension and, therefore, less water that simultaneously reaches the main gutter, thus reducing the responsibility of the drainage system to constitute drainage with a high degree of efficiency, considering that the more water it receives, the more efficiency it demands to prevent channel overflow.

The hydrographic density indicates the ability of the sub-watersheds to generate new channels and according to Lana *et al.* [30], if this index is above 2.00 channels/km², the watershed would have a great capacity to generate new watercourses.

In terms of the characteristics of the drainage network (Table 2), the total length of the main channel was 129.8 km. According to Strahler [12], the and Fig. 2, sub-watershed of the Lucite River was considered as of the fourth order. Order less than or equal to four is common in watersheds and reflects the direct effects of land use. It is considered that the more branched the network, the more efficient the drainage system will be [31].

Drainage density is one of the most important variables for the morphometric analysis of watersheds, it represents the degree of topographic dissection, in landscapes created by fluvial action, or expresses the available number of channels for flow and the control exercised by geological structures [32, 33]. Therefore, it provides an indication of the drainage efficiency of the watershed, expressed by the ratio between the sum of the lengths of all channels in the network, whether intermittent or temporary perennials and the total area of the watershed [34].

The drainage density rate can vary from 0.50 km/km² in watersheds with poor drainage to 3.50 km/km² or more in well-drained watersheds [19, 35]. In this research, the drainage density was considered low, since the value found was less than 0.021km/km², thus indicating that the studied watershed has poor drainage and consequently presents a low relationship between the length of rivers and their extension, indicating an efficient flow of water and good infiltration into the water table, that is, a lower propensity for flooding, a fact that was also observed by the low value of the Torrentiality Coefficient (Ct = 0.000588 $m^2\ m^{-1}$).

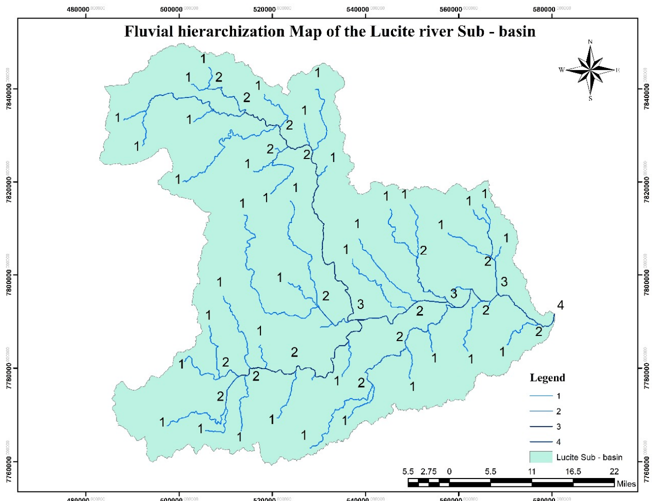

Fig. 2. Hierarchical map of the Lucite River sub-watershed.

According to Linsley *et al.* [36], basins with low drainage have soils that are more resistant to erosion or are more permeable and the relief tends to be smoother, which, in turn, ends up contributing to the rainwater runoff occurs more slowly.

Borsato *et al.* [37] explain that the study of slope factors and degree of waterproofing of slopes are fundamental to understanding surface runoff in low-lying basins drainage.

The drainage density has always been considered the most important variable in the morphometric analysis of river basins, representing the degree of topographic dissection in landscapes created by river action, or expressing the available quantity of drainage channels. The hydrological behavior of rocks has an impact on drainage density, since rocks with little infiltration allow greater surface runoff, enabling the formation of channels [38].

The maintenance coefficient (Cm) found was 47.61m² m-1. Thus, in terms of the hydrodynamic balance of the sub-watersheds, the results obtained indicate that 47.61 m² of area is needed to keep each meter of the channel perennial. Most sub-catchments with low values indicate the region with close dissection and these are moderately influenced by structural parameters [39].

The average slope of the study area presents a result of 0.02586 m/m in percentage, meaning this value represents 25.86%. The slope data are directly related to the erosive processes in the watershed, therefore there is a greater accumulation of sediment in the watershed, for this reason, it is necessary to pay attention to areas that have the lowest slopes.

Generally speaking, it can be assumed that the profile of the Lucite River is not flat along its route. It can be reaffirmed that the study area is not a floodable zone as a result of normal precipitation (Fig. 3).

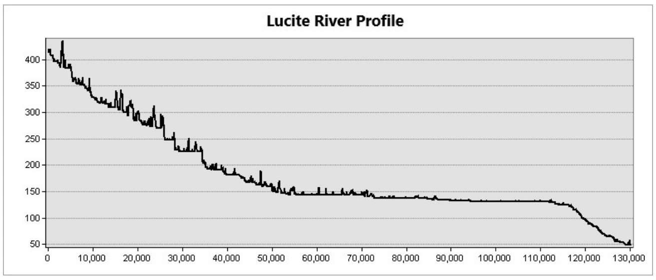

Fig. 3. Profile of the Lucite River.

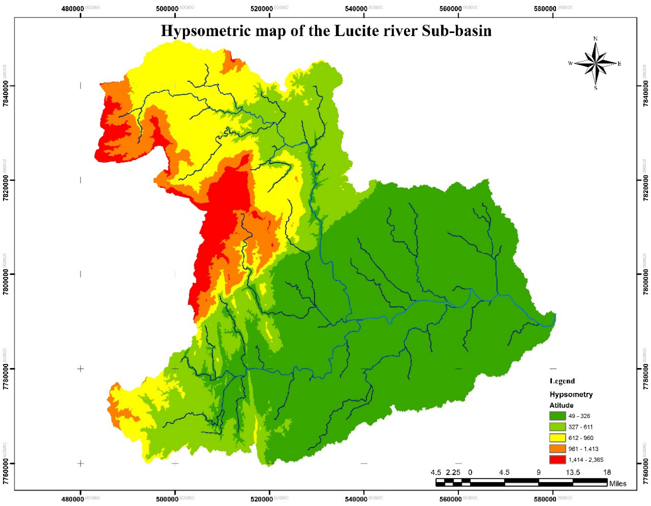

Fig. 4. Hypsometric map of the Lucite River sub-watershed.

The sub-basin is predominantly high, with the highest altitudes reaching 2,385.00 meters. The highest altitudes are located in the west of the sub-basin, decreasing from west to east (Fig. 4). As for the topographic factor, the value found for the watershed under study was practically zero, therefore, the watershed has practically no flooding capacity, and with good drainage capacity, this value was favored due to the very low values of the circularity index (0.26).

Despite the low susceptibility of the hydrographic sub-basin, it is necessary to establish standards for land use and occupation, in order to minimize losses resulting from hydrometereological extremes. Through the proposal to develop zoning for the use and occupation of land based on physiographic characteristics and vulnerability to catastrophic events. It is necessary to consider the morphometric and hydrological characteristics, the use and occupation of land and urban and rural activities to keep the population of vulnerable areas safe

IV. Conclusion

Based on the results obtained and analyzed, it was concluded that the Lucite sub-watershed has an irregular shape, and this statement is corroborated by the compactness coefficient, Form factor, and circularity index since all of them presented a value far from the unit.

The Lucite River sub-watershed is little susceptible to flooding under normal precipitation conditions, that is, disregarding hydrological events of abnormal intensities. The low drainage density obtained also denotes a greater contribution surface of the sub-watershed about its number of channels, which is a factor that contributes to the infiltration of water into the soil, supplying the water table and less loss of water and soil., due to the low velocity of surface runoff of precipitation water.

The study sub-watershed is of the fourth order, indicating that its drainage system is very branched since it has a large area. The wavy relief is predominant in the sub-watershed of the Lucite River, occupying 1325.68km². The average slope found in the sub-watershed was 25.86%, indicating the need to conserve the vegetation cover of the slope surfaces, to prevent the degradation of the natural resources present.

Morphometric analyzes using Geotechnologies are essential in river basins where climatic conditions and hydrometereological data are scarce, such as Mozambique and specifically the Lucite River sub-basin, as morphometric results can provide an indication of the susceptibility of river basins and sub-basins to floods, giving the possibility of planning.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Eufrásio João Sozinho Nhongo: Conceptualization, Methodology, Investigation, Resources, Writing - review & editing. Isidro Alexandre Simão: Conceptualization, Methodology, Supervision. Baptista João Boanha: Conceptualization, Methodology, Supervision. Castigo David Augusto Machava: Validation, Methodology; all authors had approved the final version.

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