Morphometric Analysis of Topographic Surfaces in Highly Urbanized Tropical Environments: Case of the Bonoumin and Gourou Watersheds (Abidjan, Ivory Coast, West Africa)

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Abstract:- The Bonoumin and Gourou watersheds in the city of Abidjan have been subject to repeated flooding in recent years. In order to have a better understanding of the morphometric parameters influencing the hydrological functioning of these two whatershed, this manuscript analyses their morphometric characteristics. The methodology applied consisted in analysing the digitals elevations models (DEM) of the two watersheds using GIS. These morphometric characteristics have been calculated using empirical formulae. It results from this morphometric analysis that the two watersheds are elongated in relation to their Gravelius coefficient (2.36 and 2.23 respectively for the Bonoumin and Gourou watershed). In addition, the relief of these two basins is dominated on average by low relief and no to gentle slopes. However, the high proportion from moderate to high slopes, which together cover 32.34% of the total area of the Gourou basin, compared with 25.42% of that of Bonoumin, can have a considerable influence on the speed, flow rate and volume of runoff water. Moreover, the analysis of the parameters of the hydrographics systems of the two watersheds, showed that their average slope are low (1.06% and 0.98% respectively for the Bonoumin and Gourou watershed). This leads to relatively long water concentration times at their respective outlets. (4H51min44s and 3H51min13s respectively for the Bonoumin and Gourou watershed).

Keywords:- *Morphometric Characteristics, Watersheds, Flooding, GIS, DEM.*

I. INTRODUCTION

The watershed is the basic topographical unit for any hydrology study. In the urban area, knowledge of the morphological characteristics of the watershed is of vital importance to watercourse and geohazard managers. Morphological parameters are the most decisive for the flow of water in a catchment and can influence the severity of floods to a lesser extent [1]. Therefore, characterisation of the variables of time and space that govern the hydrological cycle, is essential for effective water management in a catchment. The morphometric study of a catchment can therefore help to characterise these variables [2]. Morphometry is defined as the measurement of the shape and mathematical analysis of drainage [3]. Thus, its analysis using a qualitative method appears to be essential, as it allows us to describe various topographical parameters influencing hydrological behaviour [4]. The first morphometric studies in the field of hydrology were the work of Horton in 1940, and Strahler in 1950 [5]. But, the recent development of new information and communication technologies, mainly remote sensing and GIS in the 1980s, has considerably revolutionised the morphometric analysis of catchments with the use of digital technology [6]. As part of this digital perspective, the aim of this article is to determine the morphometric parameters of the Bonoumin and Gourou watershed that can be used for hydrological risk prevention purposes, using data from remote sensing and GIS. This article is the first in a series of articles on the study of flooding in general in the Bonoumin and Gourou watersheds in the city of Abidjan.

II. STUDY AREA

Bonoumin and Gourou watersheds (figure 1) are located in the city of Abidjan between latitudes 4°02'30" and 3°56'15" N and longitudes 5°20' and 5°25' W. Bonoumin watershed covers an area of 47.8 km^2 and is located in two municipalities of Abidjan : Abobo and Cocody. While Gourou watershed, with a surface area of 28.7 km^2, straddles four municipalities of this city : Cocody, Abobo, Adjamé and Plateau. The rivers in these two watershed are intermittent, draining mainly rainwater run-off. In terms of climate, these two catchment areas belong to the transitional equatorial climate, characterised by two rainy seasons and two dry seasons [7 ; 8]. The rainy season comprises a long season (April to July, with peak rainfall in June) and a short season (October to November). Also, the dry season is also made up of a long season (December to March) and a short season (August to September). The geology of the study area consists of sand, clay and ferruginous sandstone of the

Hauts-Plateaux [8]. In terms of hydrogeology, the Continental Terminal water table is found mainly in the two watershed [8].

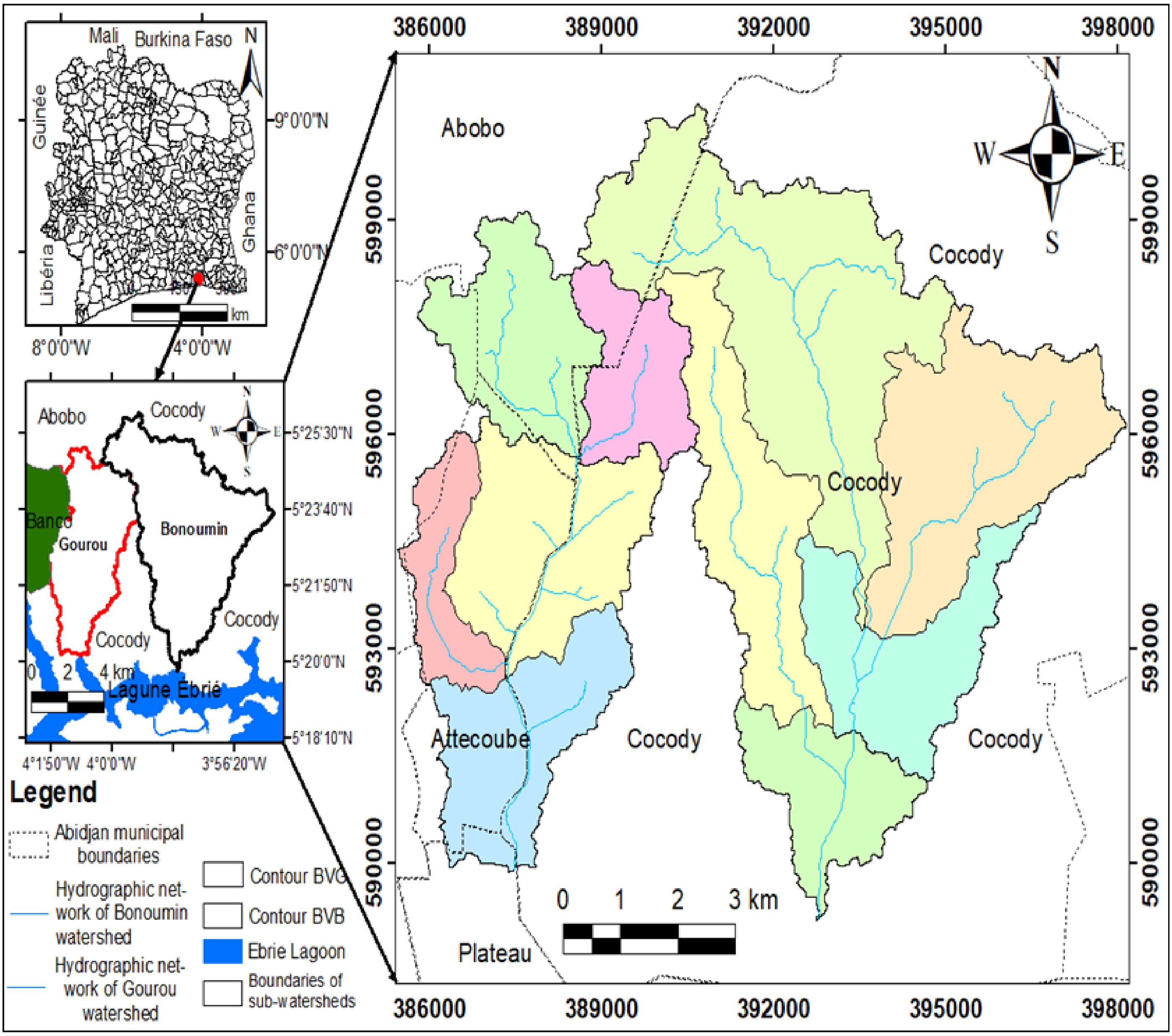

Fig 1 Overview of the Bonoumin and Gourou Catchment Areas

III. MATERIALS AND METHODS

A. Material and Data

To achieve the objectives of this study, a digital elevation model (DEM) was used. This was the Alos Palsar DEM image downloaded from the ASF (Alaska Satellite Facility) website via the link https://vertex.daac.asf.alaska.edu/ at RTC (Radiometrically Terrain-Corrected) level in FBD (Fine Beam Dual polarization) mode in GeoTIFF format. This DEM has a high resolution (12.5 m) and provides data in dual HH + HV polarisation. This image was processed in ArcGis software to highlight the morphometric parameters of each catchment.

B. Methods

The methods presented in the paragraphs below were used to calculate the various morphometric parameters of Bonoumin and Gourou watersheds. These morphometric parameters have been grouped into three entities: the geometric parameters, the relief parameters and the parameters of the hydrographic network of the two basins.

➢ *Calculation of the Geometric Parameters of the Two Watershed*

The geometric parameters of Bonoumin and Gourou watersheds were studied by determining their surface areas, their perimeters, their Gravelius coefficients (K_G) and the dimensions of their equivalent rectangles [9].

- *Calculation of Surface Areas and Perimeters*

The surface area represents the area where rainfall falls and watercourses are fed. The perimeter represents any irregularities in the contour or boundary of the catchment area [10]. These two parameters were determined automatically using ArcGis software.

- *Calculation of Gravelius Coefficients (KG)*

Defined as the ratio of the perimeter of the catchment to the perimeter of a circle with the same area, the Gravelius coefficient (equation 1) is the parameter most commonly used in the literature to characterise the shape of a catchment [11 ; 12].

$$K_G = 0,28 \times \frac{P}{\sqrt{A}} \quad \text{(Eq. 1)}$$

K_G, the Gravelius coefficient; **A**, is the area of the basin and **P**, the perimeter of the basin.

This value increases as the compactness of the system decreases, and can be as high as 3 for very elongated basins. However, when it is less than or equal to 1.12 ($K_G \leq 1.12$), it is no longer possible to assimilate the geometric shape of the catchment to an equivalent rectangle, so the catchment will be assimilated to a square ($K_G = 1.12$) or a circle ($K_G = 1$), [12].

- *Calculation of Equivalent Rectangles*

The concept of the equivalent rectangle was introduced in hydrology, with the aim of comparing the influence of the geometric characteristics of catchment areas on runoff [13]. This involves a geometric transformation that assimilates the catchment to a rectangle with the same perimeter and surface area [9]. The dimensions (length and width) of the equivalents rectangles are calculated from the following relationships (equations 2 and 3) :

$$L = \frac{K_G\sqrt{A}}{1,12}\left[1 + \sqrt{1 - \left(\frac{1,12}{K_G}\right)^2}\right] \quad \text{(Eq. 2)}$$

$$l = \frac{K_G\sqrt{A}}{1,12}\left[1 - \sqrt{1 - \left(\frac{1,12}{K_G}\right)^2}\right] \quad \text{(Eq. 3)}$$

L and **l** represent the length and width of the equivalent rectangle respectively; **K_G**, **P** and **A** represent the Gravelius coefficient, perimeter and surface area of the catchment area respectively.

➢ *Calculation of Relief Parameters*

Several parameters were used in this study to characterise the relief of the Bonoumin and Gourou catchments. These are their hypsometric curves, their characteristic altitudes (maximum, minimum, mean and median altitudes) and their slope indices [10 ; 12 ; 14].

- *Production of Hypsometric Curves of the Twowatersheds*

The hypsometric curve represents the distribution of the altitude bands characterising the watershed as a function of the surface area they occupy. It is used, in this study, to judge the age, the degree of erosion and also to compare the study two watershed. According to [15] and [16], the shape of the hypsometric curve characterises the state of maturity and the erosion cycle of the relief of his whatershed. Thus, three types of watershed are most often encountered :

- ✓ Young watersheds, with a concave shape and a small surface area in relation to the initial change in altitude, characteristic of steep basins ;
- ✓ Old watersheds, on the other hand, are convex in shape, with broad, virtually flat, stable topographies and little variation in altitude. In the urban context, these basins are characterized by a very advanced stage of backfilling of their surfaces and the subsequent waterproofing ;
- ✓ Between these two types of watershed are the balanced or mature watersheds, which represent the transition between the young and the old.

- *Determination of Characteristic Altitudes*

Hydrometeorological parameters such as temperature and precipitation vary according to altitude [17]. Thus, several altitudes will be determined from the hypsometric curve :

- ✓ *Maximum Altitude :* this is the highest altitude in the basin (highest point).
- ✓ *Minimum Altitude :* this corresponds to the lowest altitude in the basin, i.e. the outlet.
- ✓ *Mean Altitude :* this is defined as the mean ordinate of the hypsometric curve and corresponds to the ratio of the area under the curve to the surface area of the basin. The mean altitude is calculated using the following relationship (equation 4).

$$H_{moy} = \frac{1}{A_t}\sum H_i \times A_i \quad \text{(Eq. 4)}$$

- ✓ *Median Altitude :*

This is the altitude read on the hypsometric curve at the point of abscissa 50% of the total surface area of the basin. This value is close to the mean altitude if the hypsometric curve for the basin in question has a regular slope. Otherwise, it is considered to have an irregular slope [18].

- *Calculation of Slope Indexes for the Two Basins*

In order to characterise the relief of a catchment, slope indices are most often calculated by hydrologists. These are the Roche slope index (IR), the overall slope index (Ig) and the specific gradient (Ds). These indices are calculated according to the equations below :

$$I_R = \frac{1}{\sqrt{L_{eq}}}\sum_i^n \sqrt{a_i d_i} \quad \text{(Eq. 5)}$$

$$I_g = \frac{D}{L_{eq}} = \frac{H_{5\%} - H_{95\%}}{L_{eq}} \quad \text{(Eq. 6)}$$

$$D_s = I_g\sqrt{A}$$ (Eq. 7)

a_i represents the percentage of the total surface area included between 2 altitude bands hi and hi-1; d_i : difference in height between two successive altitudes $d_i = h_{i-1} - h_i$ and n: number of contour lines; **D** represents the difference in height; L_{eq} being the length of the equivalent rectangle; H5%: altitude corresponding to 5% of the total surface area of the basin and H95%: altitude corresponding to 95% of the total surface area of the basin.

Thus, depending on the value of I_g and D_s, we have the ORSTOM classification below (Table 1).

Table 1 Type of relief according to the values of the overall slope index (Ig) and the specific vertical drop (Ds) [19]

Global slope index value	Information about relief	Specific gradient value	Information about relief
I_g < 0,002 m	Very low relief	D_S < 10 m	Very low relief
0.002 m < I_g < 0.005 m	Low relief	10 m < D_S < 25 m	Low relief
0.005 m < I_g < 0.01 m	Relatively low relief	25 m < D_S < 50 m	Relatively low relief
0.01 m < I_g < 0.02 m	Moderate relief	50 m < D_S < 100 m	Moderate relief
0.02 m < I_g < 0.05 m	Relatively high relief	100 m < D_S < 250 m	Relatively high relief
0.05 m < I_g < 0.1 m	High relief	250 m < D_S < 500 m	High relief
0.1 m < I_g	Very high relief	500 m < I_g	Very high relief

- *Mapping the Slopes of the Bonoumin and Gourou Catchment Areas*

Spatial variation in the relief of a catchment is a reality that must be taken into account when determining its physical characteristics. We therefore used ArcGis 10.5 GIS software to map the different slopes of the two study catchments. The general orientation of each slope class was then specified on the basis of the classification given by the Canadian government (https://sis.agr.gc.ca/siscan/nsdb/dss/v3/cmp/slope_p.html) as shown in the table below (Table 2).

Table 2 Different slopes and terminologies according to Agriculture and Agri-Food Canada

Slope (%)	Terminology
0 – 0.5	Zero slope
0.5 - 2	Almost zero slope
2 - 5	Very gentle slope
5 - 9	Gentle slope
9 - 15	Moderate slope
15 - 30	High slope
30 - 45	Very high slope
45 - 70	Extreme slope
70 - 100	Abrupt slope
> 100	Very abrupt slope

- *Characterisation of Hydrographic Network*

Several parameters can be used to characterise the hydrographic network of a catchment [10 ; 19]. These are drainage density, hydrographic density, the confluence ratio, the frequency of watercourses, the torrentiality coefficient and the ratio of watercourse lengths.

- *Calculation of Drainage Densities (D_d)*

Considered as one of the indices used to characterise the degree of development of a watercourse, drainage density is defined as the total length of the hydrographic network per unit area of the catchment [10] (equation 8).

$$D_d = \left(\sum_{i=n}^{n} L_i\right)/A$$ (Eq. 8)

- ✓ ***D_d*** *:* drainage density (km^{-1}); ***Li*** *:* total length of all watercourses of order i (km) ;
- ✓ ***A :*** catchment area (km^2).

- *Calculation of Hydrographic Density (F)*

Hydrographic density represents the number of flow channels per unit area (equation 9).

$$F = \left(\sum_{i=n}^{n} N_i\right)/A$$ (Eq. 9)

- ✓ ***F*** : hydrographic density (km^{-2}); **Ni:** number of rivers; **A :** surface area of basin (km²)

- *Calculation of Confluence Ratio R_c*

The confluence ratio (Rc) designates the ratio of the number of talweg of a given order to those of the following order [20]. This ratio is a function of slope, physiognomy and climate. It provides information on the degree of branching of the drainage network and the evolution of the catchment areas [21]. It is given by the following relationship (equation 10).

$$R_c = \frac{N_i}{N_{i+1}} \quad \text{(Eq. 10)}$$

- ✓ **Ni :** the number of river sections of order i.

The lower this ratio, the fewer bifurcations there will be in the drainage network and the faster the sediment will be discharged downstream [22].

- *Calculation of the Streams Frequency (F_c)*

The frequency of watercourses (Fc) represents the ratio of the number of first-order watercourses to the surface area of the study catchment [13] (equation 11).

$$F_c = \frac{N_1}{A} \quad \text{(Eq. 11)}$$

- *Calculation of Torrential Coefficients (C_t)*

The torrentiality coefficient is defined as the product of the drainage density and the frequency of elementary watercourses (of order 1). It is expressed by the following formula [13] (equation 12) :

$$C_t = D_d \times \frac{N_1}{A} \quad \text{(Eq. 12)}$$

- ✓ **Ct :** torrentiality coefficient (km^{-3}); $\mathbf{D_d}$: drainage density (km^{-1}) ; $\mathbf{N_1}$ **:** number of first-order rivers ; **A :** catchment area.

This index can be more indicative and expressive than drainage density. The higher it is, the greater the torrentiality, reflecting the greater aggressiveness of the downpours.

- *Calculation of Length Ratios (R_l)*

The length ratio (calculated according to equation 13) corresponds to the ratio of the average length of watercourses of order (n+1) to the average length of watercourses of order (n).

$$R_l = \frac{L_{n+1}}{L_n} \quad \text{(Eq. 13)}$$

- ✓ $\mathbf{R_L}$ is the length ratio; $\mathbf{L_{n+1}}$ represents the total length of watercourses of order n+1 in (Km) and $\mathbf{L_n}$**,** the total length of watercourses of order n in (Km).

IV. RESULTS

A. *Geometric Parameters*

The values obtained from calculating the geometric parameters of the Bonoumin and Gourou catchments are summarised in the table below (Table 3).

Table 3 Summary of the geometric parameters of the study catchment areas

Catchments characteristics	**Geometric parameters**				
	A (in km²)	**P (in km)**	**K_G**	**Equivalent rectangle**	
				L_{eq} (in km)	**l_{eq} (in km)**
Bonoumin	47.8	58.3	2.36	27.18	1.76
Gourou	28.7	42.6	2.23	19.69	1.46

Analysis of the table shows that the surface areas (A) of Bonoumin and Gourou watersheds are 47.8 and 28.7 km² respectively. This shows that these watersheds are small, with perimeters (P) of around 58.3 and 42.6 km for Bonoumin and Gourou watersheds respectively. The Gravelus coefficient (K_G) are 2.36 and 2.23 respectively for the Bonoumin and Gourou watersheds, indicating that these two watershed are elongated. This made it possible to calculate the dimensions (lengths and widths) of the equivalent rectangles of the two watershed. The length (L_{eq}) and width (l_{eq}) of the equivalent rectangle in Bonoumin watershed are 27.18 km and 1.76 km respectively. For Gourou watershed, the values are 19.69 km and 1.46 km respectively. However, it should be noted that the Bonoumin watershed is more elongated than the Gourou watershed, as shown by the higher value of its Gravelus coefficient (2.36) and the length of its equivalent rectangle (27.18 km).

B. *Relief Parameters of the Two Watersheds*

- ➢ *Hypsometry*

Table 4 shows the percentages of surface area of the different altitude classes in the two studied watersheds.

Table 4 Distribution of altitude classes according to their surfaces areas

Bonoumin watershed			**Gourou watershed**		
Altitude classes	**A_i (km²)**	**Ai (%)**	**Altitude classes**	**A_i (km²)**	**Ai (%)**
26 - 42	1.16	2.44	**23 - 44**	1.0	3.4
42 - 54	2.28	4.78	**44 - 59**	1.9	6.6
54 - 65	3.17	6.67	**59 - 71**	2.7	9.5
65 - 75	4.46	9.39	**71 - 83**	3.7	12.9

Bonoumin watershed			Gourou watershed		
Altitude classes	**A_i (km^2)**	**Ai (%)**	**Altitude classes**	**A_i (km^2)**	**Ai (%)**
75 - 85	4.77	10.03	**83 - 96**	4.1	14.3
85 - 96	4.42	9.29	**96 - 109**	3.2	11.1
96 - 108	4.39	9.24	**109 - 121**	2.7	9.4
108 - 119	5.17	10.86	**121 - 131**	4.7	16.6
119 - 127	9.33	19.62	**131 - 145**	4.0	13.9
127 - 144	8.41	17.68	**145 - 166**	0.6	2.2
	47.56	**100**		**28.5**	**100**

- *The Hypsometric Maps of these Two Watersheds are shown by Figure 2*

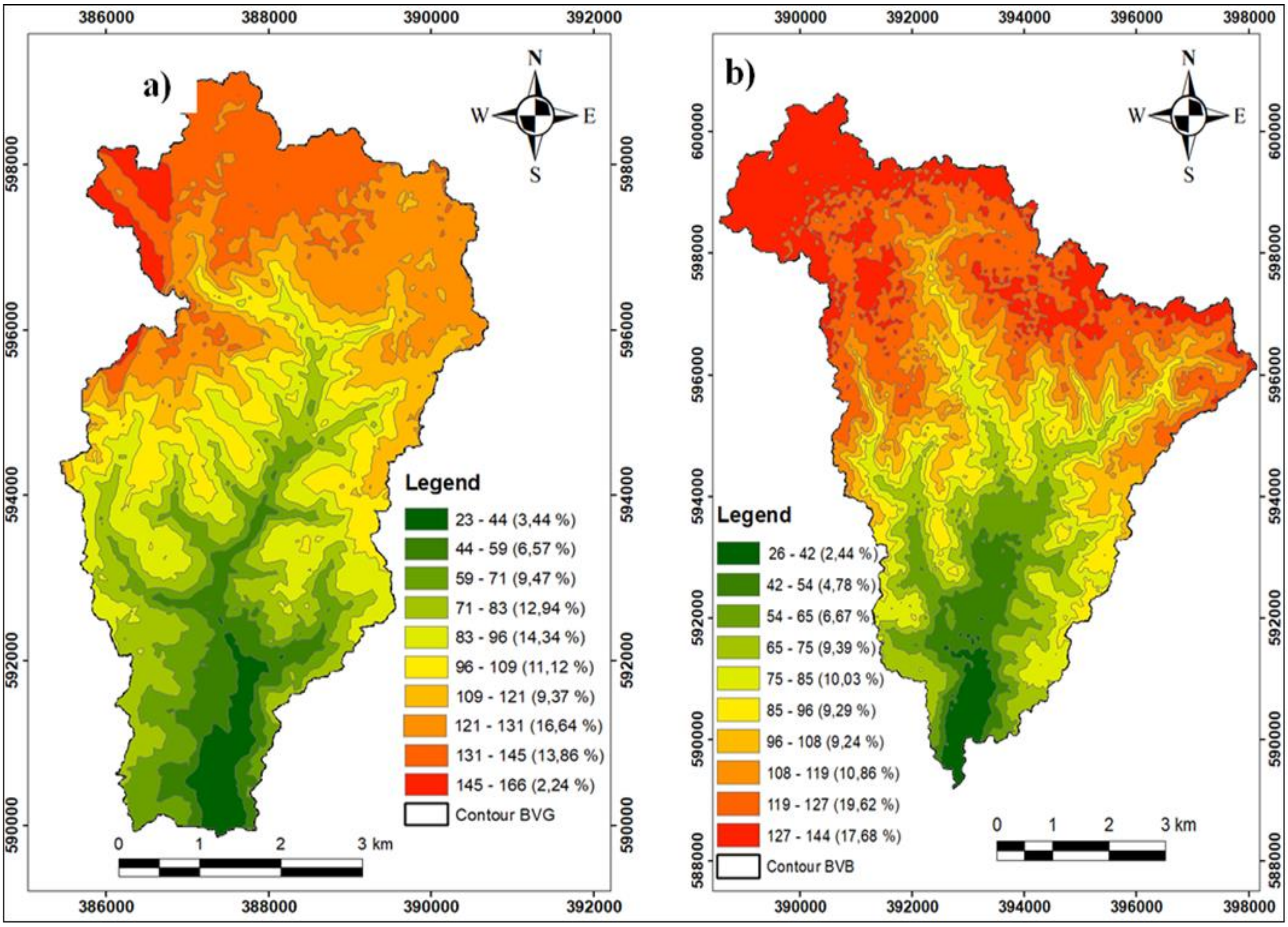

Fig 2 Hypsometric map of the Gourou (a) and Bonoumin (b) watersheds

The analysis of table 4 and Figure 3 shows that the high altitude classes (orange color) are mainly located upstream of the two watersheds. They occupy 42.11% of the total surface area of the Gourou watershed and 57.4% of that of the Bonoumin watershed. These values reflect the greater influence of relief on the Bonoumin watershed than on the Gourou watershed. Furthermore, this greater distribution of high altitudes in the Bonoumin basin than in the Gourou basin may be partly responsible for the upsurge in flooding in several areas of the Bonoumin basin. Moreover, unlike the Bonoumin basin, which is largely dominated by two altitude classes, i.e. [119 to 127m] and [127 to 144m], In the Gourou watershed, on the other hand, there is a more or less even distribution of surface areas in the different classes. This reflects a more even distribution of slopes in the Gourou watershed. Furthermore, the data obtained from the hypsometric maps enable us to construct the hypsometric curves for the two watersheds, as shown in figure 3.

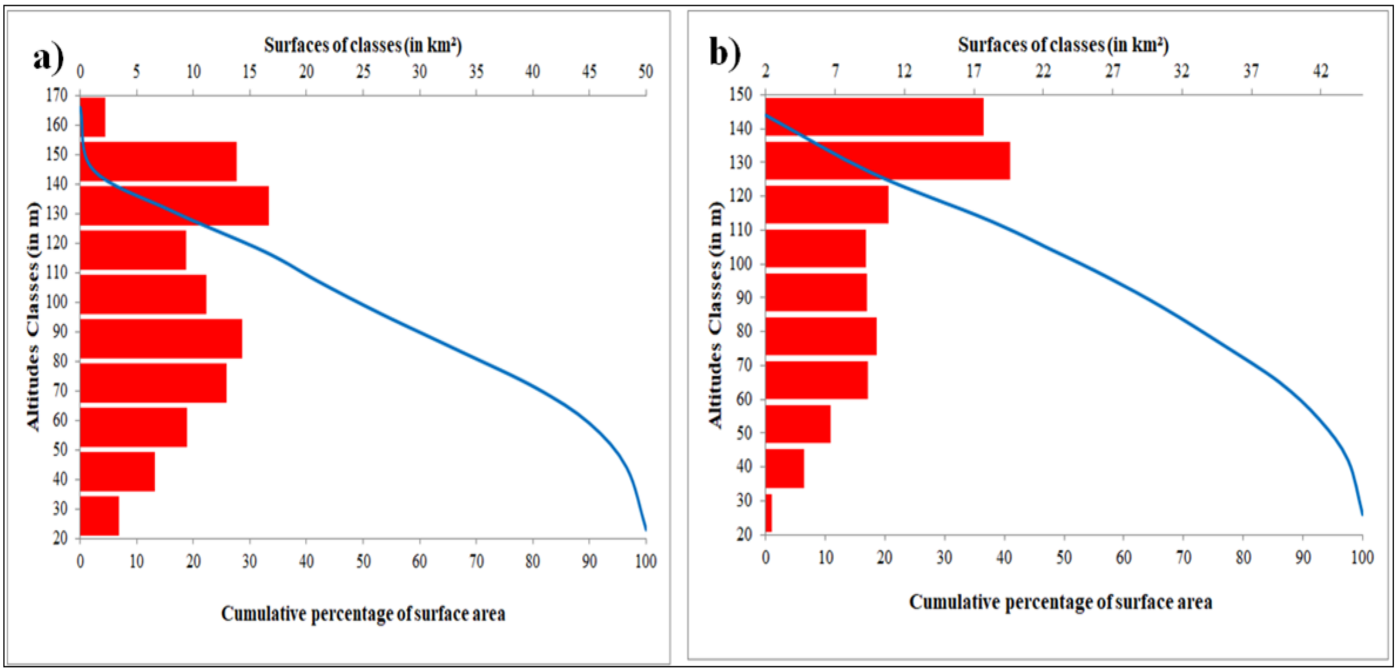

Fig 3 Hypsometric curves for the Gourou (a) and Bonoumin (b) watersheds

Observation of the figure shows that the hypsometric curves of the Gourou and Bonoumin watersheds differ in their appearance. The curve for the Gourou basin is both convex (towards higher altitudes) and concave (towards lower altitudes). On the other hand, in the Bonoumin basin, the hypsometric curve is concave at low altitudes and not convex at high altitudes, where it slopes steeply.

➢ *Typical Elevations of Study Catchment Areas*

The characteristic altitudes, comprising the extreme altitudes (minimum and maximum altitude of the basin as well as those at 5% and 95% of the total surface on the hypsometric curve), the mean and median altitude, and the relief of the two catchments, are recorded in the table below (Table 5).

Table 5 Summary of Relief Parameters of Study Catchments

Watershed characteristics	Relief parameters					
	Characteristic altitudes (in m)					
	H_{min}	H_{max}	H_{moy}	$H_{5\%}$	$H_{méd}$	$H_{95\%}$
Bonoumin	26	144	98.4	139	104	50
Gourou	23	166	97.9	141	99	50

Table 5 shows that, in general, apart from the minimum and maximum altitudes of the two catchments, which differ slightly, the other characteristic altitudes, including H5%, H50%, H95% and Hmoy, are more or less the same. This means that the relief of the two watersheds shows similarities and slight variations.

➢ *Characterization of Relief on the Two Watersheds based on the Overall Slope Index*

Table 6 gives an overview of the values obtained from the calculation of slope indices and the corresponding type of relief found in the Bonoumin and Gourou watersheds.

Table 6 Summary of slope indices and corresponding relief types

Watersheds characteristics	Relief parameters / Slope indexes			
	I_g	I_r	D_s (in m)	Relief
Bonoumin	0.003	0.63	22.4	Low relief
Gourou	0.005	0.79	24.5	Low relief

The analysis of the table 6 shows that the value of the Roche slope index (Ir) for the Bonoumin basin is 0.63, while that for the Gourou basin is 0.79. As for the overall slope index (Ig) and specific gradient (Ds), the values are 0.003 and 22.4 m respectively for the Bonoumin catchment, and 0.005 and 24.5 m for the Gourou catchment. According to ORSTOM classifications, the values of these indices indicate that the relief encountered in the two watersheds is low. This should normally result in low peak flows at the outlets of these two catchments, given the high level of urbanization on their respective surfaces.

➢ *Slope Mapping in the Bonoumin and Gourou Watersheds*

Mapping the slopes of the two watersheds (Figure 4) revealed six (06) slope classes as detailed in Table 7.

Table 7 Slope Classification of the Bonoumin and Gourou Watersheds

Slope classes of Gourou watershed				Slope classes of Bonoumin watershed			
Classes in %	**Surface**		**Slope terminology**	**Value in %**	**Surface**		**Slope terminology**
	In km²	**In %**			**In km²**	**In %**	
0 à 5	9.87	34.39	zero to very gentle slope	**0 à 5**	19.34	40.46	zero to very gentle slope
5 à 9	9.17	31.95	Gentle slope	**5 à 9**	15.75	32.95	Gentle slope
9 à 13	4.85	16.90	Moderate slope	**9 à 13**	7.34	15.36	Moderate slope
13 à 26	4.43	15.44	High slope	**13 à 24**	4.81	10.06	High slope
26 à 45	0.25	0.87	Very high slope	**24 à 45**	0.38	0.79	Very high slope
45 à 56	0.13	0.45	Extreme slope	**45 à 46**	0.18	0.38	Extreme slope

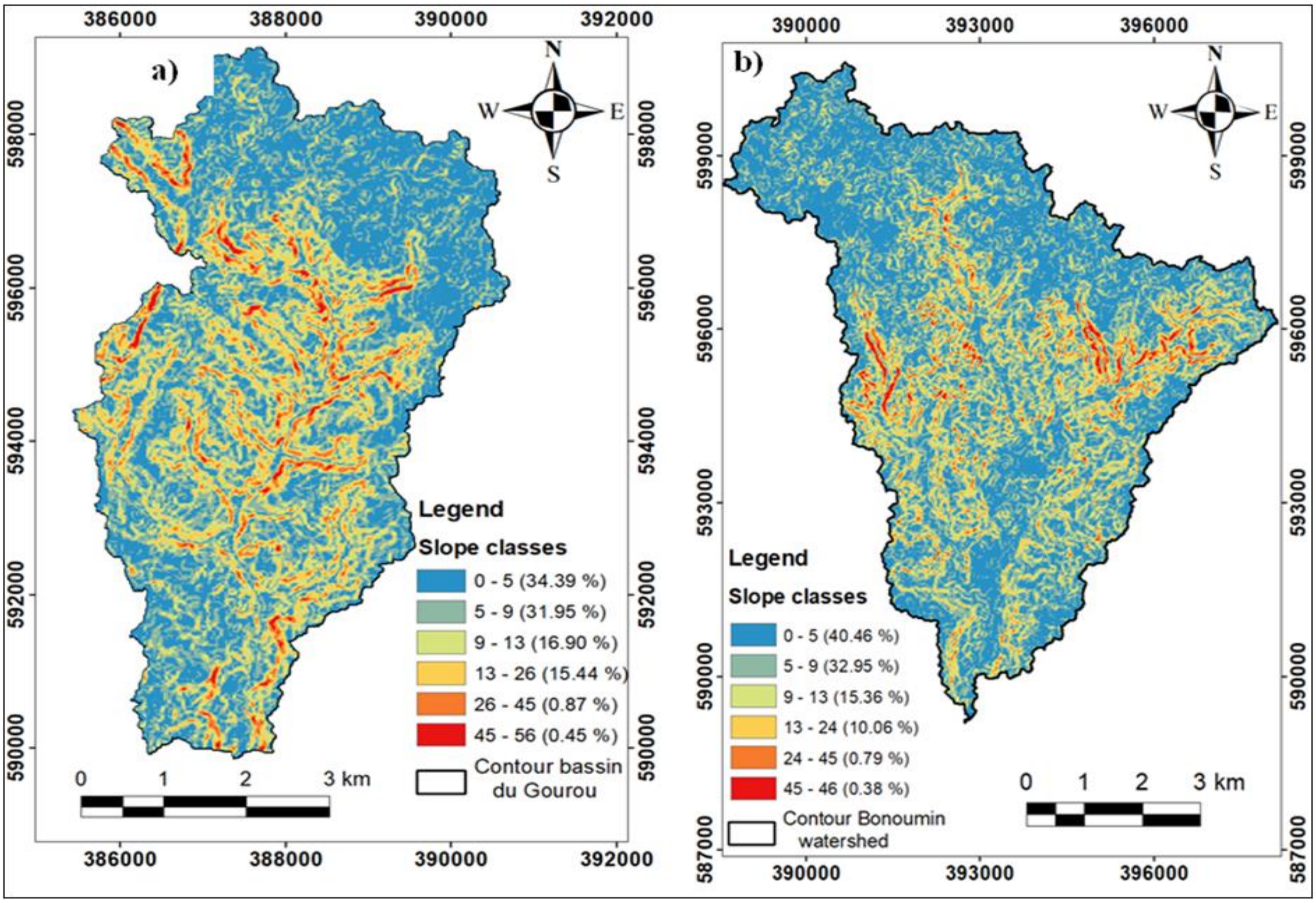

Fig 4 Slope map of Gourou (a) and Bonoumin (b) watersheds

Figure 5 and Table 6 show that six (6) classes were selected to characterize the slopes of each of the two watersheds, with areas varying from one class to the next. In the Gourou basin, for example, zero to gentle slopes together occupy 66.34% of its total surface area, or 19.04 km^2, while in the Bonoumin basin, they occupy 73.41% of the total surface area, or 35.09 km2. From these values, we can deduce that zero to gentle slopes are much more prevalent in the two watersheds studied. However, these slopes have a higher proportion in the Bonoumin basin than in the Gourou basin. As for moderate to steep slopes, they together cover 32.34% of the Gourou basin's total surface area, i.e. 9.68 km^2, versus 25.42% of Bonoumin's, i.e. a total surface area of 12.15 km^2. Lastly, very steep to extreme slopes are poorly represented, accounting for 1.32% of the total surface area of the Gourou catchment compared with 1.17% of the Bonoumin catchment. These low proportions of very steep to extreme slopes indicate that, overall, the high flows observed following extreme rainfall, responsible for flash floods in the Bonoumin and Gourou catchments, may be linked, in part, to moderate to steep slopes.

C. Hydrographic Systems Parameters

The parameters used to characterize the hydrographic networks of the Bonoumin and Gourou watersheds are summarized in Table 8, while Figure 5 shows the hydrographic network maps for these two watersheds.

Table 8 Summary of Hydrographic Network Parameters in Study Catchments

Watersheds characteristics	**Hydrographic system parameters**								
	D_d	**F**	**R_c**	**F_c**	**C_t**	**C_a**	**R_L**	**P_{moy}**	**Tc**
Gourou	1.8	1.90	4.3	1.5	2.7	0.36	0.5	0.98	3 H 51 min 13 s
Bonoumin	2.4	1.92	3.7	1.5	3.5	0.35	1.2	1.06	4 H 51 min 44 s

D_d = drainage density; **F** = hydrographic density; **Rc** = confluence ratio; **Fc** = stream frequency; **C_t** = torrentiality coefficients; **C_a** = elongation coefficients and **R_L** = length ratio

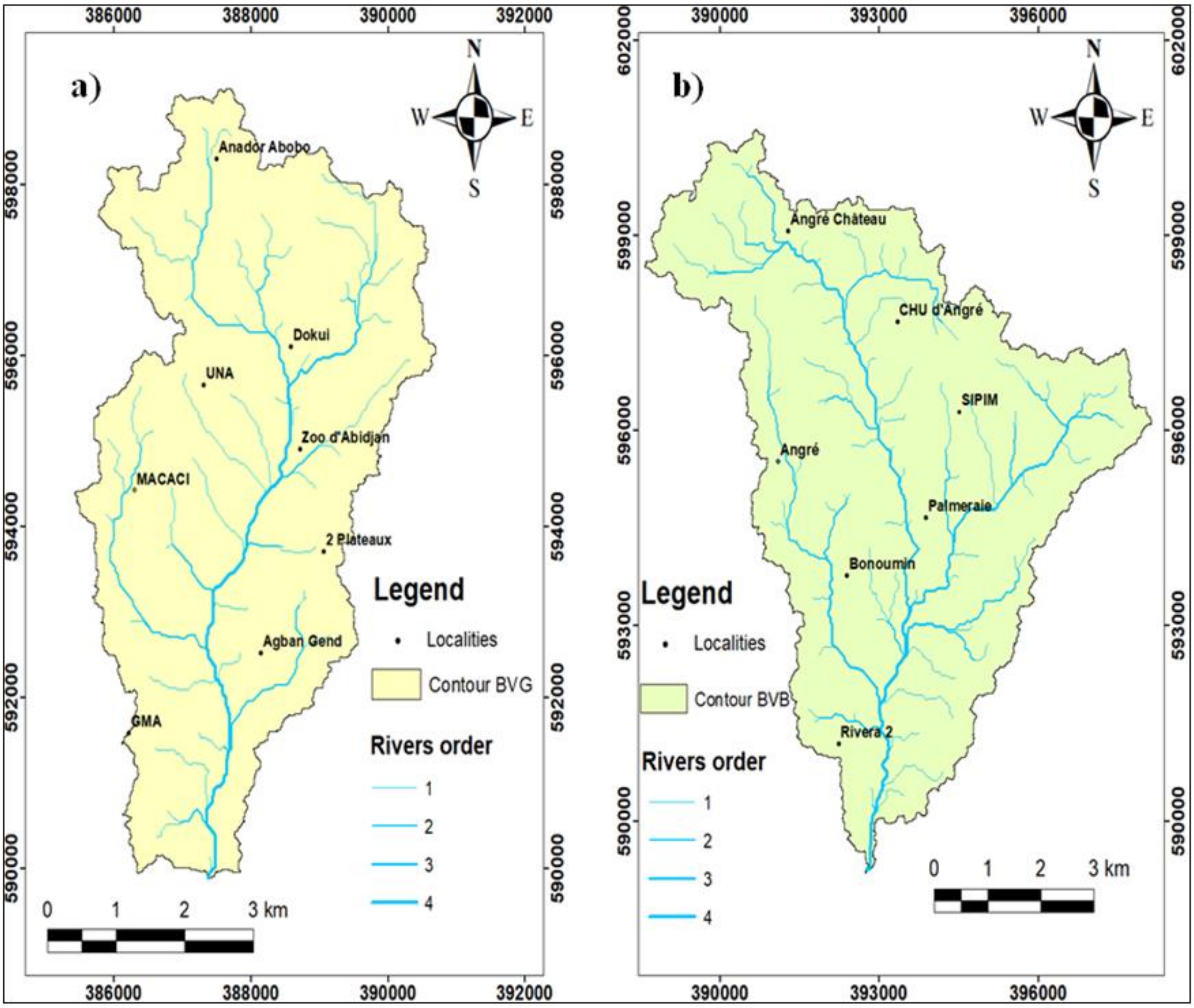

Fig 5 Map of Hydrographic Networks in the Gourou (a) and Bonoumin (b) Watersheds

The Strahler classification, applied to the hydrographic networks of these two watersheds, shows that they are both of order 4. This means that we are dealing with a highly irrigated area, given the size of these two watersheds. Table 6 shows that the drainage density (Dd) of the Bonoumin basin is 2.42 km^{-1}, greater than that of the Gourou basin, which is 1.80 km-1. This indicates that drainage in the Bonoumin basin is greater than in the Gourou basin. Hydrographic density (F) is 1.92 km^{-2} for the Bonoumin basin and 1.90 km^{-2} for the Gourou basin. The confluence ratio (Rc) for the Bonoumin watershed is 3.73, lower than that for the Gourou watershed, which has a value of 4.27. Stream frequency (Fc) in the Bonoumin watershed is 1.46 km^{-2}, while that of the Gourou watershed is 1.51 km^{-2}. The values of the torrentiality (Ct) and elongation (Ca) coefficients for the Bonoumin watershed are 3.54 km^{-3} and 0.35 respectively, whereas they are 2.72 km^{-3} and 0.36 respectively for the Gourou watershed. The Bonoumin watershed has a length ratio (LR) of 1.20, compared with 0.51 for the Gourou watershed. The values of the torrentiality (Ct) and elongation (Ca) coefficients for the Bonoumin watershed are 3.54 km^{-3} and 0.35 respectively, whereas they are 2.72 km^{-3} and 0.36 respectively for the Gourou watershed. The Bonoumin watershed has a length ratio (LR) of 1.20, compared with 0.51 for the Gourou watershed.

V. DISCUSSIONS

➢ *Geometric Characteristics of the Bonoumin and Gourou Watersheds*

Analysis of the geometric parameters showed that the Gravelus compactness index (KG) of the Bonoumin catchment is 2.36, while that of the Gourou catchment is 2.23. Thus, these results show that both watersheds are elongated in shape, as attested by several authors including [1 ; 12 ; 14 ; 23 ; 24]. Indeed, in the work of [12] and [23] on morphometric analysis of the Menoua watershed (West Cameroon) for better management of morphohydrological risks, they obtained 2.107 as the KG value. As for [24], whose study focused on the use of GIS in the morphometric analysis and prioritization of the Wadi Inaouene sub-catchments (North-East Morocco), they found KG values ranging from 1.55 to 2.36. It should also be noted that the Bonoumin watershed, with a KG of 2.37, is more elongated than the Gourou watershed, which has a KG of 2.23. According to [1], the elongated shape of a watershed can result in a long time for water to concentrate, and therefore a lower or lower peak flow at its outlet. However, given the highly urbanized nature of the Bonoumin and Gourou watersheds, they will tend to have high peak flows in certain areas, leading to catastrophic flooding in the event of heavy rainfall. In addition, the surface areas of the two sub-basins are relatively small, combined with their high level of impermeability and the state of stormwater management structures (which are insufficient, undersized and inadequately maintained), contribute to an increase in water levels in gutters during heavy rainfall.

➢ *Crelief Characteristics of the Two Study Catchment Areas*

Analysis of the shape of the hypsometric curve for the Gourou watershed has shown that it is convex (towards higher altitudes) and concave (towards lower altitudes), indicating that this is a mature watershed where erosion has reached an advanced stage. In urbanized watersheds, this erosion phenomenon can be represented by the very high level of surface sealing, as is the case in the Gourou watershed. In the Bonoumin watershed, on the other hand, analysis of the hypsometric curve has shown a steep slope towards higher altitudes (lack of convexity), but a pronounced concavity towards lower altitudes. This shape of the hypsometric curve shows that we're dealing with a young basin where the phenomenon is not significant. Furthermore, the steepness (and hence lack of convexity) of the hypsometric curve towards higher altitudes indicates that erosion is more or less weak at this point in the basin, as shown in photo 1.

Photo 1 Overview of Bonoumin Watershed's Sparsely Urbanized Headwaters

The urbanization of the Gourou watershed differs from that of the Bonoumin watershed, which is more urbanized downstream than upstream. What's more, the geology of both watersheds is dominated by sandy-clay formations, which are more or less sensitive to erosion, as evidenced by the significant silting at the outlets of these two watersheds. These assertions regarding silting at the outlet of the Gourou watershed have already been obtained by [25]. Indeed, according to work carried out in the commune of Adjamé (Gourou watershed), the origin of this silting could come from bare spots (playgrounds, uncovered slopes, etc.), i.e. sparsely urbanized areas.

➢ *Characteristics of the Bonoumin and Gourou Watersheds' Hydrographic Networks*

Observation of the hydrographic network maps for the two watersheds shows that they differ from one another. In fact, the hydrographic network of the Gourou basin is made up of a main watercourse to which are attached several tributaries (analogous to the branches of a tree). It is therefore a dendritic network. On the other hand, observation of the hydrographic network in the Bonoumin watershed reveals three main tributaries that are independent of each other, thus characterizing a radial network.

Also, the results of calculating the parameters characterizing the hydrographic network showed that the drainage density of the Gourou catchment is 1.80 km^{-1}, while that of the Bonoumin catchment is 2.42 km^{-1}. These low drainage density values indicate that the soils and subsoils of both catchments are favourable to infiltration. In addition, several studies have shown that the geology of the study area is dominated by sandy-clay formations [26], which facilitate the infiltration of water into the soil. With regard to hydrographic density, the results obtained indicate that its value in the Gourou watershed is 1.90 km^{-2}, while in the Bonoumin watershed it is 1.92 km^{-2}. As in the case of drainage density, hydrographic density values are also low. This confirms that the two watersheds studied here are potentially permeable bedrock with little relief. These results are corroborated by those obtained by [24] and the Comité interministériel d'aménagement du territoire haïtien, in its publication on the guide méthodologique pour les études de diagnostic des bassins versants [27]. The results obtained by [27] show that the drainage density and hydrographic density values for the Rivière Grise (eastern part of the Cul-de-sac watershed in Haiti) are 0.82 km/km^2 and 0.3 drain/km respectively. As for [24], in their study of the Oued Inaouene sub-catchments, obtained drainage density values ranging from 0.62 to 5.17 km/km^2. It should also be noted that the drainage and hydrographic densities of the Bonoumin and Gourou watersheds are roughly equal. This means that the two watersheds share the same bedrock.

The average slope of the main Gourou and Bonoumin rivers is 0.98 and 1.06 m/km respectively. These results show that the time of concentration of water in the two watersheds is relatively long. Indeed, the time of concentration of water in the Gourou basin is around 3H 51 min 13s, while in the Bonoumin basin it is around 4H 51 min 44s.

VI. CONCLUSION

The aim of this study was to investigate the impact of the morphometric characteristics of the Bonoumin and Gourou catchments on hydrological processes. DTM analysis revealed that both watersheds have an elongated shape. However, the Bonoumin watershed, with a Gravelius coefficient of 2.36, is more elongated than the Gourou watershed, with a Gravelius coefficient of 2.23. Analysis of relief parameters showed that the hypsometric curve of the Bonoumin basin has younger characteristics than the Gourou basin, which is more mature in terms of erosion. In addition, analysis of slope indices and classes showed that, generally speaking, the relief of the two watersheds is low. Thus, the high flows observed following extreme rainfall, responsible for catastrophic flooding in the Bonoumin and Gourou catchments, may be linked in part to the moderate to steep slopes. Analysis of the hydrographic network revealed that that of the Gourou basin is dendritic, whereas that of the Bonoumin basin is radial. In addition, the average slopes of the two watersheds were found to be low, with an irregular distribution of slopes and a higher torrentiality coefficient in the Bonoumin watershed than in the Gourou watershed. These results show that the Bonoumin watershed is more vulnerable to flooding than the Gourou watershed. Although the study of morphometric parameters carried out in this study was not exhaustive, the results can nevertheless be used to model the hydrological and hydraulic functioning of the Bonoumin and Gourou watersheds.

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