JOURNAL AFRICAIN DES SCIENCES
VOL. 3, **1** (2026) 137-148

https://jafrisci.org

ISSN (online) : 3107-0949 ; ISSN (print) : 3107-0930

OPEN ACCESS

ARTICLE DE RECHERCHE

Article Info.:
Reçu : le 06/11/2025
Accepté : le 17/01/2026
Publié : le 02/02/2026

MORPHOMETRIC AND HYDROGRAPHIC ANALYSIS OF THE CATCHMENT OF LUKAYA IN THE DEMOCRATIC REPUBLIC OF THE CONGO: IMPLICATIONS FOR HYDROGEOMORPHOLOGICAL RISK MANAGEMENT

Blaise Kamosi Zola [1], Modeste Kisangala Muke [1], Patrick N'landu wa Ndela [1], Céline Matumona Seya [2], Fils Makanzu Imwangana [1,3,*]

https://doi.org/10.70237/jafrisci.2026.v3.i1.15

Resumé

L'analyse morphométrique du bassin versant est un outil essentiel pour comprendre et évaluer les risques hydrogéomorphologiques. Cette étude porte sur l'analyse des caractéristiques géométriques et hydrographiques du bassin versant de la Lukaya à l'aide des techniques des Systèmes d'Information Géographique (SIG). L'approche méthodologique réside essentiellement sur les calculs de paramètres morphométriques, géométriques et hydrographiques dans un environnement SIG. L'objectif poursuivi est de fournir des données hydromorphologiques utiles aux aménageurs, aux experts en génie civil et en réduction des risques de catastrophes d'origine hydrométéorologique, afin de faciliter l'élaboration de plans durables d'aménagement du bassin versant de la Lukayare, la conception d'ouvrages d'assainissement et de drainage, le dimensionnement adéquat des fondations d'ouvrages, ainsi que la prise de décisions éclairées concernant la gestion du ruissellement pluvial. Les résultats révèlent un bassin versant de forme allongée (KG = 1,9), une variabilité spatiale de la pente, une faible densité du réseau hydrographique (Dd = 0,24 et F = 0,09), ainsi qu'un temps de concentration prolongé des eaux de ruissellement. Ces résultats indiquent que ce bassin versant présente une faible vulnérabilité aux risques hydrogéomorphologiques, notamment à l'érosion des sols et aux inondations. Cependant, la récurrence de tels phénomènes dans le bassin versant pourrait être exacerbée par son caractère semi-urbain et par une gestion des terres mal maîtrisée.

Mots clés : Analyse morphométrique, risques hydrogéomorphologiques, bassin versant, SIG, Rivière Lukaya

Abstract

Morphometric analysis of the catchment is an essential tool for understanding and assessing hydrogeomorphological risks. This study focuses on the analysis of the geometric and hydrographic characteristics of the Lukaya catchment using Geographic Information System (GIS) techniques. It presents the results obtained through the calculation of morphometric and hydrographic parameters such as catchment shape, topography, drainage density, and hydrographic network. The aim is to provide the useful hydromorphological data to planners, civil engineering experts and experts in reducing the risks of hydrometeorological disasters, in order to facilitate the development of sustainable plans for the catchment of Lukaya, the design of sanitation and drainage works, the proper sizing of structural foundations, as well as informed decision-making regarding surface runoff management. The results reveal an elongated catchment shape (KG = 1.9), spatial variability of slope, low drainage and hydrographic density (Dd = 0.24 and F = 0.09), accompanied by a prolonged concentration time of surface runoff. These findings indicate that the catchment exhibits low vulnerability to hydrogeomorphological risks, particularly soil erosion and flooding. However, the recurrence of such phenomena in the catchment may be exacerbated by its semi-urban nature and poorly controlled land management.

Key words : Morphometric analysis, Hydrogeomorphological risks, Catchment, GIS, Lukaya river

1. Introduction

Morphometric analysis of catchments is an essential tool for understanding and assessing hydro-geomorphological risks. By examining the shape, size, and topographic characteristics of a catchment, it is possible to identify areas that are potentially at risk of flooding, erosion, or mass movements (Baba-Hamed & Bouanani, 2016; Mashauri et al., 2023). A catchment refers to a land area where topographic slopes direct surface runoff toward a common outlet. It is subdivided into several sub-catchments, representing tributaries of the main stream. The outlet of a catchment is the lowest point of the hydrographic network through which all drained water converges. The

Correspondance : : *fils.makanzu@unikin.ac.cd* ***(F. M. Imwangana)***

[1] *University of Kinshasa, Faculty of Science and Technology, Department of Geosciences, Research and Training Unit in Natural Risk Management (URF-GRN), P.O. Box 190, Kinshasa XI, Democratic Republic of the Congo.*
[2] *National Center of Remote Sensing, Scientific Department, Kinshasa/Gombe, Democratic Republic of the Congo*
[3] *Geological and Mining Research Center (CRGM), Laboratory of Geomorphology and Remote Sensing, Kinshasa, Democratic Republic of the Congo.*

catchment divide marks the boundary between adjacent topographic catchments (Morell et al., 1999). Thus, all watercourses - whether permanent or temporary - that contribute to linear surface runoff form the hydrographic network (Hocine et al., 2008). This network can exhibit a wide range of patterns, largely influenced by four primary factors: slope, geology, climate, and human activity (Xiaomin & Sequeira, 2004).

In the context of increasing anthropogenic pressures and heightened hydrological risks, the catchment of Lukaya requires precise hydromorphological characterization. However, the lack of integrated data from morphometric and hydrographic analyses limits the effectiveness of flow management and land-use planning initiatives. Therefore, the core issue of this study is to determine how the use of GIS tools for the geometric and hydrographic analysis of this catchment can enhance the understanding of its hydrological functioning and support decision-making for sustainable land management.

The hydrological study of catchments is crucial to understanding how physiographic characteristics influence streamflow regimes, particularly during flood and low-flow periods (Baba-Hamed & Bouanani, 2016). It is therefore essential to analyze the hydro-morphometric characteristics of a catchment (Waikar & Aditya, 2014), as some of these parameters exert a significant control on the velocity of surface runoff. The physical factors of a catchment encompass geological, geomorphological, hydrographic, hydrological, and climatic attributes. Among these, morphometric and hydrographic parameters play a key role in shaping surface runoff dynamics. The response of a catchment to precipitation is strongly influenced by morphological elements such as basin size, relief, longitudinal slope, and orientation. Additional factors include lithology, soil type, vegetation cover, and the structure of the hydrographic network (Laabidi et al., 2016).

Traditional techniques for studying catchment physical characteristics have been based primarily on manual methods, which often produce inaccurate results (Bentekhici, 2006). For instance, morphometric indices are generally derived from basin area and perimeter, which are extracted using a curvimeter for perimeter and a planimeter for area, based on topographic maps. Errors related to instrument handling and the inaccuracy of some maps propagate - and sometimes amplify - throughout these operations and copies. Delineating catchments and calculating their morphometric, hydrographic, and hydrological characteristics (e.g., area, perimeter, elevation, slope, velocity, and discharge) remain challenging due to data scarcity. In the Democratic Republic of the Congo, hydrological and limnometric stations have not been operational for decades, and topographic maps offer limited accuracy for this type of analysis. Consequently, data extracted from such maps are often unreliable, introducing errors that propagate with repeated use. For example, catchment shape indices are calculated using basin area (A). If the area value is incorrect due to poor delineation, all indices derived from it will inevitably be inaccurate. Unfortunately, several catchment areas derived through this traditional method are underestimated. This is the case for the Funa basin (Makoko & Sedjabo, 1975). Such underestimation results from inconsistent delineation relative to the accepted definition, which directly affects index values. This concern is even more relevant today, as digital elevation models (DEMs) and geographic information system (GIS) tools allow for more accurate computation of these parameters, even if their accuracy remains influenced by image resolution (pixel size). Nevertheless, resolution-related uncertainties are generally less significant than errors stemming from manual catchment mapping and extraction (Bentekhici, 2006).

This study aims to analyze the catcment of Lukaya from a hydro-morphometric perspective. The main objective is to determine the physical characteristics that significantly affect surface runoff and contribute to erosion and flooding risks.

To achieve this, the study adopts a geomatics-based methodological approach to automatically extract the drainage network and delineate the catchment using a DEM, in order to quantify and analyze hydro-morphometric parameters for the prevention of hydro-geomorphological risks in the Lukaya basin. This approach has been successfully applied by several authors (e.g.: Vogt et al., 2003; Bloch et al., 2004; Kuldeep & Upasana, 2011; Tamll et al., 2011; Akawwi, 2013). The study of hydro-geomorphological parameters is of undeniable importance for the effective management of natural hazards such as erosion and flooding (Bewket & Sterk, 2005; Kouame Kassi et al., 2007; Kouame Kassi et al., 2011; Narmatha et al., 2013; Makanzu Imwangana, 2014). With the development of advanced tools such as GIS and remote sensing, it has become increasingly feasible to determine catchment shape, relief, and hydrographic typology in a more accurate and efficient manner (Saidi, 2013), thus producing results closer to reality.

2. Materials and Methods

2.1. Study Area

The Lukaya River is one of the tributaries of the N’Djili River, and its catchment therefore constitutes a sub-basin of the N’Djili. The Lukaya catchment is located to the south of the larger N’Djili basin, at the extreme southwestern edge of Kinshasa city-province, and extends into the eastern part of Kongo-Central Province. It covers an area of approximately 350 km², lying between 4°25′ and 4°46′ South latitude and 15°07′ and 15°16′ East longitude. Administratively, it falls within the Commune of Mont-Ngafula in Kinshasa city-province, as well as Kasangulu territory in Kongo-Central Province (Fig.1).

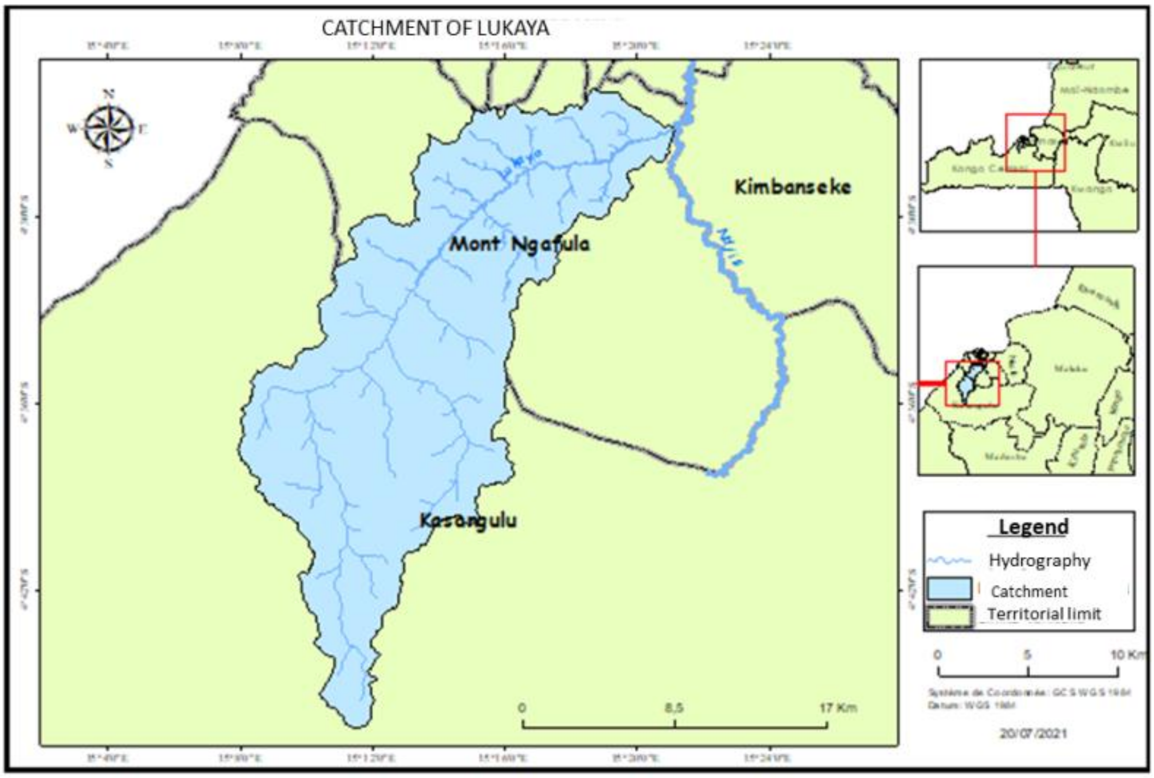

Figure 1. Geographical location of the Lukaya catchment

The climate of the Lukaya catchment is classified as humid tropical, corresponding to the Aw_4 climatic type in the Köppen classification (Peel et al., 2007), characterized by a four-month dry season and an eight-month rainy season. The mean annual temperature is relatively uniform, averaging around 25°C. The first and last rainfall events are estimated to occur around September 15 and May 25, respectively, with a short dry season typically observed between January and February, although it is sometimes irregular (Makanzu Imwangana et al., 2023). Soils within the Lukaya catchment, particularly in the Kimwenza valley and Kasangulu, are acidic, with a pH below 5, predominantly sandy, and low in organic matter. Regarding other elements - nitrogen, calcium, magnesium, potassium, and phosphorus - concentrations are very low (UNEP, 2016).

2.2. Materials used

A Digital Elevation Model (DEM) with a spatial resolution of 12.5 meters was employed to describe the morphological and hydrographic characteristics of the catchment. Using the functionalities of ArcGIS 10.8, it was possible to automatically extract information related to catchment boundaries, elevations, slope directions, and hydrographic networks.

2.3. Determination of Hydro-Morphometric Parameters

2.3.1. Characterization of the Physical Environment of the Lukaya catchment

To characterize the physical environment of the Lukaya catchment, various hydro-morphometric parameters were calculated. In this study, three groups of parameters were considered: geometric, topographic, and hydrographic. With the DEM, the flow direction map was first generated using the *Flow Direction* tool in ArcGIS. The *Basin* tool was then applied to delineate the catchment boundary. The resulting boundary data enabled the calculation of the catchment's area and perimeter, which in turn facilitated the determination of the Gravelius compactness coefficient (KG) - an indicator of catchment shape (Musy, 2005). For certain applications, a stylized catchment perimeter can be drawn by tracing its contour (Musy, 2005). In this study, the calculation was performed in a semi-automatic manner using GIS with ArcGIS 10.8, based on a DEM with a spatial resolution of 12.5 meters.

The purpose of characterizing the geomorphological parameters of the Lukaya catchment is to render the physical environment analytically measurable using mathematical tools (Kisangala, 2008). The objective of characterizing relief form parameters in this study is to make the physical environment of the Lukaya River catchment amenable to mathematical analysis (Kisangala, 2008).

2.3.2. Calculation of Parameters

- Compactness Index (KG): The Gravelius compactness index (KG) expresses the ratio between the perimeter (P) of a catchment and the perimeter of a circle having the same area (A). It is calculated as follows:

  $$KG = \frac{P}{2.\sqrt{\pi x A}} \text{ ....(éq.1)}$$

  Where
  KG = Gravelius coefficient;
  A = catchment area (km²);
  P = catchment perimeter (km).
- The equivalent rectangle was introduced by Roche (1963) as a purely geometric transformation, in which the lines parallel to the rectangle's width are aligned with the catchment outlet, such that the outlet corresponds to the shorter side or width of the rectangle (Baba Hamed & Bouanani, 2016). This approach is particularly useful for comparing catchments in order to assess the influence of their geometric characteristics on runoff behavior. The

length (Lr) and width (lr) of the equivalent rectangle are derived using the expressions presented in Equation (2), which involve both the catchment area (A) and the Gravelius compactness index (KG).

$$Lr = \sqrt{A}.\frac{KG}{1.12}\left[1+\sqrt{1-\left(\frac{1.12}{KG}\right)^2}\right], lr = \frac{KG.\sqrt{A}}{1.12}\left[1-\sqrt{1-\left(\frac{1.12}{KG}\right)^2}\right] \text{........ (éq. 2)}$$

Lr = length of the rectangle (km); lr = width of the rectangle (km).

- Mean Altitude (Hmoy): The mean elevation (Hmoy) is derived from hypsometric curves, and its measurement provides a characterization of the average height of the catchment. The mean elevation of the Lukaya catchment was calculated using the following formula (Eq. 3):

$$H_{moy} = \sum \frac{A_i.h_i}{A} \text{.......... (éq. 3)}$$

Where:

H_{moy}: Mean elevation of the catchment (m)
hi = mean altitude between two contour lines [m];
Ai = area between contour lines [km²];
A = total catchment area [km²].

- Mean Slope (Pmoy): The mean slope provides a useful indication of the overland flow travel time, the time of concentration, and directly influences the peak discharge during a rainfall event. Several methods have been developed to estimate the mean slope of a catchment. All these methods rely either on reading an actual or approximate topographic map or on using a DEM. The method applied in this study consists of calculating the weighted average of the slopes of all elemental surfaces located between two given elevations. An approximate value of the mean slope is then obtained using the relation presented in Equation (4), (Jabri, 2015).

$$P_{average} = \frac{\Delta H}{Lr} = \frac{Hmax-Hmin}{Lr} \text{....... (éq. 4)}$$

Where:

P_{moy}: Mean slope of the catchment
ΔH = elevation difference;
Lr = equivalent rectangle length (km).

- Specific Relief (Ds): Specific relief is used to characterize catchment relief. It was calculated using the global slope index and catchment area (Laborde, 2009):
  Ds =Ipg√S …….. (éq. 5)
  Where: Ds = specific relief (m); Ipg = overall slope index (m/km); S = catchment area (km²).
- Dubreuil's Overall Slope Index (Ig): This coefficient provides information on the runoff potential of a terrain. It is expressed in m/km and is calculated as the ratio between the useful relief (Dut, in meters) and the length of the equivalent rectangle (L, in km). The useful relief is extracted from the hypsometric curve as the difference in elevation between two specific points representing 5% and 95% of the total catchment area. These elevations are denoted as H5% and H95%, respectively. The useful relief thus corresponds to the elevation range encompassing 90% of the catchment area (Laabidi et al., 2016; Mardy et al., 2023).

Table 1. Classification of relief types by ORSTOM/IRD

Relief Types	Value of Dubreuil's Overall Slope Index (Ig)
Very low relief	Ig < 2 m/km
Low relief	2 < Ig < 5
Moderately low relief	5 < I g< 10
Moderate relief	10 < Ig < 20
Moderately steep relief	20 < Ig < 50
Steep relief	50 < Ig < 100
Very steep relief	Ig > 100

Source: ORSTOM/IRD (Igué, 1973)

- Stream Frequency (Fs): Stream frequency is defined as the total number of all-order thalwegs per unit area. A low value of this parameter (1 to 3.5) indicates that streams are structurally controlled by fractures, whereas a high value (4 to 10) reflects a steeper slope relative to surface runoff (Kouedjou & Anaba, 2021).
- Torrentiality coefficient (Ct): The torrentiality coefficient is defined as the product of drainage density and the stream frequency of first-order channels (Kouedjou & Anaba, 2021). It is calculated using the relationship presented in Equation (6).Ct = Dd * N1/S ………….. (éq. 6)
  Where Ct = torrentiality coefficient; Dd = drainage density; N1 = number of first-order streams; S = catchment area.
- Infiltration number: The infiltration number is defined as the product of drainage density and stream frequency. It provides information on the infiltration characteristics of the catchment (Kalaivanan et al., 2014; Sanoussi Ibrahim Mahamadou & Mamadou, 2024.). High values indicate slow infiltration and significant surface runoff (Kouedjou & Anaba, 2021).
- Time of concentration (Tc): The time of concentration is defined as the time required for a water drop originating from the most distant part of the catchment to reach the outlet. It is calculated using the formula presented in Equation (7), (Tarik El Orfi, 2023) :
  $Tc = \frac{4\sqrt{A}+1.5*L}{0.8*\sqrt{Hmean-Hmin}}$ ………… (éq. 7)
  Where L = equivalent rectangle length (km); Hmin = minimum altitude (m); Hmean = average of altitude (m); A = catchment area (km²).

3. Results and Discussion

3.1. Geometric Characteristics

3.1.1. Area and Perimeter of the Catchment

The area of the Lukaya River catchment was determined to be 350.7 km², with a perimeter of 127.9 km. The basin area (350.7 km²), calculated from a 30m resolution DEM, is significantly larger than that estimated in some previous studies (Musanga, 2019), which may influence future hydrological projections. In morphometric analysis, the size of the watershed is of paramount importance. This extent (350.7 km²) reveals a large basin. It is likely that the vast extent of the basin, combined with its stretched shape, results in prolonged concentration times and more complex hydrological dynamics (Faye, 2021).

3.1.2. Compactness Index

The Gravelius compactness index is determined from a topographic map by measuring the catchment perimeter and its area. It approaches 1 for a nearly circular, compact catchment, but exceeds 1 for an elongated basin. In the case of the Lukaya catchment, the Gravelius compactness index was calculated as follows:

$$KG = \frac{127.94}{2.\sqrt{3.14x350.71}} = 1.91$$

The compactness index value (KG > 1) reveals that the catchment of Lukaya has an elongated shape. This particular morphology results in a relatively long concentration time, favoring a gradual flow of runoff. The elongation of the catchment and the extended water evacuation time thus give the hydrological system a certain natural stability with a reduced risk of flooding. However, this stability in the catchment of Lukaya is compromised by increasing anthropogenic pressures.

Indeed, the downstream part of the catchment, predominantly semi-urban, is experiencing an unplanned expansion of built-up areas and market gardening areas. These land use changes locally modify infiltration and runoff conditions, increasing the environment's sensitivity to rain erosion. This observation corroborates the results of Kouassi et al. (2020), who showed that uncontrolled human activities such as deforestation and hillside cultivation are major factors in soil degradation in humid tropical areas.

3.1.3. Equivalent Rectangle (Length and Width)

To enable comparisons between catchments in terms of the influence of their characteristics on runoff, the concept of the equivalent rectangle is introduced. It is assumed that, for a given catchment, runoff behavior is approximately the same as that of a rectangle with the same area, the same Gravelius compactness coefficient, and the same hypsometric distribution, under similar climatic conditions, with similar soil distribution, vegetation, and drainage density. This is a purely geometric transformation, in which the lines parallel to the rectangle's width are aligned with the outlet, which corresponds to the shorter side or width of the rectangle.

By taking into account the perimeter (P), the Gravelius compactness index (KG), and the catchment area (A), the length (Lr) and width (lr) of the rectangle can be determined as follows:

$$Lr = \sqrt{350{,}71}.\frac{1{,}93}{1.12}\left[1+\sqrt{1-\left(\frac{1.12}{1{,}93}\right)^2}\right]$$

Lr = 58.55 km
lr= A/Lr
lr = 350.71 / 58.55 ≈ 6 km

The catchment length (Lr = 58.55 km) and the average width (lr = 6 km) confirm the elongated nature of the Lukaya catchment. The length-to-width ratio (Lr/lr ≈ 9.76) of the Lukaya catchment clearly highlights its elongated nature, reflecting a relatively slow hydrological response and water flow spread over a longer period. This type of morphological configuration promotes better natural regulation of flood flow, unlike compact basins where precipitation converges quickly towards the outlet (Kouedjou and Anaba, 2021). These values are comparable to those observed in several African basins of similar size. For example, Kouame Kassi et al. (2007) obtained lengths between 50 and 65 km for catchments in Ivory Coast with a similarly elongated morphology, while Kouedjou & Anaba (2021) reported average widths of 5 to 8 km in catchments in the mountainous regions of Cameroon. Similarly, Akawwi (2013) emphasizes that this elongated configuration is typical of tropical basins in Central and West Africa, where moderate slopes and geological structure control the flow direction. These morphometric similarities suggest that the catchment of Lukaya shares the same hydrological characteristics as several other African basins subject to tropical climatic regimes, marked by an intense rainy season. This type of morphology favors a progressive flow of runoff water, thus limiting flash floods but sometimes accentuating linear erosion on slopes devoid of vegetation cover.

3.2. Topographic Characteristics

The influence of relief on surface water flow is significant, as many parameters, including precipitation and temperature, vary according to the altitude and morphology of the catchment (Benzougagh et al., 2019). Additionally, the slope affects the velocity of water flow (Bentekhici, 2006).

3.2.1. Hypsometric Zones of the Lukaya Catchment

The measurements of the topographic parameters of the Lukaya catchment, along with the results of their descriptive statistical analysis, are presented in Tables 2 and 3.

Table 2. Hypsometric zones, area fraction ai (% of A), cumulative ai, and relief

Hypsometric zones (m)	Area fraction ai (% of A)	Cumulative ai (%)	Relief di (m)
281 – 300	0,59	0,59	19
300 – 350	10,61	11,20	50
350 – 400	26,46	37,66	50
400 – 450	37,04	74,70	50
450 – 500	16,56	91,26	50
500 – 550	7,18	98,44	50
550 – 600	1,26	99,70	50
600 – 650	0,28	99,99	50
> 650	0,01	100,00	7

In this case, we will extrapolate to obtain the elevation values corresponding to 5% and 95% of the total catchment area (Dubreuil, 1974).
H5% falls within the range of 0.59% to 11.20% of the area.

0.59% ↔ 281m
10.61 { } 19 and 5% - 0.59% = 4.41%
11.20% ↔ 300m
10.61% → 19 m x 4.41% / 10.61% = 7.89 m
H5% is calculated as: 281 m + 7.89 m = 288.89 m.

H95% falls within the range of 91.26% to 98.44% of the area, hence:

91.26% ↔ 450
7.18% { } 50 and 95% - 91.26% = 3.74%
98.44% ↔ 500
7.18% → 50m x 3.74% / 7.18% = 26.04m
3.74% →

Therefore, H95% = 450 m + 26.04 m = 476.04 m.

Useful relief (Dut) = H95% – H5% = 187.15 m

H95% = elevation corresponding to 95% of the total catchment area (m), and H5% = elevation corresponding to 5% of the total catchment area (m).

3.2.2. Relief Values of the Lukaya Catchment

Table 3 indicates that the global slope index (Ig) is 3.19 m/km, with a mean slope of 6.4%.

BV	Dg	Ipg	Ds	Ipm.	Hmax	Hmin	Hm
Values	187.15	3.19	59.92	6.42	657	281	443,5

With Dg = total relief (m), Ipg = global slope index (m/km), Ds = specific relief (m), Ipm = mean slope index (m/km or %), Hmax = maximum elevation (m), Hmin = minimum elevation (m), Hm = mean elevation (m).

The analysis of Table 3 reveals that the global slope index is 3.19 m/km, with an average slope of 6.4%. The maximum and minimum elevations are 657 m and 281 m, respectively, with a total relief of 187.15 m.

The moderate relief (Ig ≈ 3.19 m/km, Ds = 59.92) according to ORSTOM (Laborde, 2009; Laabidi et al., 2016) reflects a topography that favors infiltration to the detriment of runoff. The relatively low drainage density (0.24 km/km²) could indicate significant natural infiltration given that the soil is sandy (Moeyersons et al., 2015; Makanzu Imwangana et al., 2025a). However, the loss of vegetation cover and unplanned urbanization disrupt this infiltration capacity (Makanzu Imwangana et al., 2025b). This paradox is also observed in the Mefou basin in Cameroon (Kouedjou and Anaba, 2021), where urban pressure has reversed natural infiltration dynamics in favor of runoff. Similar studies in the Ganges basin in India and in the Awash region of Ethiopia (Bewket & Sterk, 2005) show that rapid anthropogenic transformations often lead to a decrease in the efficiency of the hydrographic network, favoring linear erosion phenomena and flash floods. These trends are corroborated in Morocco, in the Beht basin, by Benzougagh et al. (2016), who noted an increase in torrentiality linked to deforestation and changes in land use.

3.2.3. Hypsometric Curve of the Lukaya Catchment

The effect of topography on a hydrograph is highly significant: a steeper slope corresponds to a shorter concentration time of runoff within the drainage channels. Relief is often characterized by the hypsometric curve of the basin (Fig.2). On this curve, a given elevation is represented on the x-axis, while the y-axis indicates the portion of the basin area where each point has an altitude at least equal to that elevation. The hypsometric curve is then established by planimetrically measuring the areas corresponding to the definition of the ordinate for each contour line (Baba Hamed & Bouanani, 2016). This hypsometric curve can also serve as a reference for determining the H5% and H95% values in the calculation of the basin's global index.

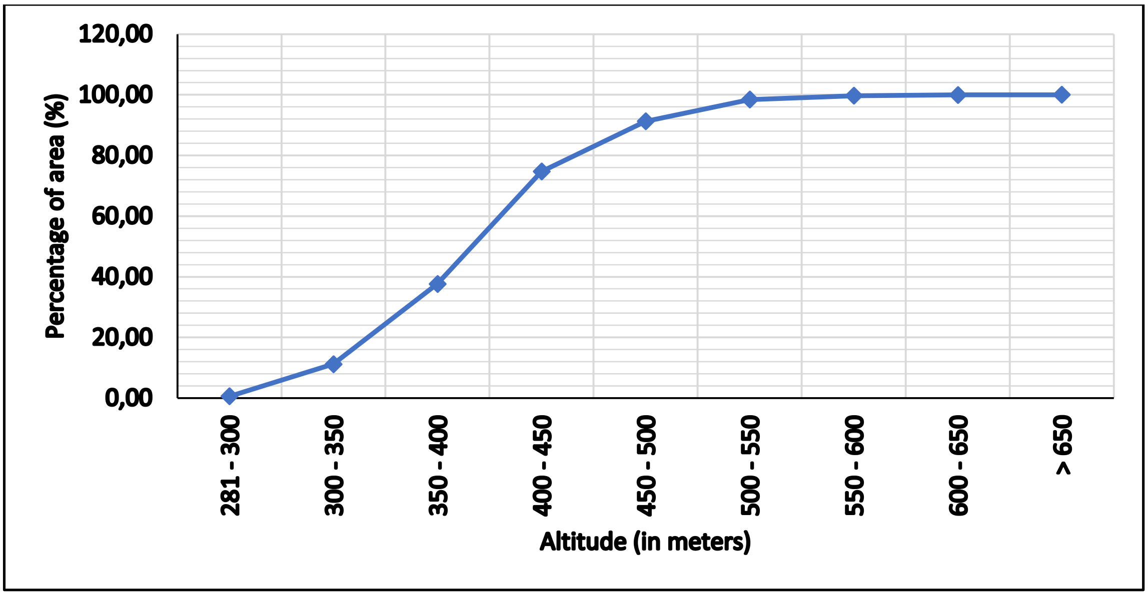

Fig.2. Hypsometric Curve of the Lukaya Catchment

This curve is established for different elevations of the areas located above the corresponding contour line. Since most meteorological and hydrological factors are functions of elevation, it is therefore relevant to study the basin's hypsometry by elevation intervals. The hypsometric curve can also be used to determine both the mean and median elevations.

3.2.4. Characteristic Altitudes

Most of the indices are presented for illustrative purposes, showing what can be done for a comprehensive catchment analysis. For the purpose of this study, we limited the assessment to the most characteristic and essential indices relevant to our research.

- The maximum and minimum elevations are obtained directly from the topographic map. The maximum elevation represents the highest point of the catchment, while the minimum elevation corresponds to the lowest point, generally located at the outlet.
- The mean elevation can be derived directly from the hypsometric curve or from the interpretation of a topographic map. The median elevation corresponds to the elevation read at the 50 percent abscissa of the basin's total surface area on the hypsometric curve. This value is close to the mean elevation when the hypsometric curve of the catchment exhibits a regular slope.

The mean elevation can be derived directly from the hypsometric curve or from the interpretation of a topographic map. In the present case, for example, considering the contour lines at 339 m and 369 m, the area between the two contours is Ai = 38.4 km², while the mean elevation between them is hi = 354 m. Since the total area of the basin is known, the mean elevation can then be calculated by referring to Table 1 for all areas enclosed between the contour lines.

$$H_{average} = \frac{39.27*350}{350.71} + \frac{92.8*400}{350.71} + \frac{129.9*450}{350.71} + \frac{58.08*500}{350.71} + \frac{25.17*550}{350.71} + \frac{4.44*600}{350.71} + \frac{1.05*650}{350.71}$$

$$H_{average} = (39.19) + (105.84) + (166.68) + (82.81) + (39.47) + (7.60) + (1.95) = 443.5 \text{ m}$$

The catchment of Lukaya is mainly dominated by intermediate elevations (350–500 m, 90%), with few low-lying areas (281–350 m, 5%) and high-lying areas (>500 m, 5%). This distribution suggests a moderately inclined relief, favoring a gradual flow of surface water. However, intermediate and high-slope areas may be particularly vulnerable to rainfall erosion if agricultural practices or urbanization modify the vegetation cover. These results corroborate with the work of Kouedjou Idriss & Anaba Banimb (2021) who showed that the catchments around Kinshasa also have a majority of intermediate areas with moderate slopes, favoring a relatively slow flow of surface water. Similarly, Kisangala (2008) reported that a dominant relief dominated by intermediate altitudes in Congolese basins leads to increased vulnerability to erosion on steeper slopes when vegetation cover is altered.

To prevent soil erosion and degradation in the intermediate and high-altitude areas of Lukaya, it is recommended to maintain or restore vegetation cover and implement anti-erosion measures on the steepest slopes. This would reduce downstream sediment transport and protect infrastructure located in low-lying areas.

3.3. Hydrographic Parameters

3.3.1. Stream Network Hierarchy

We conducted an analysis of the hydrographic network morphology to better understand the different types of drainage networks present in the catchment of Lukaya. The results of this spatial analysis are illustrated in Figure 3. The hydrographic network of the Lukaya River catchment comprises at least 33 rivers and several streams, distributed into two main sections: the upper course and the lower course. Stream coding was used for automated data processing. Several classification methods exist for stream segments, among which Strahler's (1964) classification was employed in this study. This classification allows for an unambiguous determination of the drainage network development from upstream to downstream. The extraction of the hydrographic network according to Strahler's (1964) classification and the delineation of sub-catchments were performed semi-automatically using ArcGIS software. The hierarchical organization of the Lukaya catchment's hydrographic network highlights streams of order 1 to 4. Orders 1 and 2 correspond to small streams or the heads of sub-catchments, while the Lukaya River is classified as order 4 at the catchment outlet.

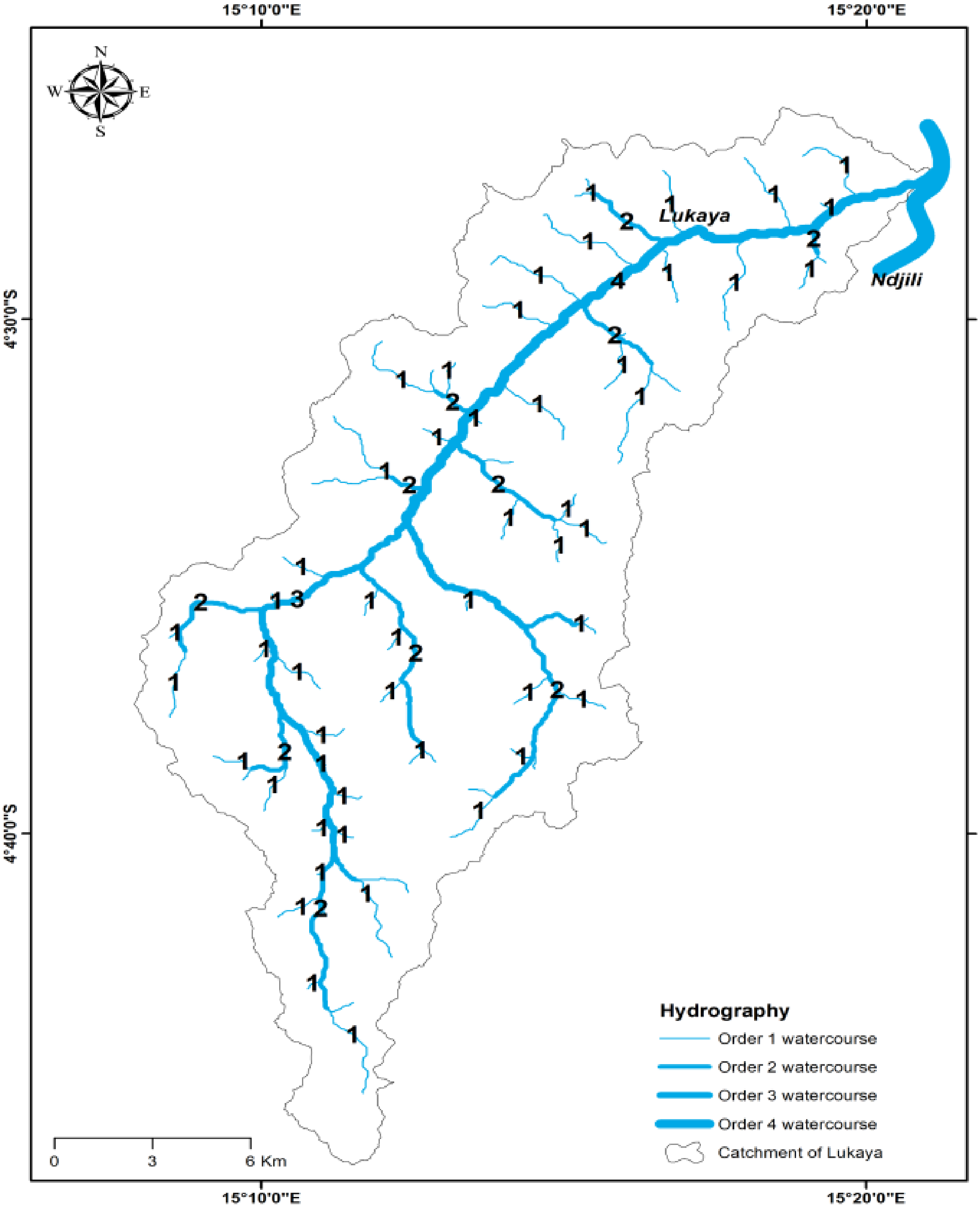

Figure 3. Hierarchy of the Hydrographic Network According to Strahler's Classification

By examining the map presented in Figure 3, it is evident that the hierarchy of the Lukaya hydrographic network, according to Strahler's (1964) method, consists of 33 third-order streams. The tributaries are generally organized in a dendritic pattern, although local variations can be observed, where the network may assume a parallel or rectangular configuration in certain areas.

Analysis of the order of rivers, according to Strahler's classification (1964), allows us to assess the hierarchy of the hydrographic network and to characterize the drainage structure, the degree of network branching, and the dynamics of surface water flow. In the Lukaya watershed, the main river (Lukaya River) is of third order, indicating a relatively young organization of the hydrographic network, where erosion and sediment transport processes are expected to be moderate (Roose, 1996). However, the density and hierarchy of the network in the basin are influenced by human activities. Deforestation, urbanization and unstructured agricultural work favor the appearance of temporary channels or ravines, artificially increasing the number of first-order watercourses during heavy rains (Kouedjou Idriss & Anaba Banimb et al., 2007), a phenomenon which contributes to the intensification of linear erosion and the accumulation of sediments in the downstream areas of the basin under study.

3.3.2. Stream Length and Longitudinal Profile

- **Characteristic Length:** A catchment can also be defined by the length of its main stream. The main stream length (L) is the curvilinear distance from the outlet to the catchment divide. In the case of a branching, the measurement is extended along the last branch to the topographic boundary of the catchment; when the two segments at the branch are of the same order, the segment draining the larger area is followed. For the Lukaya catchment, the main stream length is 55 km, extending from Tampa Village in the Kasangulu territory to N'Djili Kilambu.

- **Profile of the Lukaya River:** The Lukaya River exhibits a pronounced incised hydrographic profile (V-shaped profile) in its upper reaches, particularly in the hilly areas where the slope is steep. Along the middle course, the incision becomes less pronounced from upstream to downstream. This explains the high sedimentation observed in the middle course, as the river's slope decreases, making it shallower and prone to occasional severe flooding, such as in the Kimwenza Valley. Indeed, it is from this section that flooding typically begins, extending downstream toward the outlet at its confluence with the N'Djili River.
- **Hydrographic Density:** Drainage density is defined as the number of flow channels per unit area within a catchment.

$F = \frac{33}{350,71}$ = 0,09 Km

Where:

- **F:** drainage density (km^2)
- **Ni:** number of streams
- **A:** catchment area (km^2)
- **Drainage density**

Drainage density, introduced by Horton (1945), is defined as the total length of the hydrographic network per unit area of the catchment:

$$Dd = \frac{\sum Li}{A}$$

$$Dd = \frac{\sum 85,84}{350,71} = 0,24\ Km/Km^2$$

- **Dd:** drainage density [km/km^2]
- **Li:** stream length [km]
- **A:** catchment area [km^2]

Drainage density depends on the geology (structure and lithology), the topographic characteristics of the catchment, and, to some extent, climatic and anthropogenic conditions. In practice, drainage density values range from 3 to 4 in regions where runoff has experienced very limited development and is centralized, and can exceed 1000 in areas where flow is highly branched with minimal infiltration.

According to Schumm (1999), the inverse of drainage density, C = 1/Dd, is referred to as the 'stream stability constant'. Physically, it represents the area of the catchment required to maintain stable hydrological conditions in a unit hydrographic vector.

- **Time of Concentration:** This parameter represents the time between the end of effective rainfall and the end of runoff. It is a key parameter for characterizing catchment behavior during and after a continuous storm event (Kouedjou Idriss & Anaba Banimb, 2021). By applying the formula presented in the methodology and substituting each term with its respective value, the concentration time (Tc) for this catchment is obtained as follows:

$$Tc = \frac{4\sqrt{58,6} + 1.5 * 55}{0.8 * \sqrt{443,5 - 288}} = 11,340350 \text{ hours}$$

The concentration time of the Lukaya catchment is precisely 11 hours, 20 minutes, and 25 seconds. The conclusions regarding the morphometric and hydrographic characteristics of the Lukaya catchment are summarized in Table 4.

Table 4: Summary of the Geometric, Topographic, and Hydrographic Characteristics of the Lukaya Catchment

S Km^2	P Km	K_G	Lr Km	lr Km	Ig m/Km	Dg m	Ipm %	Ds (m)	$H_{5\%}$ m	$H_{95\%}$ m	Dd Km/Km^2	F Km^2
350.7	**127.9**	**1.9**	**58.6**	**5.9**	**3.2**	**187**	**6.42**	**59.9**	**288**	**476**	**0.24**	**0.09**

According to the calculations, the catchment of Lukaya has an area of 350.7 km^2 and an estimated perimeter of 127.9 km. Its Gravelius compactness index (KG) is 1.9, indicating an elongated catchment shape. Consequently, as described by Bentekhici (2006) in his studies on catchments, this catchment is expected to exhibit low peak flood discharges, meaning it should experience less frequent flooding during heavy rainfall events. Unfortunately, factors such as land-use practices, combined with topography and the effects of extreme weather events, contribute to very high peak flood discharges in this catchment.

The dimensions of the equivalent rectangle of the catchment are: length (Lr) = 58.6 km and width (Lr) = 5.9 km (Table 4). These values indicate that the rectangle's length is 9.9 times greater than its width. Furthermore, information derived from altimetry aligns well with that of the equivalent rectangle, showing that a large portion of the catchment area lies at elevations above 281 meters. This implies that the geometric characteristics related to slopes and elevations of the catchment can strongly influence surface runoff in the absence of adequate soil vegetation cover.

The study area exhibits a specific relief of approximately 60 m, a global slope index of 3.2 m/km, and an average slope of 6.4%. These values indicate that the catchment is characterized by moderate relief according to the ORSTOM classification (Laborde, 2009; Laabidi et al., 2016). Regarding the catchment's hydrographic network, the drainage and hydrographic densities are very low (Dd = 0.24 km/km^2 and F = 0.09 km^2), indicating a limited development of surface flow.

Compared with other catchments in the region of Kinshasa or in similar tropical contexts (Kisangala, 2008; Kouedjou Idriss

& Anaba Banimb, 2021; Makanzu Imwangana, 2014), the catchment of Lukaya presents morphometric and hydrographic characteristics typical of semi-urban basins affected by rapid and poorly controlled urbanization. This study therefore highlights that the hydrological risks in this catchment are less linked to the intrinsic geometric shape than to the increasing anthropogenic pressure (deforestation, urbanization, insufficient drainage network), which degrades the natural hydrological regulation functions.

Finally, the limitations of this study lie mainly in the absence of a chronological series of rainfall data and recent field observations on urban evolution and the secondary drainage network. A multi-temporal analysis supported by more recent satellite data and the integration of hydrodynamic models would make it possible to refine the results and better anticipate future hazards.

Conclusion

The present study aimed to highlight the morphometric and hydrographic characteristics of the catchment of Lukaya using GIS. Analysis of the morphometric parameters indicates that the Lukaya catchment exhibits an elongated shape (KG > 1) and a moderate slope (5 < Ig < 10). Its hydrographic characteristics are marked by low drainage and stream densities (Dd = 0.24 and F = 0.09), accompanied by a prolonged flow concentration time. This situation appears to be related to relief features, soil characteristics, and land cover types, notably the moderate slopes, forest cover in the upstream area, and the sandy soil permeability in the downstream part of the catchment. Catchment-scale analysis revealed spatial variability in topographic parameters. The combination of criteria such as the Gravelius index, global slope index, drainage density, and concentration time suggests that the Lukaya River catchment exhibits a reduced vulnerability to hydrogeomorphological hazards, particularly erosion and flooding. However, this vulnerability is exacerbated by the semi-urban nature of the catchment and poorly controlled land management. In this context, the implementation of integrated basin management actions, such as slope stabilization, targeted reforestation and regulation of urbanization, is essential to preserve the hydrological and ecological functions of the catchment.

References

[1] Baba Hamed, K., Bouanani, A. (2016). Caractérisation d'un bassin versant par l'analyse statistique des paramètres morphométriques : Cas du bassin versant de la Tafna. (Nord-ouest algérien). Geo-Eco-Trop. 40 (4), 277-286

[2] Mashauri, F., Mokili Mbuluyo, Nsalambi Nkongolo (2023). Influence des paramètres hydro-morphométriques sur l'écoulement des eaux des sous-bassins versants de la Tshopo, République Démocratique du Congo. Revue Internationale de Géomatique 32, 79-98. https://doi.org/10.32604/RIG.2023.044124

[3] Morell, M., Thébé, B. et L'Hote, Y. (1999). Acquisition et constitution d'une information hydrologique de base. Editions H.G.A., Bucarest, 203p. ISBN 973-98954-1-7.

[4] Hocine, F., Belhadj-Aissa, M., Haddoud, F., Ouarzeddine, M., Belhadj-Aissa, A. (2008). Simulation du comportement des écoulements d'eau en utilisant le réseau hydrologique d'un bassin versant : cas de l'oued Benimessous, Algérie. Télédétection 8 (3), 179-191

[5] Xiaomin, C., et Sequeira J., 2004. Extraction du réseau hydrographique à partir du Modèle Numérique de Terrain. Rapport du laboratoire L S I S (UMR-CNRS 6168).

[6] Waikar, M.L., and Nilawar, A.P. (2014). Morphometric Analysis of a Drainage Basin Using Geographical Information System: A Case study. *International Journal of Multidisciplinary and Current Research.* Vol.2, 179-184pp.

[7] Laabidi, A., El Hmaidi, A., Gourari, L., El Abassi, M. (2016). Apports du modèle numérique de terrain (MNT) à la modélisation du relief et des caractéristiques physiques du bassin versant du Moyen Beht en amont du barrage El Kansera (Sillon sud Rifain, Maroc). European Scientific Journal 12(29), 258-288. http://dx.doi.org/10.19044/esj.2016.v12n29p258

[8] Bentekhici, N. (2006). Utilisation d'un SIG pour l'évaluation des caractéristiques physiques d'un bassin versant et leurs influences sur l'écoulement des eaux (bassin versant d'Oued El Maleh, Nord-Ouest d'Algérie). Conférence francophone ESRI du 11 12 octobre 2006. https://www.esrifrance.fr/sig2006/bentekhici.html

[9] Makoko, M., Sedjabo, S. (1975). Étude de l'aménagement d'une rivière. Cas de la Funa au niveau du stade du 20 mai, p.147-184.

[10] Vogt, J.V., Colombo R., and Bertolo F. (2003). Deriving drainage networks and catchment boundaries: A new methodology combining digital elevation data and environmental characteristics. *Geomorphology*, 53, 281 – 298pp. DOI: 10.1016/ S0169-555X (02) 00319-7.

[11] Bloch, T., Kamp, U., and Olsenholler, J. (2004). Using ASTER and SRTM DEMs for studying geomorphology and glaciation in high mountain areas, *New Strategies for European Remote Sensing,* (ed.), 119-127.

[12] Kuldeep, P., and Upasana P. (2011). Quantitative Morphometric Analysis of a Catchment of Yamuna Basin, India using ASTER (DEM) Data and GIS, *International Journal of Geomatics and Geosciences*,Volume 2, No 1, 248-269 pp.

[13] Tamll, S.M., Sarfaraz, A.D, and Rashid, S.M. (2011). Analysis of the Geomorphometric Parameters in High Altitude Glacierised Terrain using SRTM DEM data in Central Himalaya, India, ARPN *Journal of Science and Technologie*, VOL. 1, NO. 1, 22-27 pp.

[14] Akawwi, E. (2013). Geomorphology using Geographic Information System and Global Mapper. American Journal of Environmental Science 9 (5), 398-409.

[15] Bewket, W., Sterk, G. (2005). Dynamics in Land Cover and Its Effect on Stream Flow in the Chemoga Catchment, Blue Nile Basin, Ethiopia. Hydrological Processes 19, 445-458. https://doi.org/10.1002/hyp.5542

[16] Kouamé Koffi, F., Bernier, M., Droh Lanciné, G.,Mohama, Bachir, S., Lefebvre, R., Nagnin S., Koudou, A. (2007). Intégration de données

géospatiales dans un modèle hdyrologique distribué pour la simulation des écoulements des eaux en milieu tropical humide de Côte d'Ivoire (Afrique de l'ouest). Revue de Télédétecton 7 (1-4), 217-235.

[17] Kouame Kassi, A., Kouame Koffi, F., Kouassi Amani, M., Oulare, S., Adon Gnangui, C-R., Bernier, M. (2011). Mise en place d'une base de données pour une modélisation hydrologique distribuée du bassin versant du Bandama (Côte d'Ivoire) : apport d'un modèle numérique d'altitude, de la télédétection et du SIG Physitel. Afrique Science 7(2), 94-114.

[18] Narmatha, T., Jeyaseelan, A., Mohan1, S.P., Mahalingam, S., Natchimuthu, S. (2013). Morphometric analysis of upper part of Pambar watershed, Ponnaiyar river basin, Tamil Nadu, India using Geographical Information System. J. Acad. Indus. Res. 1(11), 726-729.

[19] Makanzu Imwangana, F. (2014). Etude de l'érosion ravinante à Kinshasa. Dynamisme Pluvio-Morphogénique et Développement d'un Outil de Prévision. Thèse de Doctorat en Sciences, Faculté de Sciences, Université de Kinshasa, Kinshasa, 193p.

[20] Saidi, M. E. (2013). Apport des logiciels de SIG dans la morphométrie des bassins versants. L'exemple d'ArcGIS, Guide méthodologique d'utilisation, Université Cadi Ayyad, Marrakech, Maroc, 9p.

[21] Peel, M.C., Finlayson, B.L., McMahon, T.A. (2007). Updated World map of the Köppen-Geiger climate, Hydrology and Earth System Sciences 11, 1633-1644.

[22] Makanzu Imwangana, F., Kamosi Zola, B., Lele Nyami, B., Munongo Iyabidila, M., Ntombi Muen Kabeya, M., Phuati Phuati, G., Ozer, P. (2023). Évolution récente et détermination de la saison de pluies dans la région de Kinshasa (RDC) de 1961 à 2010. Revue Africaine d'Environnement et d'Agriculture 6(2), 13-27.

[23] UNEP (2016). Applying Ecosystem Based Disaster Risk Reduction (ECO-DRR) Intergrated Water Resource Management (IWRM) in the Lukaya basin, Democratic Republic of Congo. 96p.

[24] Musy, A. (2005). Cours d'hydrologie générale. Laboratoire d'Hydrologie et Aménagements (HYDRAM) Institut des Sciences et Technologies de l'Environnement (ISTE) Ecole Polytechnique Fédérale (EPFL). https://echo2.epfl.ch/e-drologie

[25] Kisangala, M. (2008). Analyse des paramètres morphométriques, climatologiques et hydrométriques du bassin du Kasaï, dans sa partie congolaise. Mémoire de Diplôme d'études approfondies en Sciences, Université de Kinshasa, 89 p.

[26] Roche, M. (1963). Hydrologie de surface. Ed. Gauthier – Villars, Paris. 430 p. 204 fig.

[27] Jabri, B. (2015). Utilisation d'Arc-Hydro et d'HEC-GeoHMS dans l'extraction des données pour la modélisation hydrologique spatialisée du bassin du Haut Sebou, PFE, Master Sc. Et Tech, FST FES, 104p.

[28] Laborde, J.P. (2009). Éléments d'hydrologie de surface. Cours dispensés au Cycle ingénieur et Master Hydroprotech. École Polytechnique, Université de Nice - Sophia Antipolis, 192 p.

[29] Mardy, Z., Weissenberger, S., Waaub, JP. (2023). Caractérisation du bassin versant de la rivière Mulet (Roche-à-Bateau, Haïti) à l'aide d'outils de géomatique. *Géocarrefour* (online) 97 (3). https://doi.org/10.4000/geocarrefour.22751

[30] Kouedjou Idriss, L., Anaba Banimb, R.C. (2021). Analyse morphométrique du bassin versant de la Menoua pour une meilleure gestion des risques morphohydrologiques. American Journal of Innovation Research Application Science 12, 188-197.

[31] Kalaivanan K., Gurugnanam B., Suresh M. (2014). Gis based morphometric analysis of gadilam river basin, tamil nadu, India. International Journal of Advanced Research 2(7), 1015-1022

[32] Sanoussi Ibrahim Mahamadou, M., & Mamadou, I. (2024). Caractérisation des paramètres morphométriques du sous bassin versant du goulbin Maradi au Niger. Environmental and Water Sciences, Public Health and Territorial Intelligence Journal 7(4), 1049-1055. https://doi.org/10.48421/IMIST.PRSM/ewash-ti-v7i4.45650

[33] Tarik El Orfi (2023). Quantification, modélisation et usages des ressources en eau dans le Haut Bassin de l'Oum Er Rbia (Amont du barrage Ahmed El Hansali, Maroc). Thèse de doctorat en Géographie (Hydrologie) de l'Université Sultan Moulay Slimane - Maroc et de l'Université de Lorraine – France, 356p.

[34] Musanga, MJ. (2019). Détermination de quelques paramètres indicateurs de la pollution organique de la rivière Lukaya à Kinshasa en République Démocratique du Congo. Congo science, ACASTI and CEDESURK, 1-9 p.

[35] Faye, C., Ndiaye, M., 2021. Use of geospatial tools in morphometric analysis and prioritisation of sub-catchments of the soundgrougrou (Casamance Basin). Quaestiones Geographicae 40(3), Bogucki Wydawnictwo Naukowe, Poznań, 65–84.

[36] Kouassi, J.-L. K., Wandan, N. E., Mbow, C. (2020). Correction: Kouassi, J.-L.K., et al. Assessing the Impact of Climate Variability on Wildfires in the N'Zi River Watershed in Central Côte d'Ivoire. Fire 2018, *1*, 36. *Fire, 3*(4), 69. https://doi.org/10.3390/fire3040069

[37] Benzougagh, B., Dridri, A., Boudad, L., Sdkaoui, D., Baamar, B. (2019). Apport des SIG et télédétection pour l'évaluation des caractéristiques physiques du bassin versant d'Oued Inaouene (Nord-est Maroc) et leurs utilités dans le domaine de la gestion des risques naturels. *Am. J. innov. res. appl. Sci. 8(4): 120*-130pp. http://american-jiras.com/Benzougagh-ManuscriptRef.4-ajira280319.pdf

[38] Dubreuil, P. (1974). *Initiation à l'analyse hydrologique (dix exercices suivis des corrigés). Eds.: Masson et* O.R.S.T.O.M, Paris, 216p.

[39] Moeyersons, J., Makanzu Imwangana, F., Dewitte, O. (2015). Site-and rainfall-specific runoff coefficients and mega-gully development in Kinshasa (DRCongo). Natural Hazards 79 (1), 203-233. DOI10.1007/s11069-015-1870-z.

[40] Makanzu Imwangana, F., Kamosi Zola, B., Mbiya Kangudia, J., Pangu Sanghy, S. (2025a). Gully erosion associated with peri-urbanisation: focus on

the catchments around Kimwenza in the south of Kinshasa (DR.Congo). East African Journal of Environment and Natural Resources 8(2), 136-166. https://doi.or/10.37284/eajenr.8.2.3160
[41] Makanzu Imwangana, F., Kamosi Zola, B., Mbiya Kangudia, J., Pangu Sanghy, S. (2025b). Estimation des debits de pointe de ruissellement responsables de l'érosion ravinante dans la zone de Kimwenza au sud de la ville de Kinshasa. Journal Africain des Sciences 2 (1), 133-158. ISSN (online) : 3006-2306 ; ISSN (print) : 3006-3760. https://doi.org/10.70237/jafrisci.2025.v2.i1.12
[42] Benzougagh, B., Larbi, B., Abdallah, D., Driss, S. (2016). Utilisation du SIG dans l'analyse morphometrique et la prioritisation des sous-bassins versants de Oued Inaouene (Nord-Est du Maroc). European Scientific Journal, 12 (6), 266-289.https://doi.org/10.19044/esj.2016.v12n6p266
[43] Strahler, A.N. (1964). Quantitative Geomorphology of Drainage Basins and Channel Networks. In: Chow VT (ed), Handbook of Applied Hydrology", McGraw Hill Book Company, New York, 4–76pp.
[44] Roose, É. (1996). Méthodes de mesure des états de surface du sol, de la rugosité et des autres caractéristiques qui peuvent aider au diagnostic de terrain, des risques de ruissellement et d'érosion, en particulier sur les versants cultivés des montagnes. *Bull. Réseau Érosion* 16, 87-97.
[45] Horton, R.E. (1945). Erosional development of streams and their drainage basins : hydrophysical approach to quantitative morphology, Bull. of the Geological Society of America 56, 275-330.
[46] Schumm, S.A. (1999). 'Causes and Controls of Channel Incision' In : Darby, S.E. & Simon A., 1999. 'Incised River Channels', John Wiley & Sons Ltd., New York, 19-29.