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Hydromorphological and Morphometric Analysis of the Comoé River Basin (Côte d'Ivoire): Implications for Runoff and Erosion Processes

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Abstract

The Comoé River basin is one of the major hydrological units in Côte d'Ivoire, yet its hydromorphological dynamics remain insufficiently documented despite their importance for integrated water resources management. This study aims to characterize the morphometric and hydromorphological attributes of the main sub-basins of the Comoé and to assess their influence on runoff generation and erosion processes. The methodology is based on the use of an ASTER Digital Elevation Model (30 m) combined with Geographic Information System (GIS) tools to extract and analyse parameters related to basin shape, relief, and drainage network.

Results indicate that the sub-basins are predominantly elongated (circularity index < 0.3), which results in relatively long concentration times and enhanced infiltration capacity. Drainage density (Dd < 1.5 km/km^2) and stream frequency (F < 5) confirm the low potential for direct runoff, highlighting the predominance of infiltration processes. However, the Kafolo sub-basin, characterized by steeper slopes (global slope index = 0.54; mean channel slope = 1.43 m/km), shows higher susceptibility to erosion. By contrast, downstream sub-basins display depositional features, favoured by nearly horizontal longitudinal profiles ("lentic flats").

This study underlines the key role of morphometric parameters in shaping the hydrological and erosional response of the Comoé basin. It provides valuable insights for hydrological planning, erosion risk mitigation, and sustainable water resource management in the face of climate variability and increasing anthropogenic pressures.

Keywords: Watershed; Morphometry; Infiltration; Erosion; Drainage; Comoé; Côte d'Ivoire

1. Introduction

The watershed constitutes a fundamental hydrological unit, playing a central role in the collection of precipitation and its transformation into runoff at the outlet. This transformation depends not only on climatic conditions but also on the basin's intrinsic characteristics, including its shape, relief, hydrographic network, soil properties, and vegetation cover. The study of morphometric and hydromorphological parameters therefore provides a better understanding of flow generation processes and allows for the assessment of the system's vulnerability to hydrological and geomorphological hazards [1], [2].

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In recent years, several studies have demonstrated that geomorphology and drainage indices are reliable indicators of hydrological dynamics, particularly in contexts of climatic variability and increasing anthropogenic pressure [3], [4]. Advances in the use of digital elevation models (DEMs) and geographic information systems (GIS) have enhanced the ability to extract and analyse these parameters at various spatial scales ([5], [6]).

Within this framework, the morphometric and hydromorphological analysis of the Comoé Basin in Côte d'Ivoire is of particular relevance. Indeed, this basin - one of the largest in the country - occupies a strategic position within the national hydrographic network, encompassing multiple climatic zones ranging from the northern savannas to the southeastern forest formations. The Comoé River, approximately 800 km in length, represents a vital water resource for agricultural, domestic, and energy activities ([7], [8]). It feeds several hydroelectric installations and supports agricultural productivity in the surrounding regions. Ecologically, the basin hosts the Comoé National Park, a UNESCO World Heritage Site, recognized for its exceptional biodiversity and its crucial role in regional hydrological regulation ([9], [10]).

However, the area is increasingly subject to pressures arising from climatic variability, deforestation, and the intensification of human activities ([11], [12]). These changes alter hydrological dynamics and exacerbate risks of erosion, soil fertility loss, and ecological imbalance. Consequently, a thorough understanding of the basin's morphometric structure, drainage network, and hydrological response is essential to support the integrated and sustainable management of water resources [3], [4], [13].

The objective of this study is therefore to characterize the main morphometric and hydromorphological attributes of the Comoé Basin, in order to assess their influence on runoff processes, sediment dynamics, and the system's vulnerability to hydrological hazards.

2. Material and methods

2.1. Area

2.1.1. Location

The Comoé River Basin (Figure 1) represents one of the largest hydrographic systems in West Africa, with an estimated surface area of approximately 78,000 km² [14], [15]. It originates from the sandstone plateaus of Banfora in south-western Burkina Faso, at an average altitude of around 600 m, before flowing southward across Côte d'Ivoire and discharging into the Gulf of Guinea near Grand-Bassam [16].

With a total length of about 1,160 km, the Comoé River sustains a dense and highly branched hydrographic network, which includes several major tributaries such as the Léraba, Iringa, Kongo, and Kodjoboué rivers [7], [8]. The basin spans a mosaic of contrasting climatic zones: a tropical Sudanian-type climate in the north and a humid sub-equatorial climate in the south [11]. This climatic gradient promotes significant ecological and hydrological diversity, reflected in the spatial variability of streamflows, vegetation, and soil types [13].

Ecologically, the basin encompasses the Comoé National Park, listed as a UNESCO World Heritage Site since 1983, covering an area of approximately 1,148,756 hectares [9], [16]. This park is one of the largest protected areas in West Africa, recognized for its outstanding biodiversity and its crucial role in regional hydrological regulation [10].

Furthermore, the basin plays a strategic role in the socio-economic development of Côte d'Ivoire. It serves as a major water resource for agriculture, domestic supply, and hydroelectric power generation; while also supporting agricultural productivity across several regions it traverses [7], [12]. However, the area is increasingly affected by pressures associated with climatic variability, deforestation, and intensified human activities, leading to disturbances in hydrological dynamics and the gradual degradation of soils and ecosystems [3], [4][11].

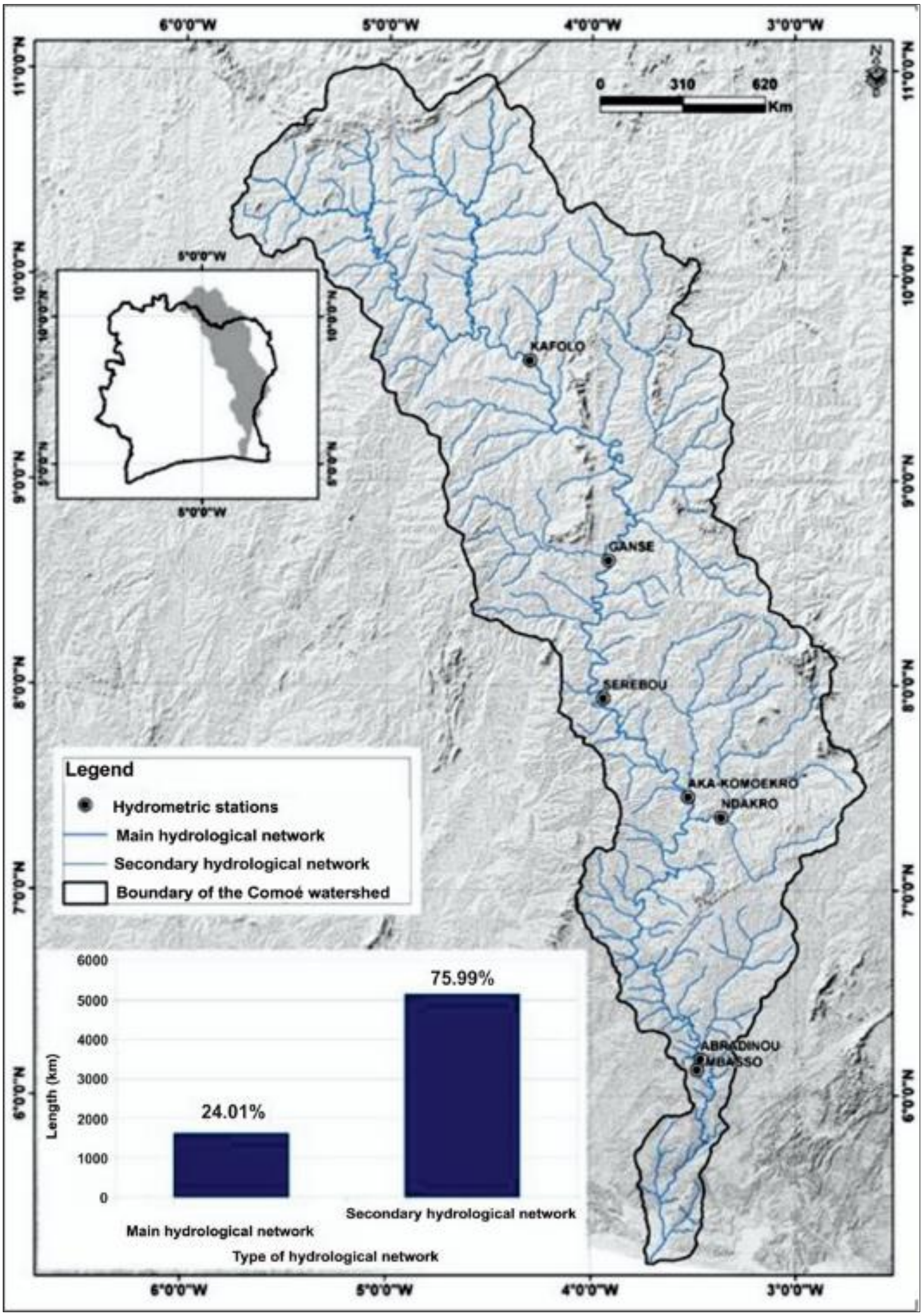

Figure 1 Location of the Transboundary Comoé Basin in West Africa

2.2. Relief of the Comoé Basin

The relief of the Comoé River Basin is relatively uniform and shows little variation. It appears as a vast peneplain, with altitudes ranging from 0 m to 750 m. Overall, two main types of landforms dominate the basin (Figure 2): plains and plateaus. The plains, with elevations between 0 m and 200 m, are located in the southern part of the basin. They include a coastal fringe extending from 0 m to about 40 m along the lagoonal areas. This fringe consists of a succession of tertiary clay-sandy sedimentary plateaus overlying the crystalline basement. Beyond the coastal zone lies the lower and middle

Comoé region, where the average elevation ranges between 50 m and 200 m. The plateaus occupy most of the basin, particularly in the central and northern regions. Their elevation varies between 200 m and 500 m and includes a few isolated summits, such as lateritic hills, which sometimes exceed 600 m in altitude [17].

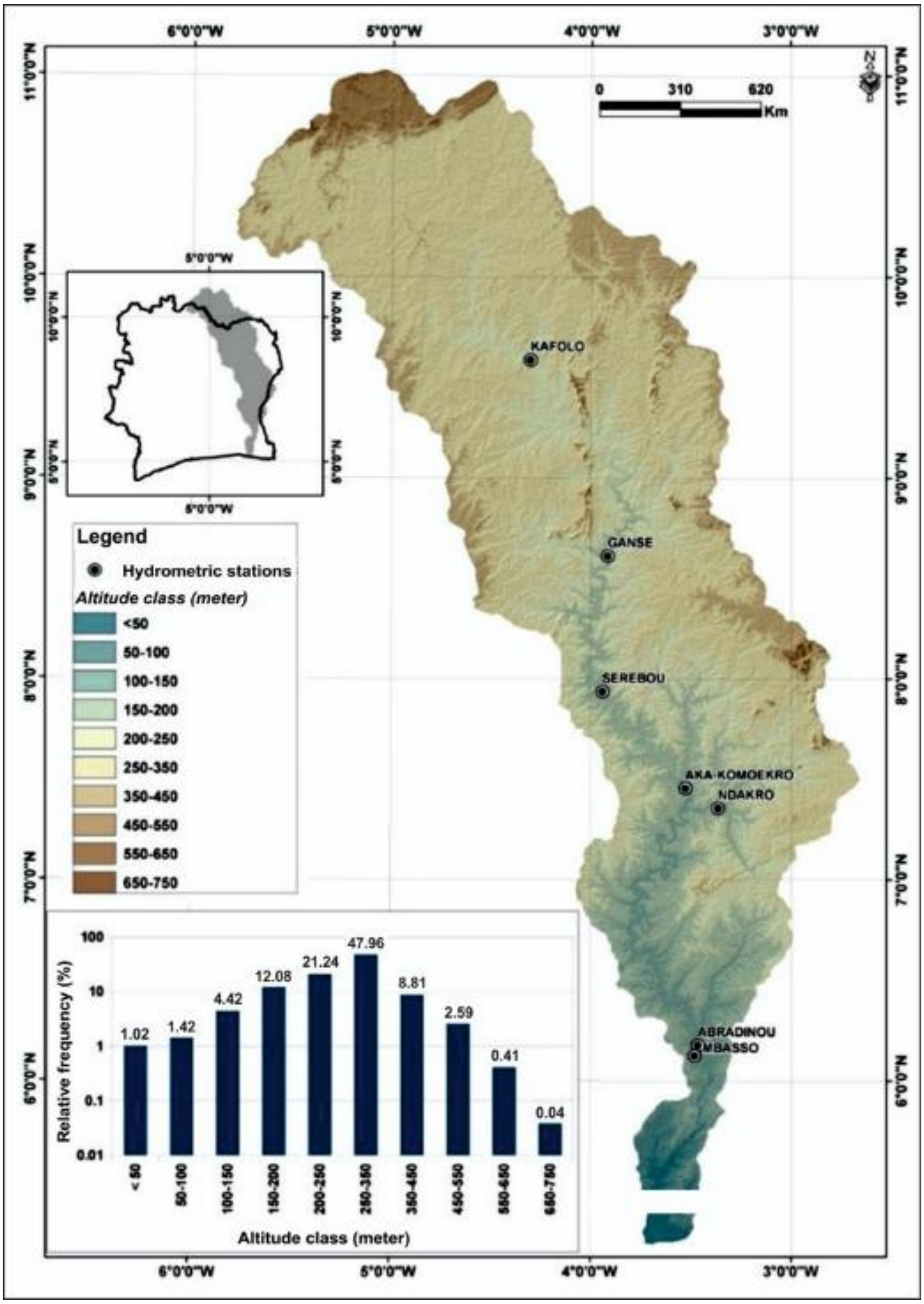

Figure 2 Relief of the Comoé Basin across Altitudinal Classes

2.3. Material

The ASTER Digital Elevation Model (DEM) with a spatial resolution of 30 m × 30 m was used as the main data source for morphometric and hydrological analyses. Data processing and extraction of morphometric parameters - such as elevation, slope, hydrographic network, and watershed delineation - were carried out within the ArcGIS 10.2

environment, using the Spatial Analyst and Hydrology toolsets. This approach enabled an accurate characterization of the basin's topography and drainage network, which is essential for understanding its hydrological functioning.

2.4. Methods

2.4.1. DEM Pre-processing

Filling the depressions (sinks) in the DEM is a prerequisite for extracting any hydrological features based on flow direction. Except in cases of lakes, endorheic systems, or karstic terrains, such depressions are considered DEM artefacts. The first step consisted in delineating the Comoé River Basin and its sub-basins, whose outlets correspond to flow measurement stations along the main course of the river.

For this purpose, the ASTER DEM (30 m × 30 m) was used after a pre-processing stage through an automated procedure in ArcGIS 10.2. The D8 algorithm developed by [18] and implemented in ArcGIS 10.2 was used to fill these depressions. Subsequently, several GIS-based routines and well-established methodologies were applied to derive parameters related to the watershed and its hydrographic network.

2.4.2. Derivation of Flow Characteristics from the DEM

Surface water flow always occurs in the direction of the steepest downslope. Once the flow direction of each cell is identified, the contributing cells and the number of upstream cells flowing into a given cell can be determined. This information can then be used to delineate watershed boundaries and stream networks.

The following diagram illustrates the process of extracting hydrological information such as watershed boundaries and drainage networks from a Digital Elevation Model (Figure 3).

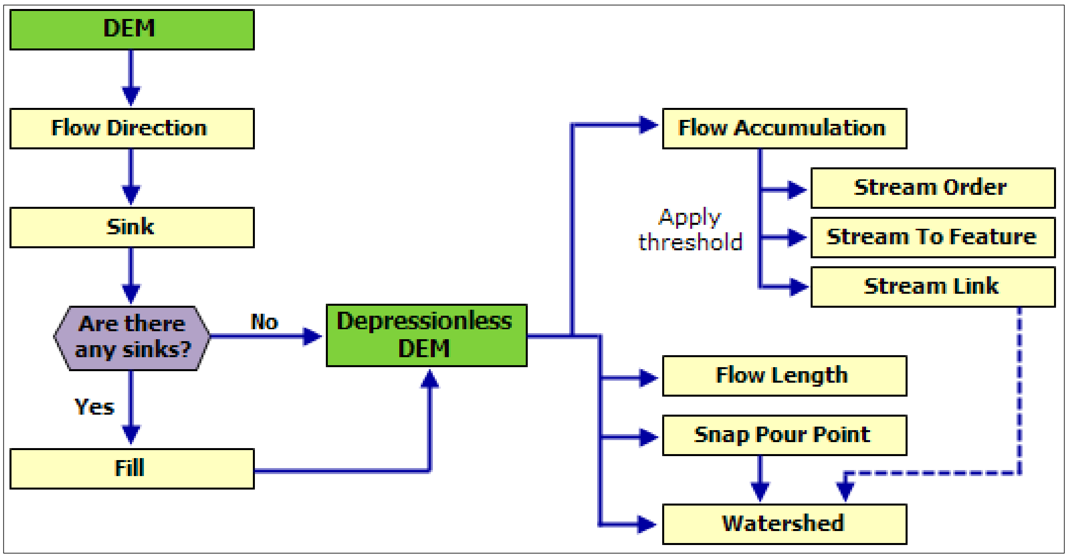

Figure 3 Diagram of Hydrological Information Modelling

2.4.3. Extraction of the Hydrographic Network

First, the boundaries of the main watershed were delineated, followed by those of the sub-basins corresponding to the gauging stations along the main course of the Comoé River (Kafolo, Sérébou, Akakomoékro, Aniassué, and M'Basso), as well as the hydrographic network itself.

Several classifications have been proposed to characterize river networks. However, the most widely used methods are those developed by [19], [20]. Both classifications are based on the concept of a stream segment, defined as the portion of the drainage network situated either between two confluences or between a source and a confluence. The segment is termed internal in the first case and external when it originates from a source.

- The [20] classification, which was adopted in this study, follows three fundamental rules:
- Any stream segment without a tributary is assigned order 1 ;

- When two stream segments of different orders (*i* and *j*, with $i > j$) join, the downstream segment takes on the higher order (***i***)
- When two stream segments of the same order (***i***) meet, the downstream segment becomes order (***i*** + 1).

This classification system enables the hierarchical organization of stream segments according to their level of connectivity (Figure 4). A stream reach is defined as a set of contiguous segments of the same order, arranged in the direction of flow. The order of the basin, also referred to as the magnitude of the drainage network and denoted by Ω, corresponds to the highest stream order within the basin - thus representing the order of the reach at the outlet.

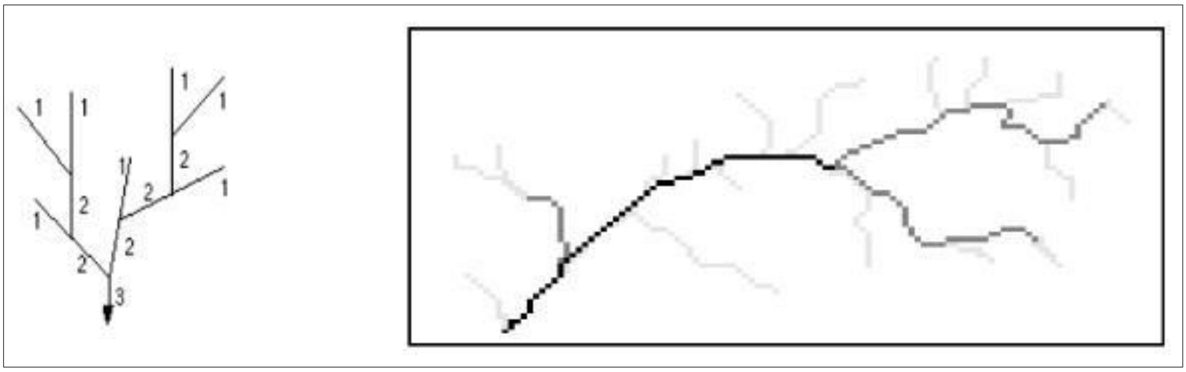

Figure 4 Strahler Classification (left) and Result Derived from a DEM (right)

2.5. Compactness Index (Ic)

The compactness coefficient [21] represents the ratio between the perimeter of a watershed and the perimeter of a circle having the same area as that watershed (Figure 5):

$$Ic = \frac{P}{2\sqrt{\pi A}} \quad (1)$$

P : Perimeter of the watershed; A : Radius of the equivalent circle.

A compactness coefficient close to 1 indicates a rather circular watershed, which generally has a greater infiltration potential than elongated ones.

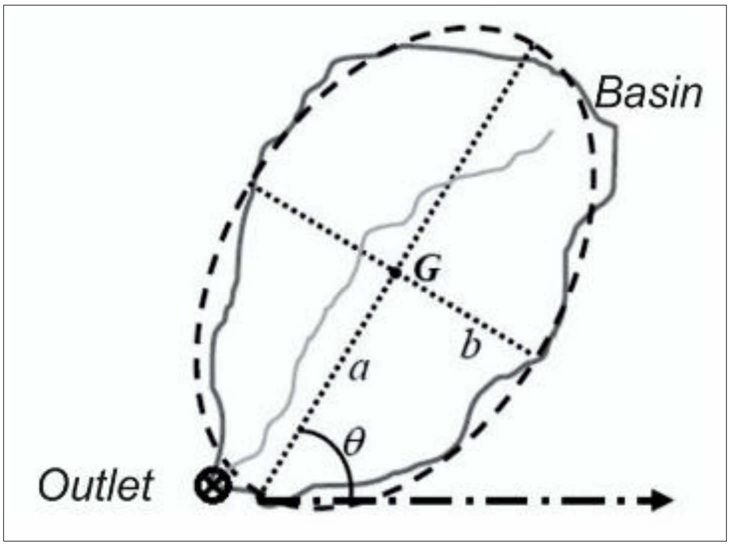

Figure 5 Equivalent ellipse of a watershed used to define a compactness index [22]

2.5.1. Watershed Circularity (Rc)

The circularity of a watershed [23] is defined as the ratio between the area of the watershed and the area of a circle having the same perimeter as the watershed:

$$Rc = \frac{4\pi A}{P^2} \qquad (2)$$

Where basin circularity values approaching 1 indicate an almost circular shape [24] and a relatively gentle slope. For such basins, infiltration tends to be more uniform, and the time taken for water to reach the outlet is shorter than that of an elongated basin [25]. Basin circularity is more strongly influenced by the length, frequency, and slope of the stream segments than by the overall slope of the watershed or the configuration of the drainage network. Low, intermediate, and high circularity values are indicative of the youthful, mature, and old stages of the tributary basin life cycle, respectively [1].

2.5.2. Characteristic Distances of the Equivalent Rectangle

The applicability of the equivalent rectangle concept to a watershed is closely related to the value of the Gravelius coefficient. Indeed, for a compactness coefficient (Ic) less than or equal to 1.12, the basin exhibits a nearly circular shape, making the geometric transformation into an equivalent rectangle impractical; in such cases, the basin can be approximated as a square.

Length of the equivalent rectangle.

$$L = \frac{K_g\sqrt{A}}{1,12}\left[1 + \sqrt{1 - \left(\frac{1,12}{K_g}\right)^2}\right] \qquad (3)$$

Width of the equivalent rectangle

$$l = \frac{K_g\sqrt{A}}{1,12}\left[1 - \sqrt{1 - \left(\frac{1,12}{K_g}\right)^2}\right] \text{ Si } K_g \geq 1, \qquad (4)$$

2.5.3. Relief Attributes

Hypsometric Curve

At the slope and basin scale, topography plays a major role in the spatial variability of soil moisture conditions. Since most meteorological and hydrological factors depend on altitude, it is useful to study the hypsometry of the watershed by elevation classes. Several pieces of information can be derived from the hypsometric curve.

Mean Elevation (E)

It is defined as the average ordinate of the hypsometric curve and corresponds to the ratio of the area under the curve to the total area of the basin. It can be estimated using the following relation:

$$E = \frac{1}{A}\sum_i a_i \frac{(h_i + h_{i+1})}{2} \qquad (5)$$

- *A:* area of the basin in km^2;
- AI: area between two consecutive contour lines i and i+1 (km^2);
- Hi: elevation of contour line i (m).

Mean Slope (S)

The mean slope is an important characteristic in surface runoff. It provides a good indication of the travel time of direct runoff and, consequently, of the concentration time (tc). It directly influences the peak discharge during a rainfall event. The mean slope can be estimated from the hypsometric curve.

$$S=\frac{2E}{L} \qquad (6)$$

Global Slope Index

The classical slope index consists of relating the elevation difference between the two extreme points to the basin length (length of the equivalent rectangle). However, to avoid extreme values, the IRD (French Institut de Recherche pour le Développement) proposed a global slope index (Ig), which will be used in this study.

The slope determines whether rivers are in an erosional or depositional phase. In higher areas, rivers often contribute to the erosion of the bedrock over which they flow. Conversely, in plains, rivers flow over beds where sedimentation predominates.

$$Ig=\frac{H_5\text{-}H_{95}}{Léq} \qquad (7)$$

- H5: Elevation corresponding to 5% of the total basin area;
- H95: Elevation corresponding to 95% of the total basin area;
- Léq: Length of the equivalent rectangle.

Limiting Slope

In general, the volume available within these depressions depends on soil roughness, which can be characterized using several indices such as Random Roughness (RR), Tortuosity (T), Limiting Elevation Difference (LD), Limiting Slope (LS), and Mean Upslope Depression (MUD). In this study, the Limiting Slope (LS) was specifically employed.

The LS factor, or erosive power of the catchment, is derived solely from the Digital Elevation Model (DEM). The erosive power of a water flow depends on the drained area and the flow pattern. It is proportional to the surface area of the runoff network and to the terrain slope. For a given cell, the erosive power is equal to the square root of the contributing area multiplied by the elevation difference between that cell and the upstream cell (Equation 8). Topographic irregularities or slope breaks, as well as a wide branching network, promote zones likely to be eroded or scoured by surface water flow [26].

2.5.4. General formula

$$LS=\left(\frac{\lambda}{22.13}\right)^{m} \times \left(65.41\sin^2\theta+4.56\sin\theta+0.065\right) \qquad (8)$$

Where :

- λ= slope length (m)
- θ= slope angle (in radians)
- m= variable slope-length exponent, depending on slope gradient

2.6. Concentration Time

It is determined for each cell as the distance along the flow path from the cell to the outlet, divided by the flow velocity. This velocity was simply defined as being proportional to the local slope when the slope value exceeded 1°, and equal to 1 otherwise. The concentration time can be estimated using several empirical formulas. [27] proposed William's formula

$$T_c=14.6\,L\,S^{-0.1}\,p^{-0.2} \qquad (9)$$

With Tc (in minutes) representing the basin concentration time, S (km^2) the basin area, L (km) the river length from the watershed divide to the outlet, and p (–) the mean river slope.

2.6.1. Longitudinal Profile of the Different River Sections (Elevation Drop of the Drainage Network)

This corresponds to the bed profile of a watercourse along its flow axis, which makes it possible to characterize the channel slope, or more generally, the thalweg of flow. This slope tends to decrease downstream (concave profile), with different fluvial styles succeeding one another from the headwaters to the outlet. The slope controls several parameters: the flow velocity in the channel, the shape of the flood hydrographs, the velocity of the flood wave, and the river's water depth. For a given discharge and width, a steeper river generally exhibits a higher flow velocity and consequently a shallower depth.

2.6.2. Attributes Related to the Hydrographic Network

This term refers to the set of natural drainage channels, whether permanent or temporary, through which water flows as surface runoff or is discharged from groundwater, either in the form of springs or as continuous seepage along the riverbed [28].

2.6.3. Drainage Density

Drainage density is defined, for a given basin of area A, as the total length of the drainage network (various flow channels) per square kilometre. If Li denotes the length of a tributary of any order or of the main stream, then the drainage density (Dd) is expressed as:

$$D_d = \frac{\sum L_i}{A} \qquad (10)$$

Drainage density is a measure of the degree of fluvial dissection. It is influenced by several factors, such as climatic conditions and vegetation [29], soil characteristics and bedrock properties [30], relief [31], landscape evolution processes [32], and substrate infiltration capacity [33]. In general, a low drainage density indicates the presence of permeable soils, dense vegetation cover, and gentle slopes, in contrast to a high drainage density. A well-drained basin typically exhibits a minimum drainage density of 2.5 km/km^2, whereas a poorly drained basin has a drainage density lower than 1.5 km/km^2 [19], [34], [25].

2.6.4. Fréquence des biefs

The stream frequency, as defined by [19], is the ratio between the total number of stream segments of all orders and the area of the watershed:

$$F = \frac{\sum N}{A} \qquad (11)$$

and can also be calculated according to the stream order of the watershed:

$$F_u = \frac{\sum N_u}{A} \qquad (12)$$

A high stream frequency (> 5) indicates significant surface runoff and a pronounced slope [34].

2.6.5. Soil Erodibility of the Basin (Factor K)

Soil erodibility depends on several physico-chemical properties, including texture, structure, permeability, and organic matter content. In general, silty and sandy-silty soils exhibit high K values, indicating strong susceptibility to erosion, whereas clayey and sandy soils tend to be less vulnerable [35].

In this study, the K factor was computed using the empirical formula proposed by [36], which relates soil granulometric and organic characteristics:

$$K = \frac{2.1\times10^{-4}(12\text{-}OM)\,M^{1.14} + 3.25(S\text{-}2) + 2.5(P\text{-}3)}{100} \qquad (13)$$

where:

- OM : organic matter content (%),
- M = (% silt + % fine sand) × (100 – % clay),
- S : soil structure code (1 to 4),
- P : soil permeability code (1 to 6).

The base soil map used was the FAO World Soil Map at a scale of 1 :5,000,000. Subsequently, an automated process was carried out in ArcGIS 10.2 using the Raster Calculator module, following a series of equations.

3. Results

3.1. Physical Characteristics of the Sub-Basins

3.1.1. Basin Shape Index or Linear Attribute

Compactness Index (Ic)

The calculation of the compactness index (or Gravelius index) shows that all the sub-basins have Ic values of 1.91, 2.15, 2.20, 2.39 and 2.40 (Table 1). The range of these values indicates that the basin is generally elongated. All sub-basins whose outlets are located along the main course of the Comoé River have Ic values greater than 1. The shape of the sub-basins becomes increasingly elongated downstream, as the index increases with channel length. The infiltration potential is inversely proportional to this order; therefore, the potential for infiltration decreases as one move towards the lower course of the Comoé. The M'Basso sub-basin, with the highest compactness index, is potentially the most resistant to infiltration.

Circularity Ratio (Rc)

The circularity index of the sub-basins varies between 0.21 and 0.17 (Table 1), confirming their elongated shape. Basins with low circularity values are characterized by non-uniform infiltration, and the time required for a drop of water to reach the outlet is longer than in a circular basin (Rc close to 1). Overall, infiltration is potentially high throughout the Comoé basin. The circularity index decreases from upstream to downstream, meaning that the concentration time is inversely proportional to it along the Comoé basin.

3.2. Volume Index

3.2.1. hypsometric Curve

The hypsometric curves reveal the features of mature (old) basins (Fig. 6). These are characterized by gentle plains near watercourses where altitude varies very little despite large surface areas. Consequently, erosion in such basins is potentially low. Approximately 50% of the cumulative surface area of Kafolo lies at an altitude of 302 m (Table 1). This value is 290 m, 280 m, 275 m, and 270 m respectively for the sub-basins of Sérébou, Akakomoékro, Aniassué, and M'Basso. The altitudinal gradient of the Comoé basin decreases progressively from upstream to downstream. Several other indices are dependent on the hypsometric curve, notably the mean elevation (E), which is subsequently used to calculate the mean slope (S) a key parameter in determining the concentration time. The values of these different parameters are presented in Table 1.

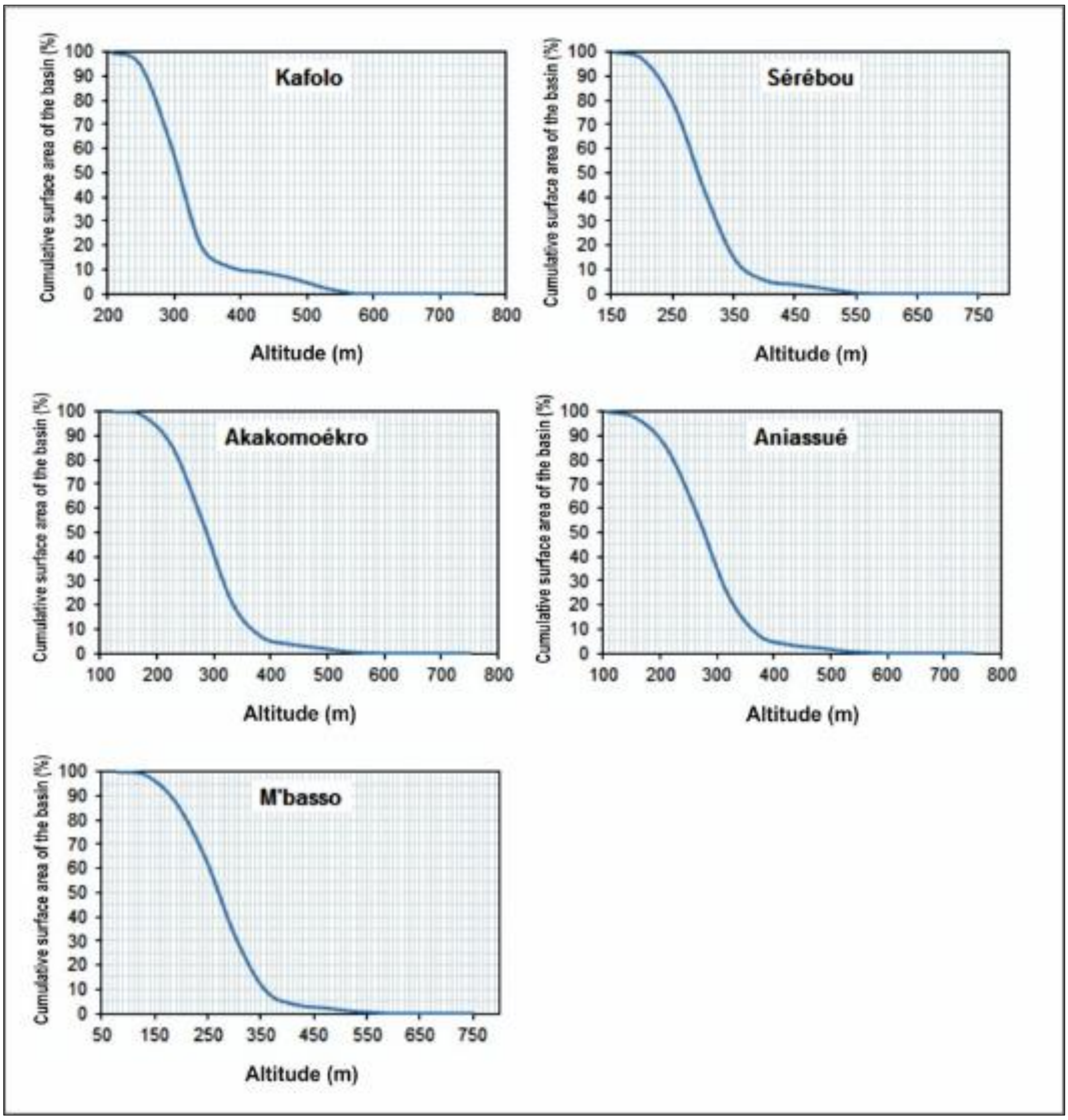

Figure 6 Hypsometric curve of the different sub-basins along the main course of the Comoé River

3.2.2. Overall Slope Index

The overall slope index (Ig) calculated for all sub-basins is presented in Table 1. It is 0.54 at Kafolo, while averaging around 0.20 in the other sub-basins. Kafolo is therefore characterized by the highest elevations within the basin. In this context, the tributary streams of this sub-basin are more likely to contribute to the erosion of the bedrock over which they flow. In contrast, in the other sub-basins with relatively flat relief (low Ig), river channels predominantly experience sediment deposition rather than erosion, as observed at Kafolo.

3.2.3. Specific Relief (Ds)

Specific relief (Ds) allows for the classification of the basin according to topographic relief. The Ds values of all sub-basins range between 50 and 100. Based on the ORSTOM classification, the majority of the sub-basins exhibit moderate relief. However, the Kafolo sub-basin shows the highest Ds value (77.75), while M'Basso, Akakomoékro, and Aniassué, with respective Ds values of 56.69, 54.72, and 52.25, display more moderate relief. Finally, the Sérébou sub-basin has a gentle relief, with Ds values between 25 and 50.

3.3. Concentration Time off flow

The concentration time (Tc) provides a useful indication of the duration required for direct runoff to travel across the basin. The Tc values calculated using William's formula are presented in Table 1. As expected, the concentration time increases with the elongation of the basin: the more elongated the basin, the higher the Tc; conversely, a more circular basin has a lower Tc. The travel time of a water particle from the watershed divide to the Kafolo gauging station (considered as the outlet) is approximately 2,241 minutes, or 37 hours. In contrast, the travel time for a particle reaching the M'Basso station is about 6,028 minutes, or roughly 100 hours. The concentration time directly influences the peak discharge during rainfall events.

Table 1 Indices derived from shape and volume parameters

Characteristics	**Sub-bassin**				
	Kafolo	***Sérébou***	***Akakomoékro***	***Aniassué***	***Mbasso***
Léq (km)	446.03	782.89	865.69	1049.96	1100.36
Perimeter (Km)	979.7	1677	1851	2217	2323
Area (Km^2)	20880	48410	56100	68250	73560
Circularity (Rc)	0.27	0.216	0.21	0.17	0.17
Compactness Index (Ic)	1.91	2.15	2.2	2.39	2.41
Alt_95% (m)	240	220	190	170	150
Alt_75% (m)	270	260	240	230	220
Alt_Median (m)	302	290	280	275	270
Alt_25%(m)	330	330	320	320	320
Alt_5%(m)	480	390	390	380	380
Alt_Min (m)	203	152	122	103	78
Alt_Max (m)	753	753	753	753	753
E (m)	319.79	298.86	291.61	280.33	272.8
S=2E/L (%)	1.43	0.76	0,67	0,53	0,5
Overall Slope Index (Ig)	0.54	0.22	0.23	0.2	0.21
Concentration Time Tc (min)	2241	4102	4583	5710	6028
Specific Relief (Ds)	78	48	55	52	57

3.4. Cross and Hydrographic Network-Related Attributes

3.4.1. Drainage Density (Dd)

Figure 7 provides a comparative representation of the drainage density for the studied sub-basins. As a reminder, a low drainage density indicates the presence of permeable soils, dense vegetation cover, and gentle slopes, unlike a high drainage density. All the sub-basins exhibit low drainage densities, with Dd values below 1.5 km/km^2. This suggests that the sub-basins are potentially favourable to infiltration, provided that the soils are permeable, slopes are gentle, and vegetation cover is significant.

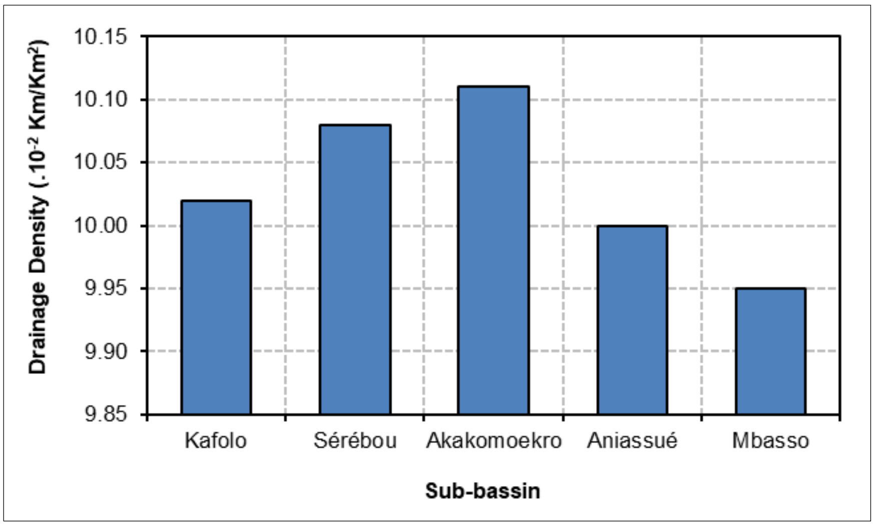

Figure 7 Comparison of Drainage Density (D_d) Across Different Sub-basins

3.5. Stream Frequency (F)

As presented in Table 2, the stream frequency for all sub-basins is less than 5. This suggests that surface runoff is relatively less pronounced across the entire basin. However, a clear trend is observed with runoff increasing from upstream to downstream, as indicated by the following order of stream frequencies:

$F_{Kafolo} > F_{Sérébou} > F_{Akakomoékro} > F_{Aniassué} > F_{Mbasso}$. It's noteworthy that the significant difference in stream frequencies implies that surface runoff in the Kafolo sub-basin is approximately two (2) times higher than in the other sub-basins.

Table 2 Cross and Hydrographic Network Indices for the Comoé Sub-basins

Caracteristic	Kafolo	Sérébou	Akakomoekro	Aniassué	M'Basso
Area (km^2)	20880	48410	56100	68250	73560
Perimeter (km)	979.70	1677.0	1851.0	2217.0	2323.0
Somme Li	2092.0	4880.0	5670.0	6825.0	7316.0
Fréq	429.00	1311.0	1497.0	1763.0	2004.0
Drainage density Dd (km/km^2)	0.1002	0.1008	0.1011	0.1000	0.0995
Stream Frequency (F)	0.0205	0.0088	0.0076	0.0063	0.0058

3.6. Longitudinal Profile of the Different River Segments

Figure 8 illustrates the elevation change (relief) of the drainage network. From the source (0 km) to approximately 28 km, the river exhibits a riffle-type facies characterized by a steeper gradient. The break in slope is clearly discernible as this segment transitions to the subsequent facies.

The remainder of the river segment (from 28 km onwards) corresponds to an equilibrium profile. In this profile, the channel slope progressively decreases from upstream to downstream, and the curve is concave up (convex to the stream bed).

The equilibrium profile represents a continuous succession of longitudinal gradients where the flow is neither actively eroding (incising) nor depositing within the substrate. This facies is the result of a balance between the processes of erosion and deposition.

The Source-Kafolo (S-K) segment is typical of a "rapid" facies, featuring small elevation differences (less than 0.5 m) between the upstream and downstream points and characterized by lotic (fast-moving) currents.

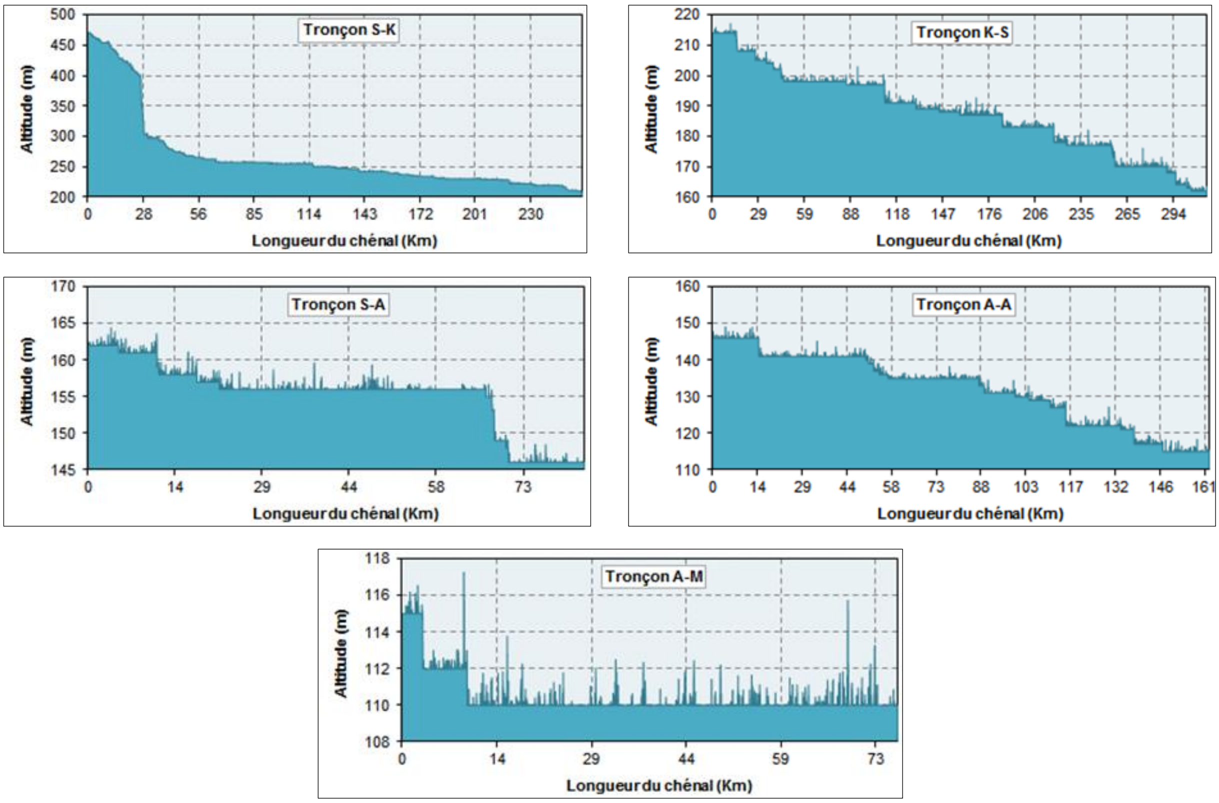

Figure 2 Longitudinal Profile of the Comoé River Main Stem (from Source to M'Basso)

This same facies persists for the first 21 kilometers of the Sérébou-Akakomoékro (S-A) segment. The continuation of the segment, spanning nearly 42 km, transitions into an almost horizontal profile termed a "lentic flat" or slow-moving pool. This feature commonly develops upstream of an obstruction, a riffle-type facies, or a rapid. In the present case, the lentic flat is succeeded by rapids with a mean upstream-downstream slope of less than 0.5. This latter facies traverses the Akakomoékro-Aniassué (A-A) channel and continues for the first 10 km of the Aniassué-M'Basso segment. The remainder of the channel up to the M'Basso outlet is characterized by another lentic flat where the flood wave propagation is very slow. This type of facies is thus favorable to sedimentary deposition (Table 3).

Table 3 Length and Mean Slope of the Different Flow Segments

Biefs	Elevation Difference (m)	Length (km)	Mean Slope (m/km)
Source-Kafolo (S-K)	256	255.44	(1.46)
Kafolo-Sérébou (K-S)	52	315.20	0.16
Sérébou-Akakomoékro (S-A)	16	83.000	0.19
Akakomoékro-Aniassué (A-A)	31	257.44	0.12
Aniassué-M'Basso (A-M)	5	76.700	0.07

3.7. Intrinsic Basin Factors in Erosion Assessment

3.7.1. LS factor (Limiting Slope): Erosive Power of Comoé Basin

This factor is derived exclusively from the Digital Elevation Model (DEM). The erosive power of a water flow depends on both the drainage area and the flow pattern. It is directly proportional to the surface area of the runoff network and the slope of the terrain.

In the case of the Comoé River Basin, the erosive power is relatively low. The LS factor ranges from 0 to 28.84 t/ha (Table 4). The highest values are observed in the Kafolo sub-basin, where the mean erosive power (LS) is estimated at

0.24 ± 0.43 t/ha. The M'Basso sub-basin follows Kafolo in terms of erosive potential, mainly due to slope steepness and contributing area. These values remain fairly similar across the other sub-basins.

Overall, the erosive power appears to be fairly homogeneous throughout the basin, with higher values occurring along the main channels, where the slopes are relatively steeper (Figure 9).

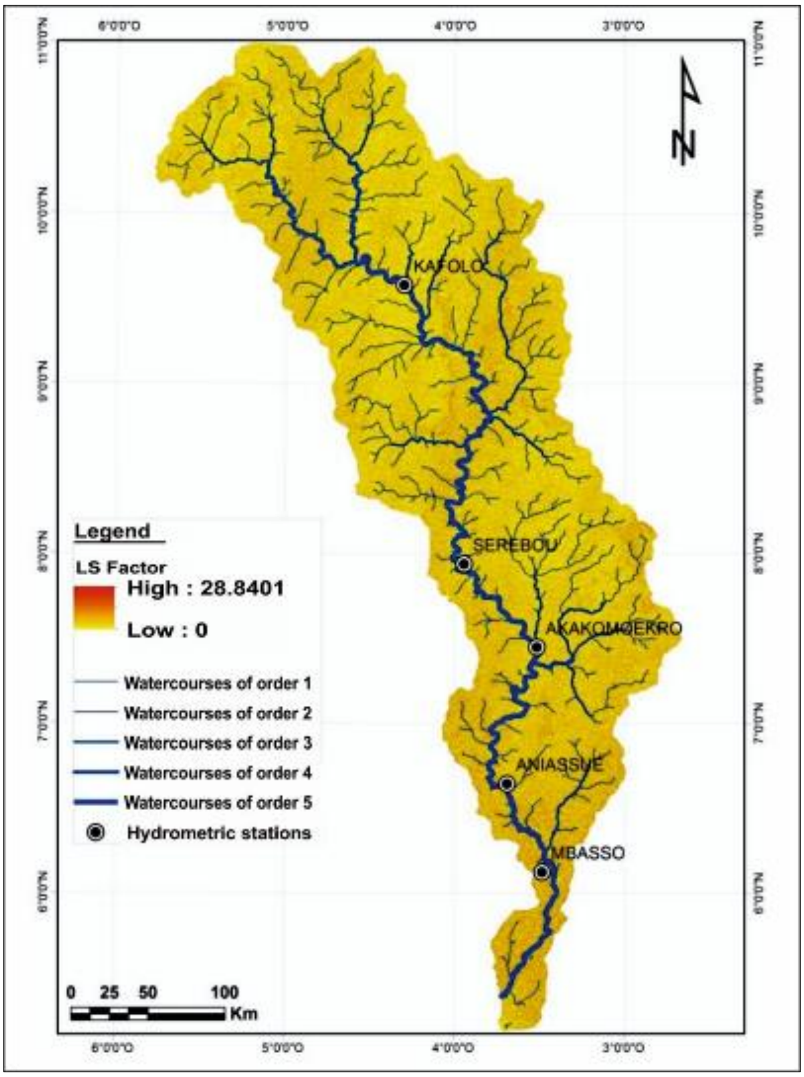

Figure 9 Erosive Power of the Comoé Basin Based on the LS (Limiting Slope) Factor

Table 4 Statistical Distribution of the LS Factor across the Entire Comoé Basin

LS-factor	Comoé	Kafolo	Sérébou	Akakomoékro	Aniassue	M'Basso
Min	0	0	0	0	0	0
Max	28.84	25.28	25.28	25.28	25.28	25.41
Moyenne	0.24	0.2	0.21	0.21	0.22	0.23
Ecart-type	0.43	0.33	0.35	0.34	0.37	0.4

3.8. Erodibility Factor (K)

This factor refers to the pedo-transfer properties of slopes during runoff processes. The spatial distribution of the K factor shows that soils in the northern part of the basin are weakly erodible (Figure 10). The extreme southern part of the basin also exhibits this characteristic. Overall, the soils throughout the Comoé Basin are less erodible, as indicated by the low K factor values.

In this context, and compared with the other sub-basins, the soils in Kafolo are the least erodible, with the lowest mean K value, whereas those in Aniassué and M'Basso are more prone to erosion. Moreover, the soils in Sérébou and Akakomoékro are moderately erodible compared with the other sub-basins studied (Table 5).

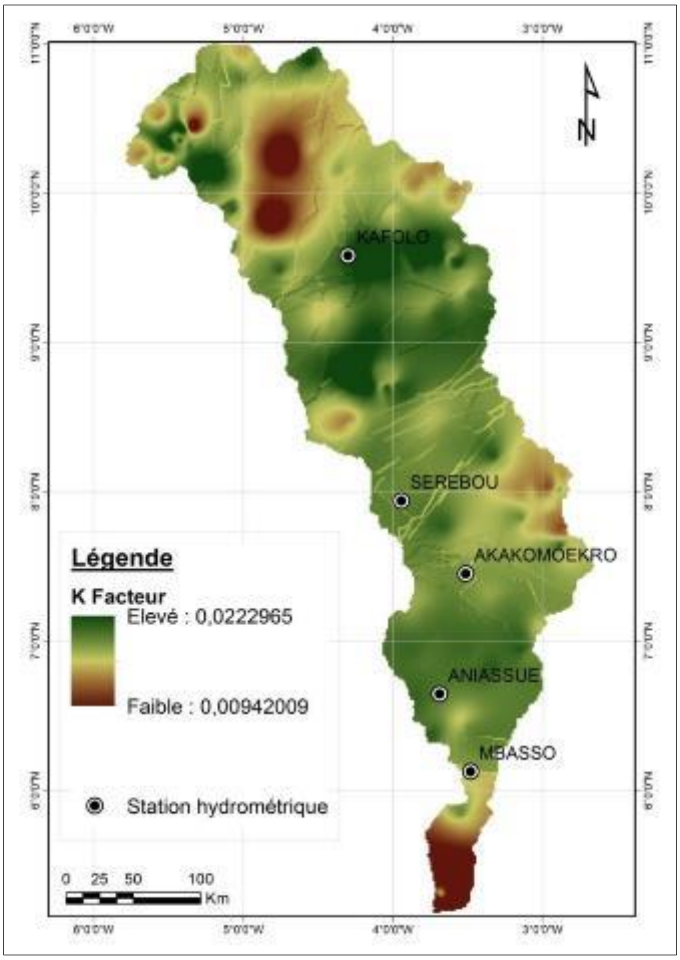

Figure 10 Erodibility Factor (K) of the Main Sub-Basins of the Comoé

Table 5 Statistical Distribution of K Factor Values across the Comoé Basin

K-facteur	Comoe	Kafolo	Serebou	Akakom	Aniassue	M'Basso
Min	0.00942009	0.01378347	0.01378347	0.01378347	0.01378347	0.01378347
Max	0.02229651	0.0222793	0.02229651	0.02229651	0.02229651	0.02229651
Moyenne	0.01861725	0.01805496	0.01871344	0.01870998	0.02229651	0.01871994
Ecart-type	0.00113177	0.00116248	0.00113156	0.00105871	0.00098304	0.00095302

4. Discussion

The morphometric and hydrological analysis of the Comoé sub-basins reveals a strong spatial heterogeneity in physical characteristics, directly influencing hydrological behaviour, infiltration, erosion, and surface runoff. These differences result in marked contrasts between the upstream sub-basins (notably Kafolo) and those located downstream (such as M'Basso).

The compactness index (Ic) and circularity ratio (Rc) show that all sub-basins have elongated shapes, indicating slow runoff and a variable infiltration potential according to longitudinal position. High compactness index values (>2) denote lower hydrological responsiveness, implying longer response times to extreme rainfall events. These findings are consistent with those of [2], who demonstrated that elongated basins dissipate runoff energy more effectively and reduce the risk of flash floods. In this context, the M'Basso sub-basin, which exhibits the highest compactness index, appears to be the most vulnerable to surface water accumulation and sedimentation.

The derived hypsometric curves suggest an advanced stage of geomorphological evolution, characterized by moderate relief and gentle slopes, particularly in the lower sections. This morphology implies limited erosion, as also observed by [20] for basins in the maturity phase. However, the high mean slope of the Kafolo sub-basin (Ig = 0.54) indicates a greater erosive potential in the upstream area, where the specific elevation difference (Ds = 77.75) confirms the dominance of mechanical erosion processes. These observations suggest that runoff energy progressively decreases downstream, promoting sedimentation in the lower-altitude areas (Aniassué and M'Basso).

Drainage density (Dd) and stream frequency (F) indicate a weakly drained network, typical of regions with permeable soils and dense vegetation cover. The low Dd values (<0.15 km/km^2) reflect predominant infiltration across the basin, highlighting the key role of vegetation in hydrological regulation [19]. However, the higher stream frequency observed in the Kafolo sub-basin suggests a more active hydrological dynamic, likely to increase surface runoff and localized erosion.

The LS (Limiting Slope) and K factors display marked contrasts depending on topography and soil type. The maximum LS factor values recorded in Kafolo confirm the significant contribution of relief to the basin's erosive energy. Conversely, the sub-basins of Sérébou, Akakomoékro, and Aniassué show lower values, indicating relatively stable soils. The results for the K factor reveal generally low erodibility, with local variations linked to soil texture and vegetation cover. These findings are consistent with [35], [36] who demonstrated that the combination of gentle slopes, dense vegetation cover, and fine-grained soils substantially reduces overall erosive potential.

Overall, the Comoé basin exhibits a well-regulated morphometric structure, with stable runoff conditions and limited flash-flood risk. Nevertheless, the upstream section (Kafolo) remains more sensitive to erosion and soil loss, particularly in the event of deforestation or unsustainable agricultural practices. Conversely, the downstream zone (M'Basso) acts as an accumulation area, promoting sediment deposition and potential groundwater recharge. These hydromorphological characteristics should be integrated into basin-wide management strategies aimed at balancing soil protection, hydrological regulation, and the sustainable use of water resources.

5. Conclusion

The morphometric and hydromorphological analysis of the Comoé basin highlights significant contrasts among the sub-basins, reflecting a spatial organization closely linked to topography, drainage shape, and local physical conditions. The shape indices, particularly compactness and circularity, indicate that the sub-basins are generally elongated, especially downstream, where high Ic values (up to 2.41) reflect longer concentration times and more limited infiltration. In contrast, the upstream sectors, such as the Kafolo sub-basin, display steeper slopes and greater erosive potential, promoting mechanical erosion and sediment mobility.

Volume and relief indices, including the hypsometric curve and specific elevation difference, confirm a decreasing altitudinal gradient from upstream to downstream, characteristic of a basin in an advanced evolutionary stage. The low mean slope (<1%) and concave hypsometric curves indicate a morphodynamically balanced system in which sedimentation locally dominates over erosion.

Furthermore, the hydrographic network attributes reveal low drainage density (Dd < 1.5 km/km^2) and stream frequency below 5, suggesting predominantly permeable soils and relatively high infiltration. These characteristics confer a rather regulating hydrological behaviour on the basin, although the upstream part remains more reactive to intense rainfall events.

The analysis of intrinsic erosion factors, particularly LS and K, indicates generally low erosive power across the basin, though locally accentuated in steep areas, notably in the Kafolo sub-basin. The K factor values reflect moderate to low soil erodibility, confirming the resistance of the substrate and the protective effect of existing vegetation cover.

Overall, these results show that the Comoé basin functions as a relatively stable hydrological system, characterized by good infiltration capacity and low susceptibility to erosion, except in some more vulnerable upstream areas. These findings highlight the need for differentiated basin management, prioritizing soil conservation and the protection of upstream areas to limit hydrosedimentary degradation and preserve the ecosystem services associated with the Comoé River.

Finally, this study underscores the relevance of the integrated morphometric approach, based on the use of DEM data and GIS tools (ArcGIS 10.2), for understanding hydrological and geomorphological processes in large tropical river basins. The results provide a valuable reference for monitoring basin evolution and implementing sustainable water resource management strategies in Côte d'Ivoire.

Compliance with ethical standards

No conflict of interest to be disclosed.

References

[1] Sreedevi PD, Owais S, Khan HH, Ahmed S. Morphometric analysis of a watershed using GIS and remote sensing techniques. Environmental Geology. 2005 ;48(7) :995–1006.

[2] Douvinet J, Delahaye D, Langlois P. Morphométrie et aléa inondation : apport des MNT pour la caractérisation des bassins versants. Géomorphologie : Relief, Processus, Environnement. 2008 ;14(1) :47–60.

[3] Rahmati O, Samadi S, Pourghasemi HR, Melesse AM. Application of GIS-based morphometric analysis for flood risk mapping. Journal of Hydrology. 2020 ;589 :125–146.

[4] Roy PD, Singh P, Sharma R. Quantitative morphometric analysis and prioritization of watersheds in relation to hydrological processes. Environmental Earth Sciences. 2021 ;80(5) :210–225.

[5] Ali S, Singh R, Sharma P, Kumar M. Morphometric analysis for hydrological response assessment in watershed management. Hydrology Research. 2022 ;53(4) :721–732.

[6] Singh R, Ali S, Sharma P. Hydrological modeling using morphometric parameters. Arabian Journal of Geosciences. 2023 ;16(12) :1–12.

[7] Kouadio K, Kouassi AM, N'Guessan Y. Hydrological response to land use change in the Comoé basin (Côte d'Ivoire). Journal of African Earth Sciences. 2018 ;144 :1–10.

[8] N'Dri B, Kouadio K, Diomandé M. Caractérisation de la variabilité climatique dans le district des Montagnes (Côte d'Ivoire). Revue Ivoirienne de Géosciences. 2021 ;2(1) :55–68.

[9] UNESCO. World Water Development Report 2020 : Water and Climate Change. Paris : UNESCO ; 2020.

[10] Kouassi K, N'Dri B, Kouadio K. Étude hydrogéologique du bassin versant de la Comoé. Revue des Sciences de l'Eau. 2022 ;35(1) :23–33.

[11] Brou YT, Koné B, Kouadio K. Analyse spatio-temporelle des précipitations dans le district des Montagnes, Côte d'Ivoire. Revue Ivoirienne de Géographie. 2019 ;3(2) :45–59.

[12] Soro N, Kouadio K, N'Dri B. Rainfall variability and water balance in western Côte d'Ivoire. African Journal of Environmental and Earth Sciences. 2023 ;10(2) :101–113.

[13] Diomandé M, Kouadio K, N'Guessan Y. Variabilité pluviométrique et impacts environnementaux dans le district des Montagnes (Côte d'Ivoire). African Journal of Environmental Science. 2020 ;6(1) :27–40.

[14] Centre d'Échange d'Informations sur la Biodiversité (CHM-Côte d'Ivoire). Rapport sur l'état de la biodiversité en Côte d'Ivoire. Abidjan ; 2022.

[15] Convention on Biological Diversity (CBD). Fifth National Report on Biodiversity in Côte d'Ivoire. Montréal : CBD Secrétariat; 2020.

[16] Office Ivoirien des Parcs et Réserves (OIPR). Rapport annuel sur la gestion des aires protégées du district des Montagnes. Abidjan : OIPR ; 2021.

[17] Rougerie G. Les milieux naturels de la Côte d'Ivoire. Paris : ORSTOM ; 1977.

[18] Jensen SK, Domingue JO. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing. 1988 ;54(11) :1593–1600.

[19] Horton RE. Erosional development of streams and their drainage basins ; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin. 1945 ;56(3) :275–370.

[20] Strahler AN. Hypsometric (area-altitude) analysis of erosional topography. Geological Society of America Bulletin. 1952 ;63(11) :1117–1142.

[21] Strahler AN. Quantitative geomorphology of drainage basins and channel networks. In : Chow VT, editor. Handbook of Applied Hydrology. New York : McGraw-Hill ; 1964.

[22] Moussa R. Quantification des processus hydrologiques à l'aide de modèles conceptuels. Thèse de doctorat. Institut National Polytechnique de Toulouse ; 1991.

[23] Miller VC. A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee. Columbia University; 1959.

[24] Singh S. Geomorphology. New Delhi : Prayag Pustak Bhawan; 1992.

[25] Reddy GPO, Maji AK, Gajbhiye KS. Drainage morphometry and its influence on landform characteristics in basaltic terrain, Central India – a remote sensing and GIS approach. International Journal of Applied Earth Observation and Geoinformation. 2004 ;6(1) :1–16.

[26] Bureau de Recherches Géologiques et Minières (BRGM). Guide méthodologique d'étude hydrogéologique. Orléans : BRGM ; 2010.

[27] Pilgrim DH, Cordery I. Flood runoff. In : Maidment DR, editor. Handbook of Hydrology. New York : McGraw-Hill ; 1993. p. 9.1–9.42.

[28] Roche M. Hydrologie de surface. Paris : Gauthier-Villars ; 1963.

[29] Moglen GE, Eltahir EAB, Bras RL. On the sensitivity of drainage density to climate change. Water Resources Research. 1998 ;34(4) :855–862.

[30] Kelson KI, Wells SG. Geologic influences on fluvial hydrology and geomorphology in the Rio Grande rift, New Mexico. Geological Society of America Bulletin. 1989 ;101(3) :413–424.

[31] Oguchi T. Drainage density and relative relief in humid steep mountains with frequent slope failure. Earth Surface Processes and Landforms. 1997 ;22(2) :107–120.

[32] Tucker GE, Catani F, Rinaldo A, Bras RL. Statistical analysis of drainage density from digital terrain data. Geomorphology. 2001 ;36(3–4) :187–202.

[33] Verstappen HT. Applied geomorphology: Geomorphological surveys for environmental development. Amsterdam : Elsevier ; 1983.

[34] Pakhmode V, Kulkarni H, Deolankar S. Hydrological drainage analysis in watershed programme planning : a case study from the Deccan basalt, India. Hydrogeology Journal. 2003 ;11(5) :595–604.

[35] Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC. Predicting soil erosion by water : A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Washington, DC : USDA ; 1997.

[36] Wischmeier WH, Smith DD. Predicting rainfall erosion losses: A guide to conservation planning. Washington, DC : USDA ; 1978.