Larhyss Journal, ISSN 1112-3680, n°56, Dec 2023, pp. 329-349

CHARACTERIZATION OF THE AFFINITIES BETWEEN THE SUBWATERSHEDS OF ORDER 4 OF THE BANDAMA RIVER BY STATISTICAL ANALYSIS OF MORPHOMETRIC PARAMETERS

KOUDOU A.[1*], GAHI Z.N.[2], ASSOMA T.V.[3], KOUAMÉ K.A.[2], AGBEVO Y.S.[1]

[1] Environmental Science and Technology Laboratory (LSTE), Department of Earth Sciences, UFR of Environment, Jean Lorougnon Guédé University (UJLoG) of Daloa, P.O Box 150 Daloa, Côte d'Ivoire
[2] Soil, Water and Geomaterials Sciences Laboratory (LSSEG), UFR of Earth Sciences and Mining Resources (UFR STRM), Félix Houphouët-Boigny University (UFHB) of Cocody-Abidjan, 22 P.O. Box 582 Abidjan 22, Côte d'Ivoire
[3] University Centre for Research and Application in Remote Sensing (CURAT), UFR of Earth Sciences and Mining Resources (UFR STRM), Félix Houphouët-Boigny University (UFHB) of Cocody-Abidjan, 22 P.O. Box 801 Abidjan 22, Côte d'Ivoire

(*) kdaime@yahoo.fr

Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received May 31, 2023, Received in revised form October 12, 2023, Accepted October 15, 2023

ABSTRACT

The objective of this study is to characterize the affinities between the subwatersheds of order 4 of the Bandama river by the statistical analysis of the morphometric parameters. It is conducted from the theoretical hydrographic network of the Bandama river. This hydrographic network is organized into a hierarchy and delineated, and its morphometric characteristics are determined. The study shows that the Bandama river is characterized by 21 subwatersheds of order 4, which mobilize slightly more than 59% of all the streams of this watershed. The standardized principal component analysis (standardized PCA) facilitated the regionalization of subwatersheds of order 4 by discriminating those with high shape values with a higher number of streams of order 1 to 4 combined from those with low shape values with a lower number of streams of order 1 to 4 combined. 7 distinct groups have been distinguished, among which the subwatersheds of order 4 with larger dimensions always stand out from the others. The main variables responsible for these groupings are area, perimeter, Gravelius compactness index, length and width. These results will contribute to a probable transposition of hydrometeorological data within the Bandama watershed for a better understanding of the irregularity of its hydrological behavior.

Keywords: Regionalization, Standardized PCA, Morphometric parameters, Subwatershed, Bandama, Côte d'Ivoire.

INTRODUCTION

The watershed is the territory drained by a river and its tributaries. It remains the water resources management unit according to the Etchemin River Restoration Committee (CRRE, 1999). In addition to the physical reasons (upstream-downstream relationship, relationship between groundwater and surface water, relationship between water quantity and water quality), the watershed is the place of existence of relationships between the human use of the territory and the quantity-quality of water (Rouissat and Smail, 2022). Its hydrological functioning is governed by climate, lithology, relief and land use (Grecu et al., 2007; Koua et al., 2019). The interaction between the morphological and morphometric characteristics of the watershed plays a decisive role in its flow (Faye, 2014) and therefore in its hydrological functioning (Baba-Hamed and Bouanan, 2016; Kamagate et al., 2017; Kouamé et al., 2017). Highlighting the relationships between subwatersheds, or at least streams within the same watershed, is a guarantee for optimizing the understanding of variations in the hydrological regime of the latter (Kouassi et al., 2017).

The Bandama watershed, the only large watershed whose entire extent is in Ivorian territory, approximately one-third of the country's area, is subject to the contrasting influences of climate (Camus, 1972 a and b; Kouamé, 2013), vegetation (ORSTOM, 1989), and highly diversified geological and geomorphological characteristics (Levêque and Dejoux, 1983), which justify the irregularity of the hydrological behavior of the Bandama River in space and time. The effectiveness of anthropogenic activities on the territory, in this case, the massive presence of storage structures (262 dams according to the Direction de Contrôle des Grands Travaux (DCGTx, 1996)), also disturbs the hydrological regime of the latter. In this context, it is more than urgent to understand the factors responsible for the irregularity of the hydrological behavior of the Bandama, especially since this hydrosystem is subject to various development aid projects (hydroelectric, hydroagricultural, agropastoral, household use, etc.) (Lassailly-Jacob, 1986; DCGTx, 1996) and subject to many phenomena of low water levels and floods (Girard et al., 1971; Monnet, 1972; Assoko et al., 2021).

A study on a finer spatial scale of the Bandama watershed therefore seems to be the appropriate way to better understand the irregularity of its hydrological behavior. The approach aiming to know the affinities or similarities and/or the oppositions or dissimilarities between the subwatersheds of the Bandama on the basis of the statistical links between their different morphometric characters proves to be more than necessary in the present study.

Until now, the morphometric characteristics of Bandama have been known (Camus, 1972 a and b; Konan et al., 2021). The characteristics of the flow network, necessary for understanding the hydrological response to rainfall events, have also been studied for

Bandama (Kouamé et al., 2011; Kouamé, 2013) and its three large subwatersheds, the Bandama rouge or Marahoué, the Bandama blanc and the N'zi (Konan et al., 2021). This study is therefore part of the regionalization approaches based on the physiographic similarities of watersheds with several combinations of descriptors. Its main objective is to characterize the affinities between the subwatersheds of order 4 of the Bandama by statistical analysis of the morphometric parameters. The choice of these subwatersheds is justified by the fact that they are part of the medium-sized watersheds (orders 4; 5 and 6), considered to be the most representative for quantitative morpho-hydrographic studies (Horton, 1945; Strahler, 1952). Studies of these watersheds are much more complex than those carried out in small watersheds (orders 1; 2 and 3), which are generally in a state of imbalance (Horton, 1945; Strahler, 1952).

Based on standardized principal component analysis (standardized PCA), the subwatersheds of order 4 will be grouped together to determine the affinities between them and the morphometric parameters that best characterize them. The knowledge of the similarities between the subwatersheds and the control of the links between their characteristic parameters open the way to a better understanding of the relationships between these parameters and the flow. The database that can be used for hydrological modeling purposes will be significantly enriched.

MATERIAL AND METHODS

Description of the study area

The Bandama watershed extends from the North to the South of Côte d'Ivoire and covers an area of 97,500 km², or approximately 30% of the country's area. It is located between longitudes 3°50' and 7°00' West and latitudes 5°10' and 10°20' North. It is drained by the main Bandama River, 1050 km long, and its main tributaries are the Bandama rouge or Marahoué, 550 km long, and the N'zi, 725 km long. The Bandama River rises in the North of Côte d'Ivoire at an altitude of 480 m between Korhogo and Boundiali and flows into its outlet, the Grand-Lahou lagoon, in the South of the country (Camus, 1972 a and b). Due to its geographical configuration, the Bandama watershed is limited in the South by the Atlantic Ocean and by five other watersheds **(**Fig. 1):

- the transboundary watershed of the Niger River in the North;
- the transboundary watershed of the Comoé River in the East;
- the transboundary watershed of the Sassandra River in the West;
- the coastal watershed of Agnéby in the Southeast;
- and the Boubo coastal watershed in the Southwest.

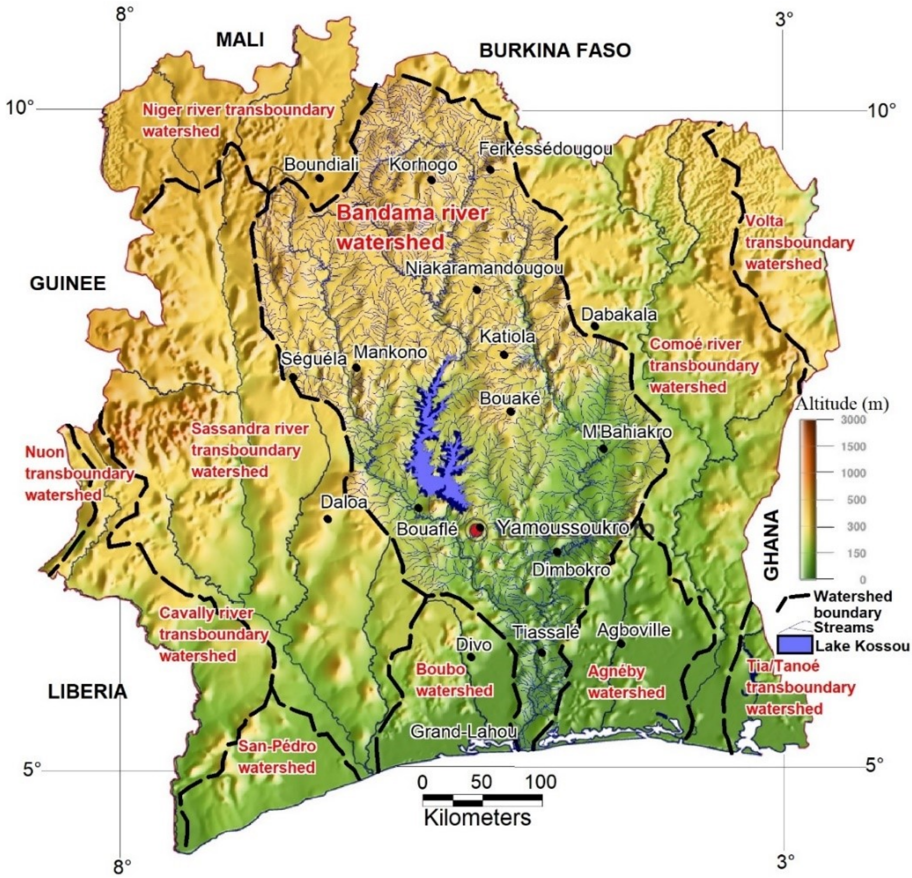

Figure 1: Location of the Bandama watershed against a background of degraded relief

Due to its size, the Bandama watershed covers different geological, geomorphological and vegetation zones and results from a diversity of climatic zones leading to different hydrological regimes. Thus, the geology of the Bandama watershed is characterized by basic rocks in the North, granitic rocks in the Center, schistose metamorphic rocks in the South and sedimentary rocks on the coast (Levêque and Dejoux, 1983). From the structural point of view, contacts between the different units follow the NNE–SSW direction (Camus, 1972 a and b). The relief of the watershed slopes from 400 m in the North to less than 100 m in the South. The undulating and monotonous relief is characterized by a succession of more or less subflattened hills (Levêque and Dejoux, 1983). From the pedological point of view, ferallitic soils are very widespread in the Bandama watershed (Dabin et al., 1960; Perraud, 1971). In the northeast of the watershed and in the N'zi Corridor, a ferruginous-type evolution is superimposed on the initial ferallitic material. Hydromorphic soils are observed only in the lower Bandama.

Climatically, the Bandama watershed is subject to various climatic regimes to which three hydrological regimes correspond (Girard and Sircoulon, 1968; Girard et al., 1971). The transitional tropical regime (two seasons: a rainy season from April to September and a dry season from November to April) in the northern part of the watershed; the attenuated transition equatorial regime in the central part (two rainy seasons and one dry season) and the transition equatorial regime (four seasons: two dry seasons and two rainy seasons) in the southern portion of the watershed (Servat et al., 1997). In relation to the climatic classification, the Bandama watershed covers different types of vegetation. The Sudanese sector in the north is covered by open forests and savannahs of the wooded, arboreous, shrubby or grassy type; the mesophile sector in the center is covered by gallery forests, dense humid, semideciduous forests and swamp forest. The ombrophile sector in the south is covered by a dense forest with several layers.

Study data and tools

The main datum of the study is the hydrographic network of the Bandama watershed. It is extracted from the DEM coverage of the ASTER GDEM mission study area (30 m): https://earthexplorer.usgs.gov/. This coverage results from the assembly of 17 slabs of square grids with a side of one arc second (30 meters) in a geographic coordinate system based on the WGS84 reference frame. The hydrographic network is corrected (reduced, modified, removed from any anthropogenic drain) on the basis of the information provided by the national topographic map.

This theoretical hydrographic network served as a framework for the various treatments using software such as:

- MapInfo 7.5 for digitizing the hydrographic network and prioritizing drains or streams;
- Microsoft Office Excel 2019 for the statistical processing of hydrographic drains;
- Statistica 7 for standardized principal component analysis (standardized PCA).

Methodological approach

Hierarchy of hydrographic network

The system of numbering river sections, based on the hierarchical position within the network of river segments between confluences and set up by Strahler (1957), makes it possible to hierarchize the hydrographic network of the Bandama. This classification, which is the most used according to the BRGM (2002) compared to that of Horton (1945) and that of Shreve (1966), is based on rules that allow us to describe without any doubt the development of the drainage network of a watershed from upstream to downstream. These rules are as follows:

- any stream without tributaries is of order one;
- the stream formed by the confluence of two streams of different order takes the order of the higher of the two;
- the stream formed by the confluence of two streams of the same order (n) is increased by one (n+1).

A watershed has the highest order of its streams, which is the order of the main stream at the outlet.

Determination of morphometric parameters of the Bandama subwatersheds of order 4

The hierarchy of the Bandama watershed facilitates the determination of the number of orders of the streams and the delimitation and calculation of morphometric parameters of the subwatersheds of order 4. The main morphometric characteristics of the subwatersheds of order 4 of the Bandama determined and their calculation formulas are shown in Table 1.

Application of standardized principal component analysis (standardized PCA) to morphometric parameters of the Bandama subwatersheds of order 4

To determine the affinities between the subwatersheds studied and to deduce the parameters that best characterize them, standardized PCA was used. It was applied to the 13 morphometric parameters (A: area, P: perimeter, KG: Gravelius compactness index; L: length, l: width, STR1: order 1, STR2: order 2, STR3: order 3, STR4: order 4, Dd: drainage density, Rc1/2: confluence ratio of order 1 to order 2, Rc2/3: confluence ratio of order 2 to order 3, Rc3/4: confluence ratio of order 3 to order 4) corresponding to variables (Riad, 2003; Koudou et al., 2015) and to the 21 subwatersheds of order 4 coded from 1 to 21 and corresponding to individuals. The processing was carried out using Statistica 7 software.

Table 1: Morphometric parameters and calculation formulas

Morphometric parameters	Definition		Means of determination
Area (A) in km²	Precipitation reception area and supply area circumscribed by the watershed line and drained by a river and its tributaries upstream of this section		derminated using Mapinfo software $A = L * l$
Perimeter (P) in km	Length of the contour of the watershed consisting of a line joining all the highest points of the watershed		derminated using Mapinfo software $P = \frac{Kc\sqrt{A}}{0,28} = 2(L + l)$
Gravelius compactness coefficient (Kc)	Ratio of the perimeter of the watershed to that of a circle of the same area		$Kc = \frac{P}{2\sqrt{\pi A}} = 0,28 \times \frac{P}{\sqrt{A}}$
Equivalent Rectangle	Length (L) of the equivalent rectangle	Purely geometric transformation of the watershed which takes a rectangular shape while keeping the same area, the same perimeter, the same compactness index and therefore the same hypsometric distribution	$L = \frac{Kc\sqrt{A}}{1,12}\left[1 + \sqrt{1 - \left(\frac{1,12}{Kc}\right)^2}\right]$
	Width (l) of the equivalent rectangle		$l = \frac{Kc\sqrt{A}}{1,12}\left[1 - \sqrt{1 - \left(\frac{1,12}{Kc}\right)^2}\right]$
Stream orders	Stream order is a classification that reflects the branching of the stream.		The classification of Strahler (1957) makes it possible to describe without ambiguity the development of the drainage network of a watershed from upstream to downstream. It is based on the following rules: - any stream without tributaries is of order one; - the stream formed by the confluence of two streams of different order takes the order of the higher of the two; - the stream formed by the confluence of two streams of the same order (n) is increased by one (n+1). A watershed has the order of the highest of its streams, which is the order of the main stream at the outlet.
Nn	Number of streams of order n		Count of stream segments
Confluence ratio or burfication ratio	Ratio of the number of streams of order n to the number of streams of order n + 1		Nn= number of streams of order n Nn+1 = number of streams of order n+1 $R_c = \frac{N_n}{N_{n+1}}$
Drainage density (Dd) in km/km²	Ratio of total stream length to watershed area		ΣLi = the total length of all streams, Dd = Drainage density in km/km² A = area of the watershed in km² $D_d = \frac{\Sigma L_i}{A}$ (Horton, 1945)

RESULTS AND DISCUSSION

Main results

Bandama stream orders and codification of subwatersheds of order 4

The hierarchy of the hydrographic network of the Bandama watershed is illustrated in Fig. 2.

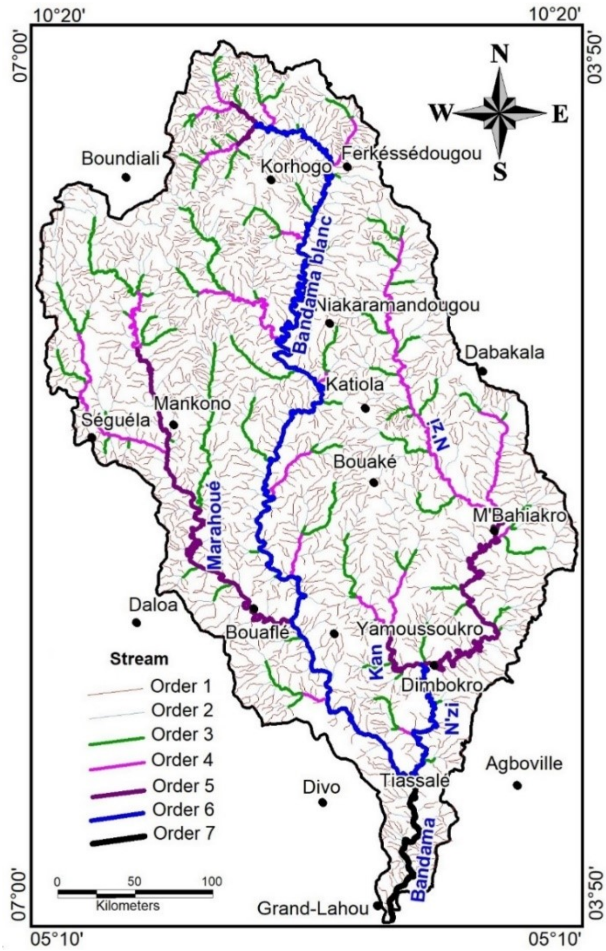

Figure 2: Hierarchy of the Bandama hydrographic network

The Bandama watershed has 1,971 streams of order 1; 923 streams of order 2; 456 streams of order 3; 221 streams of order 4; 113 streams of order 5; 155 streams of order 6 and 30 streams of order 7. The Bandama watershed is of order 7 at the outlet.

Analysis of morphometric characteristics of subwatersheds of order 4

The delimitation of the Bandama subwatersheds of order 4 reveals 21 of them (Fig. 3).

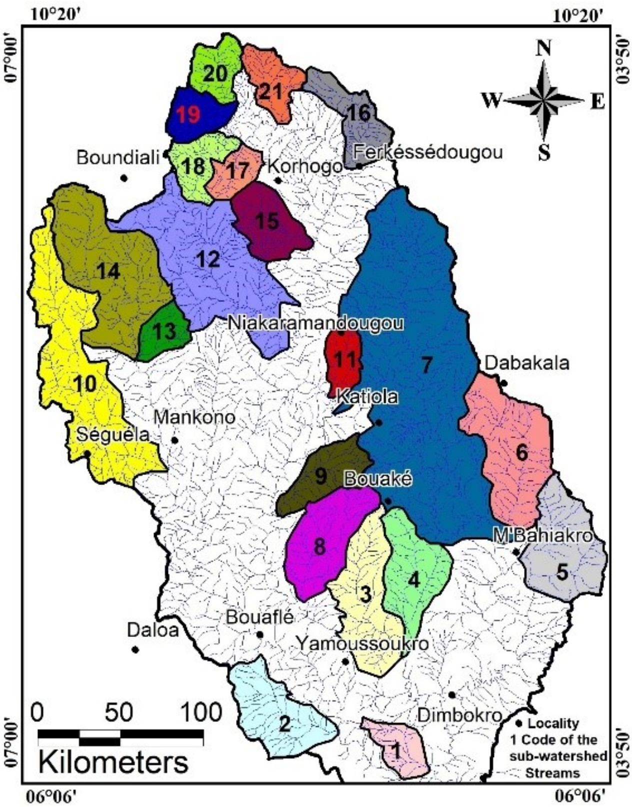

Figure 3: Codification of the Bandama subwatersheds of order 4

The Fig. 4 shows the number of streams of order 1; 2; 3 and 4 mobilized by the Bandama subwatersheds of order 4.

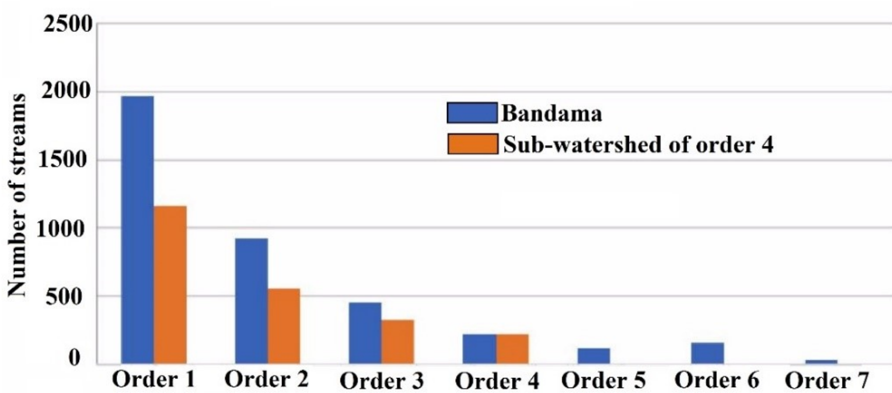

Figure 4: Number of streams of order 1; 2; 3 and 4 mobilized by the Bandama subwatersheds of order 4.

Subwatersheds of order 4 concentrate 59% of streams of order 1, 60% of streams of order 2, 72% of streams of order 3 and 100% of streams of order 4 of the Bandama. They mobilize slightly more than half, or 59%, of all Bandama streams.

Morphometric parameter quantification of subwatersheds of order 4

Values of the main morphometric characteristics of subwatersheds of order 4 are recorded in Table 2.

Table 2: Morphometric characteristics of the Bandama subwatersheds of order 4

Subwatershed	Area (in km²) (A)	Perimeter (in km) (P)	Compactness index of Gravelius (Kc)	Length (in km) (L)	Width (in km) (l)	Order 1 (STR1)	Order 2 (STR2)	Order 3 (STR3)	Order 4 (STR4)	Drainage density (in km/km²) (Dd)	Confluence ratio order 1 on order 2 (Rc1/2)	Confluence ratio order 2 on order 3 (Rc2/3)	Confluence ratio order 3 on order 4 (Rc3/4)
1	861.4	130.4	1.24	46.79	18.41	21	9	8	2	0.274	2.33	1.13	4.00
2	2,172	216.1	1.30	81.35	26.70	35	17	10	5	0.246	2.06	1.70	2.00
3	2,724	277	1.49	114.76	23.74	54	26	16	8	0.244	2.08	1.63	2.00
4	2,066	230.6	1.42	93.11	22.19	36	20	8	5	0.239	1.80	2.50	1.60
5	2,580	225.5	1.24	80.83	31.92	31	20	7	2	0.206	1.55	2.86	3.50
6	3,136	257.3	1.29	95.97	32.68	49	21	5	22	0.202	2.33	4.20	0.23
7	12,960	673.8	1.66	292.61	44.29	239	113	69	49	0.157	2.12	1.64	1.41
8	2,246	208.7	1.23	74.00	30.35	36	19	8	7	0.260	1.89	2.38	1.14
9	1,361	177.4	1.35	68.97	19.73	27	8	6	11	0.276	3.38	1.33	0.55
10	5,165	515.2	2.01	235.69	21.91	105	46	28	25	0.252	2.28	1.64	1.12
11	795.2	123	1.22	43.01	18.49	19	6	11	1	0.273	3.17	0.55	11.00
12	5,373	426.1	1.63	183.82	29.23	123	69	31	17	0.278	1.78	2.23	1.82
13	745.2	115.2	1.18	37.98	19.62	20	10	8	1	0.294	2.00	1.25	8.00
14	4,295	334.6	1.43	135.63	31.67	69	36	24	7	0.245	1.92	1.50	3.43
15	1,461	162.5	1.19	54.39	26.86	39	20	13	4	0.260	1.95	1.54	3.25
16	1,403	198.9	1.49	82.43	17.02	56	25	7	20	0.338	2.24	3.57	0.35
17	726.2	118.6	1.23	42.02	17.28	32	17	12	1	0.318	1.88	1.42	12.00
18	1,053	165	1.42	66.72	15.78	49	18	18	11	0.384	2.72	1.00	1.64
19	920.5	133.1	1.23	46.94	19.61	39	19	8	10	0.361	2.05	2.38	0.80
20	931	135.8	1.25	48.84	19.06	43	15	15	10	0.354	2.87	1.00	1.50
21	1,030	154	1.34	59.77	17.23	41	21	15	3	0.344	1.95	1.40	5.00

The Bandama subwatersheds of order 4 of different forms vary by the diversity of their morphometric characteristics.

Regionalization of the Bandama subwatersheds of order 4

Table 3 expresses the eigenvalues, the percentage of variance explained and the percentage of variance cumulative by each axis.

Table 3: Eigenvalue, percentage and cumulation

Axis	Eigenvalue	Total pourcentage variance	Cumulative eigenvalue	Cumulative pourcentage
I	8.06	62.03	8.06	62.03
II	1.79	13.80	9.85	75.84
III	1.33	10.30	11.19	86.14

The three axes (or main components) characterize the reduction in the size of the data while retaining 86.14% of the information (Table 3**)**. Interpretation of the significance of these axes, whose eigenvalues are greater than unity, allows us to extract the fundamental characteristics of the subwatersheds of order 4. A loss of less than 14% of the information contained in all data is signified by the three axes.

Table 4 shows the correlation matrix of the variables.

Table 4: Correlation matrix of variables

	A	P	K_C	L	l	STR1	STR2	STR3	STR4	Dd	RC1/2	RC2/3	RC3/4
A	1	**0.95**	0.63	**0.93**	**0.80**	**0.96**	**0.95**	**0.92**	**0.85**	-0.64	-0.20	0.11	-0.29
P		1	**0.82**	**0.99**	0.71	**0.92**	**0.92**	**0.86**	**0.83**	-0.60	-0.21	0.14	-0.37
K_C			1	**0.85**	0.22	0.69	0.66	0.62	0.67	-0.23	-0.04	0.06	-0.38
L				1	0.65	**0.92**	**0.91**	**0.86**	**0.83**	-0.56	-0.18	0.11	-0.36
l					1	0.66	0.70	0.59	0.56	-0.82	-0.38	0.33	-0.31
STR1						1	**0.98**	**0.96**	**0.89**	-0.43	-0.15	0.05	-0.30
STR2							1	**0.94**	**0.84**	-0.46	-0.27	0.09	-0.27
STR3								1	0.78	-0.37	-0.10	-0.19	-0.13
STR4									1	-0.38	0.06	0.28	-0.49
Dd										1	0.27	-0.27	0.12
RC1/2											1	-0.40	0.00
RC2/3												1	-0.48
RC3/4													1

In bold : significant correlation coefficient values

With the exception of stream confluence ratios (Rc1/2, Rc2/3, Rc3/4), which are not correlated with any variable characterizing the Bandama subwatersheds of order 4, there are many significant relationships between the variables. Variables such as area (A), perimeter (P), Gravelius compactness index (Kc), length (L), and streams of order 1; 2; 3 and 4 (STR1, STR2, STR3 and STR4) are strongly related to each other with a correlation coefficient greater than 0.8. The width (l) is also strongly correlated positively (0.80) with area (A) but negatively (-0.82) with drainage density (Dd). It has, to a lesser extent, average positive relationships with the variables listed above.

The coordinates of the variables with the main factorial axes (Table 5) show that factorial axis 1 is very well negatively correlated with area (A), perimeter (P), Gravelius compactness index (Kc), dimensions of the equivalent rectangle (length (L) and width (l)), and number of streams of order 1; 2; 3 and 4 (STR1, STR2, STR3 and STR4) and moderately positively correlated with drainage density (Dd). Factorial axis 2 is very well correlated positively with Rc2/3 but to a lesser extent negatively with Rc1/2. Factorial axis 3 is moderately negatively correlated with Rc3/4.

Table 5: Coordinates of the variables with the main factorial axes

	Axis 1	**Axis 2**	**Axis 3**
A	**-0.98**	-0.03	-0.13
P	**-0.98**	-0.04	0.01
Kc	<u>-0.74</u>	-0.26	0.34
L	**-0.97**	-0.09	0.04
l	<u>-0.77</u>	0.43	-0.30
STR1	**-0.96**	-0.18	-0.02
STR1	**-0.96**	-0.09	-0.09
STR1	**-0.89**	-0.36	-0.19
STR1	**-0.88**	-0.09	0.31
Dd	<u>0.61</u>	-0.43	0.37
Rc1/2	0.23	<u>-0.61</u>	0.40
Rc2/3	-0.19	**0.83**	0.38
Rc3/4	0.40	-0.33	<u>-0.74</u>

In bold: significant correlation coefficient values
<u>Underlined</u>: average correlation coefficient values
Normal: low correlation coefficient values

These results are summarized in Figs. 5 and 6, which illustrate the space of variables on factorial planes 1 and 2 and 1 and 3, respectively.

Analysis of the F1-F2 factorial plane (75.84%) shows that axis 1 (62.04%) is negatively determined both by the shape parameters (A, P, Kc, L, l) and the number of streams of order 1 to 4 (STR1, STR2, STR3 and STR4). Axis 2 (13.80%) positively carries Rc2/3 and is not opposed to any other parameter (Fig. 5).

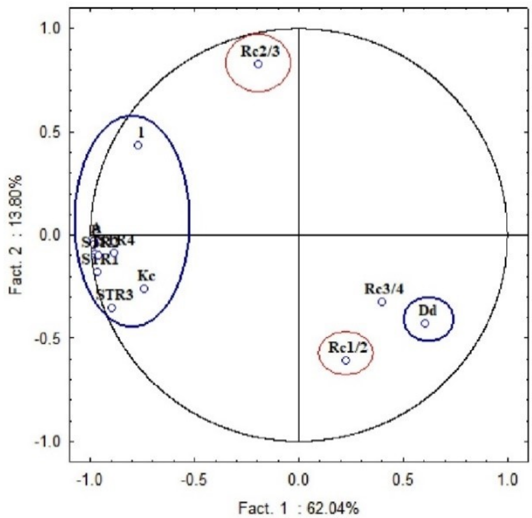

Figure 5: Distribution of variables (morphometric parameters) in the F1-F2 factorial plane

On the factorial plane F1-F3 (72.34%), axis 1 has the same meaning as before. Axis 3 positively carries Rc3/4 and is not opposed to any other parameter (Fig. 6).

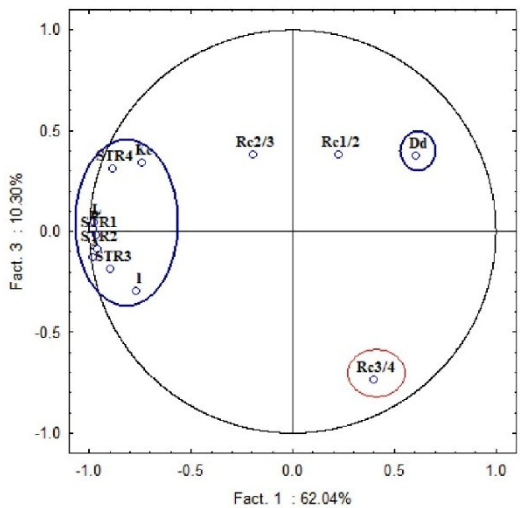

Figure 6: Distribution of variables (morphometric parameters) in the F1-F3 factorial plane.

Analysis of the space of the F1-F2 individuals shows that F1 separates large areas (negative side) from small areas (positive side) (red frame) of the subwatersheds of order 4. Four subgroups can be delimited on the basis of the size or dimension of the area and perimeter (Fig. 7):

- subwatersheds with a large area and very large perimeter (7; 10 and 12) with subwatershed 7, which clearly stands out from the whole;
- subwatersheds with large areas and large perimeters (14; 3 and 6);
- subwatersheds with small areas and large perimeters (19; 15; 16; 8; 2; 5 and 4);
- and subwatersheds with a small area and a small perimeter (13; 17; 11; 1; 20; 21; 18 and 9).

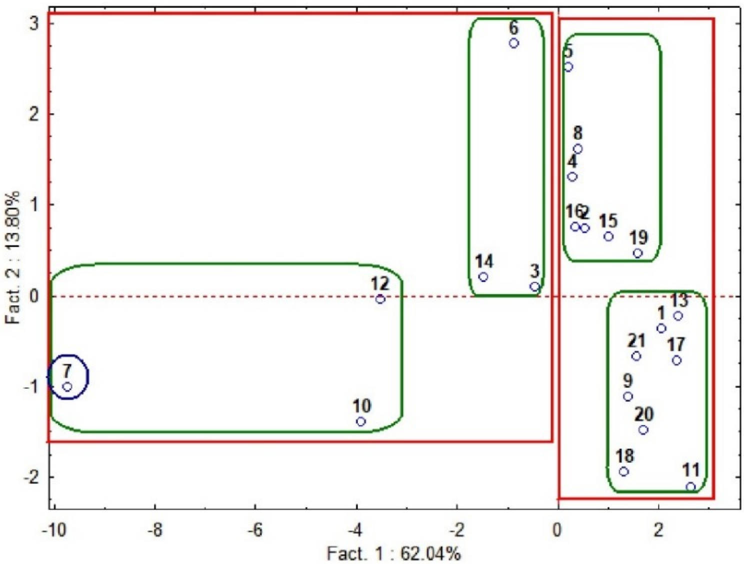

Figure 7: Distribution of individuals (coded subwatersheds of order 4) in the F1-F2 factorial plane

Analysis of the space of the F1-F3 individuals shows that F1 separates large areas (negative side) from small areas (positive side) (red frame) of the subwatersheds of order 4 as previously described. Three (3) subgroups can be distinguished in the space of the F1-F3 individuals (Fig. 8):

- subwatersheds of order 4 of large area with a very high number of streams of order 1 to 4 combined (7; 10; 12; 14; 3 and 6), of which subwatershed 7 remains the most representative;
- the subwatershed of order 4 of small area with a very high number of streams of order 1 to 4 combined (16);
- and subwatersheds of order 4 of small area with a number of streams of order 1 to 4 combined lower (13; 17; 11; 1; 19; 20; 21; 15; 18; 9; 8; 2; 5 and 4).

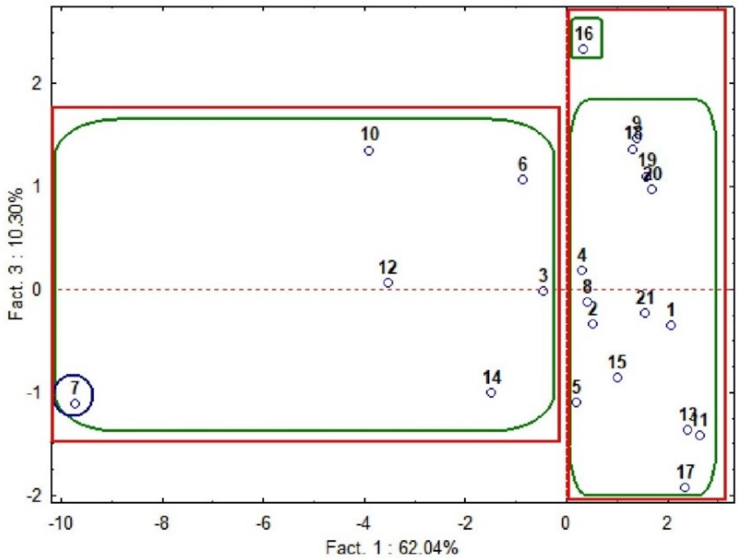

Figure 8: Distribution of individuals (coded subwatersheds of order 4) in the F1-F3 factorial plane

Finally, the standardized PCA distinguishes between subwatersheds of order 4 with high shape values (A, P, Kc, L, l) with a higher number of streams of order 1 to 4 combined and subwatersheds of order 4 with low shape values with a lower number of streams of order 1 to 4 combined.

DISCUSSION

The hierarchy of streams, according to the codification of Strahler (1957), only imposes an organization in all the connections of a hydrographic network. It implicitly assimilates the hydrographic network to a perfect tree structure. This representation of the hydrographic network is therefore simplified and effectively corresponds to reality for a certain scale. It simplifies the digital processing of the vectorized river network.

Strahler's codification method, which is widely used (Plantier, 2003; Kaddour, 2017; Boudjefna, 2018), has facilitated the comparison of Bandama subwatersheds of order 4. A diversity of areas, perimeters and shapes of subwatersheds of order 4 have been highlighted in the Bandama watershed. The perfect knowledge of these parameters contributes to a better understanding of the factors responsible for variations in the hydrological regime and consequently their contribution to the genesis of natural risks and their variability in time and space (Benzougagh et al., 2019). Determination of these parameters is considered to be of acceptable precision at the study scale, since in reality, stream order may vary according to the scale and the study medium (Laborde, 2000). This state is confirmed in the Bandama watershed by the present study and that of other authors

(Konan et al., 2021). The "real" numbers would require a hydrographic network that includes all existing streams in the field (OFEV, 2013).

The standardized PCA facilitated the identification of links between certain morphometric parameters characteristic of the Bandama subwatersheds of order 4. The high degree of correlation (positive or negative) between these parameters reflects their interdependence. The positive and significant relationship between area (A) and width (l) (correlation coefficient=0.80) means that the subwatersheds of order 4 with a large area are those with a large width (high value). On the other hand, there is a negative and significant relationship between width (l) and drainage density (Dd) (correlation coefficient=-0.82), which means that the subwatersheds of order 4 with high width tend to have low drainage density. This is spatial co-occurrence and not a causal relationship between two variables (Baron and Sanders, 2006). Furthermore, the standardized PCA highlighted the affinities between the different subwatersheds of order 4 of the Bandama. The subgroups of watersheds distinguished do not always belong to contiguous geographical areas. Therefore, geographic proximity does not significantly influence zonation (Baba-Hamed and Bouanani, 2016).

Analysis of the standardized PCA is relevant in this study because a small number of factorial axes (the first 3 out of thirteen (13)) explains a large part of the inertia (86.14%). The number of axes selected for interpretation in this study is based both on the desired explained variance threshold (greater than 80%, as recommended by some authors (Baron and Sanders, 2006) and on the upper eigenvalues to 1. This last criterion is justified by the fact that the present analysis was carried out on centered–reduced data (mean=0 and standard deviation=1) to give the same weight to all the variables, hence the term standardized ACP.

However, there are weaknesses in this approach. It is based on a subjective choice of the number of morphometric parameters for the grouping of subwatersheds. It is characterized by a lack of scientific concepts to justify this choice, resulting in a variation in the number of homogeneous groupings. The results of the grouping therefore depend on the selection of morphometric parameters used to define similarities between subwatersheds. The grouping of physically similar subwatersheds is useful for any possible extrapolation of hydrometeorological data (Baba-Hamed and Bouanani, 2016). Thus, in the Bandama watershed, the small or ungauged subwatersheds of order 4, where observed flow data are missing or insufficient to allow the calculation of the variables of interest at appropriate spatial and temporal scales and at an acceptable accuracy for practical applications, could benefit from data coming from other subwatershed "donors" of order 4 (gauged watersheds), deemed similar or belonging to the same climatically and/or hydrologically homogeneous region.

CONCLUSION

Characterization of the affinities between the Bandama subwatersheds by statistical analysis of morphometric parameters has led to several conclusive results. The Bandama watershed is characterized by 21 subwatersheds of order 4, with morphometric parameters that vary from one subwatershed to another. These subwatersheds mobilize slightly more than half of all the streams in Bandama. Affinities or similarities and/or oppositions were nevertheless detected in the Bandama subwatersheds of order 4, thus attaching them to distinct groups through standardized principal component analysis (PCA). The main morphometric parameters, which are strongly related to each other and responsible for these groupings, are area, perimeter, Gravelius compactness index, length and width, and the number of streams of order 1 to 4 combined. Thus, the subwartersheds of order 4, with high shape values and a higher number of streams of order 1 to 4 combined, always stand out from the others.

Finally, the standardized principal component analysis (PCA) facilitated the grouping or regionalization of the Bandama subwatersheds of order 4. However, interpretation of the results of this analysis remains delicate. Knowledge of the different morphometric parameters, of the link between them, and of affinities or differences between subwatersheds is of interest for hydrological modeling and for any possible extrapolation of hydrometeorological data. Furthermore, it is a guarantee for a better understanding of the irregularity of the hydrological behavior of the Bandama.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

ASSOKO A.V.S., KOUASSI A.M., NASSA R.A.-K. (2021). Statistical modeling and flood alerts in the Marahoué watershed (Bandama, Ivory Coast). International Journal of Innovation and Applied Studies, Vol.34, No 1, pp. 115-127. (In French)

BABA-HAMED K., BOUANANI A. (2016). Characterization of a watershed by statistical analysis of morphometric parameters: the case of the Tafna watershed (North–West Algeria), International journal of tropical geology, geography and ecology, No 40, Tome 4, pp. 277-286. (In French)

BARON M., SANDERS L. (2006). Data analysis, automatic mapping and principal component analysis. University of Paris 7 Denis Diderot - Yaoundé 1 convention, "Statistics, Cartography and Spatial Analysis" Summer School, 32 p. (In French).

BENZOUGAGH B., DRIDRI A., BOUDAD L., SDKAOUI D., BAAMAR B. (2019). Contribution of GIS and remote sensing to the evaluation of the physical characteristics of Oued Inaouene watershe (North–East Morocco) and their uses in the field of natural hazard management, American Journal of Innovative Research & Applied Sciences, Vol.8, No 4, pp. 120-130. (In French)

BOUDJEFNA C. (2018). Application of morphometric analysis to subwatersheds - case of the Cheliff watershed, Master's thesis, Arbaoui Abdellah National School of Hydraulics of Algeria, 75 p. (In French)

BRGM (2002). Relationship between the surface water network and groundwater in the Orchies basin. Involvement of its development in groundwater vulnerability. Study carried out as part of BRGM's public service operations (00P1R251), ERDF subsidy agreement (objective 1) n°1999-10-1413-6, and DIREN subsidy (Notil 54), Public document, 55 p. (In French)

CAMUS H. (1972 a). Hydrology of the Bandama, Vol. 1, « The Bandama Blanc », 89 p. (In French)

CAMUS H. (1972 b). Hydrology of the Bandama, Vol. 2, « The Marahoué », 81 p. (In French)

CRRE (1999). Toward an Integrated and Collaborative Water Management of the Etchemin River Watershed: A simple and achievable example for watershed water management. Water management in Quebec. Brief for the Environmental Public Hearings, 78 p. (In French)

DABIN B., LENEUF N., RIOU G. (1960). Soil map of Côte d'Ivoire at 1/2,000,000, Explanatory note. ORSTOM/P. (In French)

DCGTx (1996). Inventory and diagnosis of dams. Major Works Control Department, Sectoral Rural Development Programme (PSAR), 95 p. (In French)

FAYE C. (2014). Statistical analysis of morphometric data Method: correlation of morphometric parameters and influence on the runoff of subbasins of the Senegal River Basin. Five Continents/Romanian Journal of Geography, Vol. 4, N 10, pp. 80-108. (In French)

GIRARD G., SIRCOULON J. (1968). Overview of hydrological regimes in Côte d'Ivoire. ORSTOM Adiopodoumé Centre, Côte d'Ivoire, 56 p. (In French)

GIRARD G., SIRCOULON J., TOUCHEBEUF P. (1971). Overview of hydrological regimes. In the natural environment of Côte d'Ivoire. Submission ORSTOM 50, pp. 109-155. (In French)

GRECU F., ZĂVOIANU I., ZAHARIA L., COMĂNESCU L. (2007). Quantitative analysis of the hydrographic network in the Slănic watershed (Romania). Physical geography and environment, Vol. 1, pp. 79-93. (In French)

HORTON R.E. (1945). Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Geological Society of America Bulletin, Vol.56, N°3, pp. 275-370.

KADDOUR N.E.H. (2017). Characterization, classification and multivariable statistics of the waters of the Oued El Malah watershed (NW Algeria), Master's thesis, University of Tlemcen, Algeria, 96 p. (In French)

KAMAGATE B., DAO A., NOUFE D., YAO K.L., FADIKA V., GONE D.L., SAVANE I. (2017). Contribution of gr4j model for modeling Agneby watershed runoff in southeast of Cote d'Ivoire, Larhyss Journal, No 29, pp. 187-208. (In French)

KONAN K.C., KOUASSI K.J., TRA BI Z.A., DJAKO A. (2021). Characterization of the Bandama watershed by statistical analysis of morphometric parameters. Proceedings of the International Colloquium on the theme «Intersecting Perspectives on Territories in Food Crisis and Security in Sub-Saharan Africa», organized from 12 to 14 October 2021, Alassane Ouattara University (Bouaké-Côte d'Ivoire) by the Laboratory for Analysis of Environmental Vulnerabilities (LAVSE) and Development Research Unit (URED), pp. 603-621. (In French)

KOUA T., ANOH K., EBLIN S., KOUASSI K., KOUAME K., JOURDA J. (2019). Rainfall and runoff study in climate change context in the Buyo lake watershed (southwest Côte d'Ivoire), Larhyss Journal, No 39, pp. 229-258. (In French)

KOUAMÉ K.A. (2013). Application of the HYDROTEL distributed hydrological model to the simulation of water flows in humid tropical environments under anthropogenic pressures: case of the Bandama watershed in Côte d'Ivoire. Unique Doctoral Thesis, Félix Houphouët-Boigny University of Abidjan-Cocody, Côte d'Ivoire, 164 p. (In French)

KOUAMÉ K.A., KOUAMÉ K.F., KOUASSI A.M., OULARÉ S., ADON G.C.-R., BERNIER M. (2011). Establishment of a database for distributed hydrological modelling of the Bandama watershed (Côte d'Ivoire): contribution of a digital elevation model, remote sensing and GIS Physitel. Afrique SCIENCE, Vol. 7, No. 2, pp. 94 – 114. (In French)

KOUAMÉ K.A., KOUDOU A., SOROKOBY V.M., KOUAMÉK. F., KOUASSI A.M. (2017). Relationship between surface and underground water flow in the upper Bandama watershed in Ivory Coast, Larhyss Journal, No 29, pp. 137-152. (In French)

KOUASSI A.M., ASSOKO A.V.S, KOUAKOU K.E., DJE K.B, KOUAME K.F, BIEMI J. (2017). Analysis of the hydrological impacts of climate variability in west Africa: case study of the Bandama watershed in Ivory Coast, Larhyss Journal, No 31, pp. 19-40. (In French).

KOUDOU A., KOUAMÉ K.A., NIAMKÉ K.H., KOUAMÉ K.F., SALEY M.B., ADJA M.G. (2015). Contribution of principal component analysis to the regionalization of rainfall in the N'zi watershed (central Côte d'Ivoire), Ivorian Journal of Science and Technology, N°26, pp. 156-172. (In French)

LABORDE J.P. (2000). Element of surface hydrology, Course of University of Nice-Sophia Antipolis, France, 192 p. (In French)

LASSAILLY-JACOB V. (1986). An ephemeral example of development planning: AVB in Central Côte d'Ivoire (1969-1980). Afrivan Studies Journal, Vol. 26, No. 103, pp. 333-348. (In French)

LEVÊQUE C., DEJOUX C. (1983). Limnology of the Bandama River, Côte d'Ivoire. Hydrobiology Journal, O.R.S.T.O.M., 100, pp.113-141. (In French)

MONNET C. (1972). Contribution to the study of the dynamics and nature of suspensions of an intertropical river, Bandama, Côte d'Ivoire. Evolution of chemical elements in the waters of its estuary. Doctoral thesis of Geological Sciences, University of Nice, France, 427 p. (In French)

OFEV (2013). Hydrographic network: order of rivers for the digital hydrographic network at 1/25 000 of Switzerland. Federal Office for the Environment.

https://www.bafu.admin.ch/bafu/fr/home/themes/eaux/etat/cartes/geodonnees/reseau hydrographique--ordre-des-cours-deau-pour-le-reseau-hydro.html. Consulted on 27 November 2022.

ORSTOM (1989). Rainfall in Côte d'Ivoire. French Institute for Scientific Research for Development in Cooperation. Hydrology Laboratory, Ministry of Cooperation and Development, French Republic, 345 p. (In French)

PERRAUD A. (1971). Soils. In J. M. Avenard, M. Eldin and al. (Eds.). The natural environment of Côte d'Ivoire. Submission ORSTOM, No 50, pp. 269-390. (In French)

PLANTIER M. (2003). Consideration of physical characteristics of the watershed for comparison of global and semidistributed approaches in rain-flow modeling. Thesis of Engineer of ENGEES and DEA Méchanics and Engineering (Water Science option), National School of Water Engineering and Environment of Strasbourg, France, 93 p. (In French)

RIAD S. (2003). Typology and hydrological analysis of surface water from some representative watersheds of Morocco. Doctoral thesis, Lille University of Science and Technology & Ibnou Zohr University of Agadir, 154 p. (In French)

ROUISSAT B., SMAIL N. (2022). Contribution of water resource systems analysis for the dynamics of territorial rebalancing, case of Tafna system, Algeria, Larhyss Journal, No 50, pp. 69-94.

SERVAT E., KOUAMÉ B., DEZETTER A., PATUREL J.E. (1997). Rain-flow modelling and regionalization: the ERREAU programme in Côte d'Ivoire. CEMAGREF Edition, FRIEND, third report 1994-1997, 431 p. (In French)

SHREVE R.L. (1966). Statistical law of stream number. Journal of Geology, Vol.74, No 1, pp. 17-37.

STRAHLER A.N. (1952). Statistical analysis in geomorphic research. Journal of Geology, Vol. 62, No 1, pp. 1-25.

STRAHLER A.N. (1957). Quantitative analysis of watershed geomorphology. Transactions of the American Geophysical Union, Vol.38, No 6, pp. 913-920.