

Granulometric and Environmental Characteristics of Surface Sediment Deposits in the Ouaka River (Central African Republic)

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How to cite this paper: Ouambeti-Wickon, A. J., Ngueutchoua, G., Takenne, D. G., Wouatong, A. S. L., & Danguene, P. E. (2025). Granulometric and Environmental Characteristics of Surface Sediment Deposits in the Ouaka River (Central African Republic). *Journal of Geoscience and Environment Protection*, 13, 383-410.
<https://doi.org/10.4236/gep.2025.1312020>

Received: September 19, 2025

Accepted: December 19, 2025

Published: December 22, 2025

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Abstract

The sediments of the Ouaka River were analyzed on the basis of samples taken from the banks during the dry season. These sediments consist of gravel, sand and silt-clay. These sediments are being studied in a context where the sand from the Ouaka River is going to be used for major construction work on road infrastructure and administrative buildings. In this context, the granulometric analysis of these sediments revealed the dominance of medium sands, silt-clays and, secondarily, coarse sands. The grading curves for these sediments show a sigmoidal “S” shape, indicating that they were deposited in a river and in a depositional environment with relatively high hydrodynamic energy. These sediments, transported and deposited by various hydrodynamic energies, are linked to the massive arrival of materials from secondary watercourses tributary to the Ouaka River. Most of the gravel moves by rolling. Most sand moves by saltation. Silt-clays move essentially by suspension. The Passega diagram describes transport of these gravels by rolling over the bottom. The combined Friedman, Moiola and Weiser diagrams show sediments of fluvial origin and those influenced by sand dunes from the Chad Basin. Analysis of the linear discriminant functions reveals a turbulent fluvial environment with shallow marine beach inputs in turbulent waters. This marine influence is linked to the presence of limestone in the catchment, which is generally formed in a marine palaeoenvironmental context. As part of this study, the distribution of heavy minerals was highlighted in order to determine the origin of sediments from the Ouaka River. These sediments contain mainly tourmaline, rutile, sillimanites, opaque minerals and other heavy minerals. The majority of the sediments are mineralogically immature to sub-mature since the Zircon-Tourmaline-Rutile maturity index is less than 75%.

Keywords

Particle Size Analysis, River Deposition, Hydrodynamic Energy, Saltation Transport, Linear Discriminant Functions

1. Introduction

Grain size is a unique descriptive property and is used as an important textural character in sediment classification (Khaing et al., 2022). Grain size frequency distribution and textural factors can reflect the transport mode and sedimentation history of an area. Several researchers have attempted to infer the depositional environment and hydrodynamics from grain size data (Solohub & Klovan, 1970; Tiara & Scholle, 1979; Sly et al., 1983; Ayodele & Madukwe, 2019; Blott & Kenneth, 2000; Khaing et al., 2022; Fotie Lele et al., 2024). The transport and distribution of particles depend on several factors, including the size of the material, hydrodynamic processes (during transport and deposition) and diagenetic processes that can affect the size of certain categories of particles (Folk, 1980; Lewis & Mc Conchie, 1994; Cojan & Renard, 1995). The work of Zhou et al. (2009) and Li et al. (2017) analyzed and compared the sediment grain sizes of several column samples from the mouths of the Changjiang and Yalujiang rivers respectively, showing that variations in sediment grain size parameters are directly related to sediment dynamics, and that larger changes in grain size parameters (sorting coefficient, skewness and kurtosis) reflect more turbulent sediment environments, while smaller changes reflect more stable sediment environments. Deng et al. (2016) investigated the relationship between sediment grain size characteristics and hydrodynamics in the Changjiang River estuary since the last glacial period, showing that sedimentary environments with strong hydrodynamic conditions and large disturbances tend to have coarser sediment grain sizes, greater variability in sorting, an unstable degree of concentration of particulate components and sharp peak shapes. The hydrodynamic conditions and transport mechanism of sediments also provide clues to their provenance (Edwards, 2001; Boggs, 2009; Madukwe, 2016). The origin of sediments can be appreciated by the diversity of heavy minerals derived from rocks after their erosion, in their various sedimentary processes. These heavy minerals thus act as markers that provide information on the origin of the rocks and the conditions of sediment transport.

Little is known about sedimentation in the Ouaka River. Only the work of the Regional Public Works Department (2023), concerning the projection of infrastructures to be built, such as roads and administrative buildings, has shown that the sand of the Ouaka River in the town of Bambari is dominated by very fine grains. This work, carried out in the town of Bambari, is part of the granulometric facies distribution. The lack of knowledge about the sedimentary processes in the Ouaka River watershed leaves a hypothesis to be demonstrated in order to reconstruct the origin of the sediments and their depositional environment. It is for this

reason that this study is based on sediment characterization using granulometry. The objectives of this study are 1) to highlight the hydrodynamic behaviour of sediment grains, taking into account their distribution, size, nature and origin; 2) to understand how these sediments are transported in order to identify their depositional environment.

The results of this study will demonstrate that the specific grain size of sediments, combined with their degree of textural immaturity, directly influences their suitability for efficient use as construction aggregates. They will also improve our knowledge of the sedimentology of the Ouaka River. At international level, these results will help to highlight an intrinsic link between sediment characterization by granulometry and the sediment deposition environment.

2. Materials and Methods

2.1. Presentation of the Study Zone

The Ouaka River watershed is located in the central-east of the Central African Republic (CAR) and crosses the sub-prefectures of Bakala, Bambari and Kouango. The watershed covers an area of 29,730 km². The Ouaka River, 611 km long, is one of the tributaries of the Oubangui River which separates the Central African Republic (CAR) from the Democratic Republic of Congo. The hydrographic network of this basin is of the dendritic to subparallel type, and the geomorphology is marked by a plain whose altitude varies between 368 m and 805 m. The area is dominated by a Sudano-Aubangian climate, with alternating dry seasons (December to February) and rainy seasons (March to November). Average annual rainfall is 1372 mm and the average annual temperature is 26.8°C.

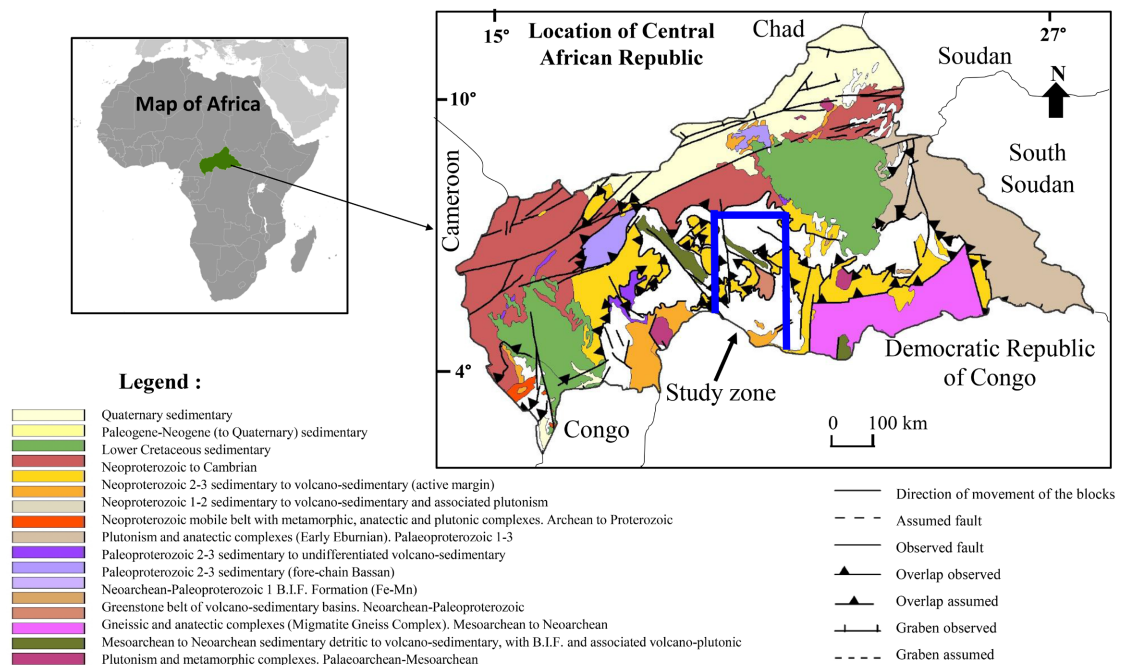


Figure 1. Geological map of the CAR showing the study zone (Directorate General of Mines, 2017).

Geologically, the Ouaka River basin is bounded to the north by the Pan-African orogenic chain, and to the south by the northern edge of the Congo Craton. The rocks represented in the study area correspond to Archean and Palaeo-Proterozoic assemblages (Directorate General of Mines, 2017; Figure 1). According to Boulvert (1996), the special feature of the Archean is the presence of a wide band of heterogeneous granite (3.6 to 2.8 Ga), 25 to 50 km long, which crosses the Bakala region in a NW-SE direction. This heterogeneous granite is made up of monzonites, tonalites and granodiorites. A large buttonhole of migmatites appears in the Bakala region. The Lower Proterozoic is represented by the essentially quartzite series, clearly metamorphosed but not migmatized, which covers a large area of the Ouaka river basin (Poidevin, 1985, 1991). These rock formations are eroded and are found in the riverbed.

2.2. Sampling, Treatment and Analysis of Sediments

Superficial sediment sampling campaigns were carried out during the dry season in the Ouaka River catchment area. All samples were taken from accessible banks, at a depth of 25 cm to 40 cm. The Global Positioning System (GPS) was used to pinpoint the precise geographical locations of the sampling points (Table 1). A total of 34 sediment samples were taken in the Ouaka River watershed, including 17 upstream of the town of Bambari (B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11, B12, B13, B14, B15, BRS1 and BRS2) and 17 downstream (K1, K2, K3, K4, K5, K6, K7, K8, K9, K10, K11, K12, K13, K14, K15, KRS1 and KRS2), were kept in coded plastic bags for laboratory analysis.

At the MIPROMALO laboratory in Yaoundé, Cameroon, the particle size analysis of the sand samples was used to determine the particle size distribution using conventional techniques (Vatan, 1967; Rivière, 1977; Chamley, 1988; N'Guessan et al., 2011). After washing each sample, the sandy fractions were separated and treated with hydrochloric acid and hydrogen peroxide to remove carbonates and organic matter, then dried in an oven at 60°C. After drying, each sand sample is sieved on a column of fifteen vibrating sieves from the AFNOR series, with mesh sizes ranging from 0.063 mm to 4 mm.

The reject from each sieve was weighed and, using the formulae of Krumbein & Pettijohn (1938) and Folk & Ward (1957) based on the unit Φ ($\Phi = -3.3219 \log(Q)$ with "Q" denoting grain diameter in mm), five particle size distribution parameters were calculated (Cailleux & Tricart, 1959; Vatan, 1967; Rivière, 1977; Ayodele & Madukwe, 2019; Sinha & Rais, 2019). These are the median (Md), mean (Mz), standard deviation or sorting (So), skewness (Sk) and kurtosis (Kg).

Table 1. Sampling sites in the Ouaka River watershed.

Sector	Location	Sample	Latitude (N)	Longitude (E)	Altitude (m)
Upstream	Gono	B15	6°91'5.41"	20°98'24.99"	687
		B14	6°88'57.30"	20°81'31.70"	662

Continued

	B13	6°82'2.31"	20°78'50.95"	604	
	B12	6°79'10.62"	20°78'14.15"	571	
	B11	6°67'52.98"	20°71'2.41"	540	
Takobanda	B10	6°60'4.95"	20°58'47.80"	528	
	B9	6°48'24.59"	20°51'4.59"	511	
	B8	6°33'26.68"	20°30'52.40"	503	
	B7	6°24'26.94"	20°27'39.59"	490	
Bakala	B6	6°19'13.10"	20°24'31.72"	468	
	B5	6°12'4.32"	20°22'47.03"	457	
	B4	6°7'12.03"	20°24'19.27"	453	
	BRS2	6°22'32.5"	20°21'39.13"	470	
Yamalé	B3	6°3'15.72"	20°26'41.41"	450	
	B2	6°5'57.09"	20°39'42.75"	446	
Togo	B1	5°97'51.29"	20°61'30.78"	440	
Bambari	BRS1	5°94'33.22"	20°92'10.24"	441	
	K15	5°98'6.32"	20°80'49.38"	435	
	K14	5°65'46.14"	20°69'37.69"	427	
	K13	5°22'55.20"	20°68'38.36"	422	
Liwa	K12	5°59'41.45"	20°60'54.54"	417	
	K11	5°51'20.18"	20°60'20.59"	411	
Boundi	K10	5°23'54.18"	20°39'9.40"	409	
	K9	5°18'9.62"	20°38'58.28"	402	
	K8	5°13'55.47"	20°36'6.30"	400	
	KRS2	5°20'12.1"	20°42'55.37"	419	
Downstream	K7	5°9'12.98"	20°28'37.17"	391	
	Ndoro	K6	5°9'4.36"	20°23'58.71"	386
		K5	5°12'37.59"	20°19'34.22"	382
	Ngadza	K4	5°13'10.21"	20°11'3.76"	379
K3		5°7'51.40"	20°2'0.88"	375	
Sioua	K2	5°6'29.55"	19°58'48.06"	372	
	KRS1	5°11'05.65"	20°07'07.14"	402	
Kouango	K1	4°59'39.27"	19°55'53.20"	369	

2.3. Granulometric Parameters

2.3.1. Mean

The mean or average grain defines the average size of sand grains. It reflects the average power of palaeoflows (Folk, 1968; Mercier, 2013; Duquesne & Carozza, 2023). It is defined by the relationship:

$$Mz = \frac{(Q16 + Q50 + Q84)}{3} \quad (1)$$

Depending on the different values of the mean, the following facies can be distinguished:

- Very coarse sands: $2000 \mu\text{m} > Mz > 1000 \mu\text{m}$ ou $-1 \Phi < Mz < 0 \Phi$;
- Coarse sands: $1000 \mu\text{m} > Mz > 500 \mu\text{m}$ ou $0 \Phi < Mz < 1 \Phi$;
- Medium sands: $500 \mu\text{m} > Mz > 250 \mu\text{m}$ ou $1 \Phi < Mz < 2 \Phi$;
- Fine sands: $250 \mu\text{m} > Mz > 125 \mu\text{m}$ ou $2 \Phi < Mz < 3 \Phi$;
- Very fine sands: $125 \mu\text{m} > Mz > 63 \mu\text{m}$ ou $3 \Phi < Mz < 4 \Phi$;
- Silts and clays: $Mz < 63 \mu\text{m}$ ou $Mz > 4 \Phi$.

2.3.2. Median

The median (Md) or the average is linked to the size of the grains as a function of the energy of deposition of the medium. It expresses 50% coarse elements and 50% fine elements. It defines the central tendency of the granulometric distribution. Its formula is:

$$Md = \Phi 50. \quad (2)$$

2.3.3. Sorting (So) or Classification Index

Sorting is a mathematical measure used to classify and assess sorting actions during transport and deposition. Sorting values reflect fluctuations in kinetic energy and therefore in the speed of the deposition agent (Sahu, 1964; Sow et al., 2020; Fotie Lele et al., 2024). It is defined by the following formula:

$$So = \frac{(Q84\Phi + Q16\Phi)}{4} + \frac{(Q95\Phi + Q5\Phi)}{6,6} \quad (3)$$

Standard deviation values provide information on sand classification and highlight 6 sediment classes (Folk & Ward, 1957; Fotie Lele et al., 2024):

- Very well classified sand: $So < 0.35$;
- Well classified sand: $0.35 < So < 0.50$;
- Fairly well classified sand: $0.50 < So < 0.71$;
- Medium-grade sand: $0.71 < So < 1$;
- Poorly classified sand: $1 < So < 2$;
- Very poorly classified sand: $2 < So < 4$.

2.3.4. Asymmetry or Skewness (Sk)

Skewness is the analysis of the particle size distribution of sediments at the point where they were deposited, according to whether they are fine or coarse (generally represented mathematically by positive or negative skewness). Its formula is:

$$Sk = \frac{(\Phi 16 + \Phi 84 - 2\Phi 50)}{2(\Phi 84 - \Phi 16)} + \frac{(\Phi 5 + \Phi 95 - 2\Phi 50)}{2(\Phi 95 - \Phi 5)} \quad (4)$$

Depending on the difference in slope, different types of curves can be distinguished:

- Very asymmetrical curves towards coarse gravel: $-1.00 < Sk < -0.30$;

- Asymmetrical curves towards coarse gravel: $-0.30 < Sk < -0.10$;
- Almost symmetrical curves: $-0.10 < Sk < 0.10$;
- Asymmetrical curves towards fines: $0.10 < Sk < 0.30$;
- Very asymmetrical curves towards the ends: $0.30 < Sk < 1.00$.

2.3.5. Acuity Index or Kurtosis (K_g)

Kurtosis expresses the ratio between the extent of the central part and the extent of the extremities of the granulometric distribution on the frequency curve. It therefore measures the angularity of the frequency curve. It is defined by the following formula:

$$K_g = \frac{(Q_{95}\Phi - Q_{5}\Phi)}{2,44(Q_{75}\Phi - Q_{25}\Phi)} \quad (5)$$

Multi-modal frequency curves are not suitable for calculating the acuity index (Chennaoui, 2004). This index will therefore only be calculated for unimodal frequency curves. Kurtosis values can be used to classify 6 types of frequency curve (Folk & Ward, 1957; Fotie Lele et al., 2024):

- Very platykurtic curve: $K_g < 0.67$;
- Platykurtic curve: $0.67 < K_g < 0.90$;
- Mesokurtic curve: $0.90 < K_g < 1.11$;
- Leptokurtic curve: $1.11 < K_g < 1.50$;
- Very leptokurtic curve: $1.50 < K_g < 3$;
- Extremely leptokurtic curve: $K_g > 3$.

2.4. Modes of Transport

The test of Visher (1969) used by Tossou et al. (2019) is used to determine the transport mode of fluvial sediments. Three modes of transport (suspension, saltation and rolling) are highlighted by placing the grain size on the x-axis and the cumulative percentages on the y-axis.

2.5. Passega Diagram

The most complete mode of transport is that of a tractive current represented by the C-M diagram (C = percentile and M = median) of Passega (1957, 1964), Houbrechts et al. (2013) and Tossou et al. (2019). This diagram can be used to interpret sediment grain size variations in terms of transport dynamics. It can also be used to identify the types of currents that transport material. The five segments of this diagram each correspond to a particular mode of transport: NO (bottom rolling deposits), OP (bottom rolling and graded suspension deposits), PQ (graded suspension and bottom rolling deposits), QR (graded suspension deposits) and RS (homogeneous or uniform suspension deposits).

2.6. Depositional Environment

The Moiola & Weiser (1968), N'guessan et al. (2011) and Sow et al. (2020) Md-So diagram is used to relate the granulometry of sediments to the environment in

which they were deposited. This method makes it possible to deduce the origin of the sands (rivers, beaches, continental dunes, coastal dunes) from the location of the point clouds obtained. Friedman (1967) and Tossou et al. (2019) Sk-So diagram can also be used to characterize sediments from a palaeo-environmental point of view.

2.7. Linear Discriminant Functions

The interpretation of variations in energy and fluidity factors, based on the statistical method for studying sediments, appears to have an excellent correlation with the various processes and the deposition environment (Sahu, 1964; Ayodele & Madukwe, 2019; Sinha & Rais, 2019). It is in this context that the analysis of the linear discriminant function of sediments was established with the aim of characterizing the depositional environment on the basis of the following equations (where Mz is the granulometric mean, So is the graphical standard deviation included sorting, Sk is the asymmetry and Kg is the graphical kurtosis):

- Discrimination between wind and beach environments (Y1)

$$Y1 = -3.5688 Mz + 3.7016 So^2 - 2.0766 Sk + 3.1135 Kg \quad (6)$$

If Y1 is less than -2.7411, it is a wind deposit and if it is greater than -2.7411, it is a beach.

- Discrimination between beach and shallow agitated marine environment (Y2)

$$Y2 = 15.6534 Mz + 65.7091 So^2 + 18.1071 Sk + 18.5043 Kg \quad (7)$$

If Y2 is less than 65.3650, it is a beach deposit and if it is greater than 65.3650, it is a shallow agitated marine environment.

- Discrimination between shallow, agitated marine environments and river environments (Y3)

$$Y3 = 0.2852 Mz - 8.7604 So^2 - 4.8932 Sk + 0.0482 Kg \quad (8)$$

If Y3 is less than -7.419, the environment is fluvial, and if it is greater than -7.419, the environment is shallow marine.

- Discrimination between rivers and turbidity (Y4)

$$Y4 = 0.7215 Mz + 0.403 So^2 + 6.7322 Sk + 5.2927 Kg \quad (9)$$

If Y4 is less than 10.000, the environment is fluvial and if it is greater than 10.000, the environment is turbid.

2.8. Heavy Minerals Analysis

Twenty out of thirty-four sediment samples collected in the field were washed under tap water (i.e. 200g on each sample) on a 50 μ m sieve to eliminate particles smaller than this mesh diameter.

After washing, the samples were oven-dried at 105°C for 24 hours. After drying, the dry sediment obtained was divided into four parts in order to obtain a sample that was well representative of the sediment as a whole.

Bromoform (CHBr₃) with a density of 2.89 is the dense liquor used for mineral separation. The separating funnel is filled about 3/4 full with bromoform. The sand is poured into the funnel, and with the tap closed, a glass stirrer is used to impart a rotary movement to the liquor, in order to make the heavy minerals fall to the bottom of the funnel. The liquor is rotated several times until separation is complete. After a few minutes' rest, the tap is opened and the heavy minerals are collected in the funnel fitted with the filter paper. As soon as the heavy minerals have been recovered, the tap is closed. The filter paper lets through the bromoform, which is collected in the Erlenmeyer flask. On a hot plate, the slides are baked and soaked in Canada balsam. Once the balsam has turned yellow, more heavy minerals are added to the slide until the desired concentrate is obtained. The slide thus obtained is immersed in an alcoholic solution to remove the balsam. Ideally, 100 to 200 transparent grains per slide are ready to be observed and counted under a polarising microscope.

The "ZTR" index, which is the combined percentage of zircon, tourmaline and rutile among non-opaque heavy minerals, was calculated using the formula of Hubert (1962):

$$ZTR = \frac{(Z + T + R) \times 100}{\text{Non - Opaque}} \quad (10)$$

ZTR index < 75% implies immature to sub-mature sediments and ZTR > 75% indicates mineralogically mature sediments (Hubert, 1962; Tossou et al., 2019).

3. Results

3.1. Granulometric Facies of the Ouaka River bed

The proportions of the different granulometric facies of the Ouaka River sediments are shown in **Table 2**. Analysis of this **Table 2** revealed that sediments in the upstream zone are dominated by medium sand particles with an average concentration of 41.2% ± 14.44, followed by fine sand (average concentration of 21.65% ± 10.79), silt-clay (average concentration of 21.45% ± 10.5), coarse sand (average concentration of 11.05% ± 9.01) and gravel (average concentration of 4.66 ± 4.24). In the downstream zone, on the other hand, the average concentration of coarse sand (33.43% ± 12.8) is dominant, followed by silt-clay (30.92% ± 6.79), medium sand (24.87% ± 7.9), fine sand (6.41% ± 1.07) and gravel (4.37% ± 1.98). Generally speaking, we note a spatial evolution of deposition from medium sand particles upstream to fine sand particles downstream, with the presence of a high concentration of coarse sand downstream. This spatial distribution of granulometric facies is a function of the hydrodynamics that drain the sand particles, whose diameters decrease regularly from upstream to downstream. However, the presence of a few coarse materials in the downstream zone is linked to inputs from secondary watercourses, which may be responsible for the sedimentation of these materials in this zone.

The cumulative semi-logarithmic curves for sediments in the Ouaka River have

a generally sigmoidal shape (**Figure 2(a)**, **Figure 2(b)**). Overall, these curves show a predominance of the fraction between 0.02 and 2 mm (sand and silt-clay). To a first approximation, and based on the observation of these granulometric curves, the sand is predominantly made up of medium grains in both the upstream and downstream zones. This granulometric facies indicates that deposition occurred as a result of moderate to strong variation in the transport current (Tricart, 1965; Tossou et al., 2019, Fotie Lele et al., 2024). In the same vein, Rivière (1977) states that hyperbolic or sigmoid curves indicate a progressive reduction in the strength of the transport agent from upstream to downstream. Such facies are most often found in sediments deposited by surface currents or bodies of water. Sedimentation occurred by free accumulation. These analyses reinforce the impact of hydrodynamics, highlighted by the variation in the proportions of the different granulometric facies in the Ouaka River sediments.

Table 2. Distribution of granulometric facies (%) in Ouaka River sediments.

Sector	Sample	Gravel (4 à 2 mm)	Coarse sand (2 à 0.5 mm)	Medium sand (0.5 à 0.25 mm)	Fine sand (0.25 à 0.063 mm)	Silt-clay (0.063 à 0.02 mm)
Upstream	B15	7.88	21.05	28.03	12.83	30.21
	B14	9.05	20.05	27	12.99	30.91
	B13	10.71	19.10	24.14	13.05	33
	B12	9.10	17.17	29.01	15.19	29.53
	B11	9.97	17.91	27.81	13.24	31.07
	B10	7.68	25.01	26.42	10.72	30.17
	B9	8.95	18.08	29.43	13.02	30.52
	B8	0.16	0.73	51.51	42.07	5.53
	B7	0.12	0.97	56.29	35.52	7.1
	B6	0.14	0.65	51.16	41.98	6.07
	B5	0.12	0.82	53.31	39.4	6.35
	BRS2	0.12	5.90	45.69	20.36	27.93
	B4	0.93	1.66	61.98	22.16	13.27
	B3	0.43	2.19	63.93	15.96	17.49
	B2	0.22	1	62.29	26.46	10.03
	B1	7.51	17.33	30.59	16.52	28.05
	BRS1	6.10	18.27	31.76	16.52	27.35
	Av	4.66	11.05	41.20	21.65	21.45
Sd	4.24	9.01	14.44	10.79	10.50	
Downstream	K15	0.09	0.99	49.41	44.11	5.40
	K14	8	22.12	26.88	13.56	29.44
	K13	7.68	16.05	31.65	15.89	28.73
	K12	7.25	23.33	26.35	12.86	30.21
	K11	6.58	16.86	32.93	15.07	28.56

Continued

KRS2	4.18	33.51	23.77	0.65	37.89
K10	4.18	40.38	21.71	0.65	33.08
K9	2.55	38.82	24.01	0.97	33.65
K8	3.08	41.41	21.36	0.26	33.89
K7	2.59	30.89	30.88	1.53	34.11
K6	4.31	44.94	17.96	0.28	32.51
K5	2.82	36.20	25.03	1.28	34.67
K4	4.5	46.27	16.95	0.33	31.95
KRS1	4.5	43.25	18.90	0.33	33.02
K3	4.06	46.43	16.66	0.21	32.64
K2	3.95	45.19	17.83	0.33	32.70
K1	3.91	41.7	20.57	0.70	33.12
Av	4.37	33.43	24.87	6.41	30.92
Sd	1.98	12.80	7.90	1.07	6.76

Av: Average; Sd: Standard deviation.

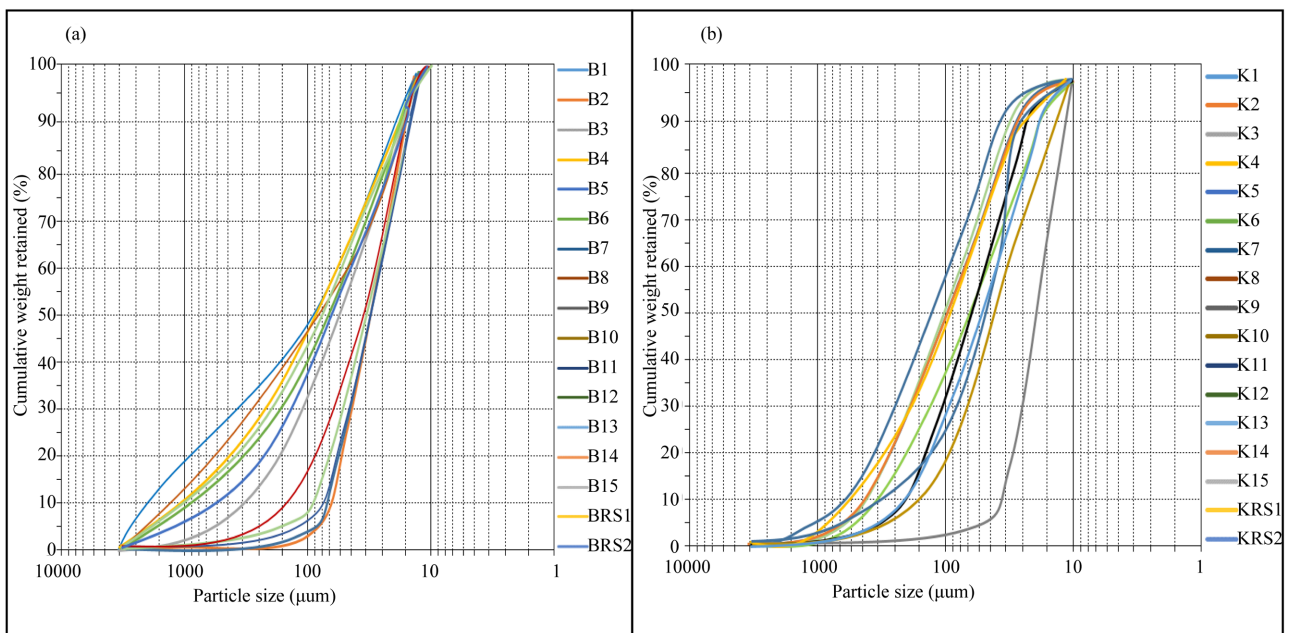


Figure 2. Cumulative granulometric curves of sediments from Ouaka River: (a) upstream sector; (b) downstream sector.

3.2. Granulometric Parameters of Sediments

3.2.1. Graphique Mean Size (M_z)

The mean graphical size of the river sediments varies from -0.19Φ to 1.99Φ , with an average of $0.83\Phi \pm 0.91$ in the upstream zone and from -0.03Φ to 1.97Φ , with an average of $0.28\Phi \pm 0.44$ in the upstream zone (Table 3). Analysis of Table 3 shows that medium to fine sands are dominant in the Ouaka River. Coarse to very coarse sands can be observed in certain sampling sites in the upstream zone, particularly in the localities of Gono and Takobanda. Medium sands dominate in the

localities of Bakala and Bambari, and also in the downstream zone. The presence of coarse particles in this river corroborates the theory of significant particle inputs from secondary watercourses, particularly tributaries.

3.2.2. Sorting (S_o) or Classification Index

The sorting values (S_o) for sediments in the Ouaka River, presented in **Table 3**, vary between 1.07Φ and 1.34Φ (mean $1.22\Phi \pm 0.08$) upstream and between 1.08Φ and 3.61Φ (mean $2.09\Phi \pm 0.66$) downstream. These results are typical of river environments and provide ample evidence that medium to very fine sands are very poorly classified and coarse to very coarse sands are poorly classified. The poorly classified sands were transported by a slightly irregular current, whereas the highly classified sands were transported by a fairly irregular current. This fairly irregular current comes from the tributary streams of the Ouaka River, which influences the classification of the sediments. This poor grading may be linked to the presence of numerous obstacles such as islands, which reduce hydrodynamics and concentrate particles of all sizes in different sectors of the Ouaka River.

3.2.3. Skewness (S_k)

The sediments of the Ouaka River have skewness index (S_k) values that vary between -2.1 and -0.08 , with an average of -0.36 ± 0.48 in the upstream zone and between -0.61 and -0.08 , with an average of -0.26 ± 0.15 in the downstream zone (**Table 3**). The exceptions are samples B2 = 0.29 and B7 = 0.02 in the upstream zone, where the curves are almost symmetrical and asymmetrical towards the ends, respectively. Generally speaking, the skewness values of the sands are mostly negative. This trend reflects a preponderance of asymmetrical curves towards coarse sand and very asymmetrical curves towards coarse sand. This indicates the influence of several sources of sedimentary input (tributary materials, runoff and gully water) with currents of varying intensity but generally strong in the Ouaka River.

3.2.4. Kurtosis (K_g)

The upstream zone of the Ouaka River records very varied values of the acuity index or kurtosis (K_g). Most of the values oscillate between 2.54 and 3.93, characteristic of very to extremely leptokurtic frequency curves. On the other hand, the K_g values of sediment samples B2, B5, B6 and B7 show platykurtic curves and those of B3, B8 and BRS2 show leptokurtic curves. In the downstream zone, very leptokurtic curves dominate (1.7 to 2.93). With the exception of samples K7 = 1.23 is leptokurtic and K15 = 1.09 is mesokurtic.

This variation in kurtosis values may be due to occasional variation in the flow characteristic of the depositional medium (Sinha & Rais, 2019). The values thus obtained provide information on the quality of the grading and also on the multiplicity of different sources of input (several granulometric stocks). Taken together, this suggests a highly contrasted hydrodynamic variation from various sources of supply. Such variation may also be due to seasonal changes in the hydrological regime of the watercourses (period of sediment collection in the dry

and rainy seasons in the Ouaka River), linked to rainfall variability (Tossou et al., 2019).

Table 3. Granulometric parameters of sediments in the Ouaka River.

Location	Sample	Md	Mz	So	Sk	Kg
Upstream	B1	1	0.10	1.34	-0.53	2.54
	B2	1.66	1.72	1.20	0.29	0.68
	B3	2.58	1.99	1.13	-2.10	1.43
	B4	1.60	1.67	1.15	-0.17	3.35
	B5	1.90	1.9	1.13	-0.09	0.77
	B6	1.90	1.9	1.11	-0.08	0.87
	B7	1.82	1.81	1.13	0.02	0.82
	B8	1.92	1.89	1.07	-0.19	1.48
	B9	0.60	-0.07	1.21	-0.40	3.93
	B10	0.30	-0.19	1.26	-0.28	3.35
	B11	0.50	-0.10	1.30	-0.35	2.87
	B12	0.70	0	1.28	-0.42	2.87
	B13	0.20	-0.17	1.24	-0.21	3.35
	B14	0.40	-0.15	1.28	-0.31	3.12
	B15	0.60	-0.03	1.30	-0.38	2.87
	BSR1	1.20	0.47	1.34	-0.57	2.56
	BSR2	1.60	1.30	1.26	-0.42	1.29
Av	1.20	0.83	1.22	-0.36	2.24	
Sd	0.70	0.91	0.08	0.48	1.07	
Downstream	K1	0.20	0.20	3	-0.13	1.79
	K2	0.10	0.10	2.83	-0.12	2.17
	K3	0.30	0.17	2.65	-0.31	2.46
	K4	0.10	0.07	2	-0.15	2.53
	K5	0.40	0.37	1.91	-0.21	1.95
	K6	0.10	0.10	2	-0.12	2.53
	K7	0.60	0.47	3.61	-0.32	1.23
	K8	0.20	0.23	1.50	-0.08	2.70
	K9	0.40	0.33	1.83	-0.17	1.70
	K10	0.20	0.20	2.12	-0.15	2.17
	K11	1.10	0.13	1.73	-0.57	1.71
	K12	0.60	-0.03	1.56	-0.36	2.05
	K13	1.20	0.17	1.50	-0.61	2.05
	K14	0.60	-0.03	1.30	-0.36	2.93
	K15	2	1.97	1.08	-0.23	1.09
KRS1	0.2	0.07	2.83	-0.27	2.11	
KRS2	0.4	0.3	2.12	-0.27	2.17	
Av	0.51	0.28	2.09	-0.26	2.08	
Sd	0.49	0.44	0.66	0.15	0.47	

Av: Average; Sd: Standard deviation.

3.3. Modes of Transport

Application of the test of **Visher (1969)** used by **Tossou et al. (2019)** to sediments from the Ouaka River produced the results shown in **Figure 3(a)** and **Figure 3(b)**. This test shows the relationship between sediment grain size and transport mode. Three populations of sand are found in the study zone:

- The population A includes sands transported by rolling;
- The population B includes sands transported by saltation;
- The population C is characterized by the transport of grains by suspension.

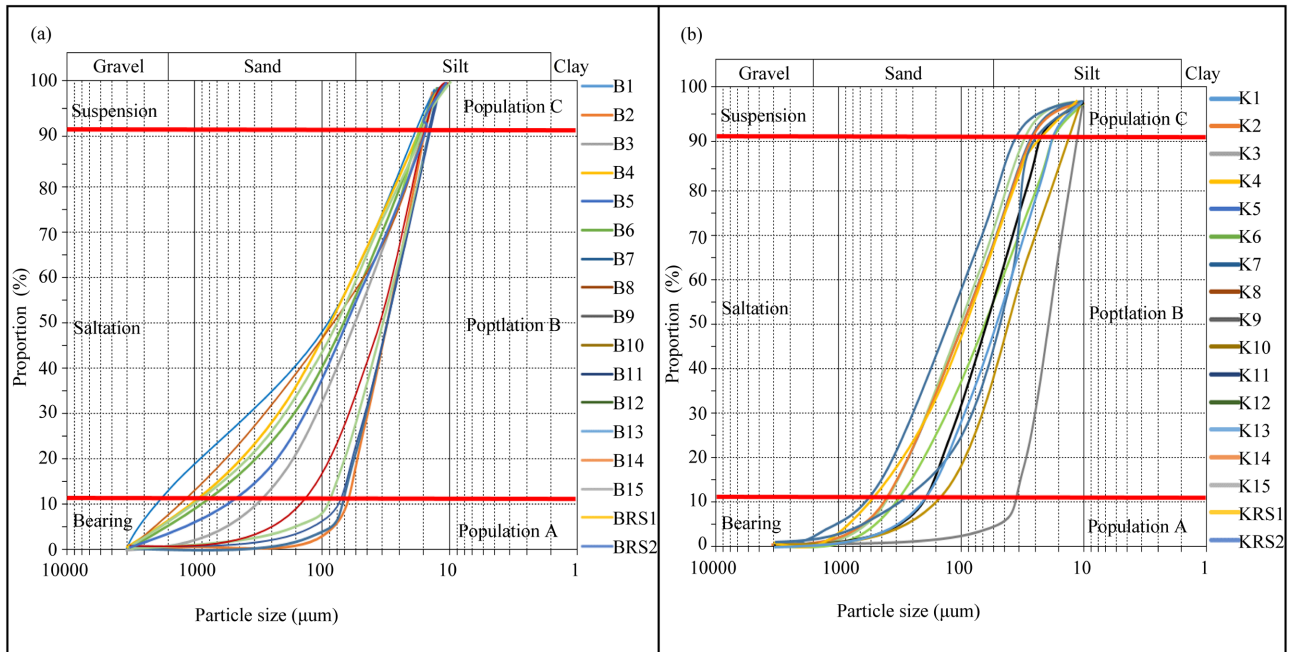


Figure 3. Semi-logarithmic grain size curves of sandy facies: (a) upstream sector; (b) downstream sector.

Table 4. Percentage of sediment by different modes of transport.

	Population A (0% - 10%)	Population B (10% - 90%)	Population C (90% - 100%)
Population size (upstream sector)	72	81	17
% by population (upstream sector)	42%	48%	10%
Population size (downstream sector)	52	84	34
% by population (downstream sector)	31%	49%	20%

Analysis of **Table 4** shows that the population B is the largest in the Ouaka River watershed, at 48% in the upstream sector and 49% in the downstream sector. This demonstrates the hegemony of saltation transport of sands and silts. Transport by rolling only concerns the coarse fractions, as shown by population A. Population A is not very dominant in the upstream and downstream sectors, with concentrations of 42% and 31% respectively. Transport by suspension (population C) only concerns fine fractions (silt). Their concentrations vary between 10% upstream

and 20% downstream.

Table 5 has been drawn up to corroborate the relationship between the different types of sediment transport and the different particle size classes.

In the upstream sector, gravel was mainly transported by rolling (76%), followed by coarse sand (47%), medium sand (47%), fine sand (41%) and silt-clay (14%). Saltation transport carried coarse sand (53%), medium sand (53%), fine sand (59%) and silt-clay (51%). Finally, silt-clay (35%) was only transported by suspension. On the other hand, in the downstream sector, the mode of transport of gravel (88%) and coarse sand (56%) is dominated by rolling. Transport by saltation mainly ordered the transport of medium sands (94%) and fine sands (94%). As in the upstream sector, silt-clay (65%) is mainly controlled by suspension transport.

Table 5. Specification of the type of transport according to particle size classes.

Sector	Population (%)	Gravel (4 to 2 mm)	Coarse sand (2 to 0.5 mm)	Medium sand (0.5 to 0.25 mm)	Fine sand (0.25 à 0.063 mm)	Silt-clay (0.063 to 0.02 mm)
Upstream	Population A	76%	47%	47%	41%	14%
	Population B	24%	53%	53%	59%	51%
	Population C	0%	0%	0%	0%	35%
Downstream	Population A	88%	56%	6%	6%	4%
	Population B	12%	44%	94%	94%	31%
	Population C	0%	0%	0%	0%	65%

3.4. Diagram of Passega

Passega’s C-M diagram (1964), reproduced by Houbrechts et al. (2013) and Tossou et al. (2019), is used to link the nature of sediment types to the energy of the transport medium.

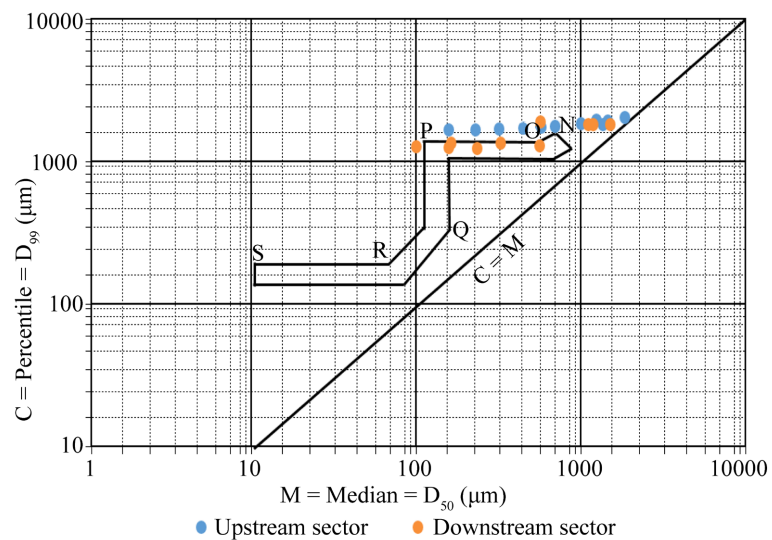


Figure 4. Diagram C-M for sediments from the Ouaka River.

The results (Figure 4) of this relationship show that the dispersion of the samples analyzed from the Ouaka River marries the portions of bottom rolling deposits (NO) and bottom rolling deposits and graded suspensions (OP). Examination of these data shows that the sediments in this river are characterized by bottom roll generated by bottom turbulence, linked to hydrodynamics, corresponding to the movement of coarse elements such as gravel. The mode of transport by suspension corresponds to settling conditions in which the speed of the bottom is zero or too low to produce any sort of classification. These settling conditions are characteristic of silty-clay fractions.

3.5. Environment of Sediment Deposition

So vs Md and So vs Sk diagrams, characteristic of the evolution of granulometric parameters, are used to determine the depositional environment of Ouaka River sediments. They are also used to characterize sediments from a paleoenvironmental perspective.

The So vs Md diagrams for the upstream sector (Figure 5(a)) and the downstream sector (Figure 5(b)) show the dispersion of sediments in the river domain. This means that 100% of the sediment grains originate from the Ouaka River watershed.

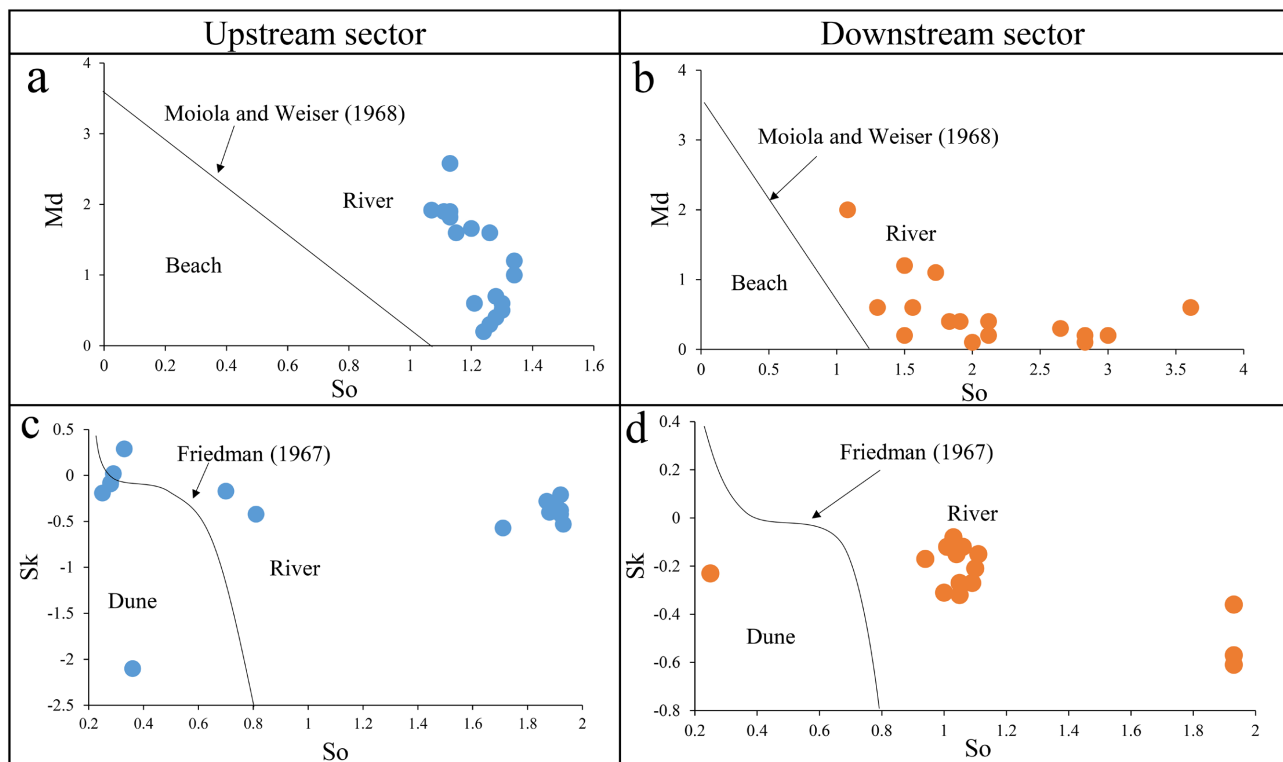


Figure 5. Diagrams So vs Md and So vs Sk: (a) and (c) upstream sector; (b) and (d) downstream sector.

Sediment dispersion in the So vs Sk diagrams, shows the importance of a river-like environment in the upstream (Figure 5(c)) and downstream (Figure 5(d))

sectors. Inputs from the dune domain have a negligible influence on sediment deposition in the Ouaka River.

3.6. Linear Discriminant Function

The different values of the linear discriminant functions of the Ouaka River sediments are shown in **Table 6**. Analysis of **Table 6** shows that the discrimination values between the wind and beach environments (Y1) range from 0.53 to 16.96, with an average of 10.27 in the upstream sector, and from 1.16 to 22.75, with an average of 22.19 in the downstream sector. These Y1 values are greater than -2.7411 , indicating a beach deposition environment for Ouaka River sediments.

The values of the discriminant function between beach and shallow agitated marine environment (Y2) for the sediments analyzed range from 103.4 to 171.9 (mean 145.7) in the upstream zone and from 99.61 to 199.9 (mean 175.5) in the downstream zone. They are higher than $Y2 = 65.3650$, suggesting a shallow, agitated marine environment. With the exception of sample K11 in the Liwa locality (north of the study area), the value is $58.37 < 65.3650$, indicating a beach deposit.

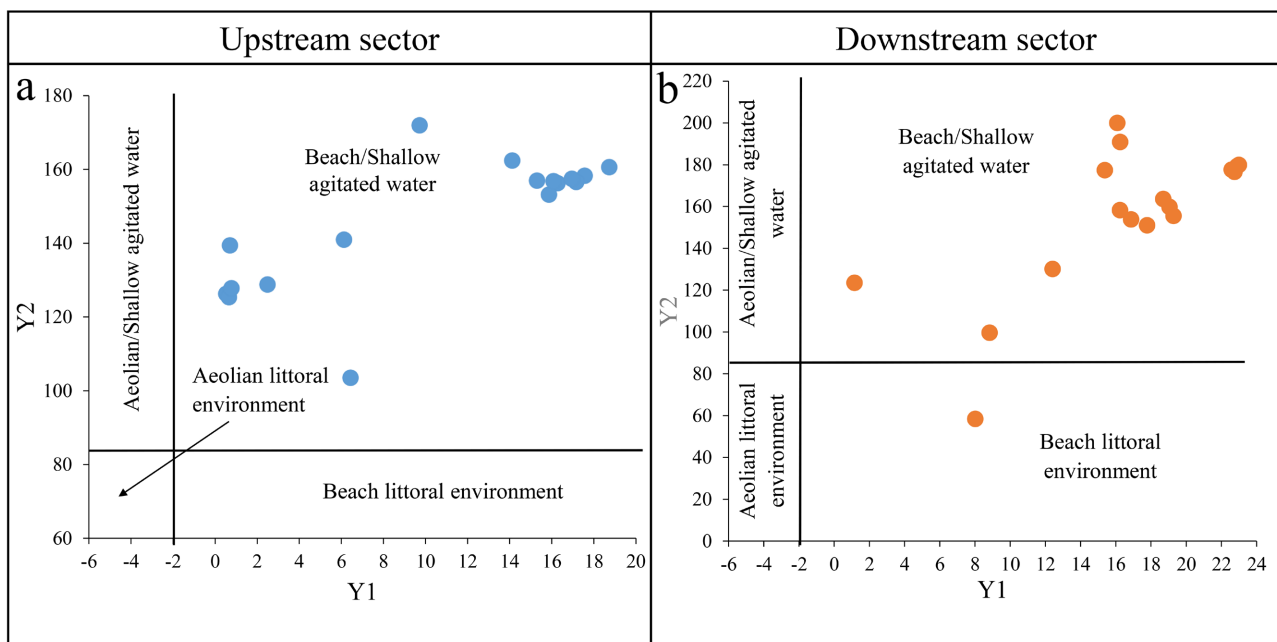


Figure 6. Environmental discrimination diagrams based on the linear discriminant function Y1 vs Y2: (a) upstream sector; (b) downstream sector.

Discrimination between shallow, agitated marine environments and river environments (Y3) is also calculated. The results of this calculation range from -12.99 to -8.49 (mean -10.93) in the upstream zone and from -38.48 to -7.98 (mean -36.81) in the downstream zone. These results are lower than $Y3 = -7.419$, indicating a dominant east-fluvial environment. All but two samples, B3 = -0.27 at Yamalé and K11 = -1.79 at Liwa, suggest the influence of a shallow marine deposit.

Finally, calculation of the discrimination function between fluvial and turbid environments (Y4) shows that in the upstream zone, 10 out of 17 samples exceed $Y4 = 10$ (i.e. 58.8%) and in the downstream zone, 12 out of 17 samples exceed $Y4 = 10$ (i.e. 70.5%). The results of this calculation indicate the dominance of a turbid depositional environment and a weak influence of a fluvial depositional environment.

The Y1-Y2 binary diagrams studied in the upstream and downstream sectors (**Figure 6(a)**, **Figure 6(b)**) clearly showed the dominance of an agitated marine beach deposition environment.

The Y2-Y3 binary diagrams (**Figure 7(a)**, **Figure 7(b)**), on the other hand, indicate an agitated fluvial environment, influenced by a shallow marine beach environment in agitated waters.

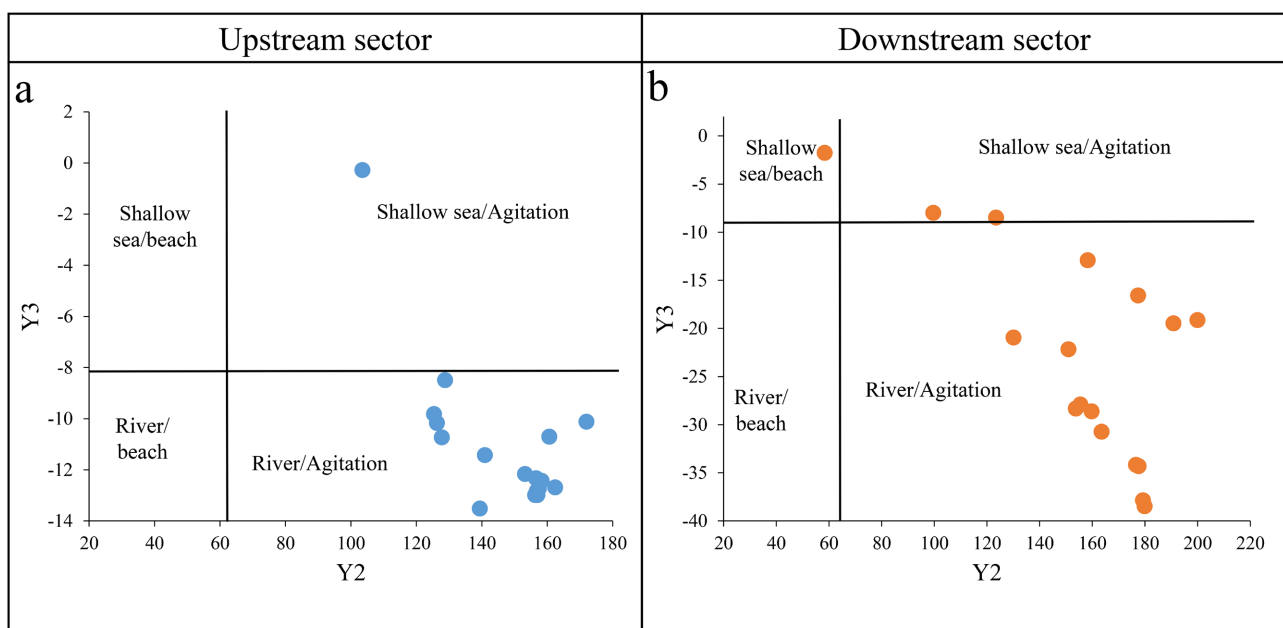


Figure 7. Environmental discrimination diagrams based on the Y2 vs Y3 linear discriminant function: (a) upstream sector; (b) downstream sector.

On the basis of the above, certain results demonstrate the influence of a marine and beach deposit in the middle of a continental environment. These results lead us to formulate two paleoenvironmental hypotheses regarding the presence of these sediments of marine origin:

- These sediments could be carried by runoff-induced hydro-sediment transport. Indeed, the geographical location of the Ouaka watershed makes it a corridor for the passage of hydro-sedimentary flows; These sediments may be derived from limestone residues formed in a marine environment. The presence of carbonate formations in the study area is confirmed by the work of Poidevin (1985, 1991) and Boulvert (1996). Geochemical analyses to demonstrate the presence of carbonate clasts in these sediments could be carried out at a later

date.

Table 6. Values of linear discriminant functions for sediments in the Ouaka River.

	Upstream sector												
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
Y1	15.30	0.71	6.44	9.72	0.53	0.65	0.78	2.50	18.74	17.57	16.28	15.87	17.16
Y2	156.9	139.3	103.4	171.9	126.2	125.3	127.7	128.7	160.5	158.2	156.2	153.1	156.5
Y3	-12.99	-13.51	-0.27	-10.12	-10.17	-9.82	-10.73	-8.49	-10.70	-12.43	-12.98	-12.16	-12.33
Y4	10.67	7.37	-4.62	18.32	5.35	5.93	6.30	8.38	18.65	16.35	13.44	13.02	16.81
	Upstream sector (Continued)						Downstream sector						
	B14	B15	BSR1	BSR2	Average		K1	K2	K3	K4	K5	K6	K7
Y1	16.96	16.09	14.12	6.13	10.27		8.83	19.04	17.77	22.75	18.69	22.58	12.41
Y2	157.4	156.8	162.3	140.9	145.7		99.61	159.7	150.9	176.6	163.5	177.6	130.1
Y3	-12.73	-12.82	-12.68	-11.42	-10.93		-7.98	-28.62	-22.17	-34.17	-30.73	-34.30	-20.95
Y4	14.98	13.29	10.77	5.58	10.63		9.15	12.10	12.15	14.04	10.64	14.27	5.74
	Downstream sector (Continued)												
	K8	K9	K10	K11	K12	K13	K14	K15	KRS1	KRS2	Average		
Y1	16.08	16.86	22.99	8.02	16.25	15.37	16.23	1.16	19.28	22.88	22.19		
Y2	199.9	153.7	179.8	58.37	190.8	177.4	158.2	123.4	155.5	179.2	175.5		
Y3	-19.12	-28.33	-38.48	-1.76	-19.47	-16.58	-12.91	-8.48	-27.89	-37.86	-36.81		
Y4	14.82	9.44	12.43	5.52	9.39	7.77	13.74	6.11	10.75	11.70	11.22		

3.7. Distribution of Heavy Minerals

In the sediments of the Ouaka River, the most abundant heavy minerals (**Table 7**) in the upstream part are opaque minerals (63% - 72%), tourmaline (9% - 13%), rutile (5% - 10%), sillimanite (3% - 8%), kyanite (1% - 5%) and garnet (1% - 5%). On the downstream side, after the opaque minerals (72% - 79%), we find tourmaline (6% - 12%), rutile (2% - 7%), sillimanite (2% - 5%), anatase (1% - 5%) and garnet (1% - 4%). Other heavy minerals such as zoisite, augite, epidote, hypersthene and diopside are weakly/rarely observed in some samples.

With regard to the ZTR index, all the samples analyzed from the Ouaka river catchment had a ZTR < 75%, indicating immature to sub-mature sediments.

Analysis of **Table 7** below shows that in the upstream zone, tourmaline, rutile and sillimanite are the main non-opaque heavy minerals, the most abundant in the samples. Anatase and kyanite are concentrated in the Gono, Takobanda and Bakala localities. Garnet showed a high frequency in samples B1 and B14. In the downstream zone, anatase is added to tourmaline, rutile and sillimanite to form the four main non-opaque heavy minerals. In addition, garnet tends to be more frequent in the southern samples of the study area, particularly in K3, K7, K10, K14 and K15.

Table 7. Distribution of heavy minerals in Ouaka River sediments.

Sector	Upstream									
	B1	B3	BRS2	B5	B7	B9	B11	B13	B14	B15
Sample	B1	B3	BRS2	B5	B7	B9	B11	B13	B14	B15
Zircon	1	-	1	1	-	-	1	-	1	-
Rutile	6	8	5	7	9	9	8	10	7	7
Tourmaline	11	9	9	9	12	10	9	13	12	11
Sillimanite	4	5	8	3	4	7	5	7	3	9
Chloritoïde	1	1	-	1	-	1	-	1	-	2
Garnet	5	1	1	1	1	-	2	-	5	3
Hypersthene	-	-	1	-	2	-	-	-	2	-
Anatase	2	-	3	4	1	3	1	3	-	-
kyanite	1	4	2	2	4	2	5	4	2	3
Staurotide	-	2	-	1	1	-	1	1	-	1
Epidote	-	1	-	1	-	-	1	1	-	-
Zoïsite	-	1	1	-	1	1	-	-	1	-
Augite	-	-	1	-	1	1	-	-	1	-
Diopside	-	-	1	1	-	1	-	1	1	1
Opaque minerals	69	68	67	69	68	65	67	59	72	63
Total	100	100	100	100	104	100	100	100	107	100
ZTR index	58.06	53.12	45.45	54.84	58.33	54.29	54.55	56.1	57.14	48.65
Sector	Downstream									
	K1	KRS1	K3	K4	K7	K8	K10	K11	K14	K15
Sample	K1	KRS1	K3	K4	K7	K8	K10	K11	K14	K15
Zircon	-	-	-	1	-	1	-	1	-	-
Rutile	5	2	4	7	5	5	6	4	7	6
Tourmaline	9	6	8	10	8	7	9	12	8	10
Sillimanite	4	3	2	4	3	4	3	5	5	2
Chloritoïde	-	-	-	2	-	-	1	-	-	2
Garnet	1	1	2		2	1	2	-	3	4
Hypersthene	-	-	-	1	-	-	-	1	-	1
Anatase	3	3	5	2	1	1	4	1	2	1
kyanite	-	-	2	1	1	1	1	-	1	1
Staurotide	-	1	1	-	1	-	-	2	-	1
Epidote	1	-	1	1	1	-	1	1	-	-
Zoïsite	-	1	-	2	1	1	-	-	1	-
Augite	1	-	1	1	-	-	-	1	-	1
Diopside	1	2	-	1	1	1	-	2	1	-
Opaque minerals	75	81	74	77	76	78	75	79	72	79
Total	100	100	100	109	100	100	102	108	100	100
ZTR index	56	42.1	46.15	56.25	54.17	59.09	55.56	58.62	53.57	57.14

4. Discussion

The hydrodynamic behaviour of the Ouaka River underlies the spatial distribution of different sediment grain sizes. In the river's upstream zone, medium-grained sand dominates, while in the downstream zone, silt-clay is influential. However, in the latter zone, coarse sand is also present. This granulometric repartition was observed in the work of [Rashedi & Siad \(2016\)](#) on beach sediments along the Abu Dhabi coast, where medium sand represents 47.4% and fine sand occupies 33.3%. This evolution towards fine grain size suggests a long distance covered by the sediments before their deposition. The presence of coarse sand in this beach along the Abu Dhabi coast, as in the case of the Ouaka River, is linked to an increase in hydrodynamic energy that drains coarse material downstream ([Folk, 1980](#); [Sow et al., 2020](#); [Fotie Lele et al., 2024](#)). This also depends on grain sizes in the parent rock, the extent of weathering and the transport distance. In the same vein, the work of [Krishna et al. \(2020\)](#) in the Vamanapuram River (southwest coast of India), has clearly demonstrated that each sand fraction shows a similar downstream trend. As the river enters the estuary, grain size varies from very coarse to very fine sand.

Concerning the granulometric parameters in [Table 3](#), the M_z values show a dominance of medium to fine sand in the Ouaka River. These values are roughly similar to those calculated (0.38Φ to 3.09Φ , with a mean of 1.01Φ) by [Ghaznavi et al. \(2019\)](#) in the Kachchh region of western India, which show samples belonging mainly to medium-grained sands. This demonstrates the influence of regular hydrodynamic energy. In contrast, the 6.99Φ value of [Krishna et al. \(2020\)](#), is represented by very fine sand to silt-clay in the Vamanapuram River. But in the estuary, this value varies from medium sand to very fine sand. This variation in grain size is linked to fluctuating hydrodynamic energy, runoff and gulying. The S_o calculated for the Ouaka River showed that medium to very fine sands are very poorly classified, and coarse to very coarse sands are poorly classified. This type of classification is identical to that of the Vamanapuram River estuary ([Krishna et al., 2020](#)). This suggests that river sediments are generally very poorly sorted or classified due to high variability in hydrodynamic energy ([Ayodele & Madukwe, 2019](#); [Sinha & Rais, 2019](#); [Sow et al., 2020](#); [Fotie Lele et al., 2024](#)). In contrast, the S_o in the Kachchh region ranges from 0.18Φ to 0.99Φ with an average of 0.46 . This is an indication of good sediment sorting, representing currents with slight velocity variability. Mean S_k values for Ouaka River sediments range from -0.36 ± 0.48 in the upstream zone to -0.26 ± 0.15 in the downstream zone, reflecting very coarse asymmetry. These mean values are on the same scale ($-1.00 < S_k < -0.30$) compared to that calculated (-0.86) by [Rashedi & Siad \(2016\)](#) in beach sediments from the Abu Dhabi coast. In general, these sediments show a trend towards more material in the coarse eastern tail. Finally, the K_g of the Ouaka River varies between 2.54 and 3.93, characteristic of very leptokurtic to extreme leptokurtic distribution curves. Nevertheless, some sediments are leptokurtic, mesokurtic and platykurtic. The work of [Rashedi and Siad \(2016\)](#) in Abu Dhabi coastal beach sediments (0.78

to 2.35) and Ngagoum-Kontchipe et al. (2021) in the Nyong River in Cameroon (0.3 to 4.32) are also very leptokuric, extreme leptokuric, leptokurtic, mesokurtic and platykurtic. This suggests the dominance of a sand population with the presence of a subordinate population of coarse-grained particles.

The characterization of the type of transport in the different granulometric classes of Ouaka River sediments is shown in **Table 5**. This table shows that in the upper zone, saltation transport dominates (coarse sand: 53%, medium sand: 53%, fine sand: 59% and silt-clay: 51%), followed by rolling transport (gravel 76%, coarse sand: 47%, medium sand: 47%, fine sand: 41% and silt-clay: 14%) and suspension transport (silt-clay: 35%). Similarly, in the downstream zone, saltation transport dominates (coarse sand: 44%, medium sand: 94%, fine sand: 94% and silt-clay: 31%), followed by rolling transport (gravel: 88% and coarse sand: 56%) and suspension transport (silt-clay: 65%). This distribution of transport type according to granulometric classes is similar to that of sediments from the Adjin lagoon in Côte d'Ivoire (N'Guessan et al., 2011), where saltation is dominant (sand: 92.85%), followed by rolling (gravel: 88.16%) and suspension (silt-clay: 70.30%). Similarly, work by Irie et al. (2015) on sediments from the Ebrié lagoon in Côte d'Ivoire showed a high proportion of saltation (sand: 92.85%), followed by rolling (gravel: 88.16%) and suspension (silt-clay: 70.30%). The predominance of sand transport by saltation suggests that this sand originates from the surrounding sandy formations, either by reworking due to the influence of the hydrodynamic current on the banks, or by contributions from secondary water-courses tributary to the main river. Regarding rolling transport, Passega's diagram confirms that this type of transport has led to the deposition of gravel from the Ouaka River. The work of Sinha & Rais (2019) in the Rajmahal catchment in eastern India argued that this type of deposition by the rolling process is linked to the influence of irregular hydrodynamic energy.

Concerning the depositional environment of the Ouaka River sediments, the So vs Md diagram by Moiola & Weiser (1968) shows that 100% of the sediments originate from a fluvial-type environment. In contrast, the So vs Sk diagram by Friedman (1967) shows that, in addition to the dominant fluvial environment (88.23%), 11.77% of sediments are in the dune domain. This contribution of the dune domain to the Ouaka River sediments is thought to be linked to the proximity of the Chad watershed, located to the north of the study area, which is dominated by sand, transported by the wind and deposited in the river. Regional aeolian processes play a crucial role by acting as a mechanism for transferring materials by saltation (bouncing of medium-sized sand grains on the ground), suspension (suspension of dust and silt in the atmosphere) and traction (rolling of large sand grains on the ground) over long distances before deposition in the Ouaka River watershed. Contrary to the work of Irie et al. (2015) in the sediments of the Ebrié lagoon in Côte d'Ivoire and Tossou et al. (2019) in the surface sediments of the coastal lagoon in Benin, the sediments attributed to the dune/beach domain are expected to come from both the underwater beach sediment pool brought up by long swells and redistributed between the dune/beach and river domains in the

lagoon (Gbessi, 2011). Using the statistical parameters obtained by the graphical method on sediments from the Ouaka River, the Y1-Y2 binary diagrams (**Figure 6(a)**, **Figure 6(b)**) showed an influence of a beach/dune deposition environment and those Y2-Y3 (**Figure 7(a)**, **Figure 7(b)**) indicate an agitated fluvial environment. The influence of a beach/dune depositional environment (Y1-Y2) of this river is identical to that of the work of Rashedi & Siad (2016), Ayodele & Madukwe (2019) and Ghaznavi et al. (2019). In contrast, the Y2-Y3 diagram results of Rashedi & Siad (2016) indicate that almost 50% of the samples are deposited in agitated shallow marine sediments, while the remaining 50% are agitated by fluvial sediments. In the Ouaka River, on the other hand, fluvial sediments are highly agitated. Unlike the Ouaka River, which is an intertropical zone like the Adogo River in Nigeria, diagrams Y2-Y3 show the dominance of shallow marine deposits (Maju-Oyovwikowhe & Sunday, 2022). The marine deposit of sediments in the Adogo River may be linked to the retreat of the Atlantic Ocean in geological times.

The mineralogical variety of the Ouaka River sediments suggests a distant source of minerals. The presence of epidote and diopside in these sediments indicates a metamorphic and magmatic origin with calc-alkaline tendencies (Alali et al., 2014). This type of rock outcrops in abundance in the study area, particularly quartzites, schists, granites, etc. (Poidevin, 1985, 1991). The assemblage of augite and hypersthene in these sediments from the aforementioned river emphasises the existence of basic igneous rocks in the vicinity of the study area, demonstrating their incompatibility with a multi-cycle source, such as an ancient shoreline, i.e. a relic of continental shelf deposits (Cascalho, 2019). Garnets are compatible with granites. This means that the main granite outcrops present in the Bakala locality are the most likely primary sources of these garnets in the Ouaka River watershed. The consideration of granites as probable sources of garnets is confirmed by the work of Tangari et al. (2024) in modern beaches and fluvial sands of the Cordillera Betica in southern Spain. The zircon + tourmaline + rutile assemblage is considered to be the most stable minerals in sediments (Pettijohn et al., 1972). However, in the sediments of the Ouaka River, the absence of zircon in certain samples was noted. Consequently, zircon has undergone intense alteration and its concentration decreases or disappears with distance from the source zone. This is justified by the high hydrodynamic energy. Furthermore, the origin of sediments from a rocky source that is poor in or devoid of zircon (such as certain ultramafic or pre-existing sedimentary rocks) would confirm the absence/insufficiency of zircon in certain samples. Similarly, the process of transport by water can separate zircon from sand.

The immaturity of sediments in the Ouaka River obtained for a ZTR < 75%, is due to the renewal of the riverbed under the effect of saltation and fluctuating water flow velocity. This immaturity is confirmed by the work of Ayinla (2016) in the Bida basin in north-western Nigeria.

5. Conclusion

The granulometric approach has shown that the Ouaka River watershed is domi-

nated by medium sand and silt-clay downstream, with the presence of coarse sand in small proportions due to material inputs from secondary streams. The granulometric parameters of the Ouaka River sediments show that medium and coarse sands, very poorly classified and poorly classified respectively, and highly asymmetrical towards coarse sands, are dominant. The frequency curves show a sigmoidal or hyperbolic shape, indicating more or less homogeneous dynamics and sediment heterogeneity.

Quantitative analysis shows that the majority of sediments, notably coarse, medium and fine sands, move by saltation. However, some sediments move by rolling and suspension. The mode of transport for medium and fine sands is dominated by saltation, with 53% and 59% respectively upstream, and 94% by fraction downstream. Transport by rolling is the dominant mode for gravels, with a concentration of 76% upstream and 82% downstream. Silt-clays are mainly transported by suspension (35% upstream and 65% downstream).

The study of the deposition environment showed that sediment deposition in the Ouaka River does indeed originate from a river-type environment. The presence of the dune domain in these Ouaka River sediments bears witness to the wind transport of sand dunes from the Chad watershed, in the northern region of the Central African Republic. Statistical parameters of Ouaka River sediments found from the graphical method (Y1-Y2 and Y2-Y3 binary diagrams) showed the hegemony of beach/dune deposition and fluvial agitation environments.

Heavy mineral analysis was used to study the granulometric facies of sediments in the Ouaka River. The research revealed that the sediments come from a variety of sources. The ZTR indices indicate that the sediments in this river are immature.

Acknowledgements

We would like to thank the reviewers not mentioned in this document for their analyses and constructive comments, which helped to improve the quality of this article.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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