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Granulometric and Mineralogical Characterization of Sands from the Middle Course of the Kasai River (Ilebo Territory, Kasai Province, DRC)

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Abstract: This study addresses sediment dynamics within the fluvial system of the middle Kasai Basin, specifically between Ilebo town (pk605) and the confluence with the Loange River (pk525). The primary aim is to characterize the granulometric and mineralogical evolution of sand bars in the Kasai River, which pose navigational challenges in this section of the basin. The study seeks to answer the following question: How do the granulometric and mineralogical characteristics of sands transported by the middle course of the Kasai River evolve? The research employs laboratory granulometric techniques. Twenty sand samples were collected from sand bars along the middle and navigable course of the Kasai River during the flood recession period, ranging from upstream to downstream. Sieving was conducted using an AFNOR-type sieve column, followed by sedimentometric analyses and the calculation of various Folk & Ward textural parameters using the Excel program Gradistat. Additionally, six samples underwent automated mineralogical analysis using a QEMSCAN FEG Quanta 650. Granulometric analysis revealed that the sands from the middle course of the Kasai River are unimodal, with fine to medium grains in the granulometric fraction ranging from 186.2 μm to 426.8 μm. Most of these sands are moderately to well graded, with grains showing granulometric symmetry and, less commonly, fine asymmetry. Their kurtosis is largely mesokurtic, with occasional leptokurtic and platykurtic characteristics, indicating multiple depositional environments. The study demonstrates that the evolution of these granulometric parameters is uneven along the middle course of the Kasai River, though overall, the parameters exhibit limited variation. This suggests minimal and regular sediment inputs, consistent with the relative regularity of granulometric variations in environments characterized by free sedimentation. Automated mineralogical analysis identified a diverse mineralogical assemblage, dominated by quartz, followed by calcite, iron oxides, orthoclase, plagioclase, and kaolinite. Additionally, a group of minerals that do not exceed the 0.55% threshold—such as illite, apatite, ilmenite, muscovite, chlorite, biotite, montmorillonite, rutile, pyrophyllite, siderite, zircon, and dolomite—was identified. Consequently, the mineralogical evolution is not uniform throughout the middle course of the Kasai River, showing a sawtooth variation. This study clarifies the evolution of the granulometric parameters of Kasai River sands, which are influenced by the river's hydrodynamic regime. It also elucidates the mineralogical evolution, linked to the petrographic nature of source areas, which are distributed based on their mechanical resistance to abrasion, chemical alteration, and the morphology of the riverbed. The findings from this research contribute significantly to the field of sedimentology and integrated river management.

Keywords: Characterization, granulometric, mineralogical, sands, middle course, Kasai River

INTRODUCTION

The Kasai River, the primary collector of the Kasai catchment area, holds significant potential for economic growth in the Democratic Republic of Congo. It is the country's second most important natural communication route after the Congo River, linking the southern railway (Ilebo-Lubumbashi) with the western railway (Kinshasa-Matadi). Due to the challenges of maintaining road infrastructure, a large portion of the population relies heavily on river navigation in the Kasai Basin for the exchange of goods and services (Tshimanga et al., 2016). Accurate information is essential to support strategies for the integrated management of this resource, particularly concerning sediment dynamics and water level monitoring for navigation.

In recent decades, the Kasai River has faced numerous hydroclimatological and hydrosedimentological challenges, exacerbated by ecological imbalances caused by deforestation in the Kasai Basin due to human activities. This likely explains the increased silting of waterways, driven by the intensification of regressive erosion processes in the basin (Kisangala, 2008, 2014; Mushi et al., 2019; Laraque et al., 2020; Tshimanga et al., 2022). Furthermore, as noted by Kisangala (2008, 2014) and Tshimanga et al. (2016), the navigability of the Kasai River—and river navigation in the DRC overall—faces significant challenges. These include the emergence of natural obstacles in certain channels, groundings, and reduced anchorage depths, primarily due to increased silting. These issues often lead to accidents with high human and economic costs, as well as delays in docking river vessels, complicating the supply of essential goods to Kinshasa.

The ever-changing sand bars in the middle reaches of the Kasai River, between the town of Ilebo (pk605) and the confluence with the Loange River (pk525), present substantial navigational challenges. These issues may be attributed to the hydrosedimentological, hydrodynamic, and hydroclimatological characteristics of the Kasai Basin. The abundance of sand influences the morphology of the middle course of the Kasai River, creating sedimentary obstacles to navigation. These sandy deposits hinder navigation throughout the middle and navigable course of the river, particularly during medium and low water periods (Kisangala, 2008, 2014).

Research conducted as part of a sediment sampling program on the Kasai River indicates that this river and its tributaries contribute significantly to the sediment load of the Congo River and are among the main erosion hotspots in the Congo Basin. These factors have major implications for river navigation and hydropower generation (Mushi et al., 2019, 2022). This study seeks to answer the following key questions: What are the granulometric and mineralogical characteristics of the sands transported by the middle course of the Kasai River in this study section? How are these characteristics evolving? Where do the sand deposits, which create sedimentary obstacles to navigation on the Kasai, originate? And is it the same stock of sand transported from upstream that forms these deposits?

The sands under investigation are believed to result from a mixture of materials originating upstream in the catchment area, sediments from riverbed excavation, and sediments likely contributed by tributaries.

This study is part of a broader investigation into sediment dynamics within the fluvial system of the middle Kasai Basin and its integrated management. The primary aim is to characterize the granulometric and mineralogical evolution of the sand bars in the Kasai River, which create sedimentary obstacles to navigation in this study section. The goal is to gain a clearer understanding of the dynamics of these sandy deposits and the challenges they pose to navigation in this part of the Kasai Basin.

Additionally, as highlighted by Trigg & Tshimanga (2020), Trigg et al. (2022a, 2022b), and Tshimanga et al. (2022), the limited information on the water dynamics of the Congo Basin and its major tributary, the Kasai, hampers the full realization of the basin's potential and complicates investment in its water resources development. By exploring the granulometric and mineralogical characteristics of the Kasai River sands to better understand the sedimentary dynamics and navigability challenges, this study makes a significant contribution to the fields of hydrosedimentology and integrated river management.

STUDY AREA

Location

The study area is located in the territory of Ilebo, within the Kasai Province of the DRC. It spans longitudes 20°02' to 20°37' East and latitudes 4°15' to 4°24' South. This area includes part of the section between Ilebo (pk605) and Kese (pk253) on the Kasai River. The specific section under study extends from the town of Ilebo (pk605) to the confluence with the Loange River (pk525), covering a distance of approximately 80 km (Figure 1).

Geology of Ilebo

The Ilebo area is part of the Upper Cretaceous-Cenomanian (Cn) period, belonging to the Kwango Group. This region is characterized by the Upper Kasai Series, specifically Layer II, composed of local sandstones, mudstones, and conglomerates. However, in the Ilebo Malu-Malu sector, as well as much of the middle course of the Kasai River, Layer I of the Upper Kasai Series is exposed. This layer belongs to the Bokungu Group of Albian-Aptian age (Figure 2). These rocks are generally coherent sandstones, interbedded with clayey sandstones or mudstones that are often micaceous, with red or wine-red brown hues, and contain ostracod and phyllopod fossils (Lepersonne, 1974).

It is important to note that the Kwango Group and the Bokungu Group, along with the Loïa Group at the base, form the current Sankuru Supergroup (Cretaceous). This Supergroup is overlain by the Kalahari Supergroup, which consists of polymorphous sandstones (Palaeogene) and ochre sands (Neogene) from bottom to top.

According to Lepersonne (1974), all these formations are covered by more recent (Quaternary) deposits. These consist of more or less clayey sands and silts, often red in color, sometimes associated with armorstone or layers of ferruginous grit, frequently with gravel at the base, and are found in flat areas and terraces.

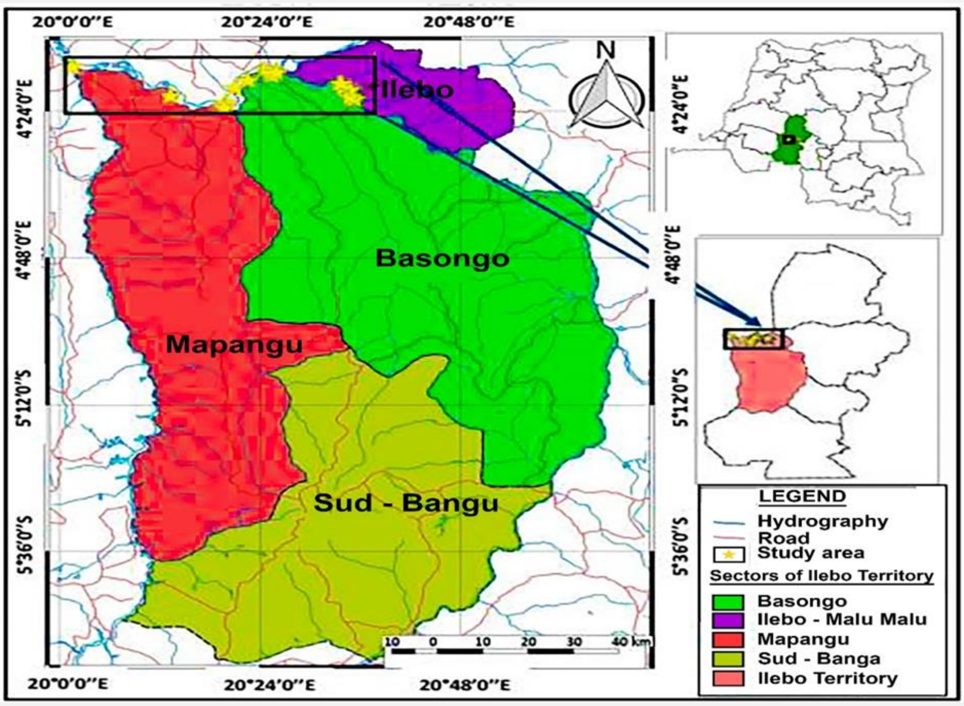

Figure 1. Location of study area.

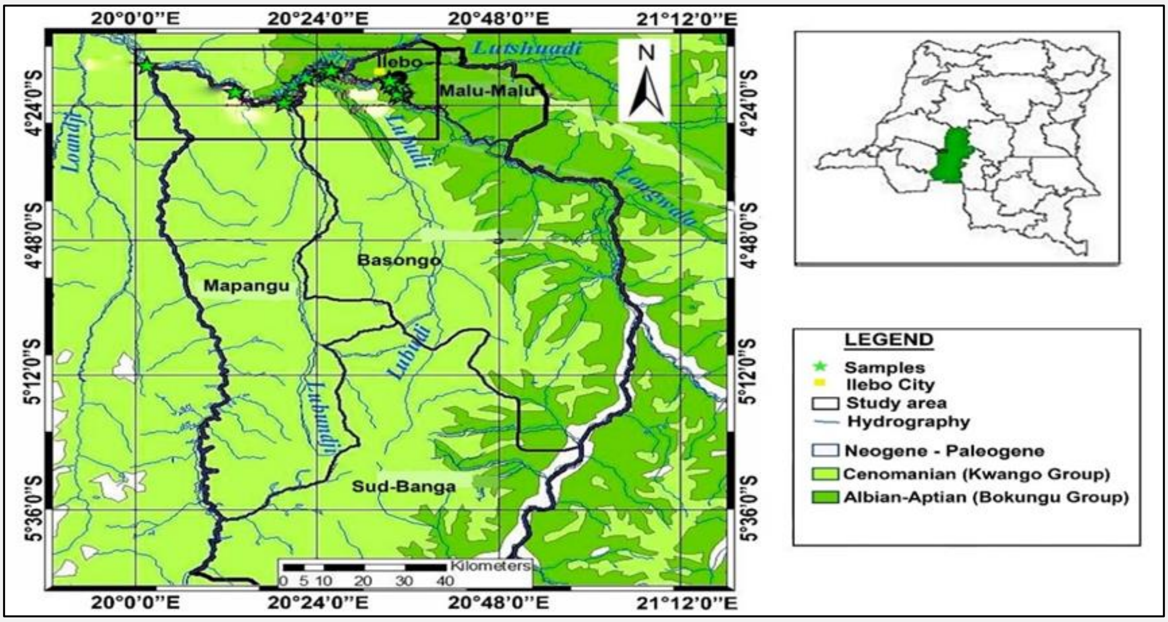

Figure 2. Geological map of the middle course of the Kasai River (Ilebo Territory).

METHOD

To achieve the objectives of this study, we began by consulting bibliographic and documentary sources, focusing on the scientific literature related to sediment dynamics and the challenges of river navigation, both generally and in the specific study region. This review of existing literature informed our arguments and discussions on the sedimentary dynamics of the middle course of the Kasai River and the associated navigation challenges, based on granulometric and mineralogical analyses of the river's sands within the Ilebo territory.

Following this preliminary research, field investigations were conducted. Sand samples were collected from sandbars along the Kasai River during the flooding period between June and July 2017, spanning from Ilebo town (pk605) to the confluence with the Loange River (pk525). The sampling was carried out in the direction of the river's flow to better characterize the evolution of the various parameters studied. Sampling during flooding is crucial because this is when sand tends to settle on the bars (Censier, 1996; Trigg et al., 2022). The spacing between different samples ranged from 2 to 5 km or more, depending on the number and layout of the sandbars. The samples were collected along this navigable middle course, which is dotted with sandbars and sandy islands, some of which are well-developed. The sand samples were spatially referenced using a GPS.

To collect the sand samples, we used a machete to dig cylindrical holes approximately 20 to 40 cm deep, avoiding organic matter, which was irrelevant to the study. The sediment sampling techniques were based on those described by Fournier et al. (2012). The sand samples were then preserved in well-protected plastic bottles before being sent to the laboratory for granulometric and mineralogical analysis.

ArcGIS software was used to spatially represent the sampling points, as shown in Figure 3, which identifies three sandbar concentration zones:

- High concentration zone (Samples MK1-12): This zone begins near the locality of Kazaba, approximately 8 kilometers downstream from the confluence with the Lutshuadi River, and is dominated by the Ilebo Pool (pk605).
- Medium concentration zone (Samples MK13-16): This zone surrounds the confluence of the Sankuru River, a few kilometers upstream of Basongo, and is characterized by a mixture of sands carried by the Sankuru River.
- Low concentration zone (Samples MK17-20): This zone lies between Basongo and the confluence with the Loange River, with an average spacing of about 7 km between observed sandbars. Here, the Loange River contributes reddish sandy alluvium to the left bank at the edge of the study section.

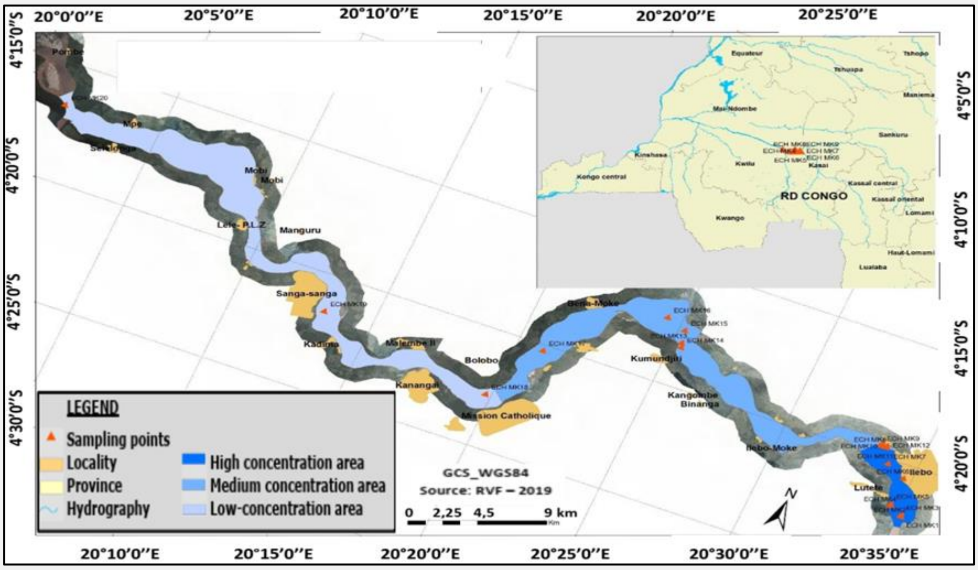

Figure 3. Geolocation of Kasaï bar sand concentration zones.

The 20 sand samples were sieved using an AFNOR-type sieve column for grain sizes > 32 μm, and sedimentometry was used for grain sizes < 32 μm. These analysis techniques, which allow for the rapid assessment of different grain size percentages, follow the principles established by Fournier et al.

(2012). The various granulometric parameters analyzed, such as mean size, mode, median, classification coefficient or standard deviation (SD), skewness (Ski), and kurtosis (KG), were calculated using the Excel program GRADISTAT (Blott & Pye, 2010). These particle size parameters are derived from the Folk & Ward (1957) method and are expressed in μm and phi (ø). They help characterize the environment in which the sediment was deposited and, in favorable cases, identify the agent and mode of transport (Deconinck & Chamley, 2011; Fournier et al., 2012; Cojan & Renard, 2021).

Using ArcGIS software, we extrapolated the geospatial distribution of the average grain size of the sands in the Kasai River. This extrapolation allowed us to visualize the general trend in the evolution of these sands' average grain size.

Mineralogical analysis was conducted to determine the nature and percentage content of each mineral comprising the grains of bar sand from the middle course of the Kasai River. We performed an automated quantitative identification of the minerals using QEMSCAN (Quantitative Evaluation of Minerals by SCANning).

Six samples of these sands were subjected to automated mineralogical analysis using a QEMSCAN FEG Quanta 650 with a 15 kV electron beam at the QEMSCAN laboratory in the Earth Sciences department of the University of Geneva. The QEMSCAN FEG Quanta 650 is an automated mineralogy instrument that quantitatively evaluates minerals using a scanning electron microscope (SEM) coupled with two energy dispersive X-ray spectrometry (EDS) detectors. The 15 kV acceleration voltage was chosen to provide better resolution for analyzing sediments that may contain very fine, inconspicuous grains, such as clay minerals. The results for the various minerals detected are expressed as a percentage of the total mass of the analyzed sample (Pirrie et al., 2004).

Finally, we used the Hjulström diagram to establish the relationships between erosion, transport, and sedimentation, which forms the theoretical basis of sediment dynamics. This diagram considers the current velocity (hydrodynamic conditions) and the size of sedimentary particles (Hjulström, 1935). Additionally, Sternberg's law (1875) and the mineral classification scale were used, accounting for mechanical resistance to abrasion according to Freise (1931) and Thiel (1945) and chemical resistance to alteration based on the work of Pettijohn (1941), Morton & Hallsworth (1994). These analyses enabled us to assess the evolution of the granulometric and mineralogical parameters of the bar sands of the Kasai River, compare them with other regions, and contribute to a better understanding of the sedimentary dynamics of these sands as well as the navigation challenges on this study section.

Certain statistical analyses and the Excel application were used to process, analyze, and visualize some of the numerical data related to the various processes studied.

RESULTS

Changes in Granulometric Parameters

The granulometric analysis focused on bar sands from the navigable middle course of the Kasai River, extending from the town of Ilebo (pk605) to the confluence with the Louange River (pk525). The granulometric parameters of the sediments reflect varying degrees of erosion, transport, and sedimentation mechanisms across different parts of the sampling environment, forming the basis of sediment dynamics (Deconinck & Chamley, 2011; Gandhi & Raja, 2014; Cojan & Renard, 2021; Tine et al., 2022).

After sieving and conducting sedimentometry on the sand samples, the results obtained are presented in Table 1 below. These results were analyzed and processed using the Excel application Gradistat (version 8.0). This software was employed to determine particle size parameters using the graphical method of Folk & Ward (1957), including mean, median, mode, standard deviation (SD), skewness, and kurtosis, alongside detailed descriptions.

Based on the frequency of occurrence of descriptions of these various particle size parameters, the following general observations can be made:

- The sands of the Kasai River range from fine sands (50%) to medium sands (50%).
- They are generally moderately well sorted (50%), well sorted (45%), and very rarely moderately sorted (5%).
- They frequently exhibit particle size symmetry (70%) and less frequently fine asymmetry (30%).
- They are largely mesokurtic (75%) and rarely leptokurtic (15%) or platykurtic (10%).
- Finally, they are predominantly unimodal sands (99.5%).

The Excel application was also used to visualize changes in these particle size parameters, as shown in Figure 4.

Table 1. Results of Particle Size Analysis of Sands from the Middle Kasai

N° ECH.	Granulo-metric Param-eter	Folk and Ward method		Descriptions	N° ECH.	Granulo-metric Param-eter	Folk and Ward method		Descriptions
		Geo-metric (μm)	Loga-rithmic (Ø)				Geo-metric (μm)	Loga-rithmic (Ø)	
MK1	Average	289,4	1,789	Medium sand	MK11	Average	325,7	1,619	Medium sand
	Median	292,6	1,158			Median	321,2	1,638	
	Mode	302,5	1,747			Mode	302,5	1,747	
	Ranking	1,420	0,506	Mwr		Ranking	1,382	0,466	Well classified
	Skewness	-0,087	0,087	Symmetrical		Skewness	0,006	-0,006	Symmetrical
	Kurtosis	1,072	1,072	Mésokurtique		Kurtosis	1,047	1,047	Mesokurtic
MK2	Average	201,8	2,309	Fine sand	MK12	Average	240,0	2,059	Fine sand
	Median	207,4	2,269			Median	244,1	2,035	
	Mode	215,0	2,237			Mode	302,5	1,747	
	Ranking	1,293	0,370	Well classified		Ranking	1,428	0,514	Mwr
	Skewness	-0,098	0,098	Symmetrical		Skewness	-0,105	0,105	Symmetrical
	Kurtosis	1,323	1,323	Leptokurtic		Kurtosis	1,094	1,094	Mesokurtic
MK3	Average	219,6	2,187	Fine sand	MK13	Average	238,4	2,069	Fine sand
	Median	221,9	2,172			Median	244,4	2,033	
	Mode	215,0	2,237			Mode	302,5	1,747	
	Ranking	1,585	0,664	Mwr		Ranking	1,480	0,566	Mwr
	Skewness	-0,023	0,023	Symmetrical		Skewness	-0,052	0,052	Symmetrical
	Kurtosis	0,969	0,969	Mesokurtic		Kurtosis	1,022	1,022	Mesokurtic
MK4	Average	323,5	1,628	Medium sand	MK14	Average	305,7	1,710	Medium sand
	Median	318,2	1,652			Median	306,2	1,707	
	Mode	302,5	1,747			Mode	302,5	1,747	
	Ranking	1,375	0,460	Well classified		Ranking	1,427	0,513	Mwr
	Skewness	0,038	-0,038	Symmetrical		Skewness	-0,076	0,076	Symmetrical
	Kurtosis	1,030	1,030	Mesokurtic		Kurtosis	1,229	1,299	Leptokurtic
MK5	Average	279,0	1,842	Medium sand	MK15	Average	198,8	2,331	Fine sand
	Median	288,6	1,793			Median	202,1	2,307	
	Mode	302,5	1,747			Mode	215,0	2,237	
	Ranking	1,326	0,407	Well classified		Ranking	1,569	0,650	Mwr
	Skewness	-0,135	0,135	Fa		Skewness	-0,058	0,058	Symmetrical
	Kurtosis	1,279	1,279	Leptokurtic		Kurtosis	0,865	0,865	Platykurtic
MK6	Average	188,1	2,410	Fine sand	MK16	Average	293,0	1,771	Medium sand
	Median	195,8	2,353			Median	292,0	1,776	
	Mode	215,0	2,237			Mode	302,5	1,747	
	Ranking	1,324	0,405	Well classified		Ranking	1,404	0,490	Well classified
	Skewness	-0,154	0,154	Fa		Skewness	0,009	-0,009	Symmetrical
	Kurtosis	1,044	1,044	Mesokurtic		Kurtosis	0,957	0,957	Mesokurtic
MK7	Average	256,2	1,964	Medium sand	MK17	Average	186,2	2,425	Fine sand
	Median	251,9	1,989			Median	194,1	2,365	
	Mode	215,0	2,237			Mode	215,0	2,237	
	Ranking	1,551	0,634	Mwr		Ranking	1,322	0,403	Well classified
	Skewness	0,039	-0,039	Symmetrical		Skewness	-0,195	0,195	Fa
	Kurtosis	0,952	0,952	Mesokurtic		Kurtosis	1,029	1,029	Mesokurtic
MK8	Average	344,3	1,538	Medium sand	MK18	Average	193,0	2,373	Fine sand
	Median	339,7	1,558			Median	189,7	2,398	
	Mode	302,5	1,747			Mode	215,0	2,237	
	Ranking	1,378	0,463	Well classified		Ranking	1,602	0,680	Mwr
	Skewness	0,033	-0,033	Symmetrical		Skewness	0,069	-0,069	Symmetrical
	Kurtosis	1,024	1,024	Mesokurtic		Kurtosis	0,965	0,965	Mesokurtic
MK9	Average	270,2	1,888	Medium sand	MK19	Average	202,6	2,304	Fine sand
	Median	280,3	1,835			Median	219,5	2,187	
	Mode	302,5	1,747			Mode	302,5	1,747	
	Ranking	1,326	0,407	Well classified		Ranking	1,742	0,800	Mwr
	Skewness	0,038	-0,038	Fa		Skewness	-0,177	0,177	Fa
	Kurtosis	1,030	1,030	Mesokurtic		Kurtosis	0,814	0,814	Platykurtic
MK10	Average	426,8	1,228	Medium sand	MK20	Average	192,3	2,378	Fine sand
	Median	439,5	1,186			Median	189,3	2,401	
	Mode	427,5	1,247			Mode	215,0	2,237	
	Ranking	1,439	0,525	Mwr		Ranking	1,606	0,683	Mwr
	Skewness	-0,197	0,197	Fa		Skewness	0,066	-0,066	Symmetrical
	Kurtosis	1,016	1,016	Mesokurtic		Kurtosis	0,967	0,967	Mesokurtic

**Mwr: Moderately well ranked; Fa: Fine asymmetry*

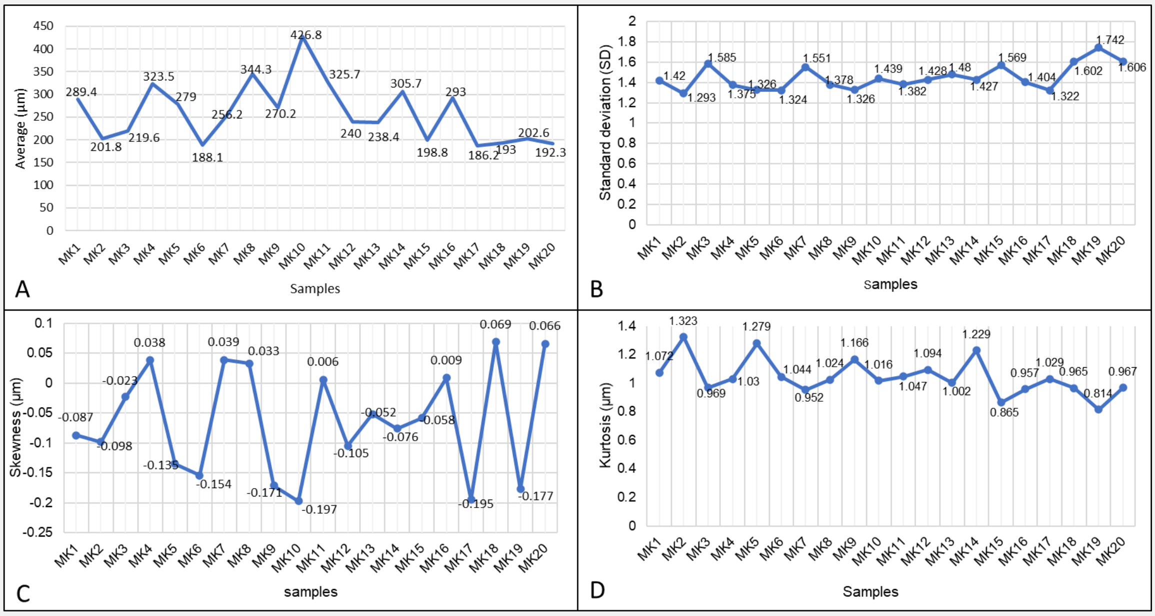

Figure 4. Evolution of Granulometric Parameters of Bar Sands from the Kasai River (A: Mean; B: Standard Deviation (SD); C: Skewness (Ski); D: Kurtosis (KG)).

The results indicate that the sands of the middle course of the Kasai River are fine to medium sands with a grain size fraction ranging between 186.2 µm and 426.8 µm. These are unimodal sands that are generally moderately well sorted to well sorted (sorting coefficient between 1.29 and 1.742), largely exhibiting granulometric symmetry with occasional fine asymmetry (skewness between -0.197 and 0.069) and mostly mesokurtic sharpness, with occasional leptokurtic and platykurtic characteristics (kurtosis between 0.814 and 1.323).

The evolution of these granulometric parameters is not linear; instead, there is a sawtooth variation across the three sandbar concentration zones studied, from pk605 to pk525. This evolution can be characterized as follows:

- In the high concentration sandbar zone (Samples MK1-12), the sands tend to become coarser and increasingly well sorted. This zone is dominated by the Ilebo Pool, whose bottom is exclusively sandy (Devroey, 1939).
- In the medium and low concentration sandbar zones (Samples MK13-16 and MK17-20, respectively), the sands tend to become increasingly fine and moderately well to moderately sorted.
- Finally, throughout the study area from pk605 to pk525, the sands tend to exhibit increasingly symmetrical grain sizes and predominantly mesokurtic sharpness.

Using ArcGIS software, a geostatistical extrapolation of the average grain size distribution of sand in the middle reaches of the Kasai River can be visualized, showing a general trend towards increasingly finer grains downstream (Figure 5).

Evolution of the Mineralogical Composition

Six samples of bar sands from the Kasai River, representing the three previously identified concentration zones, were subjected to automated mineralogical analysis using a QEMSCAN FEG Quanta 650. This quantitative mineral identification technique (QEMSCAN - Quantitative Evaluation of Minerals by SCANning with SEM/EDS) enabled the identification of a mineralogical suite in the sands of the Kasai River, comprising 18 minerals, which can be categorized as follows:

- Fourteen primary minerals (resistant and imported): zircon, quartz, orthoclase, plagioclase, iron oxides, rutile, ilmenite, apatite, siderite, dolomite, calcite, muscovite, biotite, and pyrophyllite.
- Four secondary minerals (less resistant, neo-formed): kaolinite, chlorite, illite, and montmorillonite.

The percentage content of these minerals in the Kasai River sand samples is detailed in Table 2 below.

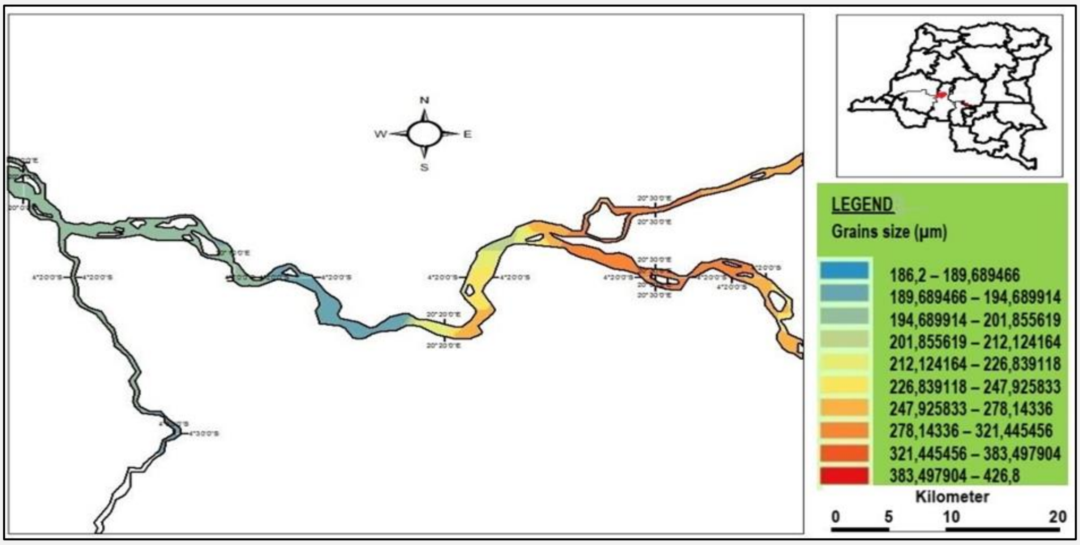

Figure 5. Geospatial Distribution of the Average Grain Size (µm) of the Sands Under Study.

Table 2. Percentage (%) mineral content of sands from the Kasaï River.

Minerals	MK2	MK8	MK13	MK15	MK17	MK18
Zircon	0,04	0,02	0,03	0,05	0,03	0,02
Quartz	98,3	96,87	93,95	99,07	93,73	97,81
Orthose	0,51	0,54	0,07	0,04	0,99	0,52
Plagioclase	0,33	0,43	0,14	0,01	0,75	0,23
Oxydes de fer	0,02	0,03	0,02	0,04	1,88	0,01
Rutile	0,01	0,08	0,51	0,04	0,03	0,01
Ilménite	0,03	0,02	0,1	0,06	0,03	0,01
Apatite	0,06	0,14	0,28	0,01	0,19	0,06
Sidérite	0,01	0,02	0,03	0,06	0,54	0,01
Dolomite	0	0,02	0,02	0	0,03	0
Calcite	0,01	0,48	2,66	0,01	0,15	0,08
Biotite	0,01	0,01	0	0	0,03	0,01
Kaolinite	0,03	0,51	0,71	0,38	0,18	0,69
Muscovite	0,02	0,03	0,04	0,01	0,03	0,02
Chlorite	0,01	0,02	0,05	0,04	0,06	0,03
Illite	0,03	0,06	0,07	0	0,1	0,08
Montmorillonite	0,01	0,01	0,07	0	0,02	0,03
Pyrophyllite	0,01	0,02	0,22	0,2	0,15	0,2
Total	99,44	99,31	98,97	100,02	98,92	99,82

This table reveals that the mineralogical composition across the middle course of the Kasai River remains consistent for the six sand samples analyzed. The composition is highly varied but largely dominated by quartz (ranging between 93.95% and 99.07%), followed by calcite (0.01% - 2.66%), iron oxides (0.01% - 1.88%), orthoclase (0.04% - 0.99%), plagioclase (0.01% - 0.75%), and kaolinite (0.18% - 0.71%). Additionally, a group of minerals that do not exceed the 0.55% threshold—such as illite, apatite, ilmenite, muscovite, chlorite, biotite, montmorillonite, rutile, pyrophyllite, siderite, zircon, and dolomite—were identified.

The mineralogical evolution of the sands within the bars of the Kasai River is illustrated in Figure 6. This figure indicates that the mineralogical composition of the sands within the bars of the Kasai River has not evolved linearly, showing a sawtooth variation. This variation occurs despite the effects of transport, mineral density, and resistance to alteration. The evolution of mineral content follows two main trends:

- An increasing trend in the content of certain minerals, such as iron oxides, rutile, siderite, apatite, chlorite, muscovite, pyrophyllite, dolomite, illite, calcite, and kaolinite.

- A decreasing trend in the content of minerals such as zircon, ilmenite, biotite, quartz, plagioclase, orthoclase, and montmorillonite.

Since all these minerals belong to the same granulometric fraction (ranging between 426.8 μm and 186.2 μm), their distribution according to density reflects the variations in hydrodynamics during the deposition of sands on the bars (Censier, 1996; Deconinck & Chamley, 2011; Fournier et al., 2012; Cojan & Renard, 2021).

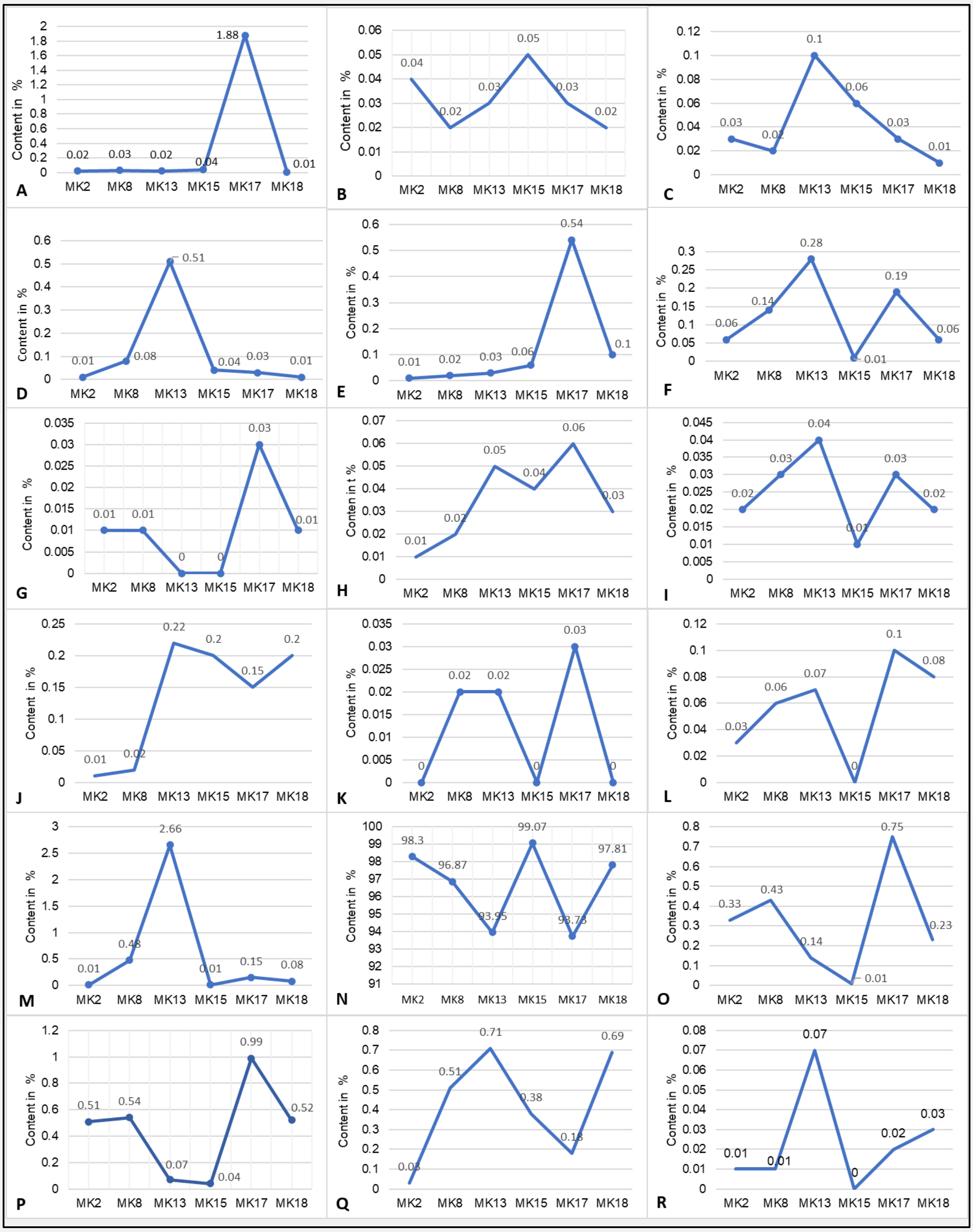

Figure 6. Evolution of the mineralogical composition of the bar sands of the middle course of the Kasaï river (in %): A: Iron oxides; B: Zircon; C: Ilmenite; D: Rutile; E: Siderite; F: Apatite; G: Biotite; H: Chlorite; I: Muscovite; J: Pyrophyllite; K: Dolomite; L: Illite; M: Calcite; N: Quartz; O: Plagioclase; P: Orthose; Q: Kaolinite; and R: Montmorillonite.

DISCUSSION

It should be noted, along with Censier (1996), Deconinck & Chamley, 2011, Gandhi & Raja, (2014), Mushi et al, (2019),Cojan and Renard (2021) and Tine et al, (2022), that the granulometric parameters of sediments transported by a river are therefore essentially linked to processes occurring in the course of that river, in particular the action of the transporting current, fragmentation, grain abrasion and sedimentation. In the same way, this assertion can be disproved to highlight the probable relationship between the granulometric parameters of the bar sands of the Kasaï River in this study section and certain factors in the river,such as the speed of the transporting current and the hydrodynamic conditions at the time of their deposition.

Thus, by referring to the relationship between the average size (μm) of sand grains and the current velocity (cm/s) using the Hjulström diagram (Hjulströrm, 1935; Deconinck & Chamley, 2011; Cojan and Renard, 2021), we find that the sand grain fraction under study (fraction between 426.8 - 186.2μm) corresponds to an average current speed varying approximately between 1.2cm/s and 3cm/s on the curve separating the particle transport and sedimentation domains. This implies that, in general, a current velocity greater than approximately 3cm/s will be required to transport medium and fine sand grains from the Kasai River, whereas a current velocity of less than 3cm/s will be required to transport fine sand grains from the Kasai River. at around 1.2cm/s all these sand particles would be deposited on the bars. This allows us to understand that for this grain size range, the hydrodynamic conditions of the river responsible for the formation of these sandy deposits are of low to medium energy.

On the other hand, a current speed well in excess of the above-mentioned values is bound to result in massive transport of particles, or even fragmentation or abrasion, i.e. the process of erosion of the sand particles, which can occur at a current speed in excess of around 20cm/s.

However, the work carried out to date by the Régie des Voies Fluviales - RDC on determining the current speed of the Kasaï River shows values of between 1.1 and 6 cm/s, with an average speed of 4.42 cm/s on the section concerned by this research (RVF - RDC report, 2019). In other words, the fragmentation and abrasion of grains in these sands (particle erosion) appear to be impossible in the case of the Kasaï River.

With regard to the evolution of granulometric parameters, we believe, in line with Sternberg's law (1875) and the assertions made by Deconinck & Chamley, 2011 and Cojan and Renard (2021) concerning the comparison of granulometric parameters specific to various samples from the same series or sedimentary level, that the elements transported by a watercourse are progressively finer and tend to be better and better classified. However, the granulometric evolution of the sands of the Kasaï river does not confirm this law or the assertions of the aforementioned authors insofar as, from upstream to downstream, the elements are sometimes fine, sometimes medium, sometimes well classified and sometimes moderately well classified (Figure 4). Similar observations were made on the lower course of the Oubangui by Censier (1996).

The granulometric parameters change in a sawtooth pattern from pk605 to pk525, while their overall size varies little. This trend shows that it is not the same stock of sand that is transported along the entire length of the middle course of the Kasai River. This granulometric approach shows that there are inputs, which are more or less regular, given the relative regularity of the granulometric variations, which also reveal a general trend towards a decrease in the average grain size from upstream to downstream by geostatistical extrapolation using ArcGis software, as shown in Figure 5.

Be that as it may, it should be noted that the sands of the middle course of the Kasai River are fine to medium unimodal sands,this indicates a relatively distant single source of supply and a low- and medium-energy repository environment.

These sands are moderately well graded to well graded with the value of the grading coefficient varying from 1.29 to 1.742 (Figure 4), which may be due to the addition of sediments of different grain size originating either from the reworking of old sediments or from alluvial action, or from the absence of a strong convergence of currents throughout the year. Similar observations have been made in other regions by Gandhi and Raja (2014), Touré et al (2016), Moukandi N'kaya et al (2022) and Tine et al (2022).

In the region studied, the sands are largely granulometrically symmetrical and rarely finely asymmetrical (Skewness coefficient between -0.197 and 0.069 - Figure 4). This implies the prevalence of an environment with low and moderate variation in the medium to low energy carrier current. With a sharpness that is generally mesorkurtic and rarely leptokurtic or platykurtic (Angularity coefficient - Kurtosis between 0.814 and 1.323 - Figure 4), the bar sands of the middle course of the Kasaï river reflect an environment with trivial and moderate variation in energy and the absence of strong convergence of weak to medium intensity currents during the year.

It is important to emphasise that all these granulometric parameters show an evolution that is not straightforward and jagged from upstream to downstream (Figure 4).

According to Folk and Ward (1957), Thomas, Kemp and Lewis (1972), Deconinck & Chamley, 2011, Cojan and Renard (2021), this probably reflects a mixture of elements predominantly from a more or less distant original population (non-natives) with nearby elements (natives) that could have been deposited in a virtually calm environment with moderate current intensity and regularity throughout the year.

Work by Touré et al, (2016), Moukandi N'kaya et al, (2022), Tine et al, (2022) shows that the homogeneity and good classification of sands explain the regularity and low intensity of the energy of transport and deposition currents. The granulometric parameters of sediments play an important role in sediment dynamics. We can understand with these authors that the evolution of the granulometric parameters of the sands of the middle course of the Kasaï river indicates a sedimentation made by the free accumulation, i.e. a deposit which was carried out because of a banal and moderate variation in the competence of the current of transport which moreover in the case in point is clearly related to the little variable morphology of the catchment area with an index of compactness of Gravélius - KG of 1, 29, a Roche slope index - Ip of 7.33% and an overall index - Ig of 0.4989, but also to the very alarming current hydroclimatological conditions in the region (Kisangala, 2008 and 2014, Mushi et al. , 2019 and Mushi et al., 2022).

Then, on the basis of scales of mechanical resistance to abrasion (Friese, 1931; Thiel, 1940 and 1945) and chemical resistance to alteration (Pettijhon, 1994; Dryden and Dryden, 1946; Cailleux and Tricart, 1959; Friis, 1974; Morton, 1985; Morton and Hallsworth, 1994), the minerals in the bar sands of the middle course of the Kasai River were classified into:

- ✓ Resistant and imported primary minerals: zircon, quartz, orthoclase, plagioclase, iron oxides, rutile, ilmenite, apatite, siderite, dolomite, calcite, muscovite and biotite.
- ✓ Neo-formed minerals with low resistance, known as secondary minerals: kaolinite, chlorite, illite, montmorillonite and pyrophyllite.

According to Sternberg's law (1875), the mineralogical composition of river sands will become poorer in low-strength minerals and relatively richer in high-strength minerals from upstream to downstream.

Thus, as Figure 6 shows, increases in the percentages of certain neo-formed minerals with low resistance, such as kaolinite, chlorite, illite, montmorillonite and pyrolysis pyrolysis, montmorillonite and pyrophyllite in the sands studied from upstream to downstream would be the result of neoformation by alteration of the minerals contained in the southern detrital formations of the Congolese basin, but also diagenetic neoformation, as in the case of pyrophyllite, which is often associated with salts linked to mixed chemical facies with fine detritus, located in the deep zones of the basins, as shown by the work carried out by Chennaux et al. (1967).

We can understand that the mineralogical evolution of the sands studied can be explained either by admitting contributions by the neoformation of secondary minerals originating from detrital material on the bed of the middle course of the Kasaï rich in minerals fairly labile to alteration such as orthose, plagioclase, muscovite, biotite and, in the case of pyrophyllite, diagenetic neoformation linked to mixed chemical and fine detrital facies in the deep areas of the basins, as well as, to a lesser extent, from bank erosion in this bare region of rainforest and dense evergreen forest as a result of human activity, as suggested by Mushi et al. , (2019).

In addition, it should be noted with Best (1988) and Chaumont et al. (1994) that for a mineral to reflect the origin of the particles, its physical properties must be as similar as possible to those of all the particles in the bed. Thus, in the context of this research, potassium feldspars (Orthose) and calc-sodium feldspars (Plagioclase) are more effective since they have a structure and density similar to those of quartz, the mineral that dominates the mineralogical composition of the particles in the bar sands of the middle course of the Kasaï river. This indicates that the presence of these minerals is the result of detrital material rich in these minerals, such as the arkosic sandstones and ancient feldspathic sediments in the southern part of the Congolese basin.

However, the spatial variations in the minerals found in the sands of the middle reaches of the Kasai River may be closely linked to the morphology of the riverbed. Minerals such as zircon, iron oxides, rutile, ilmenite, apatite and siderite may originate from igneous rocks of acidic and basic composition in the upstream region of the Kasai basin. Similarly, these minerals may be linked to ancient sediments that have undergone recycling, as shown by the work carried out by Chaumont et al (1994).

Finally, for Devroey (1939) and Mushi et al (2019), the average width of around 1 to 2 km and the low cohesion of the bank formations of the middle course of the Kasaï River in this study region would certainly justify the lateral erosion contributions of these banks, but in reality these contributions remain minimal compared with those due to the excavation of the riverbed itself. This is demonstrated by the non-clear and jagged variation in the granulometric parameters and mineralogical composition of the sands studied.

As noted by Censier (1996), Deconinck & Chamley (2011), Gandhi & Raja (2014), Mushi et al. (2019), Cojan & Renard (2021), and Tine et al. (2022), the granulometric parameters of river-transported sediments are primarily influenced by the river's processes, including the action of the transporting current, fragmentation, grain abrasion, and sedimentation. This study challenges this assertion by highlighting the probable relationship between the granulometric parameters of the Kasai River's bar sands and certain river factors, such as the speed of the transporting current and the hydrodynamic conditions at the time of deposition.

By referring to the relationship between the average size (µm) of sand grains and the current velocity (cm/s) using the Hjulström diagram (Hjulström, 1935; Deconinck & Chamley, 2011; Cojan & Renard, 2021), we find that the sand grain fraction under study (426.8 - 186.2 µm) corresponds to an average current speed varying approximately between 1.2 cm/s and 3 cm/s on the curve separating the particle transport and sedimentation domains. This implies that, generally, a current velocity greater than approximately 3 cm/s is required to transport medium and fine sand grains from the Kasai River, whereas a velocity of less than 3 cm/s would result in the deposition of fine sand grains. At around 1.2 cm/s, all these sand particles would be deposited on the bars. This suggests that, for this grain size range, the hydrodynamic conditions responsible for forming these sandy deposits are of low to medium energy.

Conversely, a current speed significantly exceeding the above-mentioned values would likely result in massive particle transport, fragmentation, or abrasion—processes that could occur at speeds exceeding approximately 20 cm/s. However, data from the Régie des Voies Fluviales - RDC on the current speed of the Kasai River indicates values between 1.1 and 6 cm/s, with an average speed of 4.42 cm/s in the section of this study (RVF - RDC report, 2019). This suggests that the fragmentation and abrasion of grains in these sands (particle erosion) are improbable in the Kasai River.

Regarding the evolution of granulometric parameters, we concur with Sternberg's law (1875) and the findings of Deconinck & Chamley (2011) and Cojan & Renard (2021), which suggest that elements transported by a watercourse progressively become finer and more well-sorted. However, the granulometric evolution of the Kasai River sands does not fully support this law or the assertions of these authors. From upstream to downstream, the sand grains are sometimes fine, sometimes medium, and vary between well-sorted and moderately well-sorted (Figure 4). Similar observations were made on the lower course of the Oubangui by Censier (1996).

The granulometric parameters exhibit a sawtooth pattern from pk605 to pk525, with little variation in overall size. This trend indicates that it is not the same stock of sand being transported along the entire middle course of the Kasai River. This granulometric approach suggests the presence of inputs, more or less regular, given the relative consistency of the granulometric variations. These also reveal a general trend towards a decrease in average grain size from upstream to downstream, as shown by geostatistical extrapolation using ArcGIS software (Figure 5).

Nevertheless, it is important to note that the sands of the middle course of the Kasai River are fine to medium, unimodal sands, indicating a relatively distant single source of supply and a low- to medium-energy depositional environment. These sands are moderately well-graded to well-graded, with the grading coefficient varying from 1.29 to 1.742 (Figure 4), likely due to the addition of sediments of different grain sizes originating either from the reworking of older sediments, alluvial action, or the absence of a strong convergence of currents throughout the year. Similar observations have been made in other regions by Gandhi & Raja (2014), Touré et al. (2016), Moukandi N'kaya et al. (2022), and Tine et al. (2022).

In the studied region, the sands are largely granulometrically symmetrical and rarely finely asymmetrical (skewness coefficient between -0.197 and 0.069 - Figure 4). This implies the prevalence of an environment with low to moderate variation in the medium- to low-energy carrier current. With sharpness generally mesokurtic and rarely leptokurtic or platykurtic (kurtosis coefficient between 0.814 and 1.323 - Figure 4), the bar sands of the middle course of the Kasai River reflect an environment with trivial to moderate variation in energy and the absence of strong convergence of weak to medium-intensity currents throughout the year.

All these granulometric parameters exhibit a non-linear and jagged evolution from upstream to downstream (Figure 4). According to Folk & Ward (1957), Thomas et al. (1972), Deconinck & Chamley (2011), and Cojan & Renard (2021), this likely reflects a mixture of elements predominantly from a more or less distant original population (non-native) with nearby elements (native) that could have been deposited in a relatively calm environment with moderate current intensity and regularity throughout the year.

The works of Touré et al. (2016), Moukandi N'kaya et al. (2022), and Tine et al. (2022) demonstrate that the homogeneity and good sorting of sands indicate the regularity and low intensity of the energy of transport and deposition currents. The evolution of the granulometric parameters of the middle course of the Kasai River sands suggests sedimentation through free accumulation—a deposition resulting from a trivial and moderate variation in the transporting current's competence. This is likely related to the relatively uniform morphology of the catchment area, with a Gravelius compactness index (KG) of 1.29, a slope index (Ip) of 7.33%, and an overall index (Ig) of 0.4989. These findings are also supported by the current hydroclimatological conditions in the region (Kisangala, 2008, 2014; Mushi et al., 2019, 2022).

Based on scales of mechanical resistance to abrasion (Freise, 1931; Thiel, 1940, 1945) and chemical resistance to alteration (Pettijhon, 1994; Dryden & Dryden, 1946; Cailleux & Tricart, 1959; Friis, 1974; Morton, 1985; Morton & Hallsworth, 1994), the minerals in the bar sands of the middle course of the Kasai River were classified into: (1) Resistant and imported primary minerals: zircon, quartz, orthoclase, plagioclase, iron oxides, rutile, ilmenite, apatite, siderite, dolomite, calcite, muscovite, and biotite; (2) Low-resistance neo-formed secondary minerals: kaolinite, chlorite, illite, montmorillonite, and pyrophyllite.

According to Sternberg's law (1875), the mineralogical composition of river sands becomes poorer in low-strength minerals and relatively richer in high-strength minerals from upstream to downstream. Figure 6 shows that increases in the percentages of certain low-resistance neo-formed minerals, such as kaolinite, chlorite, illite, montmorillonite, and pyrophyllite, in the sands from upstream to downstream are likely the result of neoformation by alteration of the minerals in the southern detrital formations of the Congolese basin, as well as diagenetic neoformation, particularly in the case of pyrophyllite, often associated with salts linked to mixed chemical facies with fine detritus in the deep zones of the basins, as indicated by the work of Chennaux et al. (1967).

The mineralogical evolution of the studied sands can be explained either by contributions from the neoformation of secondary minerals originating from detrital material on the bed of the middle course of the Kasai, which is rich in minerals susceptible to alteration, such as orthoclase, plagioclase, muscovite, and biotite, or by diagenetic neoformation linked to mixed chemical and fine detrital facies in the deep areas of the basins. Additionally, bank erosion in this region, largely stripped of rainforest and dense evergreen forest due to human activity, may contribute to the mineralogical composition, as suggested by Mushi et al. (2019).

It is important to note, as emphasized by Best (1987) and Chaumont et al. (1994), that for a mineral to reflect the origin of the particles, its physical properties must closely resemble those of all the particles in the bed. In this research context, potassium feldspars (orthoclase) and calc-sodium feldspars (plagioclase) are particularly significant because they have a structure and density similar to quartz, the dominant mineral in the bar sands of the middle course of the Kasai River. This indicates that these minerals originate from detrital material rich in these minerals, such as the arkosic sandstones and ancient feldspathic sediments in the southern part of the Congolese basin.

However, the spatial variations in the minerals found in the middle reaches of the Kasai River may be closely linked to the morphology of the riverbed. Minerals such as zircon, iron oxides, minerals such as zircon, iron oxides, rutile, ilmenite, apatite, and siderite may originate from igneous rocks of acidic and basic composition in the upstream region of the Kasai basin. These minerals might also be linked to ancient sediments that have undergone recycling, as demonstrated by the work of Chaumont et al. (1994).

Finally, according to Devroey (1939) and Mushi et al. (2019), the average width of around 1 to 2 km and the low cohesion of the bank formations in the middle course of the Kasai River likely justify the minimal lateral erosion contributions from the banks compared to those resulting from excavation of the riverbed itself. This is supported by the non-uniform and jagged variation in granulometric parameters and mineralogical composition observed in the sands studied.

CONCLUSION

The granulometric analysis conducted in this study reveals that the sands from the middle course of the Kasaï River are unimodal, with fine and medium grains ranging between 186.2 μm and 426.8 μm. This indicates a relatively distant single source of supply and a low to medium energy depositional environment, with current speeds estimated at approximately 1.2 to 3 cm/s based on the Hjulström diagram. The sands are predominantly moderately well-graded to well-graded, likely due to the addition of sediments of varying grain sizes from either the reworking of old sediments or alluvial action, or the absence of strong current convergence throughout the year. Most grains exhibit granulometric symmetry with minimal fine asymmetry, and their sharpness is generally mesokurtic, with rare leptokurtic or platykurtic forms. This suggests multiple depositional environments characterized by sedimentation through free accumulation, reflecting moderate variation in current competence. This is linked to the relatively stable morphology of the Kasai watershed in this study section and the prevailing hydroclimatological conditions.

The study also demonstrates that granulometric parameters exhibit a jagged evolution from upstream to downstream along the middle course of the Kasaï River, from pk605 to pk525, with minimal overall variation. This suggests that different sand stocks are transported along the river's course. The granulometric evolution indicates inputs that are regular but minimal, as evidenced by the trend towards decreasing average grain size from upstream to downstream, as shown by geostatistical extrapolation using ArcGIS software.

In addition, the automated mineralogical analysis identified a mineralogical suite of 18 minerals present throughout the middle reaches of the Kasaï River. The suite is dominated by quartz (93.95% to 99.07%), followed by calcite (0.01 - 2.66%), iron oxides (0.01 - 1.88%), orthoclase (0.04 - 0.99%), plagioclase (0.01 - 0.75%), and kaolinite (0.18 - 0.71%). Other minerals, including illite, apatite, ilmenite, muscovite, chlorite, biotite, montmorillonite, rutile, pyrophyllite, siderite, zircon, and dolomite, are present but do not exceed 0.55% in concentration. These minerals were classified into resistant, imported primary minerals and neo-formed, low-resistance secondary minerals, based on their mechanical resistance to abrasion and chemical alteration.

The mineralogical evolution shows a sawtooth variation throughout the middle course of the Kasaï River, with two distinct trends: an increase in the content of certain minerals and a decrease in others. This variation can be attributed to the neoformation of secondary minerals from detrital material in the riverbed and to diagenetic processes, such as the formation of pyrophyllite associated with mixed chemical and fine detrital facies. Human activity in deforested areas may also contribute to mineral contributions from bank erosion. Orthoclase and plagioclase presence suggests contributions from detrital material rich in these minerals, such as arkosic sandstones and ancient feldspathic sediments in the southern Congolese basin.

Given that all these minerals fall within the same granulometric fraction (426.8 - 186.2 μm), their distribution reflects the variable hydrodynamics at the time of deposition. However, the spatial distribution of minerals in the sands may be closely linked to the riverbed morphology. For instance, minerals like zircon, iron oxides, rutile, ilmenite, apatite, and siderite may originate from upstream igneous rocks and ancient sediments that have undergone recycling.

This study provides a detailed account of the granulometric parameters and mineralogical composition of sands in the middle course of the Kasaï River, revealing the variability in sedimentary processes related to hydrodynamic conditions and riverbed morphology. This research contributes significantly to sedimentology and integrated river management. Future research should focus on the sources of sediments and sedimentation processes in the Kasaï basin, utilizing advanced technology for field data collection, analyzing geomorphological units, heavy minerals, sand grain characteristics, and conducting further geochemical analysis. It is also crucial to extend the study to include high-water periods and major tributaries to better understand sediment origins, dynamics, and navigation challenges in the Kasaï basin, given the socio-economic and environmental importance of this resource in the DRC's sustainable development.

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