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Characterisation of the Sediment Dynamics of the Sands of the Middle Course of the Kasai River (Territory of Ilebo, Province of Kasai/DR Congo)

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Abstract

The sand bars, in perpetual transformation, observable in the middle course of the Kasai river on the section between the city of Ilebo (pk605) to the confluence of the Loange river (pk525), pose enormous navigability problems. This may be dependent on hydrosedimentological characteristics of the Kasai River. This abundance of sand thus conditions the morphology of the middle course of the Kasai River in the section under our study. It therefore constitutes sedimentary navigation obstacles. The objective of this study is the granulometric and mineralogical characterization of the bar sands of the Kasai River in this study section. Particle size analyzes reveal these are moderately well classified to well classified unimodal sands (Classification coefficient between 1.29 to 1.742) largely presenting grain size symmetry and rarely fine asymmetry (Asymmetry coefficient—Skewness between −0.197 to 0.069) with mesorkurtic and rarely leptokurtic and platykurtic acuity (Angulosity coefficient—Kurtosis between 0.814 to 1.323). All these parameters evolve in sawtooth patterns from upstream to downstream. And then, an automated mineralogical analysis of the sands of the Kasaï River using a Qemscan FEG Quanta 650 made it possible to determine a very varied mineralogical procession with a sawtooth evolution. It is largely dominated by quartz (between 93.73% 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%). Finally, this mineralogical procession is characterized by a group of minerals which do not reach the threshold of 0.55% such as: illite, apatite, ilmenite, muscovite, chlorite, biotite, montmorillonite, rutile, pyrophyllite, siderite, zircon and dolomite. The evolution of the mineralogical procession of the sands of the bars is not as clear as in the case of particle size parameters.

Keywords

Characterization, Granulometric, Mineralogical, Sands, Middle Course, Kasai River

1. Introduction

The Kasai River, the main collector of the Kasai watershed, is the second most important natural communication route in the country after the Congo River in the Democratic Republic of Congo. This route acts as a relay between the southern railway (Ilebo—Lubumbashi) and the western railway (Kinshasa—Matadi) (Devroey, 1939). Moreover, in recent decades this river has faced several hydroclimatological and hydrosedimentological problems due to ecological imbalances caused by the destruction of the forest ecosystem in the Kasai basin (Kisangala 2014; Mushi et al., 2019; Laraque et al., 2020).

For Kisangala (2014) and Tshimanga et al. (2016), the navigability of the Kasai River and river navigation in the DRC in general pose some serious problems including the emergence of natural obstacles in certain specific passes, strandings and the decline wet which sometimes cause accidents.

Thus, the sand bars, in perpetual transformation, observable in the middle course of the Kasai River on the section between the city of Ilebo to the confluence of the Loange River, pose enormous navigability problems. This may be dependent on hydrosedimentological characteristics of the Kasaï River. This abundance of sand thus conditions the morphology of the middle course of the Kasai River in the section under our study. It therefore constitutes sedimentary navigation obstacles (Kisangala, 2008).

In addition, the work carried out as part of the implementation of a sediment sampling program on the Kasai River shows that this river with its tributaries represents the most sediment flows in the Congo River, also constitutes one of the main erosion hotspots in the Congo Basin with significant consequences for river navigation and hydroelectricity (Mushi et al., 2019; Mushi et al., 2022).

Hence the urgent need to carry out a study to determine the grain size and mineralogical characteristics of these sandy deposits blocking the entire middle and navigable course of the Kasai River, thus limiting the possibilities of navigation during the period of medium and low water. This can provide useful information on the characterization of the erosion process of the Kasai basin in the region under study, on its sedimentary dynamics and on the geological nature of the region from which these sands come.

Thus, the fundamental questions of this study are as follows:

- What is the particle size distribution of the sands transported by the Kasai River and their mineralogical characteristics?
- How to characterize the sedimentary dynamics of the Kasai River in the study region?

The hypotheses of the study are:

- The determination of the particle size and mineralogical distribution of sands, constituents of the major sedimentary obstacles to the navigability of the Kasai River, proves essential in the characterization of the process of regressive erosion of the Kasaï basin;
- All the results of the granulometric and mineralogical analysis of these sands, compared to the geological data of the watershed, will make it possible to understand the sedimentary dynamics of the Kasai River in this study region. The sands under study would result from a mixture of material coming from the upstream of the watershed, sediments resulting from the digging of its bed, the erosion of its banks and those probably coming from its tributaries.

The objective of this study is the granulometric and mineralogical characterization of the bar sands of the Kasai River in its middle and navigable course in the region located between the city of Ilebo and the confluence with the Loange River. It seeks to circumscribe the problem of navigability of the Kasai River in the silted areas of its middle course, the probable source of these sands but also their sedimentary dynamics by highlighting the relationship which would exist between the hydrosedimentological conditions and the evolution mineralogical processions of these sands on the section under study.

In addition, it should be noted that the work carried out by Trigg and Tshimanga (2020), Trigg et al. (2022a, 2022b) and that of Tshimanga et al. (2022) has shown that with limited information on the dynamics of the waters of the Congo basin and the Kasai its major tributary, it is difficult to realize the optimal benefit of the potential of this basin, and just as difficult to invest in the development of its water resources. Thus, forecasting navigation water levels and sediment dynamics constitute precise information necessary to provide adequate management strategies for these water resources.

This study is based more precisely on 2 axes:

- The study of the grain size evolution and variabilities of the physical conditions controlling sedimentary processes linked to the hydrodynamic regime of the Kasai River;
- The study of the evolution of the procession of minerals linked to the petrographic nature of the feeding areas whose distribution is clearly dependent on their mechanical resistance to abrasion and their resistance to chemical alteration.

2. Study Area

2.1. Location

The study environment is located in the territory of Ilebo, Kasai province in the

DRC. It is between 20˚02' and 20˚37' East longitude on the one hand and between 4˚15' and 4˚24' South latitude on the other hand.

This environment covers part of the section between Ilebo (pk605) and Kese (pk253) on the Kasai river which constitutes the main collector of the Kasai basin. The section under our study extends from the city of Ilebo (pk605) to the confluence of the Loange River (pk525), i.e. a length of approximately 80 km (Figure 1).

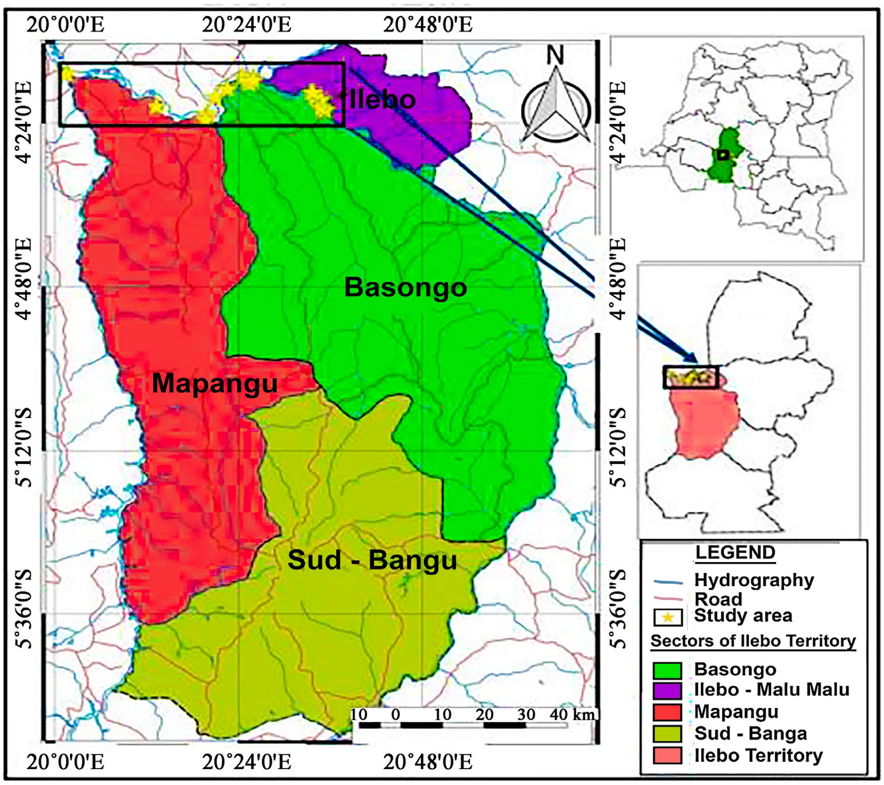


Figure 1. Location of the study area.

2.2. Geology of Ilebo

As a whole, the Ilebo territory is part of the Cretaceous Supra-Cenomanian (Cn) belonging to the Kwango group. These are Layers II of the Upper Kasai Series made up of locally argillite sandstones and conglomerates. However, in the Ilebo Malu-Malu sector but also in a large part of the middle course of the Kasai River, Layers I of the Upper Kasai Series belonging to the Bokungu group of Albian-Aptian age outcrop (Figure 2). They are also generally coherent sandstones, with beds of clayey sandstone or argillite, often micaceous, red or wine-colored, red-brown, containing ostracod and phyllopod fossils (Lepersonne, 1974).

According to this same author, all these formations are covered by recent formations (from the Quaternary). These are more or less clayey sands and silts, often red, sometimes associated with ironclads or layers of ferruginous grit, often with gravel at the base, occupying flattening areas and terraces.

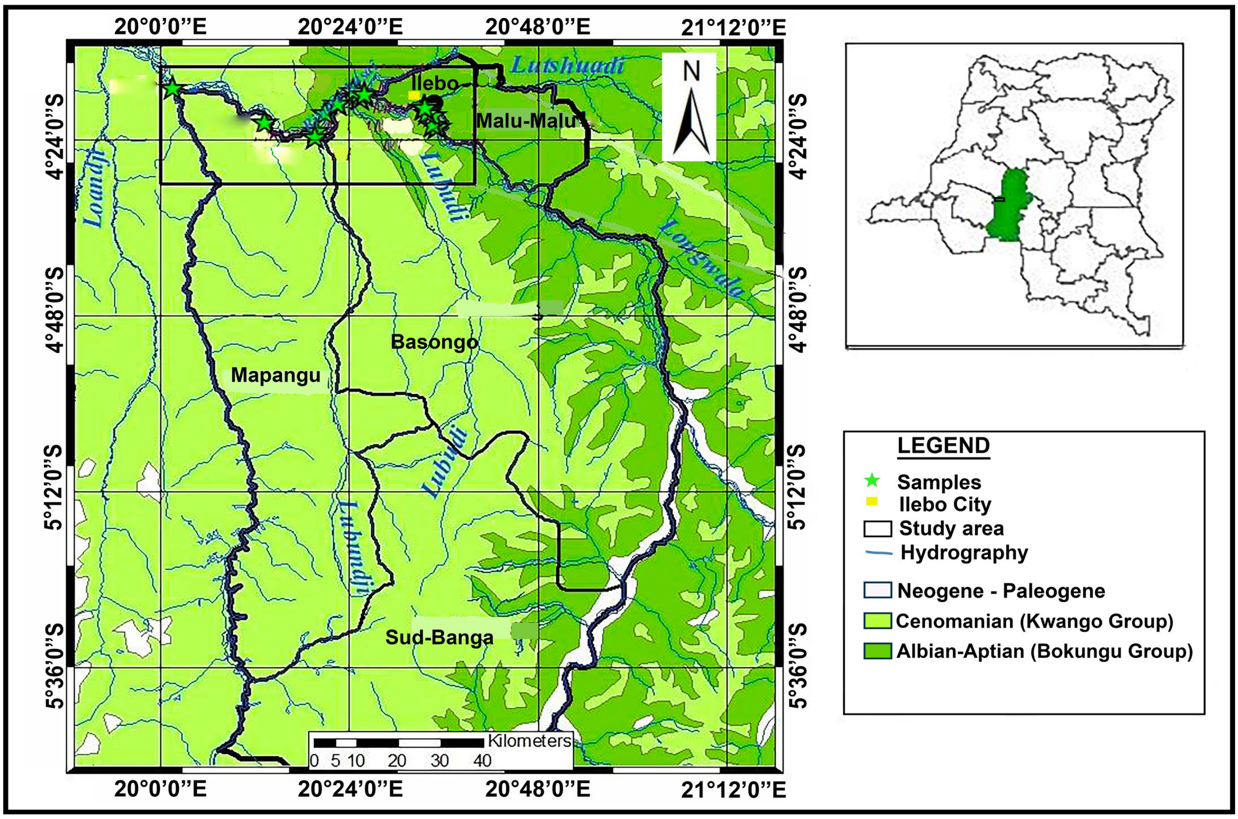


Figure 2. Geological map of the middle course of the Kasai River (Ilebo Territory).

3. Methodology

To achieve the objective assigned as part of this study, sand samples were taken during the recession period between June and July 2014. It is on this average, navigable course dotted with bars and sandy islands, in places, well developed that we took samples of sand spatially referenced between around 20 to 40 cm depth to avoid organic matter in cylindrical holes dug using a machete.

Thus, 20 sand samples taken as part of this study were the subject of a particle size analysis by sieving using an AFNOR type sieve column and by sedimentometry at the sedimentology and land geology laboratory superficial from the Department of Geosciences of the Faculty of Science and Technology of the University of Kinshasa. A spatial representation of the sampling points is shown in Figure 3. This makes it possible to distinguish three (3) zones of concentration of sand bars:

- The zone of high concentration (Samples MK1-12): this zone starts from the locality of Kazaba about 8 kilometers downstream from the confluence of the Lutshuadi river. It is dominated by the Ilebo Pool (km 605) whose bottom is exclusively sandy (Devroey, 1939);
- The medium concentration zone (Samples MK13-16): this area around the confluence of the Sankuru River a few kilometers upstream of Basongo. This area would be characterized by a mixture of sand carried by the Sankuru River;

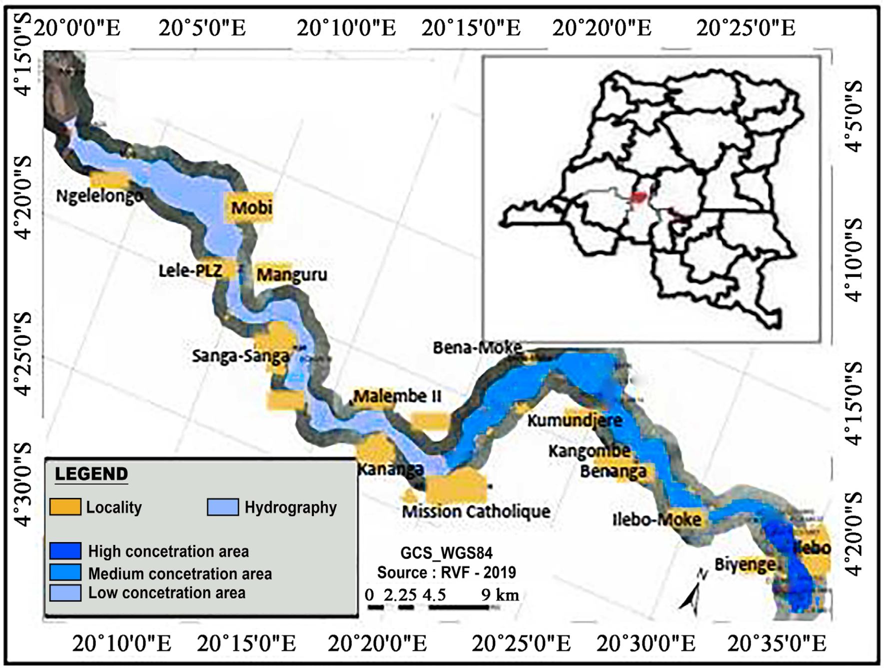


Figure 3. Geolocation of Kasai bar sand concentrations zones.

- The zone of low concentration (Samples MK17-20): it is located between Basongo and the confluence of the Loange river. This area has an average spacing of around 7 km between the observed bars. It is in this area that the Loange River brings its reddish sandy alluvium to the left bank at the borders of our study section.

The usual particle size parameters analyzed are mean size, mode, median, classification coefficient or standard deviation (SD), asymmetry coefficient or skewness (Ski) and acuity or kurtosis (KG).

To calculate these parameters, we used the method of (Folk, 1954; Folk & Ward, 1957). Using the Gradistat v8.0 application allowed us to calculate these statistical parameters and the resulting descriptions.

In addition, 6 of the sand samples were subject to automated mineralogical analysis with a Qemscan FEG Quanta 650 from the Qemscan laboratory of the earth sciences department of the University of Geneva. The results for different minerals detected are as a percentage of the mass of the sample analyzed and the size of each mineral grain in μm.

Note that the Qemscan FEG Quanta 650 is an automated mineralogy device which consists of a scanning electron microscope (SEM) equipped with two energy dispersive a map of polished sections. Mineral recognition is performed on each measured point (corresponding to an elementary image of the image) by matching the brightness of the backscattered electrons (ESB or BSE) and the low number energy dispersive X-ray spectra thus obtained (Pirrie et al., 2004).

Then, we used Sternberg's law (1875) and a mineral classification scale taking into account their mechanical resistance to abrasion (Freise, 1931; Thiel, 1945) and their chemical resistance to alteration (Pettijohn, 1941; Morton & Hallsworth, 1994).

Certain statistical operations have made it possible to process and analyze digital data relating to different processes. All the bibliographic contributions made up of all the scientific literature concerning the region and the theme of the study have made it possible to support our arguments, our interpretations and our discussions regarding the origin of the bar sands of the middle course of the Kasai and the sedimentary dynamics of the middle Kasai basin. These are based on the granulometric and mineralogical evolution of the sands of the middle course of the Kasai River.

4. Results

4.1. Evolution des Differents Paramettres Granulometriques

The sand samples from the sandy bars and islands which allowed this study to be carried out were carried out during the period of recession between June and July 2014. Due to the fact that, during the recession, the sand is deposited at the level of the bars (Censier, 1996).

The 20 sand samples were taken from upstream to downstream of the middle course of the Kasai River (between the city of Ilebo and the confluence with the Loange River) following a spacing between samples of 2 to 5 km or even more. This spacing was carried out according to the number and arrangement of the sand bars observed.

Thus, after sieving and sedimentometry of these sand samples, the results obtained were processed using the Gradistat v8.0 application (Blott & Pye, 2010). This application made it possible to determine the particle size parameters of the sands studied in particular: the mean, the median, the mode, the classification index (standard deviation), the asymmetry (the skewness) and the angulosity—acuity (the kurtosis). These results are recorded in **Table 1**, below.

Table 1. Particle size parameters of sands from the middle course of the Kasai.

N° ECH.	Particle size parameters	Folk and Ward method		Descriptions
		Geometric µm	Logarithmic ø	
MK1	Average	289.4	1.789	Medium sand
	Median	292.6	1.158	
	Fashion	302.5	1.747	
	Ranking	1.420	0.506	Moderately well ranked
	Skewness	−0.087	0.087	Symmetrical
	Kurtosis	1.072	1.072	Mesokurtic
MK2	Average	201.8	2.309	Fine sand
	Median	207.4	2.269	
	Fashion	215.0	2.237	

Continued

	Ranking	1.293	0.370	Well ranked
	Skewness	−0.098	0.098	Symmetrical
	Kurtosis	1.323	1.323	Leptokurtic
MK3	Average	219.6	2.187	Fine sand
	Median	221.9	2.172	
	Fashion	215.0	2.237	
	Ranking	1.585	0.664	Moderately well ranked
	Skewness	−0.023	0.023	Symmetrical
	Kurtosis	0.969	0.969	Mesokurtic
MK4	Average	323.5	1.628	Medium sand
	Median	318.2	1.652	
	Fashion	302.5	1.747	
	Ranking	1.375	0.460	Well ranked
	Skewness	0.038	−0.038	Symmetrical
	Kurtosis	1.030	1.030	Mesokurtic
MK5	Average	279.0	1.842	Medium sand
	Median	288.6	1.793	
	Fashion	302.5	1.747	
	Ranking	1.326	0.407	Well ranked
	Skewness	−0.135	0.135	Fine asymmetry
	Kurtosis	1.279	1.279	Leptokurtic
MK6	Average	188.1	2.410	Fine sand
	Median	195.8	2.353	
	Fashion	215.0	2.237	
	Ranking	1.324	0.405	Well ranked
	Skewness	−0.154	0.154	Fine asymmetry
	Kurtosis	1.044	1.044	Mesokurtic
MK7	Average	256.2	1.964	Medium sand
	Median	251.9	1.989	
	Fashion	215.0	2.237	
	Ranking	1.551	0.634	Moderately well ranked
	Skewness	0.039	−0.039	Symmetrical
	Kurtosis	0.952	0.952	Mesokurtic
MK8	Average	344.3	1.538	Medium sand
	Median	339.7	1.558	

Continued

	Fashion	302.5	1.747	
	Ranking	1.378	0.463	Well ranked
	Skewness	0.033	−0.033	Symmetrical
	Kurtosis	1.024	1.024	Mesokurtic
MK9	Average	270.2	1.888	Medium sand
	Median	280.3	1.835	
	Fashion	302.5	1.747	
	Ranking	1.326	0.407	Well ranked
	Skewness	0.038	−0.038	Fine asymmetry
	Kurtosis	1.030	1.030	Mesokurtic
MK10	Average	426.8	1.228	Medium sand
	Median	439.5	1.186	
	Fashion	427.5	1.247	
	Ranking	1.439	0.525	Moderately well ranked
	Skewness	−0.197	0.197	Fine asymmetry
	Kurtosis	1.016	1.016	Mesokurtic
MK11	Average	325.7	1.619	Medium sand
	Median	321.2	1.638	
	Fashion	302.5	1.747	
	Ranking	1.382	0.466	Well ranked
	Skewness	0.006	−0.006	Symmetrical
	Kurtosis	1.047	1.047	Mesokurtic
MK12	Average	240.0	2.059	Fine sand
	Median	244.1	2.035	
	Fashion	302.5	1.747	
	Ranking	1.428	0.514	Moderately well ranked
	Skewness	−0.105	0.105	Symmetrical
	Kurtosis	1.094	1.094	Mesokurtic
MK13	Average	238.4	2.069	Fine sand
	Median	244.4	2.033	
	Fashion	302.5	1.747	
	Ranking	1.480	0.566	Moderately well ranked
	Skewness	−0.052	0.052	Symmetrical
	Kurtosis	1.022	1.022	Mesokurtic

Continued

MK14	Average	305.7	1.710	Medium sand
	Median	306.2	1.707	
	Fashion	302.5	1.747	
	Ranking	1.427	0.513	Moderately well ranked
	Skewness	−0.076	0.076	Symmetrical
	Kurtosis	1.229	1.299	Leptokurtic
MK15	Average	198.8	2.331	Fine sand
	Median	202.1	2.307	
	Fashion	215.0	2.237	
	Ranking	1.569	0.650	Moderately well ranked
	Skewness	−0.058	0.058	Symmetrical
	Kurtosis	0.865	0.865	Platykurtic
MK16	Average	293.0	1.771	Medium sand
	Median	292.0	1.776	
	Fashion	302.5	1.747	
	Ranking	1.404	0.490	Well ranked
	Skewness	0.009	−0.009	Symmetrical
	Kurtosis	0.957	0.957	Mesokurtic
MK17	Average	186.2	2.425	Fine sand
	Median	194.1	2.365	
	Fashion	215.0	2.237	
	Ranking	1.322	0.403	Well ranked
	Skewness	−0.195	0.195	Fine asymmetry
	Kurtosis	1.029	1.029	Mesokurtic
MK18	Average	193.0	2.373	Fine sand
	Median	189.7	2.398	
	Fashion	215.0	2.237	
	Ranking	1.602	0.680	Moderately well ranked
	Skewness	0.069	−0.069	Symmetrical
	Kurtosis	0.965	0.965	Mesokurtic
MK19	Average	202.6	2.304	Fine sand
	Median	219.5	2.187	
	Fashion	302.5 107.5	1.747 3.237	
	Ranking	1.742	0.800	Moderately rated

Continued

	Skewness	−0.177	0.177	Fine asymmetry
	Kurtosis	0.814	0.814	Platykurtic
MK20	Average	192.3	2.378	Fine sand
	Median	189.3	2.401	
	Fashion	215.0	2.237	
	Ranking	1.606	0.683	Moderately well ranked
	Skewness	0.066	−0.066	Symmetrical
	Kurtosis	0.967	0.967	Mesokurtic

Source: Created from results from the Sedimentology and Surface Geology Laboratory of the Department of Geosciences, Faculty of Science & Technology of Unikin (2015).

Indeed, the evolution of grain size parameters of sand bars of the Kasai River is summarized as follows (**Figure 4**).

These results show that the sands of the middle course of the Kasai River are fine to medium sands extending in the particle size fraction located between 186.2 µm and 426.8 µm. These are moderately well-classified to well-classified unimodal sands (Classification Coefficient between 1.29 to 1.742) largely presenting grain-size symmetry and rarely fine asymmetry (Asymmetry Coefficient—Skewness between −0.197 to 0.069) with mesorkurtic sharpness and rarely lepto and platykurtic acuity (Angulosity coefficient—Kurtosis between 0.814 to 1.323).

The evolution of these particle size parameters is not clear. This evolution is sawtooth from pk605 to pk525 and can be summarized as follows:

- In the zone of high concentration of sand bars (Samples MK1-12), the sands tend to be more and more average, and more and more well classified. This area is dominated by the Ilebo Pool, the bottom of which is exclusively sandy according to Devroey (1939);
- In the zone of medium and low concentration of sand bars (Samples MK13-16 and MK17-20), the sands are increasingly fine and increasingly moderately well graded to moderately graded.

In addition, it should be noted that these sands tend to present an increasingly symmetrical grain size and an increasingly mesorkurtic angulosity throughout the study region from pk605 to pk525. There is no clear evolution and in any case this evolution is always up and down.

4.2. Mineralogical Evolution

6 samples of bar sands from the Kasaï River were subjected to automated mineralogical analysis using a QEMSCAN FEG Quanta 650 from the QEMSCAN laboratory of the Department of Earth Sciences of the University of Geneva.

Quantitative mineral identification by QEMSCAN (Quantitive Evaluation Mineral by SCANning—SEM/EDS) made it possible to determine the mineralogical procession of the sands of the Kasai River which includes 18 minerals including:

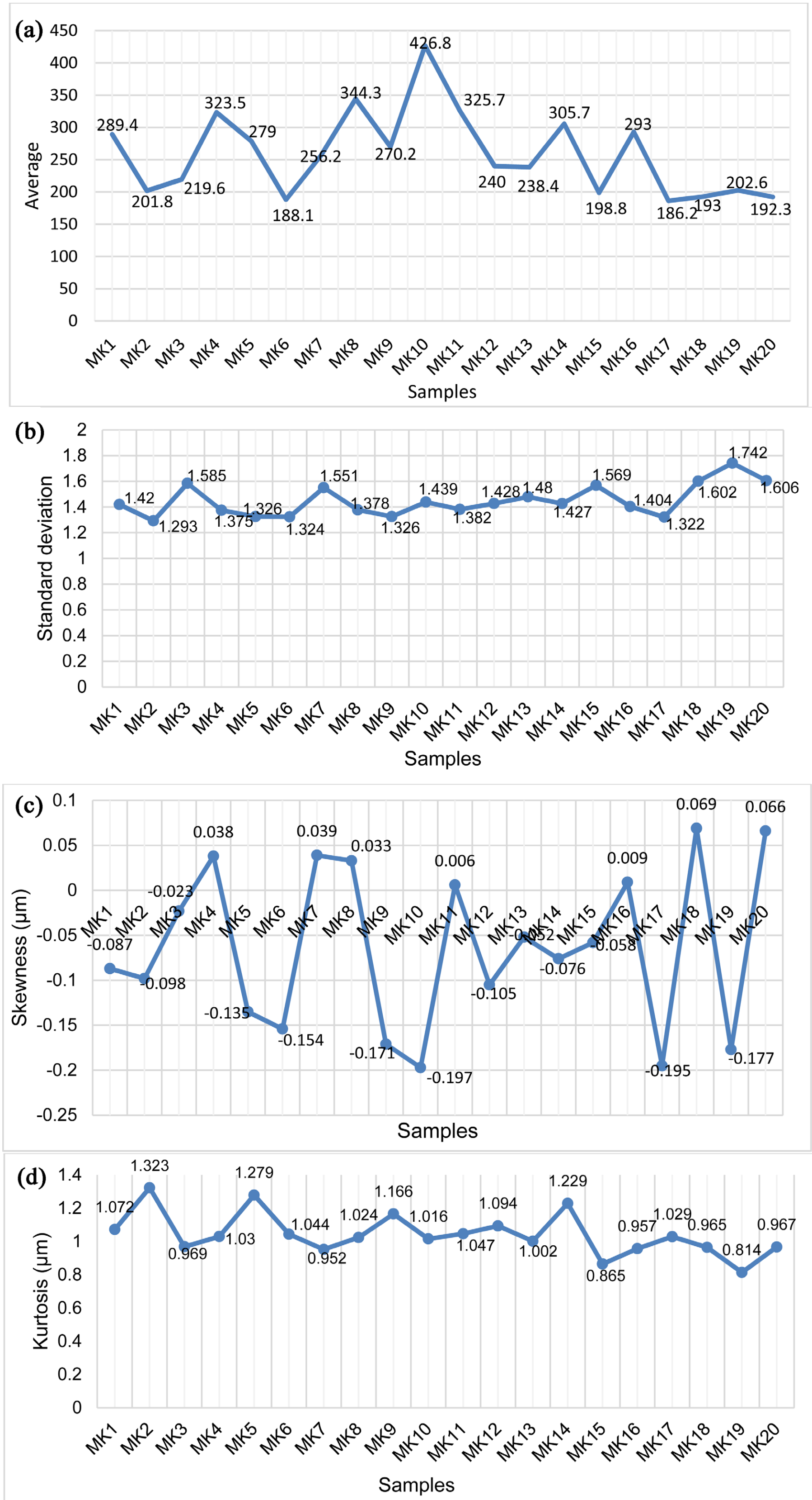


Figure 4. Evolution of particle size parameters of bar sands from the Kasai River ((a) Average; (b) Standard deviation (SD), (c) Skewness and (d) Kurtosis).

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

The percentage contents of these minerals in the sand samples from the Kasai River are recorded in Table 2, below:

Table 2. Percentage content (%) of minerals in the sands of 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
Orthosis	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
Iron oxides	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
Ilmenite	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
Siderite	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

Source: Created from the results of the QMESCAN Laboratory of the Department of Earth Sciences of the University of Geneva (2017).

Depending on their densities, these minerals can be classified as follows (Figure 5).

Thus, the mineralogical evolution of the sands of the bars of the Kasai River is summarized in Figure 6, below.

The mineralogical procession of sands from the bars of the Kasai River is very varied. It is largely dominated by quartz (between 93.73% 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%). Finally, it is

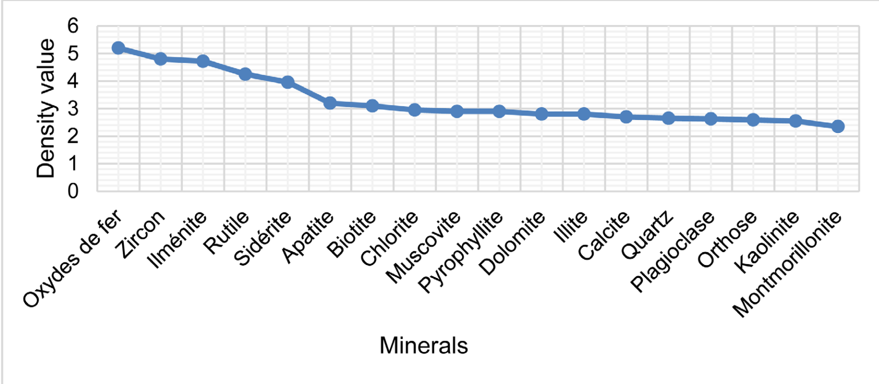


Figure 5. Minerals in the sands of the Kasaï River according to their densities.

characterized by a group of minerals that do not reach the threshold of 0.55% such as: illite, apatite, ilmenite, muscovite, chlorite, biotite, montmorillonite, rutile, pyrophyllite, siderite, zircon and dolomite.

The evolution of the mineralogical procession of the sands of the bars of the Kasai River is not as clear as in the case of particle size parameters. This mineralogy presents a sawtooth variation despite the action of transport, their density and their resistance with two trends from pk 605 to pk525 (**Figure 6**).

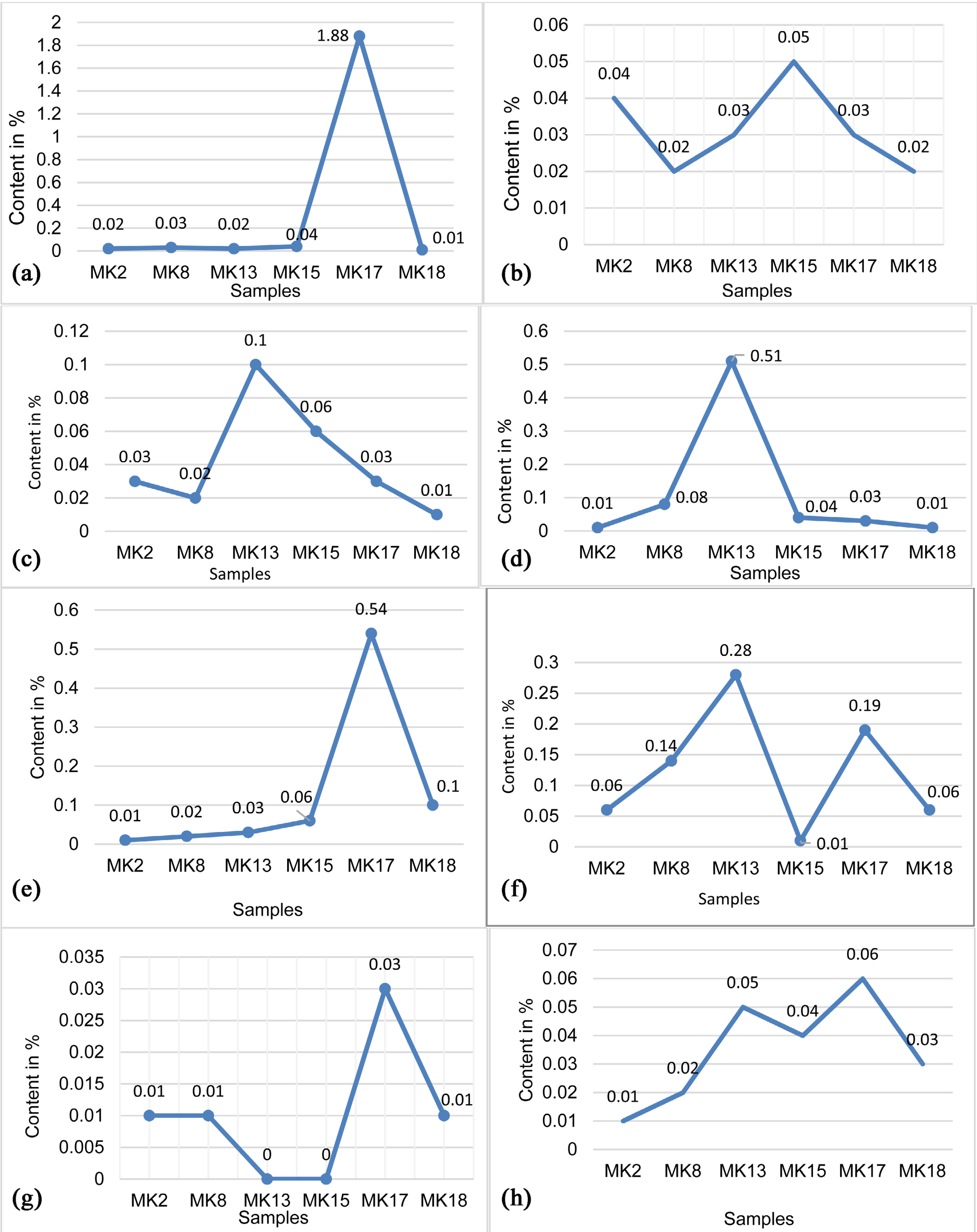
- A trend towards an increase in the content of certain minerals, particularly with minerals such as iron oxides, rutile, siderite, apatite, chlorite, muscovite, pyrophyllite, dolomite, illite, calcite and kaoli-nite.
- A tendency to decrease the content of the remaining minerals: zircon, ilmenite, biotite, quartz, plagioclase, orthoclase and montmorillonite.

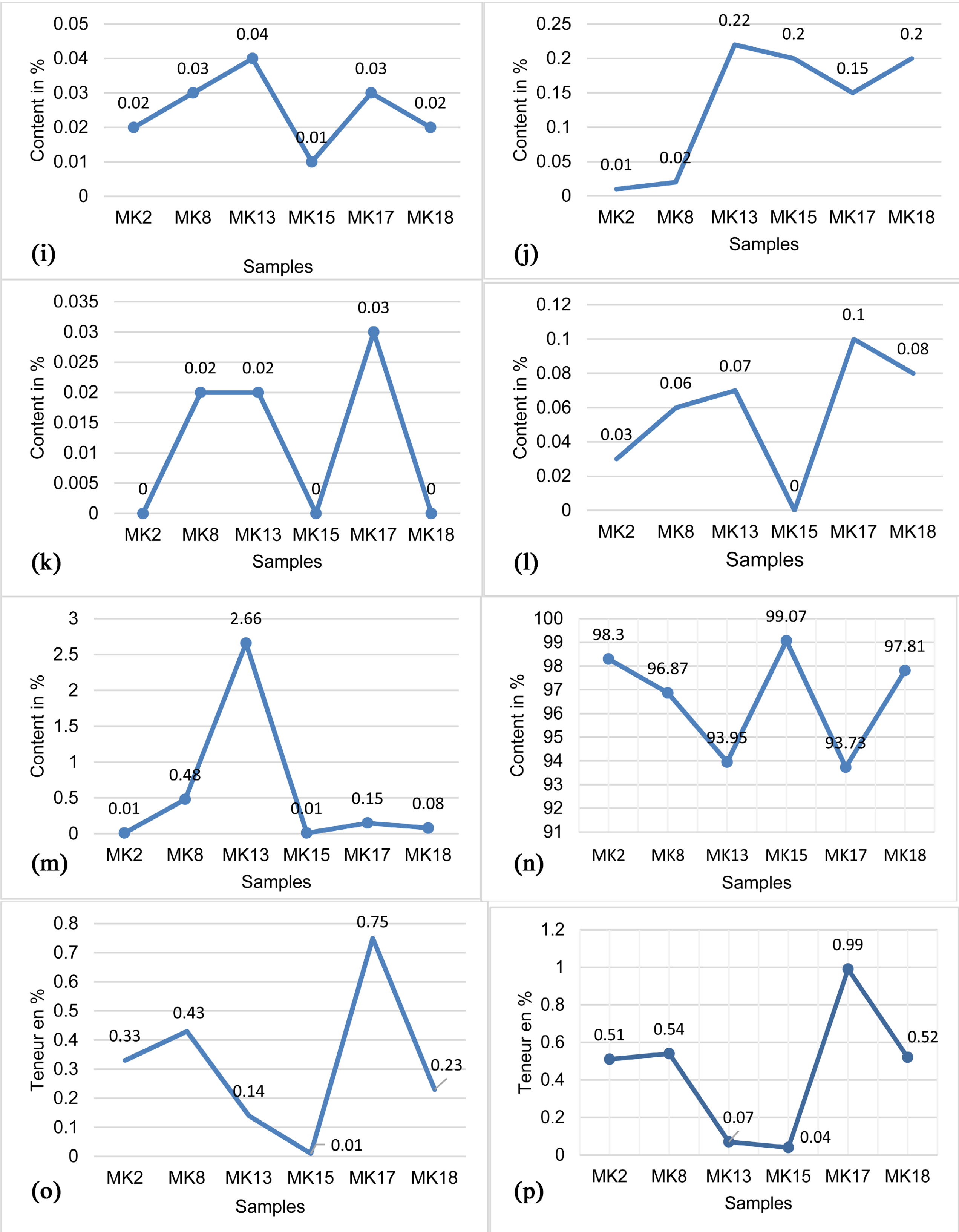
To the extent that all these minerals belong to the same particle size fraction, their distribution according to their density reflects the difference in variable hydrodynamics at the time of deposition of the sands on the bars (Censier, 1996).

5. Discussions

For Censier (1996), Chamley and Deconinck (2011), Gandhi & Raja (2014), Mushi et al. (2019), Tine et al. (2022), the grain size evolution of sediments transported by a river is therefore essentially linked to processes occurring at the level of the course of this river including the action of transport, fragmentation, abrasion of grains and sedimentation. In the same way, this statement can be rejected for the sands of the course middle of the Kasai River.

Of the evolution of particle size parameters, we think with Sternberg's law (1875) and the assertions raised by Chamley and Deconinck (2011) regarding the comparison of particle size parameters specific to various samples from the same series or from the same sedimentary level as the elements transported by a watercourse are progressively finer and finer and tend to be better and better classified. However, the granulometric evolution of the sands of the Kasai River does not confirm this law nor 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**).


(a)
Content in %
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.02
0.03
0.02
0.04
1.88
0.01
MK2 MK8 MK13 MK15 MK17 MK18
Samples
(b)
Content in %
0.06
0.05
0.04
0.03
0.02
0.01
0
0.04
0.02
0.03
0.05
0.03
0.02
MK2 MK8 MK13 MK15 MK17 MK18
Samples
(c)
Content in %
0.12
0.1
0.08
0.06
0.04
0.02
0
0.03
0.02
0.1
0.06
0.03
0.01
MK2 MK8 MK13 MK15 MK17 MK18
Samples
(d)
Content in %
0.6
0.5
0.4
0.3
0.2
0.1
0
0.01
0.08
0.51
0.04
0.03
0.01
MK2 MK8 MK13 MK15 MK17 MK18
Samples
(e)
Content in %
0.6
0.5
0.4
0.3
0.2
0.1
0
0.01
0.02
0.03
0.06
0.54
0.1
MK2 MK8 MK13 MK15 MK17 MK18
Samples
(f)
Content in %
0.3
0.25
0.2
0.15
0.1
0.05
0
0.06
0.14
0.28
0.01
0.19
0.06
MK2 MK8 MK13 MK15 MK17 MK18
Samples
(g)
Content in %
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0.01
0.01
0
0
0.03
0.01
MK2 MK8 MK13 MK15 MK17 MK18
Samples
(h)
Content in %
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.01
0.02
0.05
0.04
0.06
0.03
MK2 MK8 MK13 MK15 MK17 MK18
Samples


Content in %
0.05
0.04
0.03
0.02
0.01
0
0.02
0.03
0.04
0.01
0.03
0.02
MK2 MK8 MK13 MK15 MK17 MK18
(i)
Samples
Content in %
0.25
0.2
0.15
0.1
0.05
0
0.01
0.02
0.22
0.2
0.15
0.2
MK2 MK8 MK13 MK15 MK17 MK18
Samples
(j)
Content in %
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
0.02
0.02
0
0.03
0
MK2 MK8 MK13 MK15 MK17 MK18
(k)
Samples
Content in %
0.12
0.1
0.08
0.06
0.04
0.02
0
0.03
0.06
0.07
0
0.1
0.08
MK2 MK8 MK13 MK15 MK17 MK18
(l)
Samples
Content in %
3
2.5
2
1.5
1
0.5
0
0.01
0.48
2.66
0.01
0.15
0.08
MK2 MK8 MK13 MK15 MK17 MK18
(m)
Samples
Content in %
100
99
98
97
96
95
94
93
92
91
98.3
96.87
93.95
99.07
93.73
97.81
MK2 MK8 MK13 MK15 MK17 MK18
(n)
Samples
Teneur en %
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.33
0.43
0.14
0.01
0.75
0.23
MK2 MK8 MK13 MK15 MK17 MK18
(o)
Samples
Teneur en %
1.2
1
0.8
0.6
0.4
0.2
0
0.51
0.54
0.07
0.04
0.99
0.52
MK2 MK8 MK13 MK15 MK17 MK18
(p)
Samples

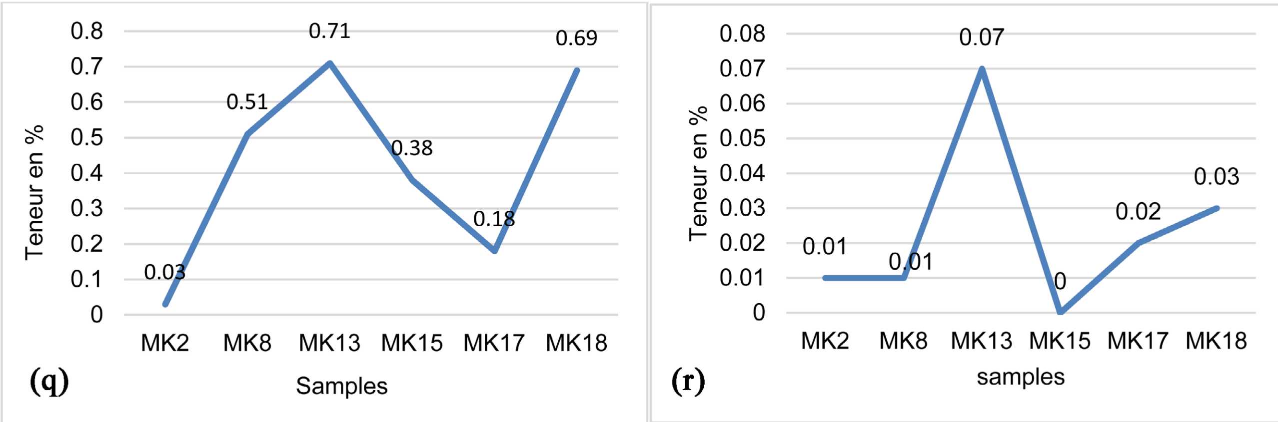


Figure 6. Mineralogical evolution of the sands of the Kasai River (in %): ((a) Iron oxides, (b) Zircon, (c) Ilmenite, (d) Rutile, (e) Siderite, (f) Apatite, (g) Biotite, (h) Chlorite, (i) Muscovite, (j) Pyrophyllite, (k) Dolomite, (l) Illite, (m) Calcite, (n) Quartz, (o) Plagioclase, (p) Orthoclase, (q) Kaolinite and R: Montmorillonite.

We are witnessing a sawtooth evolution of particle size parameters from pk 605 to pk 525, while overall, their size varies little. This development demonstrates that it is not the same stock of sand that is transported all along the middle course of the Kasai River. This granulometric approach demonstrates that there are contributions, which moreover, are more or less regular given the relative regularity of the granulometric variations which, moreover, still reveal a tendency towards a reduction in the average size of the grains of upstream to downstream by geostatistical extrapolation using ArcGis software.

Regardless, it should be noted that the sands of the middle course of the Kasai River are fine (125 - 250 µm) to medium (250 - 500 µm) unimodal sands extending in the grain size fraction located between 186.2 µm and 426.8 µm. These sands are moderately well graded to well graded, largely exhibiting grain size symmetry and rarely fine asymmetry with mesorkurtic sharpness and rarely leptokurtic and platykurtic sharpness. All these parameters show an evolution that is not clear and seesaw from upstream to downstream (**Figure 4**).

This probably reflects, according to Folk and Ward (1957), Thomas, Kemp and Lewis (1972), Cojan and Renard (2006), Chamley and Deconinck (2011), a mixture of predominantly elements from an original population more or less distant (allochthonous) with nearby (autochthonous) elements which could have been deposited in an almost calm and regular environment.

Also, the work carried out by Touré et al. (2016), Moukandi N'kaya et al. (2021), Tine et al. (2022) show that the homogeneity and good classification of sands explain the regularity and the low energy intensity of transport and deposition currents. Sediment size plays 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 sedimentation made by free accumulation, that is to say a deposition which took place due to a banal and moderate variation in the competence of the transport current which remains in the present case is clearly linked to the little variable morphology of the watershed in this study section (Kisangala, 2014, Mushi et al., 2019; Mushi et al., 2022). Then, on the based on scales of mechanical resistance to abrasion (Freise, 1931; Thiel, 1940, 1945) and chemical resistance to alteration (Pettijohn, 1941; Dryden & Dryden, 1946; Cailleux & Tricart, 1959; Friis, 1974; Morton, 1985; Morton & Hallsworth, 1994), the minerals of the middle Kasai sands can be classified as:

- Resistant and imported so-called primary minerals: zircon, quartz, orthoclase, plagioclase, iron oxides, rutile, ilmenite, apatite, siderite, dolomite, calcite, muscovite and biotite.
- Newly formed and weakly resistant so-called secondary minerals: kaolinite, chlorite, illite, montmorillonite and pyrophyllite.

Taking into account Sternberg's law (1875), the mineralogical processions of the sands of a river go from upstream to downstream, becoming depleted in weakly resistant minerals and relatively enriched in resistant minerals.

Thus, as illustrated in **Figure 6**, the increases in the percentages of certain newly formed and weak minerals such as kaolinite, chlorite, illite, montmorillonite and pyrophyllite in the Kasai sands from upstream to downstream would be consecutive to the contributions in a neoformation by the alteration of the minerals contained in the southern detrital formations of the Congolese basin but also in a diagenetic neoformation as in the case of pyrophyllite which is often associated with salts linked to mixed chemical facies at fine detrital, located in the deep areas of the basins as highlighted in the work carried out by Chennaux et al. (1967).

We can note that the granulometric and mineralogical evolution of the sands of the middle course of the Kasai river in our study region could be explained by admitting contributions in the neoformation of secondary minerals originating from detrital material on the bed of the course. middle of the Kasai rich in minerals quite labile to alteration such as orthoclase, plagioclase, muscovite, biotite and as for pyrophyllite in the diagenetic neoformation linked to the mixed chemical facies with fine detrital of the deep zones of the basins but also to to a lesser extent those coming from the erosion of the banks in this denuded region of rainforest and dense humid evergreen forest by anthropogenic activities including changes in land use upstream and the increase in mining as suggested by Mushi et al. (2019).

Note with Best (1987) and Chaumont et al. (1994) that for a mineral to reflect the origin of the particles, its physical properties must be as close as possible to those of all the particles in the bed. Thus, in this study, potassium feldspars (Orthose) and calc-sodium feldspars (Plagioclase) are more effective since they have a structure and density similar to those of quartz, a mineral which dominates the mineralogical procession of sand particles from bars of the Kasai River. The presence of these minerals would be the result of detrital materials rich in these minerals such as arkosic sandstones, ancient feldspathic sediments from the southern part of the Congolese basin.

However, the spatial variations of minerals detected in the sands of the middle course of the Kasaï River can be closely linked to the morphology of the bed of the said river. Minerals such as zircon, iron oxides, rutile, ilmenite, apatite and siderite could come from igneous rocks of acidic and basic compositions in the region upstream of the Kasai basin. Likewise, these minerals can be linked to ancient sediments which have undergone recycling, as highlighted in the work carried out by Chaumont et al. (1994).

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

6. Conclusion

With a length of 2000 km from its source in Angola to its outlet at Kwamouth, with its 789 km waterways from Kwamouth to Ndjoku Punda (Charlesville) via Ilebo (pk605) and the second most important river communication route in the country, the Kasai River is dotted with sandy bars and islands, in places, well developed, on its section between the city of Ilebo and the confluence of the Loange River (pk525), i.e. a length of approximately 80 km.

Thus, the granulometric and mineralogical evolution of the sands of the middle course of the Kasaï river from the port city of Ilebo to the confluence with Loange makes it possible to circumscribe the origin of the sands and the sedimentary dynamics of the middle Kasai basin.

This development demonstrates that it is not the same stock of sand that is transported all along the middle course of the Kasaï River. These sands come mainly from the upstream of the watershed to which are added sands resulting largely from the alteration and erosion of the Cretaceous sandstone and sandstone-conglomeratic formations of the upper part of the Sankuru Supergroup but also from ancient sediments recycled from the southern part of the Congolese basin. This granulometric and mineralogical approach demonstrates that there are contributions, which moreover are more or less regular given the relative regularity of the granulometric and also mineralogical variations of the sands under study. Moreover, the variations are closely linked to the hydrodynamic and hydromorphological conditions of the Kasai basin.

In addition, this large quantity of sand obstructs the entire navigable middle course of the Kasaï River on our study section, thereby reducing the possibilities of navigation during the medium and low water periods. The spatial representation of the sampling points makes it possible to distinguish three (3) zones of concentration of sand bars in the middle Kasai: The zone of high concentration, the zone of medium concentration and the zone of low concentration.

It should be noted that the first zone is the section that is quite difficult to navigate due to the high concentration of sand bars, especially during low water periods when these sand bars widen to benefit the downstream wetlands. These sandbanks are constantly wandering and constitute obstacles on the navigation pass, thus limiting the possibilities of navigation at the Ilebo pool area. This large quantity of sand is to a lesser extent linked to the specific degradation of the banks, that is to say to the process of regressive erosion of the Kasai basin.

From the above, the Congolese State must work hard to better understand the factors acting in the Kasai sub-basin, which will make it possible to better define the origin of the sediments (bottom load and suspended matter), to evaluate the specific solid flows and the rate of bank erosion on the Kasai River.

Conflicts of Interest

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

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