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Sedimentology and prediction of the sand dynamics of the buyo dam lake using the Hjulström model

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Abstract

The objective of this study aims to characterize the sedimentation and mode of transport of sandy sediments in Lake Buyo. The granulometric, morphoscopic and mineralogical analyzes of the surface sediments from the bottom of the lake collected in March 2021 and the use of the Hjulström model, made it possible to determine the sedimentological characteristics and predict the sedimentary processes in the lake. The sedimentological study makes it possible to identify four lithological facies: sands, muds, gravels and mixed sediments. Sands and gravels are the most abundant, with a predominance of sub-angular forms (75.37%). The sands are mainly very poorly classified and transported by saltation (67%). The mineralogical procession consists of garnet, pyroxene, quartz, muscovite, feldspar, limonite and biotite. During the hydrological seasons, the waters of the lake are very calm in the vicinity of the flood spillway and favor the settling of most of the sandy particles present in the water column. The water intake area is where there is a high chance of remobilization or erosion of sand (coarse to fine).

Keywords: Sedimentology; Morphoscopy; Mode of transport; Hjulström model; Lake Buyo

1. Introduction

Continental waters, and dammed lakes in particular, are resources with major strategic implications for the economy and the environment. Hydroelectric dams are built to fulfill one or more functions, in particular the production of hydroelectric power, irrigation and water supply. As part of its energy policy, the Ivorian government has undertaken the construction of seven (7) major hydroelectric dams (Kossou, Buyo, Taabo, Ayamé 1 & 2, Fayé and Soubré). The lakes in these dams are home to a diverse range of fauna and promote the development of trade, agriculture and fishing. However, the reservoirs of these dams are increasingly faced with hydrosedimentary problems. Studies have shown that these reservoirs are threatened by problems of silting and silting up (Kouassi, 2007; Konan *et al.*, 2022). In addition, Furthermore, deforestation and intense agricultural activities would encourage erosion phenomena upstream of these water reservoirs (Koua, 2014). Likewise, the transport of sediments which causes the addition of nutrients accelerates the process of siltation, siltation and eutrophication of lakes.

Lake Buyo does not remain on the side-lines of all these listed problems (Fig. 1). Despite the dangers inherent in filling the lake over time, no sedimentological study has been carried out. Indeed, sedimentological data are not available and this does not make it possible to know the origin, nature and spatial distribution of sediments in the reservoir (Mélèdje, 2014). However, sedimentation phenomena could have negative impacts on the structures, in particular the reduction

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of water storage capacity and the obstruction of valves (Kouassi, 2007). Faced with this state of affairs, the determination of the sedimentological characteristics appears to be an essential aspect of the sustainable management of the Buyo dam. The present study based on granulometric, mineralogical and morphoscopic analyses aims to characterize the sedimentation of the downstream sector of Lake Buyo.

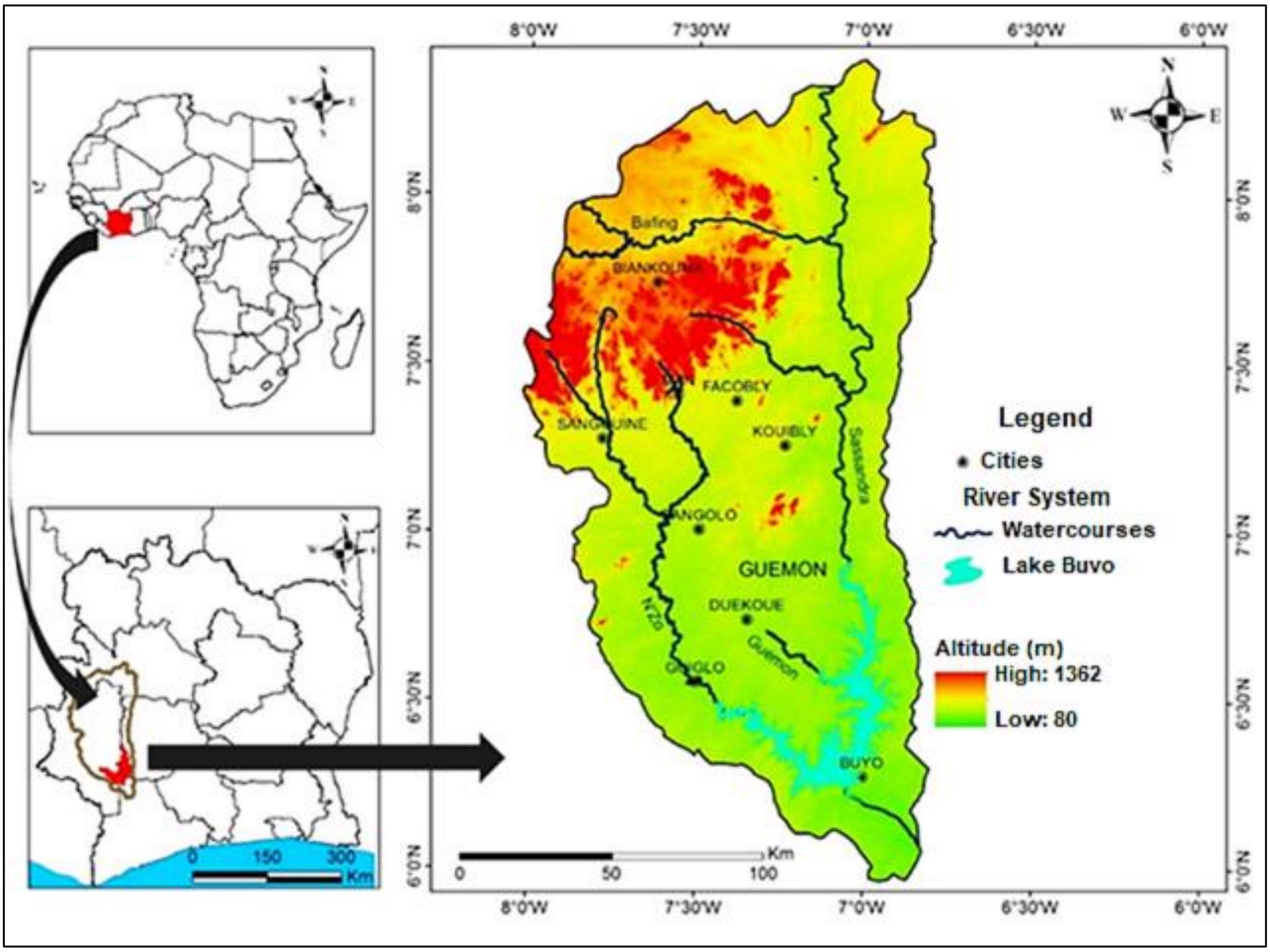

Figure 1 Location of Lake Buyo

2. Methodology

2.1. Study area

Lake Buyo, the study area is located in the southwest of Ivory Coast, 513 km from Abidjan. It owes its existence to the construction of a hydroelectric dam in 1980 on the region's main river, the Sassandra, whose average surface area is estimated at 600 km^2. Lake Buyo is between 06°54' and 07°31' west longitude and 01°14' and 07°03' north latitude. It constitutes the second hydroelectric lake in Ivory Coast after that of Kossou with an area of 920 km^2 and a catchment area of 75,000 km^2. The water reservoir, object of investigation is the downstream sector of Lake Buyo, the Buyo zone, corresponding to the lake zone of the reservoir, created by the hydroelectric installations of the Ivorian Electricity Company (CIE). The hydrological regime of the lake depends on that of the Sassandra river.

2.2. Sediment sampling

For the sedimentological study, twenty-one (21) sediment samples were taken using a Van Veen grab. A Garmin type GPS was used to determine the positions of the sampling points.

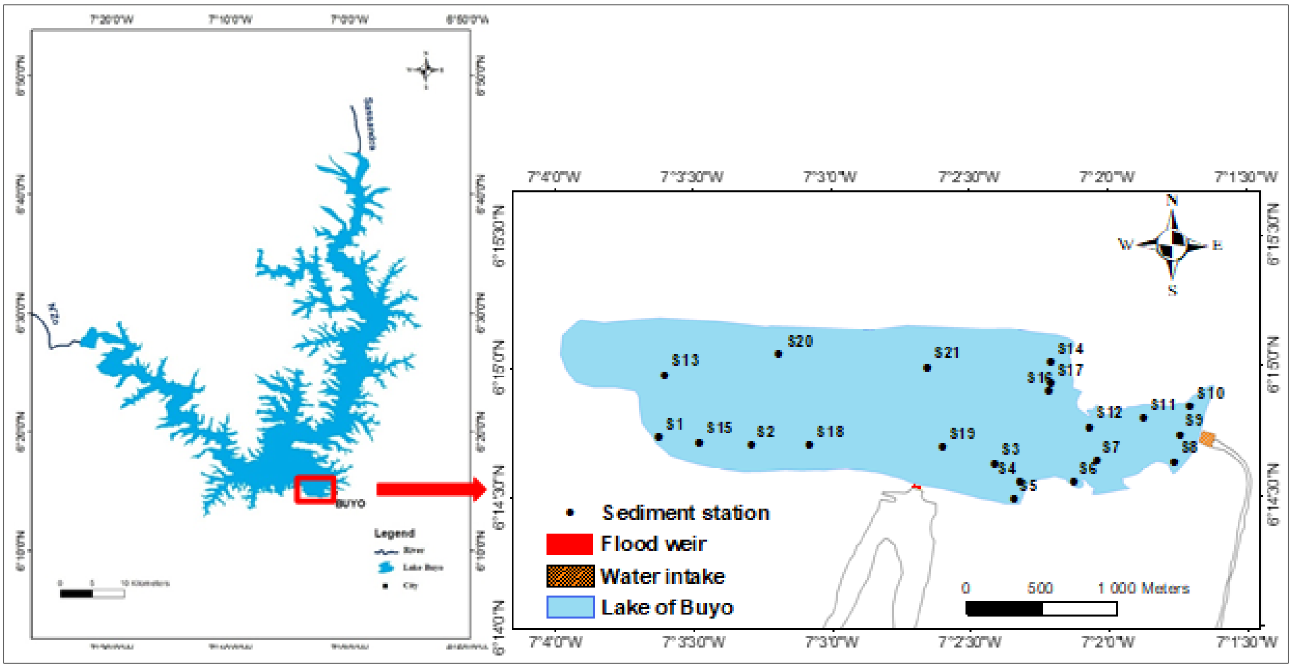

Figure 2 Positioning map of sediment sampling points

2.3. Sediment treatment

2.3.1. Macroscopic description of surface sediments

This operation consisted of making a visual and tactile description of the sediment. The visual description focused on the lithological nature, the color and the presence or absence of plant and animal debris. The color of the sediment was determined using the “Rock-color chart”.

2.3.2. Particle size analysis of sands

Of the twenty-one (21) samples taken, sixteen (16) sand samples were used for particle size analysis. 120 to 150 g of sand were used for this analysis. The sand was washed several times and attacked with hydrogen peroxide to remove the very fine fraction of the sediment and the organic matter respectively. It was attacked with hydrochloric acid diluted to 16% to remove the carbonates. After removing the carbonates, the sediment was washed again and dried in an oven at 60 °C. 100 g of this treated sediment was used for sieving on a column of 16 AFNOR type sieves.

2.3.3. Determination of particle size parameters

The calculation of the particle size parameters was carried out according to Folk and Ward (1957) *in* Gboko (2023).

Average grain size

The calculation of the particle size average is done using the following formula:

$$M_Z = \frac{Q_{16} + Q_{50} + Q_{84}}{3} \text{........ (1)}$$

Q represents the diameter of the particles; For example, Q_{16} is the particle diameter corresponding to a weight percentage of 16%. The average expresses the size of the sandy sediments and makes it possible to characterize the following facies:

very coarse sands: 2000 µm > Mz > 1000 µm;

coarse sands: Mz > 500 µm;

medium sands: 500 µm > Mz> 250 µm;

fine sands: 250 µm > Mz > 125 µm;

very fine sands: 125 µm > Mz > 63 µm;

silts and clays: Mz < 63 µm.

Standard deviation or ranking (Q in unit Φ)

The standard deviation provides information on the sorting of sandy sediments and provides information on the regularity of flows at the time of sedimentation (Losson and Corbonnois, 2006).

The standard deviation is calculated as follows:

$$\boldsymbol{\sigma} = \frac{Q_{84} - Q_{16}}{4} + \frac{Q_{95} - Q_{5}}{6{,}6} \quad \text{.............. (2)}$$

The standard deviation measures the dispersion of sizes in relation to the average of a Gaussian curve of the sample and makes it possible to distinguish:

σ < 0.35: Very well graded sands;

0.35 < σ < 0.50: Well graded sands;

0.50 < σ < 0.71: Fairly well graded sands;

0.71 < σ < 1: Moderately graded sands;

1 < σ < 2: Poorly graded sands;

2 < σ < 4: Very badly classified sands.

Asymmetry (skewness)

The asymmetry indicates the preponderance or not, of fine particles (positive values) or coarse (negative values) relative to the sample mean. It is determined from the following formula:

$$\boldsymbol{SK} = \frac{Q_{16} - Q_{84} + 2Q_{50}}{2\left(Q_{84} - Q_{16}\right)} + \frac{Q_{5} - Q_{95} + 2Q_{50}}{2\left(Q_{95} - Q_{5}\right)} \quad \text{.............. (3)}$$

With Q = -Log2.d (mm), Skewness reflects the degree of asymmetry in the distribution curve compared to the median. We have:

+1.00 > SK > + 0.30; Very positive SK: strong asymmetry towards the fine elements;

+ 0.30 > SK > + 0.10; Positive SK: asymmetry towards fine elements;

+ 0.10 > SK > - 0.10; particle size symmetry of the sample;

- 0.10 > SK > - 0.30; Negative SK: asymmetry towards coarse elements;

- 0.30 >SK > - 1.00; Very negative SK: strong asymmetry towards coarse elements.

Median (Md), with Md = Q_{50} .... (4)

2.4. Paleoenvironmental reconstruction of sediments

2.4.1. Modes of transport

The mode of sediment transport was determined using the test in Visher (1969). Three modes of transport (suspension, saltation and rolling) are highlighted by putting the size in phi units of the particle size classes on the abscissa and the cumulative percentages on the ordinate.

2.4.2. Mineralogy of sediments

A single approach made it possible to have an idea of the mineralogical composition of the sediments. It consisted of observing the minerals in the untreated sand with hydrochloric acid and a binocular magnifying glass.

2.4.3. Morphoscopy of quartz grains

The study of the appearance of the surface of the quartz grains made it possible to evaluate the importance of wear and to have an idea of the nature of the transport agent and its origin. Pettijohn (1949) *in* Saaidi (1991) proposed five (5) classes based on grain shape. It distinguishes between angular, sub-angular, sub-rounded, round and very round. The surface state of the quartz grains is given by the method of Saaidi (1991). We thus distinguish the grains: shiny blunt, matt round, unworn and the variants.

2.5. Prediction of sand dynamics

2.5.1. Simplifying assumptions

The prediction of sand dynamics was made from the Hjulström diagram. It required the establishment of a certain number of simplifying assumptions. Our proposed approach was based on the following hypotheses:

The flow of water is considered permanent uniform. It is characterized by constancy of hydraulic parameters. Our calculations will not take into account the difference in temperature or viscosity of the fluid in the water column;

Collision or other interactions between particles are neglected;

The analysis applies to non-cohesive sediments;

Four (4) particle size classes were chosen: very coarse sand (Dmoy = 4.075 mm), coarse (Dmoy = 0.725 mm), medium (Dmoy = 0.515 mm) and fine (Dmoy = 0.18 mm).

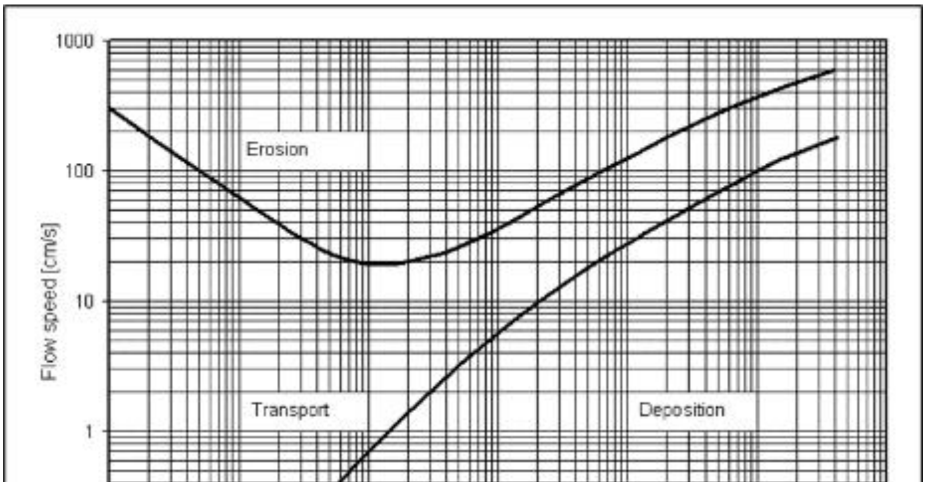

Figure 3 Hjulström diagram (1935)

2.5.2. Determination of current speeds

In order to take into account, the variation in incoming and outgoing liquid inputs during a hydrological season and their influence on current intensities, the average annual incoming and turbine flow rates (q) over a period of five (5) years (2015-2020) were used to calculate the average speed (U) in the lake following the formula:

$$U = q / S \quad \ldots\ldots\ldots\ldots(5)$$

Or
U: average flow velocity;
S=B×h (S: section S of the channel).

Our speed calculations required reasoning by section (Fig. 4). Two (2) sections were identified for our analyses. Each section is represented by a rectangle characterized by its width B and its height h which corresponds to the depth.

These are:

Section A: h=22 m and B=2147,41 m

Section B: h=10 m and B= 287.23 m

Furthermore, to understand the influence of the operating modes of the Buyo dam on sedimentary processes, the prediction of sand dynamics was done according to three (3) scenarios:

- Scenario 1: liquid intake and average turbine operation (April-May);
- Scenario 2: high liquid intake and intense turbination (June-October);
- Scenario 3: low liquid intake and intense turbination (Nov-March).

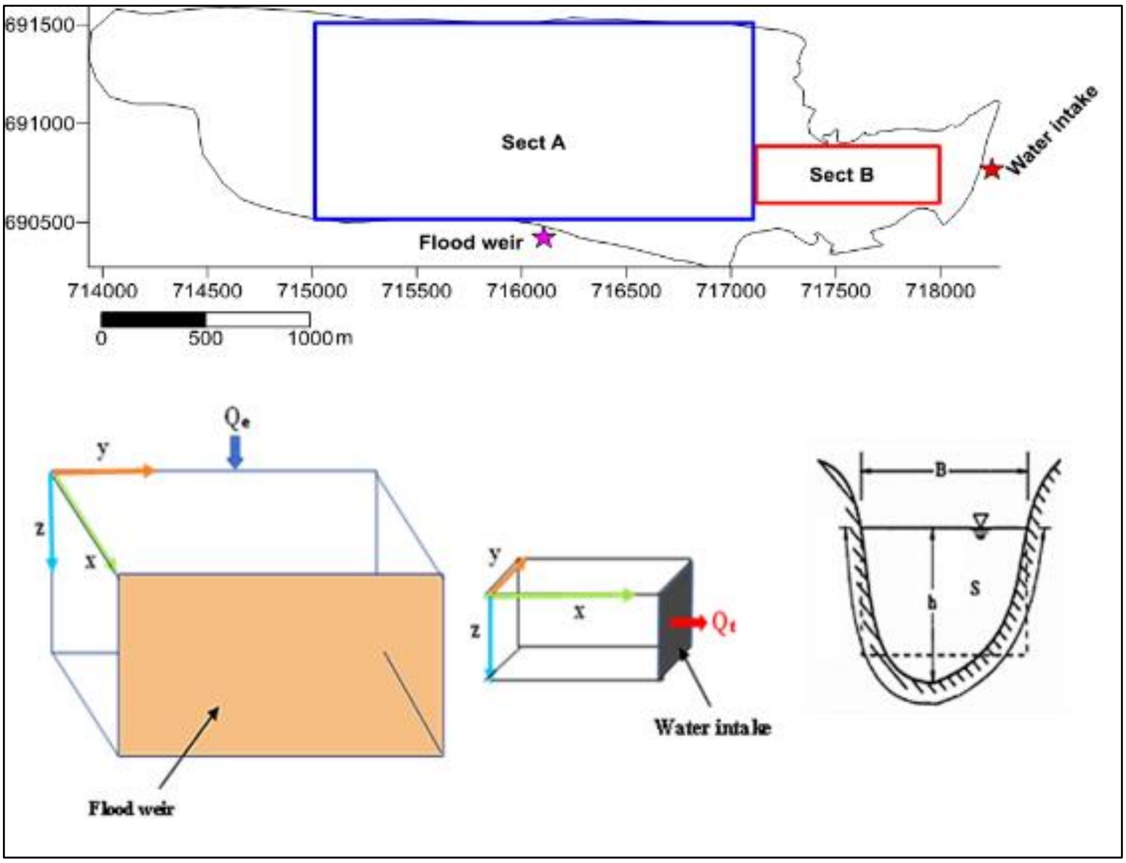

Figure 4 Schematic representation of sections

3. Results

3.1. Sedimentological characteristics of the lake

3.1.1. Lithological description

The macroscopic analysis of the surface sediments of the downstream sector of Lake Buyo highlights four major lithological facies. These are muds, sands and gravels. We also note the presence of gravelly sand.

- the vases are brown in color. We identified organic slime with a creamy appearance or “cream” slime;
- the sands range from fine to very coarse. They have variable colors ranging from red to brown (10R4/6); There we find some plant debris;
- the gravels are red in color (10R6/6) and vary in size;
- gravelly sands are generally red in color.

Table 1 Description of the sediments of Lake Buyo

Echts	**X (long)**	**Y (late)**	**Sedimentological Descriptions**
S1	714597	690741	gravelly sand
S2	715204	690682	vase
S3	716838	690554	gravelly sand
S4	717004	690423	sand
S5	716955	690300	gravelly sand
S6	717355	690424	gravelly sand
S7	717509	690573	gravel
S8	718026	690567	gravelly sand
S9	718062	690759	gravelly sand
S10	718135	690956	gravelly sand
S11	717821	690873	gravelly sand
S12	717459	690815	sand
S13	714630	691182	gravel
S14	717200	691266	gravel
S15	714859	690707	sand
S16	717196	691068	gravelly sand
S17	717200	691117	gravel
S18	715595.955	690680.705	vase
S19	716477.832	690672.306	vase
S20	715394.384	691327.414	vase
S21	716377.046	691235.027	vase

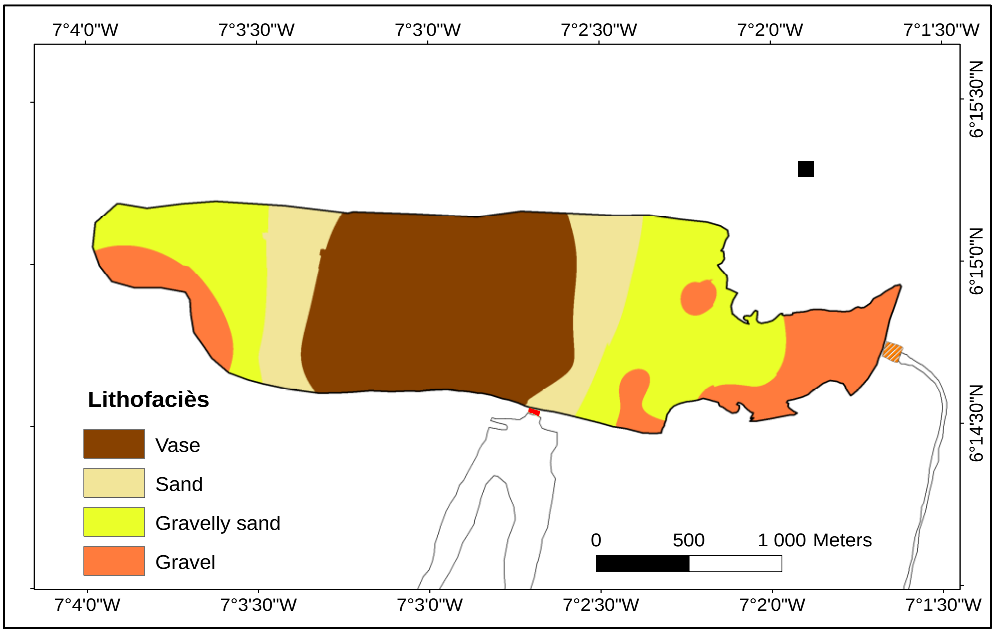

Figure 5 Distribution of lithological facies of Lake Buyo

3.1.2. Sand grain size

The relative proportions of the grain size classes show that very coarse sands are the most abundant with 68.95%. Coarse sands (9.64%), medium sands (8.31%), fine sands (10.95%) and very fine sands (2.14%) are poorly represented.

3.1.3. Sand particle size indices

Average sand

The different averages (MZ), of the sands of the downstream sector of Lake Buyo, give us four (4) types of sand:

- Fine sands (125 <Mz< 250 µm): these sands are mainly located in the central part of the lake;
- Medium sands (250 <Mz< 500 µm): these sands are found in the central part;
- Coarse sands (500 <Mz< 1000 µm): these sands are present in the central part and in the South-East of the lake;
- Very coarse sands (1000 <Mz< 2000 µm): More abundant, these sands are found in the South-West and South-East of the lake.

Table 2 Granulometric classes of sediments from Lake Buyo

Echts	*Stg	*Sg	*Sm	*Sf	*Stf
S1	92.17	7.14	1.02	0.23	0
S3	100.61	0.74	0	0	0
S4	25.26	27.28	23.29	21.65	2.55
S5	89.77	1.19	0.66	0.9	0.4
S6	93.7	4.46	1.29	0.77	0.1
S7	98.35	0.95	0.48	0.26	0.08
S8	72.15	13.02	8.12	5.55	0.9
S9	63.94	25.49	8.19	2.08	0.38
S10	100	0	0	0	0
S11	56	19.79	16.18	6.66	1.29

12	10.46	31.9	32.74	21.6	2.47
S13	95.88	1.32	0.68	1.4	0.56
S14	99.18	0.15	0	0	0.13
S15	1.21	6.20	12.39	60.89	19.10
S16	37.50	9.07	22.01	28.82	2.44
S17	66.73	5.50	5.92	17.89	3.91
AVERAGE	68.95	9.64	8.31	10.95	2.14

*Proportion (in %) particle size: Stg: very coarse sands; Sg: coarse sands; Sm: medium sands; Sf: fine sands; Stf: very fine sand

Sand classification

The standard deviation (σ) values range from 0.19 to 2.08. Generally speaking, sands are generally very poorly classified. These very poorly classified sands are mainly located towards the water intake.

Sand asymmetry

The skewness (Sk) values of the sands vary between 0.4 and -0.26. These values make it possible to distinguish three (3) types of asymmetry:

- Asymmetry towards coarse elements: these sands are represented at 81.25%;
- Almost symmetrical: they are represented at 12.5%;
- Very asymmetrical towards the ends: these sands are the least represented with a proportion of 6.25%.

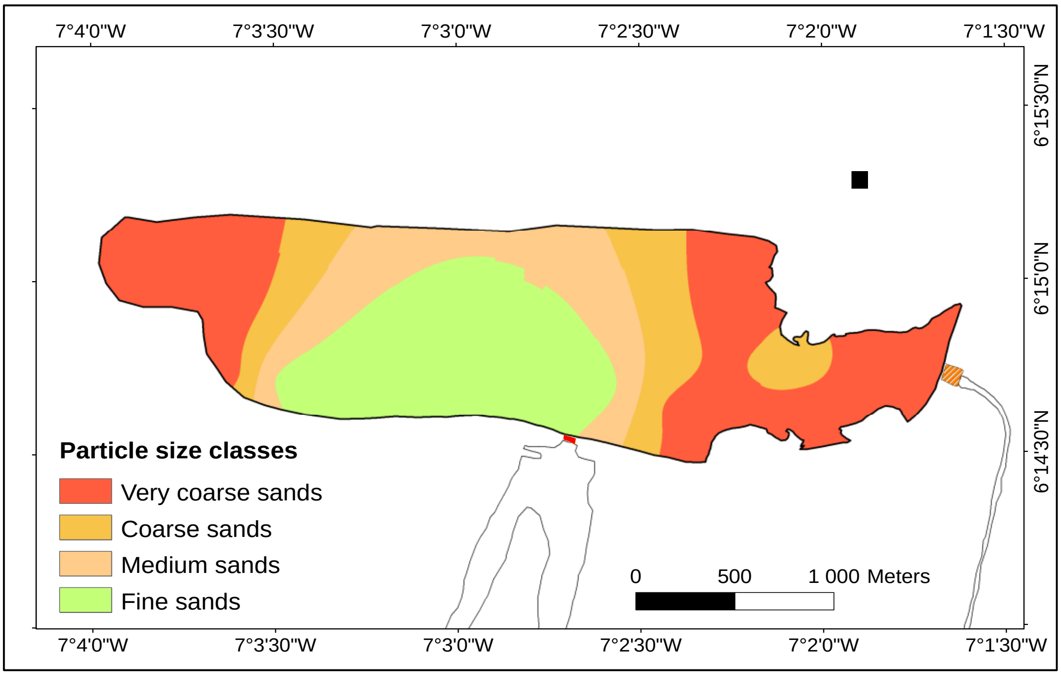

Figure 6 Spatial distribution of sand types in the downstream sector of Lake Buyo

3.2. Reconstruction of the paleoenvironment

3.2.1. Supplier sources and mineralogy

The analysis of the modal appearances of each sediment makes it possible to generally distinguish two (2) types of frequency curve. These are the unimodal and bimodal appearance.

The bimodal look is the most represented look (90% of samples). It indicates that there are two supplying sources or that there is mixing of sediments by the confluence of watercourses or an irregularity of water flows. It reflects a mixture of very coarse, coarse and medium sands. The sediments would be brought mainly into the lake by the Sassandra River and the wind.

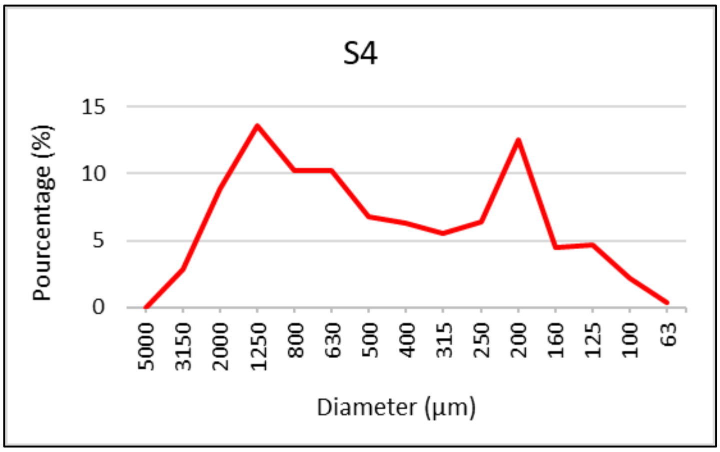

Figure 7 Bimodal appearance

Observation with a binocular magnifying glass of the sands revealed the presence of heavy minerals and light minerals. The heavy minerals are garnet (1%) and pyroxene (1%). The light minerals encountered consist of quartz (75%), muscovite (12%), feldspath (5%), limonite (4%) and biotite (2%).

The minerals identified come from the Paleo-Proterozoic and Archean Ivorian basement crossed by the Sassandra River and the tributaries of the N'Zo, more precisely from the Birrimian (schists, greywackes) and Archean (granites, migmatites, mylonites) formations in which the lake is embedded.

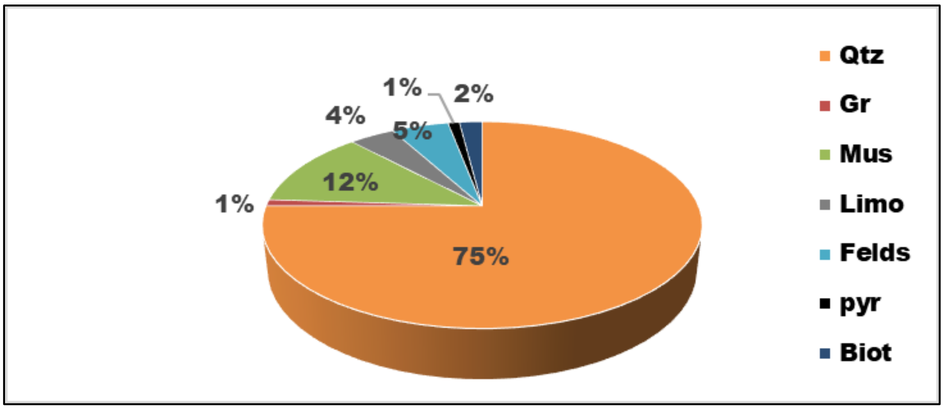

Figure 8 Heavy and light minerals of the coarse fraction (500 µm)

3.2.2. Morphoscopy and sand transport agent:

The analysis shows that the quartz grains mostly have shapes ranging from sub-angular (75.37%) to sub-rounding (20.14%). Other shapes are also visible such as angular shapes (0.49%), and rounded shapes (4%).

Regarding the appearance of the grains, more than 90% of quartz grains are blunt shiny and 10% are dull round.

The sub-angular, blunt, shiny quartz grains indicate that the sediments underwent short transport in aquatic environments (transport by water). While the sub-rounded grains, with a matt appearance, are characteristic of long aeolian transport (transport by the wind).

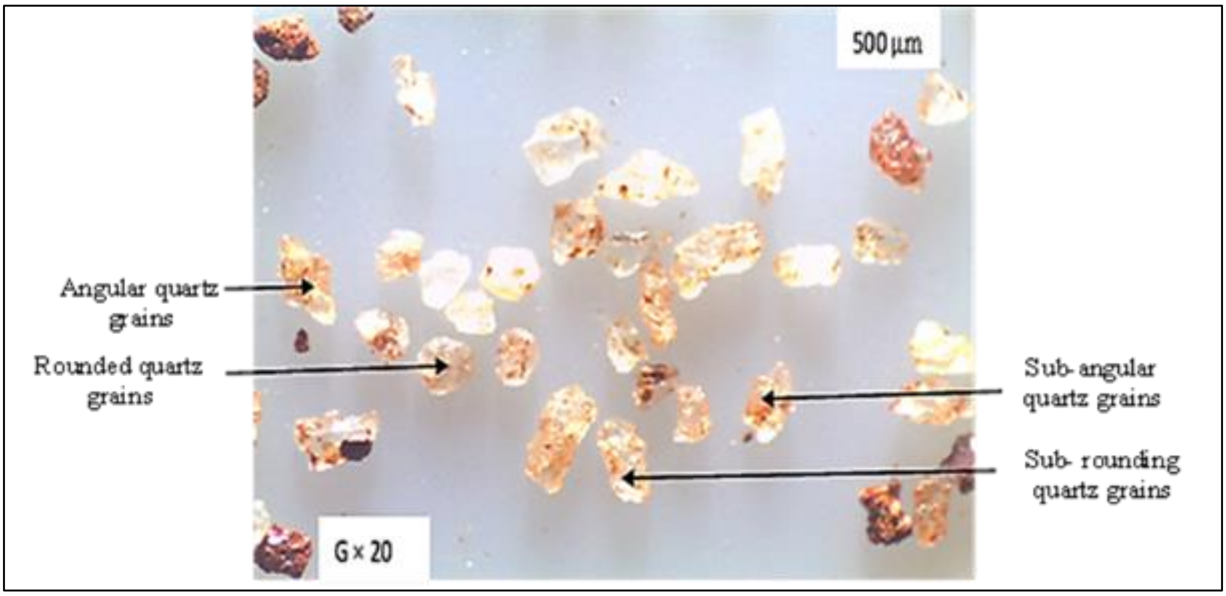

Figure 9 Shapes of quartz grains from the downstream sector of Lake Buyo

Figure 10 Surface aspects of quartz grains from the downstream sector of Lake Buyo

3.2.3. Mode of transport

The test of Visher applied to the sands of the downstream sector of Lake Buyo makes it possible to distinguish three populations. These are:

- The sand population transported by bedload: it has a proportion of 23%;
- The sand population transported by saltation: the proportion of this population is 67%;
- The sand population transported by suspension: their proportion is 10%.

This analysis shows that the main mode of sand transport in the downstream sector of Lake Buyo is saltation.

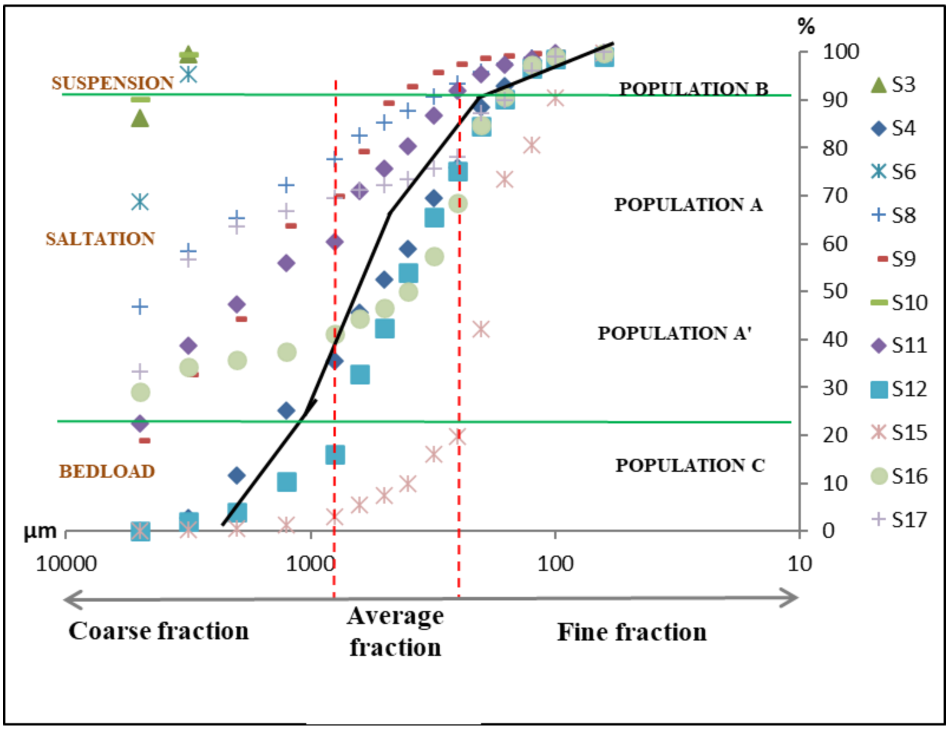

Figure 11 Diagram of Visher (1969) applied to the sediments of the downstream sector of Lake Buyo

3.3. Prediction of sedimentary processes

3.3.1. Current speeds

Table 3 Average Lake flow speeds depending on the operating conditions of the Buyo Dam

		Sector A		**Sector B**	
		Qe average annual	**Average Speed**	**Qt average annual**	**Average Speed**
Start of flood	April	119,458	0,0025	313,367	0,1364
	May				
Flood	June	951,607	0,0201	587,064	0,2555
	July				
	August				
	September				
	October				
Early low water	November	331,329	0,0070	475,389	0,2069
	December				
Low water	January	101,918	0,0022	463,128	0,2015
	February				
	March				
Flow (m^3/s)					
Speed (m/s)					

Qe*: Incoming flow; Qt*: turbine flow

3.3.2. Sand dynamics

Scenario 1: Liquid supply and average turbine operation (April-May)

During this period, the sands present in the water column tend to be deposited in sector A. However, in sector B only very coarse sands are deposited (Fig.12). Coarse, medium and fine sands are generally transported.

Scenario 2: high liquid intake and turbines (June-October)

This is the period when the lake receives more water (annual average flow of 951 m^3/s). Very coarse, coarse and medium sands present in the flood spillway area (sector A) tend to settle and fine sands remain transported.

However, in the water intake area (sector B), most of the coarse, medium and fine sands are eroded under the effect of turbining (Fig. 13).

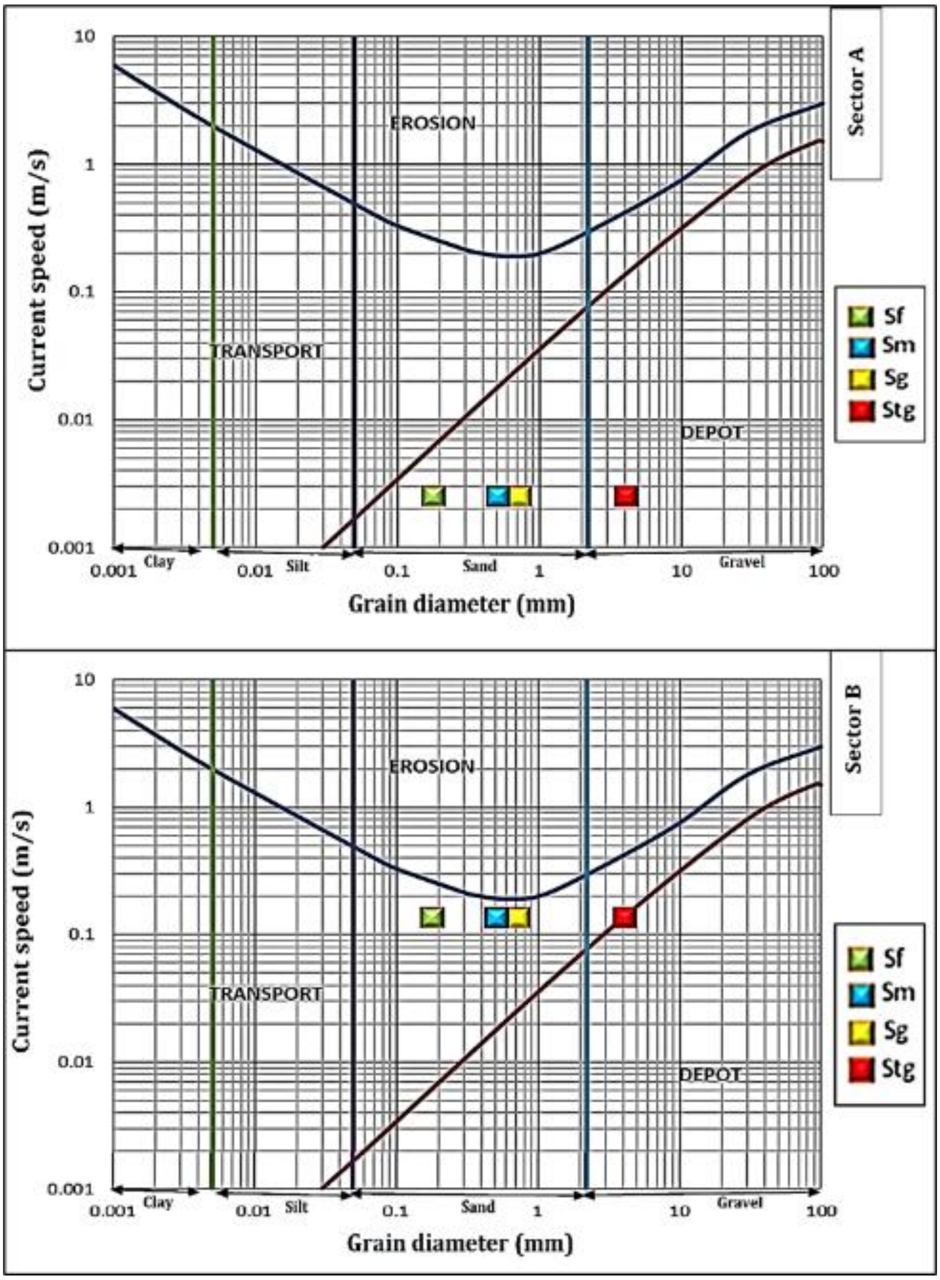

Figure 12 Hjulström diagram applied to sands in scenario 1

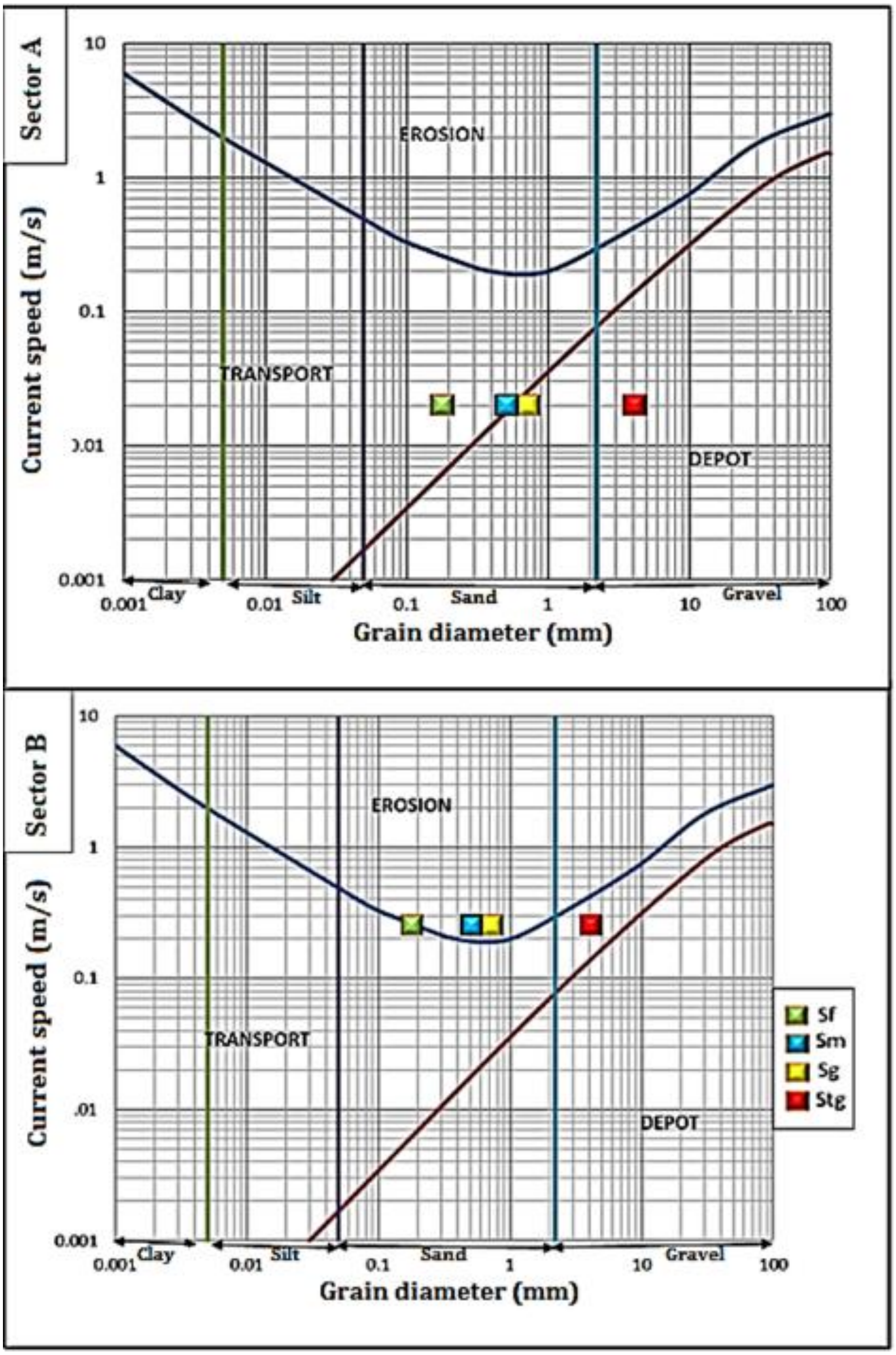

Figure 13 Hjulström diagram applied to sands in scenario 2

Scenario 3: low liquid intake and high turbines (Nov-March)

During this period, incoming liquid supplies drop considerably (annual average flow rate 101.9 m^3/s), causing current speeds to gradually decrease in the flood spillway area (sector A). The reduction in the competence of the currents favors the deposition of sand. On the other hand, in the water intake area, turbinate remains intense, coarse to fine sands are eroded (Fig. 14).

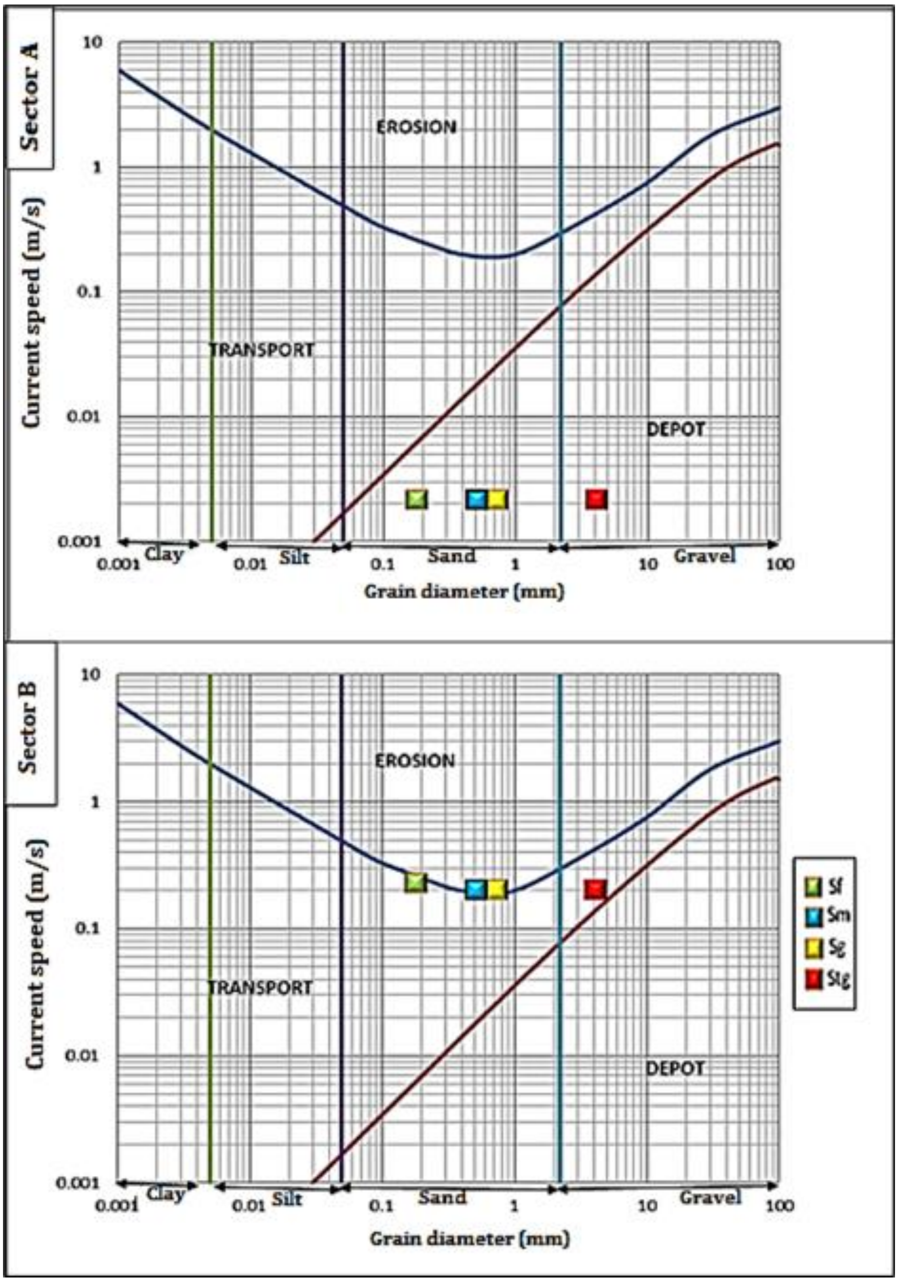

Figure 14 Hjulström diagram applied to sands in scenario 3

In general, the analysis shows us that the waters are generally very calm (average speed less than 0.021 m/s) in the flood spillway area during the hydrological seasons, and this favors the deposition of the majority of particles. sand present in the water column. However, most of the coarse, medium and fine sands located in the vicinity of the water intake are eroded for turbine flow rates greater than 313 m^3/s.

4. Discussions

4.1. Nature of sediments

The sediment typology of Lake Buyo consists of sand, mud, gravel and gravelly sand. 50% of the sediments collected are mixtures of sand and gravel distributed almost over the entire bottom of the lake. This character is typical of dam lakes. The presence of these lithological facies is consistent with those identified by Kouassi (2007) on Lake Taabo, which notes the presence of gravels and coarse sands rich in iron oxide around the islands and the lake dike. However, the distribution of sand in Lake Buyo is not homogeneous. This observation confirms the hypothesis of Chamley (1988) according to which the sediments deposited in lakes are heterogeneous.

Generally speaking, very coarse sands are the most abundant and generally very poorly classified. This could be explained by the erosion and transport of most of the coarse to fine sands, due to the strong currents observed in the water intake area. These sands are generally coarser than those described by Kouassi (2007), Kouassi *et al.*, (2007) in the lakes established on the large rivers such as Lake Taabo on the Bandama, Lake Ayamé on the Bia and this could be explained by the transport fairly short sediments which mainly come from the immediate environment of the downstream sector of Lake Buyo.

4.2. Origin, agent and mode of transport

Morphoscopy made it possible to highlight quartz grains dominated by sub-angular (75%) and sub-rounded (20.14%) shapes, generally with blunt and shiny (90%) and matte (10%) aspects. The large proportion of shiny, blunt subangular grains reflects relatively short transport in an aqueous medium. The variation in shapes shows that the sediments are transported by various agents and currents.

The character of modal appearances is in 90% of cases bimodal. The sediments would therefore be brought into the lake by the Sassandra River and the wind.

The sands are mainly transported by saltation (67%). This is explained by the variation in the competence of the currents observed in this sector of the lake due to turbining. These results are consistent with the results obtained by Kouassi (2007) on Lake Taabo which describes 75% saltation in the sediments.

The main minerals encountered are garnet, pyroxene, quartz, muscovite, feldspar, limonite and biotite. These identified minerals would come from the Paleo-Proterozoic and Archean Ivorian basement crossed by the Sassandra River, more precisely from the Birrimian (schists, greywackes) and Archean (granites, migmatites, mylonites) formations in which the lake is embedded.

4.3. Prediction of sedimentary processes

Predictions of sand mobility made using the Hjulström diagram show a tendency for most of the sands present in the flood spillway area to be deposited. In fact, the incoming flow rates (from 100 m^3/s to 950 m^3/s) recorded do not have the energy necessary for reworking the sand. However, only coarse, medium and fine sands are eroded in the headrace. This could be explained by the geometry of the channel and the intensity of the turbines which generate speeds greater than 0.2 m/s capable of eroding coarse to fine sands. Very coarse sands, on the other hand, tend to be transported by thrusting and saltation, and subsequently deposited when the competence of the currents decreases in the vicinity of the water intake. These results are consistent with field observations which show grain size heterogeneity of sands in the old bed of the Sassandra River and a rarefaction of coarse to fine sands in the headwater canal.

5. Conclusion

The sedimentological study of the sediments of the downstream sector of Lake Buyo makes it possible to identify four lithological facies. These are sands, muds, gravels and gravelly sands. Sands and gravels are the most abundant. The particle size analysis shows five (5) classes of sand. These are the most abundant very coarse sands with 68.95%, coarse sands (9.64%), medium sands (8.31%), fine sands (10.95%) and very fine sands. (2.14%). These sands are mostly very poorly classified and mainly transported by saltation (67%). The majority shapes are sub-angular and sub-rounded. The main luster of the quartz grains is blunt gleaming showing shiny grains. The minerals present in the sediments are quartz (75%), muscovite (12%), feldspar (5%), limonite (4%), biotite (2%), garnet (1%) and pyroxene (1%). The prediction of sand mobility shows that coarse, medium and fine sands are eroded in the headrace for turbine flow rates greater than 313 m^3/s. Whereas, very coarse sands are mostly transported and deposited when current speeds decrease. During the hydrological seasons, the waters are very calm in the vicinity of the flood spillway and this encourages the settling of most of the sandy particles present in the water column. The flood spillway area acts as a sand trap for the lake.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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