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Granulometric analysis and environment of deposits of superficial sands of the Adjin lagoon (Côte d'Ivoire)

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Abstract:
The grading analysis and the bathymetric surveys made in Adjin lagoon, allowed to characterize sandy sediments and morphology of the bottom of this lagoon. On the bottom of the lagoon, sediments are mainly constituted by mud located at the bottom while on the border of the lagoon, we essentially meet sands. Pebbles and gravels are located at certain points around the lagoon, and near the outlets of Djibi and Bété Rivers. Most of the sands of the Adjin lagoon result from a riverine type of environment. The majority of sands move by saltation. The means of transportation of fine sands is dominated by suspension. Mean sands move essentially by saltation. Rolling transport is the dominant transportation for coarse sands. This study allowed to realize bathymetric maps and sediment distribution maps, as well as the determination of the deposit environment of sands.

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1. Introduction

Côte d'Ivoire lagoon environment surface covers 1200 km^2. Lagoon area is located in the littoral zone of southern Côte d'Ivoire. The littoral zone establishes the interface between the continental, river and marine environment. It is constituted by three main lagoons including the Ebrié lagoon. This lagoon is in permanent relation with the sea by the channel of Vridi (opened in 1950). In period of floods, it is connected to the ocean by the temporary mouth of Comoé in Grand-Bassam (closed since 1975) and is fed with fresh water proceeding from Comoé, Agnéby and Mé Rivers. The internal Adjin and Potou lagoons situated on the north side of Ebrié lagoon are connected by a natural channel and represent almost one tenth of the surface of the stretch of water (43 out of 523 km^2), (TASTET, 1979).

The Adjin lagoon, the subject of this study, is situated between 5°21' and 5°30' North latitude and 3°45 ' and 3°57 ' West longitude, with an area of 20.2 km^2. It is an interior lagoon belonging to the big Ebrié lagoon system, it is fed with fresh water by Mé, Djibi and Bété Rivers (see figure 1). It forms, with the neighboring ecosystems, real subsistence supports for the surrounding populations. Fishing is the main economic activity of the populations installed on the border of the lagoon. The result of this activity is an unfavourable change of the natural characteristics of these brackish environments, where there are complex phenomena linked with the exchanges between fresh and marine waters.

This study will deal with the size grading and the deposit environment of the superficial sands in the Adjin lagoon. The grading analysis will underline the hydrodynamic behavior of sand grains according to their distribution, their size, their nature and their origin. Then the study will be interested in the way of transportation of these sands in order to determine their deposit environment. It will end by a comparison between the different grading parameters of sands through a statistical analysis.

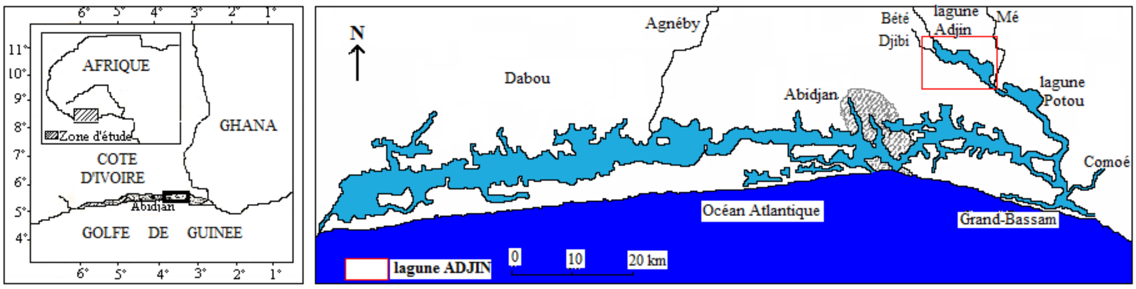


Figure1. Location of Adjin lagoon.

2. Material and methods

2.1 Bathymetric survey

The bathymetric surveys were made using a Lowrance's echo sounder, model LMS-160 and Global Map^{TM} 1600, coupled with a GPS receiver for the acquisition. The depths were measured with a frequency of 160 kHz which prevents the emitted signal from penetrating into the mud (LOWRANCE, 1998) and the reading was made directly on the screen of the central processing unit. The corrections were made to determine the real depth at every point. These corrections concern the immersion depth of the transducer and the dynamic tide (ABE, 2005).

The real depths are treated and analyzed to draw outlines of maps and iso values curves in the plan of Adjin lagoon.

2.2 Sampling of superficial sediments

A Van Veen grab has been used to sample the superficial sediments of the Adjin lagoon. These punctual samplings were positioned by a GARMIN GPS receiver whose precision is approximately 2 m (WOGNIN, 2004). For the grading study, the loose sediments, after conditioning (washing and separation of the fraction superior to 63 µm; chemical attacks by hydrochloric acid and hydrogen peroxide for the respective elimination of carbonates and organic matter; drying in the oven) have been sieved using a column of fifteen vibrating sieves of the AFNOR series. The mesh of the sieves vary between 63 µm and 5 mm (N'GUESSAN *et al.*, 2008). The cartography of the grading of the superficial sediments in Adjin lagoon was realized.

From FOLK and WARD (1957) formulae based on unit Φ (where $\Phi=-\log_2 d$, with d defining the diameter of particles in millimetres) six granulometric parameters were calculated. They are: the median (Md), the mode (Mb), the average grain (M), the indication of sorting (IT), the standard deviation or classification or Sorting (So) and the asymmetry or the Skewness (Sk). Maps of distribution of the sediments (pebbles and gravels, sands, mud) were realized.

2.3 The Visher test

It puts in relation the size grading and the means of transporting. VISHER (1969) draws a curve with the cumulative percentages on the Y-axis and the size (phi unit (Φ)) of the corresponding grading classes on X-axis. This method allows to define three transport means which are: suspension, saltation and rolling (crawling, thrusting or "surface creep").

2.4 Determination of deposits environment

The Md-So and Sk-Md diagrams, establish a discrimination between sands of beaches, rivers, coastal dunes and continental dunes (BOUMIR, 1985). The scatter diagram of MOIOLA and WEISER (1968) puts in relation the size grading and the deposit environment. The parameters are calculated from a geometric progression of the sieves of 1/4 Φ. This method gives the origin of sands (rivers, beaches, continental dunes, coastal dunes) from the clouds of points obtained.

2.5 Analysis in main constituents (ACP)

This method underlines similarity between the different granulometric parameters. It shows the difference of behavior of sedimentary groups towards one or several tested samples, so defining a zonation of the lagoon by indicating the events responsible for this cutting (SORO, 2003). An analysis in main constituents (ACP) with the Statistica software was made on all the individuals or statistical units.

3. Results and discussion

3.1 Morphology of the Adjin lagoon

Figure 2 presents the bathymetric map of the Adjin lagoon. The depths vary from 0 to 14 m, but they can reach 20 m at the outlet of the River Mé. Two deep areas are clearly identifiable in the lagoon (NGUESSAN, 2008).

a) The great depths are located in the middle of the lagoon: 14 m.
b) In the East, the deeper bottoms are situated in the continuation of the natural channel connecting the Adjin lagoon to the Potou lagoon.

Some shallow bottoms are met in the Southeast near the mouth of the Mé River, in the Northwest, next to Anyama and in the outlets of Djibi and Bété Rivers. They would correspond to the under-lagoon extension of alluviums of these rivers (TASTET, 1979). In the South, not far from the village of Adjin, are located most of the small depths. They have a direction approximately parallel to that of the natural channel.

3.2 Sedimentology of superficial sediments of the Adjin lagoon

3.2.1 Lithology of superficial sediments

The macroscopic analysis of superficial sediments of the Adjin lagoon gives four lithologic facies: pebbles and gravels; sands; mud and "mixed" sediments (N'GUESSAN *et al.*, 2008).

a) The color of the pebbles and gravels is yellowish brown.
b) Sands go from very fine to coarse. Their color is yellowish brown. Some fragments of plants and shells can be observed.

c) The color of mud varies from olive black to olive grey and with a varying compactness. Organic mud of creamy aspect or "cream" of mud has been identified (TASTET, 1979).

d) "Mixed" sediments are constituted by muddy sands and sandy mud. Their color varies from olive black to olive grey. They contain some fragments of plants and shells.

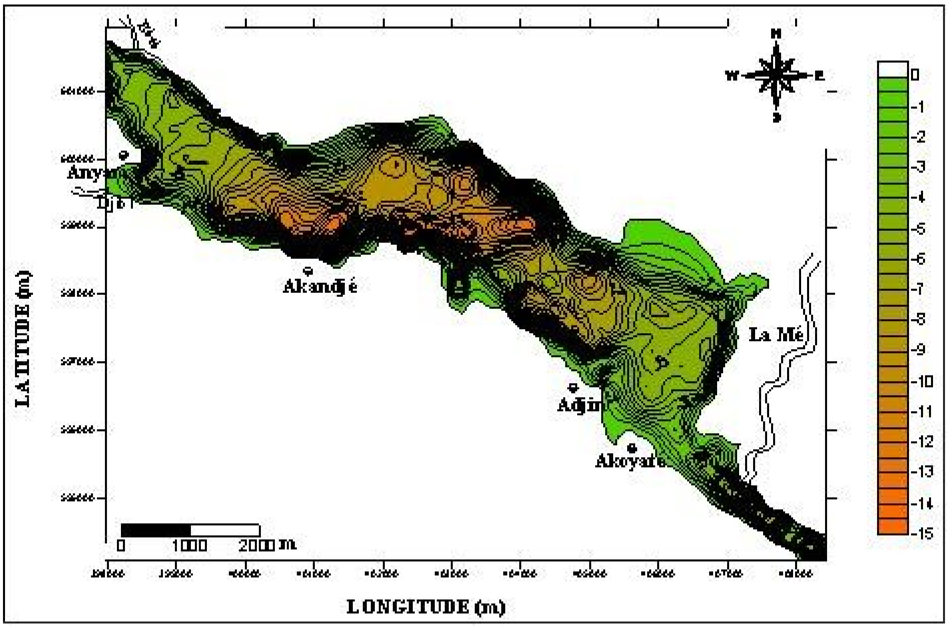


Figure 2. Bathymetric map of the Adjin lagoon.

3.2.2 Distribution of the superficial facies of the Adjin lagoon

Figure 3 presents the distribution of the sedimentary facies of Adjin lagoon. Pebbles and gravels are located in the North and in the Northwest of the lagoon. These zones correspond to the outlets of Rivers Djibi and Bété, and to the mouth of the Mé River. These sediments are concentrated in shallow waters (about one metre). Sands occupy the banks of the Adjin lagoon. They come from the surrounding sand formations starting from the banks, or from the contributions of the rivers. They concentrate primarily in depths less than 5 m. It could be explained by the fact that the water streaming which transports most of the sands reaches an almost null velocity in the lagoon. The current is not strong and not capable of transporting the bigger grains of sand. The current deposits the sands on the banks in low depths. The mud is met in the depths higher than 5 m. It is located in the deeper parts of the lagoon (see figure 3). This accumulation is due to the deposit by decantation and the remodeling of the borders by the swash (TASTET & GUIRAL, 1994). Muds, of smaller size stay in suspension in the water and deposit by decantation in deep waters (SANCHEZ & LEVACHER, 2007).

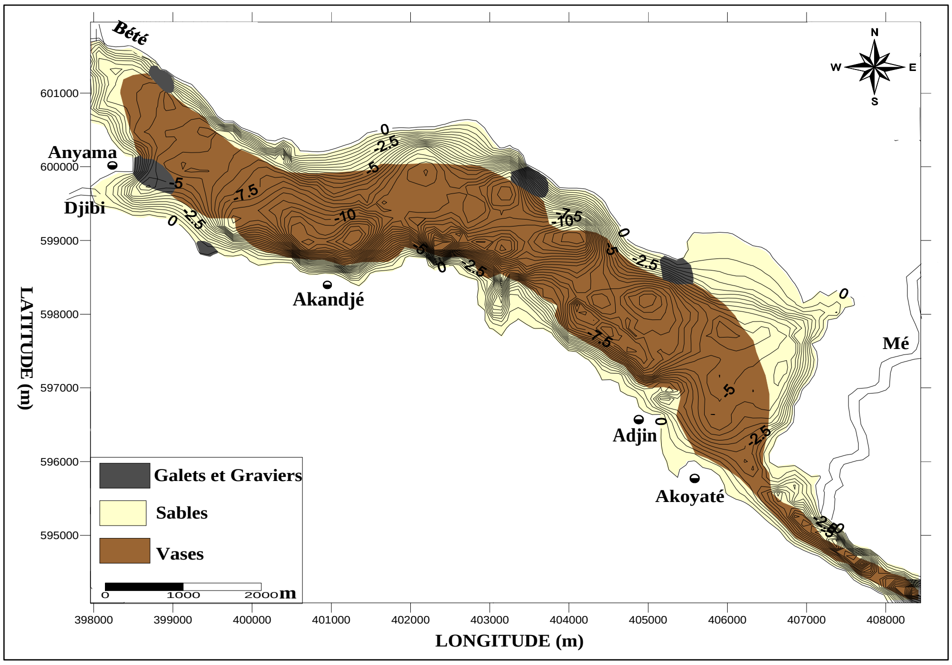


Figure 3. Distribution of the superficial facies of the Adjin lagoon.

3.3 Transport means and environment of the Adjin lagoon sediment deposit

3.3.1 Transport means of sediments

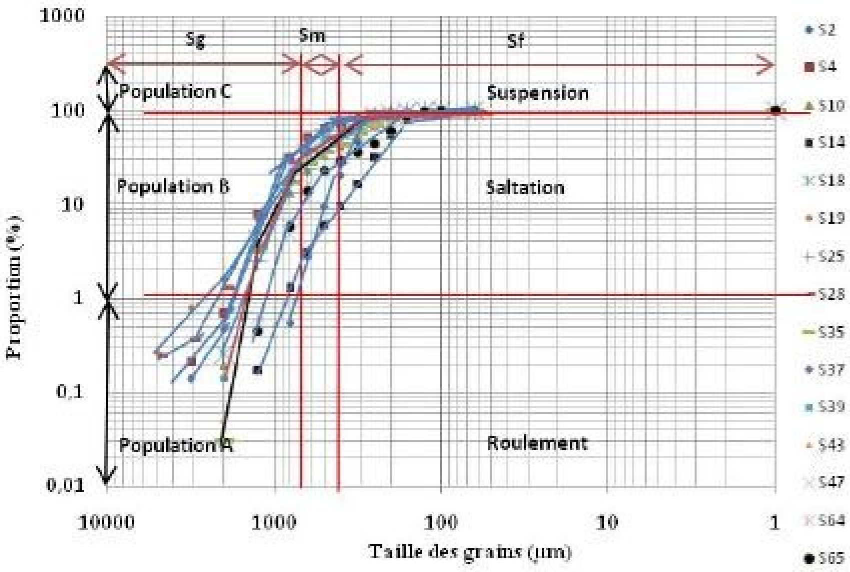
The VISHER test (1969) carried out on the superficial sediments of the Adjin lagoon gives the results presented on figure 4. It makes it possible to show the relation between the particle size of sediments and their ways of transport. Three populations of sand are distinguished:

a) Population A: sands transported by rolling.
b) Population B: sands transported by saltation.
c) Population C: grains transported in suspension.

The analysis of table 1 shows that population B is the most significant. It represents a proportion of 38%. The two other remaining cases are divided between population C (33%) and population A (29%). This quantitative analysis shows that the majority of sediments move by saltation. Nevertheless, some sediments are transported by thrusting and by suspension.

Table 1. Proportion of sediment according to the various ways of transportation.

	Population A (0-10%)	*Population B (10-90%)*	*Population C (90-100%)*
Number of samples	*70*	*90*	*80*
% by population	*29%*	*38%*	*33%*



Sg: coarse sands; Sm: medium sands; Sf: fine sands
Figure 4. Visher test indicating the transport means of sediments in Adjin lagoon.

Besides, the characterization of the kind of transport in the different granulometric classes is represented by table 2 shows that:

a) The transport means of fine sands (Ø < 0.315 mm) is dominated by transport by suspension (70% of the fine material). Nevertheless 30% of these fine sands are carried by saltation.
b) Medium size sands included between 0.315 and 1.25 mm move essentially by saltation (93% of this material)). Possibly 7% of these medium sands move by thrusting.
c) Transport by thrusting or rolling is the most important means of transport for the coarse sands (Ø > 1.25 mm) with a proportion of 88% of coarse material. Besides, 12% of this coarse material is transported by saltation.

Table 2. Characterization of the type of transport according to the grading classes.

	Movement (%)	*Saltation(%)*	*Suspension(%)*
Coarse sands	*88.16%*	*11.84%*	*0.00%*
Medium sands	*7.15%*	*92.85%*	*0.00%*
Fine sands	*0.00%*	*29.70%*	*70.30%*

3.3.2 Environment of the Adjin lagoon sediment deposits

The Md-So and Sk-Md diagrams of the evolution of the granulometric grading parameters of sands of the Adjin lagoon allow to determine their deposit environment. The Md-So diagram of figure 5 presents the dispersion of points. It is made between the domain of beaches and the domain of rivers. In the analysis, 96% of the points come from rivers (see table 3). This means that 96% of the sediments are sands of fluvial origin (MOIOLA & WEISER, 1968). They are transported by Djibi, Bété and Mé Rivers before being deposited in the lagoon. The majority of these sands comes from Djibi and Bété Rivers and from the North border of the Adjin lagoon (see figure 5). However, a negligible proportion of sands (4%) comes from beaches. Thus, the main part of the sands of the Adjin lagoon comes from a river environment.

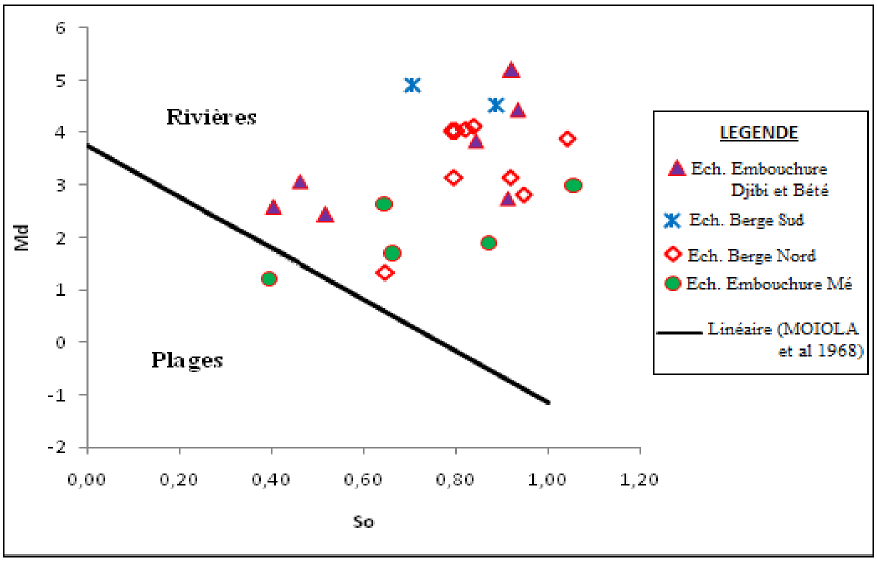


Figure 5. Md-So diagram (MOIOLA & WEISER, 1968).

Table 3. Proportion of sediment according to the deposit environment (Md So diagram).

	Rivers	*Beaches*
Number of samples	*22*	*1*
% by environment	*95.65%*	*04.35%*

Figure 6 presents the Sk-Md scatter diagram. The distribution of points covers the continental dunes environment (52%) and the coastal dunes (48%). These proportions (see table 4) do not allow the characterization of the origin of these sands. It could be explained by the fact that the Adjin lagoon plays a role of interface between the continental environment and the marine environment. The lagoon is supplied by a main basin which drains the Precambrian basement regions (Mé 140 km long, with a drainage basin of 4300 km^2 (DURAND & SKUBICH, 1982; PORT AUTONOME D'ABIDJAN, 2001)), to which are added the contributions of Djibi and Bété Rivers (VARLET, 1978). Sediments could be drained by the coastal dunes (48%) by rivers and by streaming waters before being deposited in the lagoon. However, the domain of the continental dunes would be the environment of the Adjin lagoon sand deposits (MOIOLA &WEISER, 1968).

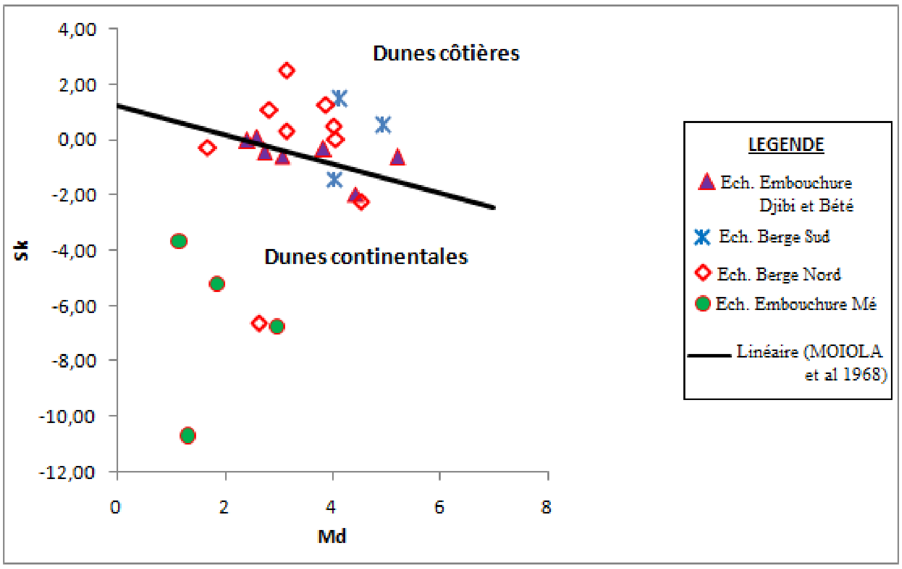


Figure 6. Sk-Md diagram (MOIOLA & WEISER, 1968).

Table 4. Proportion of sediment according to the deposit environment (Sk-Md diagram).

	Coastal Dunes	*continental Dunes*
Number of samples	*11*	*12*
% by environment	*47.83%*	*52.17%*

3.4 Analyses with main constituents of the grading parameters of sands of Adjin lagoon

The correlation matrix represented by table 5, shows the relations between the grading parameters of sediments taken 2 by 2. Its analysis shows that there is a very good correlation (r=0.97) between the Median (Md) and the Average (M); the Median and the Mode (Mb); the Mode and the Average. The correlation is reasonable (r=0.52) between Skewness (Sk) and M, Sorting (So) and M. There is an anticorrelation (r=-0.60) between the Sorting index and the other studied grading parameters (Md, So, Mb, M and Sk).

These different correlations reveal the interactions between the Median, the Average and the Mode. There are also relations between the Average, the Skewness and the Sorting. These interdependencies could be explained either by a common origin (or the same factorial plan) or by an identical process which controls their evolution in the environment. The negative value of the correlation coefficient between IT and the other parameters, expresses opposite interactions. These granulometric parameters have neither the same factorial plan nor the same mechanism determining their evolution in the environment.

Table 5. Matrix of correlation.

	Sk	**Md**	**So**	**Mo**	**IT**	**M**
Sk	1,000000					
Md	0,471705	1,000000				
So	0,098023	0,484355	1,000000			
Mo	0,320980	**0,898407**	0,472546	1,000000		
IT	**-0,321373**	**-0,598719**	**-0,941755**	**-0,534237**	1,000000	
M	**0,523871**	**0,971311**	**0,580608**	**0,842830**	**-0,723511**	1,000000

The table of the eigenvalues shows that the first two factorial axes express respectively 67.39% (Fact. 1) and 18.25% (Fact. 2) of the expressed variance. These factors supply 85.64% of statistical information alone. The analysis in main constituents (ACP) will only take into account these three factors for the analysis of the factorial plans. This approach will allow to estimate the evolution of the various granulometric parameters according to the factorial axes Fact.1 and Fact. 2.

Table 6. Eigenvalues.

	Eigenvalues	**% Total**	**Cumulated eigenvalues**	**Cumulated (%)**
1	4,043226	67,38710	4,043226	**67,3871**
2	1,095112	18,25187	5,138339	**85,6390**
3	0,693601	11,56002	5,831940	97,1990
4	0,130476	2,17461	5,962416	99,3736
5	0,032008	0,53347	5,994424	99,9071
6	0,005576	0,09293	6,000000	100,0000

3.5 Factorial plan Fact 1-Fact 2

The factorial plan Fact. 1 is bipolar and includes more than 67% of the values. Its positive pole is defined by Mb, M, Md and its negative pole by IT. IT evolves in an opposite way relatively to Mb, M and Md which are strongly correlated. The factorial plan Fact. 2, is bipolar, it represents more than 18% of the information. The positive side is marked by So, and the negative side by Sk (see figure 7). The correlation coefficients between these granulometric parameters admit this hypothesis. They are subjected to the same phenomenon and have a common origin (see figure 7).
The good correlation between the Median, the Average and the Mode, with correlation coefficients next to 1, indicates a strong proportionality between these grading parameters. Thus, the medium grain of superficial sands of Adjin lagoon belongs to the most important grading class and with a size of particles corresponding to a cumulative

percentage of 50%. These three parameters are influenced by the speed of the current. IT is also influenced by the current velocity and moves inversely in relation to the other grading parameters.

So and Sk are influenced by the weight of sands of Adjin lagoon, but move in opposite directions. Thus, the classification of the Adjin lagoon sands is linked to the ascendancy of fine or unrefined elements in sediments. They evolve inversely and are influenced by the weight of sediments.

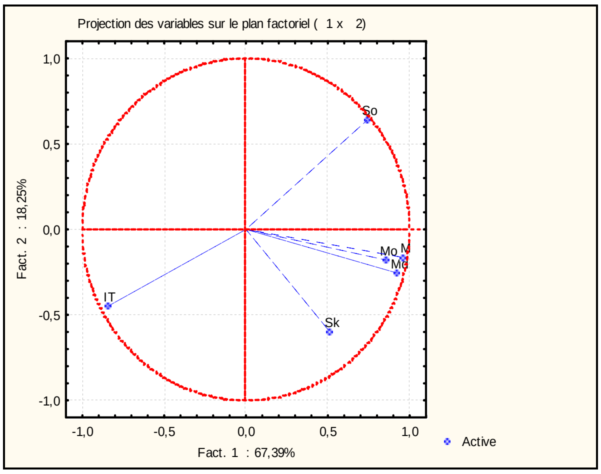


Figure 7. Space of the variables of the factorial plan Fact.1 X Fact.2
Space of the statistical units.

We distinguish two families: F1 and F2 (see figure 8). The first family (F1) of statistical unit includes points 1, 2, 4, 7, and 19-21. These samples come from outlets of Mé, Djibi and Bété Rivers in Adjin lagoon. The transport current is thus stronger in that case. This shows that the granulometric parameters are influenced by the velocity of the sediment transporting current. Family 2 (F2) gathers points 3, 5, 6, 8-18, 22, and 23. The samples of this family are located on the northern and southern borders and in the lagoon channels. The streaming waters deposit the sediments in the lagoon with a weaker current. In the channels the current is low, with a quieter deposit environment. This could explain the influence of the granulometric parameters by the current speed and the weight of sands that the current transports.

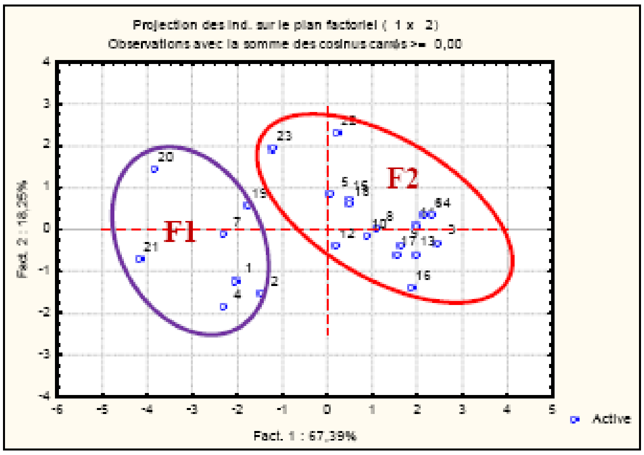


Figure 8. Space of the statistical units in the plan Fact. 1-Fact. 2.

4. Conclusions

The Adjin lagoon is characterized by depths from 0 to 14 m which can reach 20 m at the outlet of River Mé. There is a channel which has a maximum depth of 14 m and in the East and another channel situated in the continuation of the natural channel connecting Adjin and Potou lagoons. The small depths are located in the Northwest, the South and in the Southeast of Adjin lagoon.

The lithological and granulometric study of the superficial sediments, indicates that pebbles and gravels are located at certain places on the border of the lagoon, in depths of about one metre, and near the outlets of the Djibi and Bété Rivers. Sands on the border of the lagoon are less than 5 m deep. The muds are concentrated in the channels in depths superior to 5 m.

The study of the environment of deposits shows that the main part of the sands of the Adjin lagoon comes from a *river* environment. They are transported by the Rivers Djibi, Bété and Mé before being deposited in the lagoon. The majority of these sands come from Djibi and Bété Rivers and from the northern border of Adjin lagoon. Sediments could be drained from the coastal dunes (48%) by rivers and streaming water before being deposited in the lagoon. However, the area of the continental dunes would be the environment of deposit for the sands of the Adjin lagoon.

The quantitative analysis shows that the majority of sediments move by saltation. However, some sediments move by thrusting and by suspension. The means of transport of the fine sands is dominated by suspension (70% of the fine material). Medium sands move essentially by saltation (93% of this material). Transport by rolling is the main way of transportation for the coarse sands with a proportion of 88% of this material.

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