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Sedimentary hydrodynamics of Bizerte Lagoon

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Abstract:
Within the framework of the MODEM research project "operational modeling for marine ecosystem development", a research study was carried out on the sedimentary hydrodynamics of the Bizerte lagoon. The grain-size distribution analysis of surface sediments, acquired at several depths, allowed to identify the sediment nature and specifying factors and processes involved in their transport and deposition. This study showed that sediments coming from coastal erosion are under a hydrodynamic system, essentially controlled by the effect of currents, which depends on wind. Currents are strong in shallow waters in the northern and southern areas, but weak in deep waters inside the Bizerte lagoon.

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1. Introduction

Bizerte lagoon is located in the northern coast of Tunisia (37°08′–37°15′N, 9°48′–9°57′E) (Figure 1), and covers 128 km^2. It is connected to the Mediterranean sea through a navigation channel (1500 m long, 300 m wide and 12 m deep) and to Ichkeul Lake through the Tinja channel, which is narrow, winding and approximately 5-km long (ANPE, 1990; OUAKAD, 1982; OUAKAD, 1993).

The lagoon is fed by several streams (Figure 1). It is bordered to the north by small coastal basins, to the south by Medjerda valley, to the east by a catchment basin along the coastal areas of Ras El Djebel and to the west side by Garaât Ichkeul connected to the lagoon via Tinja channel, the main source of supply water during rainy seasons (KALLEL, 1989).

The natural balance between freshwater supply and sea water exchange is responsible for the high biodiversity of the lagoon. Since the beginning of the last century, this lagoon is mainly used for aquaculture and fisheries. The first aquaculture test site of *Crassostrea angulata* was created in 1952, in the northeastern part of the lagoon. From 1963, this activity was relayed by the culture of mussels *(Mytilus galloprovincialis*). According to GIMAZANE (1981), mussels have a good growth, similar to that in Thau lagoon (France). During the 80's, mussels cultivation has been well developed in the lagoon of Bizerte (GREDOPAR, 1986).

However, there has been urban development along the lagoon, wherein industrial areas have been established, such as "El Fouledh" steel plant, "SOCOMENA" shipbuilding industry in Menzel Bourguiba and the ciment factory of Bizerte. Some of these settlements have affected the catchment area and several dams were built upstream Ichkeul lake and the lagoon. Among these dams, we mention: Sejenane (in 1994), Ghezala (in 1984) and Melah and Douimis (in 2005), (DGBGTH, 2006).

These settlements have disturbed the natural water balance of the lagoon. Freshwater input has decreased from 270×10^6 m^3 year^{-1} to 120×10^6 m^3 year^{-1}. Thus, water balance depends on the management infrastructure programs that deeply modify the hydrological characteristics of the lagoon, especially the salinity parameter (HARZALLAH, 2003).

Based on KAMENS *et al*. (1984; 1989); the main sediment inputs to the lagoon are: (1) a non-calcareous mud and sand carried by Tinja channel from Ichkeul lake, (2) sand coming from marine organisms, (3) limestone and solid material due to soil erosion of adjacent cropland and brought by rivers (Figure 1), (4) silt and clay in atmospheric compounds and Mediterranean sea inputs.

The Bizerte region has a Mediterranean climate, with a hot and dry summer and mild and rainy winter. The wind blows from the west sector and mainly from the northwest (speed between 5 to 9 m s^{-1} and up to 15 m s^{-1}). East winds are less frequent and Siroccos (south-east summer winds) are generally dry and hot (HIDROTECNICA PORTUGUESA, 1995).

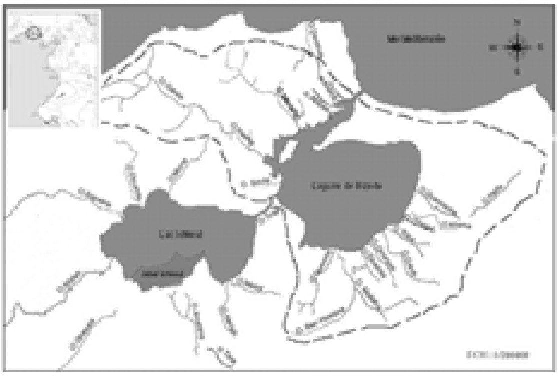


Figure 1. Geographic localization of Bizerte lagoon and catchment basin borders (---).

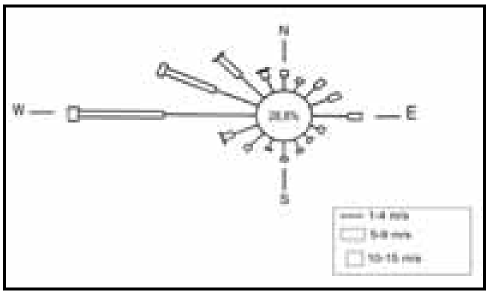
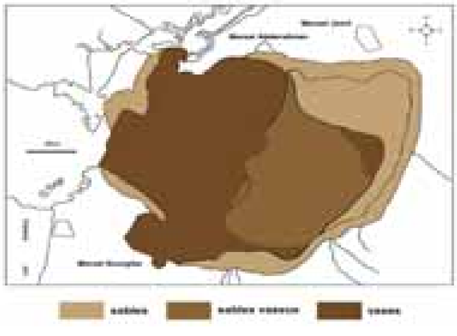


Figure 2. Wind rose in Bizerte area (HIDROTECNICA PORTUGUESA, 1995).

Hydrodynamics data (HARZALLAH, 2003; BEJAOUI & HARZALLAH, 2005 and BEJAOUI, 2009) have mentioned that this region is characterized by a high energy. Not only waves contribute to sediment mixing, but also the continuous superficial deposits.

SOUSSI (1981) and KAMENS *et al*. (1984) works show that sediment distribution in Bizerte lagoon depends on inputs and bottom lake morphology (see Map 1); The following facies can be distinguished:

- sandy facies, where more than 50% of the deposits are made of coarse fraction (> 63µm),
- silty to clay-silty facies, typical in the eastern part, where 20 to 50% of the sediments are represented by fractions between 2 and 63 microns,
- clay facies in the central and western parts of the basin, where the fraction less than 2 microns represents more than 50% of the deposit.



Map 1. Sediment distribution in Bizerte lagoon (SOUSSI, 1981).

Therefore and within MODEM project, the main objectives of this work are to estimate hydrodynamic characteristics of the Bizerte lagoon using granulometry analyses and to make a comparison with previous data and hydrodynamic numerical models.

2. Water circulation modeling

HARZALLAH (2003), BEJAOUI and HARZALLAH (2005), BEJAOUI *et al*. (2008) and BEJAOUI (2009) have studied water circulation using hydrodynamic models. The model used for the lagoon of Bizerte is based on circulation and thermodynamics primitive equations in sigma coordinates (BLUMBERG & MELLOR, 1987). The grid is an orthogonal curvilinear Arakawa type C. It consists of 61×52 mesh and 11 vertical levels. Spacing in longitude and latitude are respectively between 75-495 m and 218-686 m (BEJAOUI *et al*., 2008).

Surface waters are subject to northwestern wind stresses (average of December, January and February) and move towards the southeast in the whole lagoon. The strongest currents are situated in the north, west and southern edges. At the centre of the lagoon, the currents are relatively low. Whereas, in deep waters, wind stresses decrease and circulation is reversed towards the north-west.

Water masses are directed to the south-east due to wind shear and return to the north-west through the central area of the lagoon (HARZALLAH, 2003; BEJAOUI, 2009).

Simulation of surface, deep current and barotropic component during summer (average of June, July and August) is similar to winter circulation. However, the current intensity is lower as a result of the decrease of the wind. We note that the average wind direction during summer is north-west, which justifies the similarity of the current structure for both summer and winter periods (BEJAOUI, 2009).

An important particularity of water circulation is the presence of three cells with a gyre circulation. The first one is located in the north, the second in the south and the third in the west (Figure 5). The scale of the figures indicates the intensity and direction of the flow. Positive values indicate that the direction of the flow is counter clockwise. Negative values indicate an opposite direction.

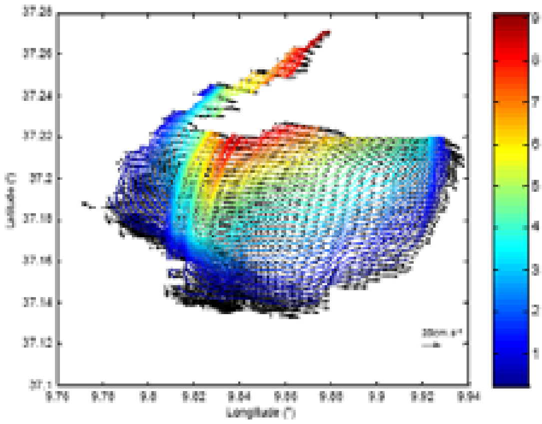


Figure 3. Average winter surface circulation generated by northwestern wind (BEJAOUI, 2009).

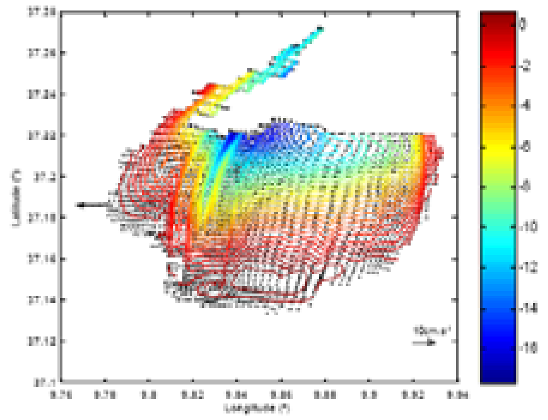


Figure 4. Average winter deep circulation generated by northwestern wind (BEJAOUI, 2009).

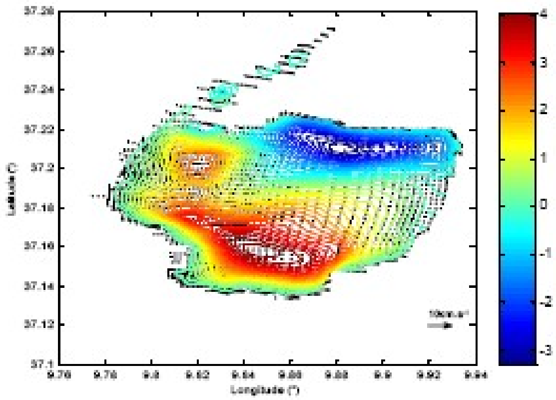


Figure 5. Average winter barotropic circulation and current lines (in Sv ou $10^6\ m^3\ s^1$). Three cells in gyre circulation in the north, south and west (BEJAOUI, 2009).

3. Materials and methods

Two sampling campaigns of surface sediments were carried out in the Bizerte lagoon during September 2007. The first was realized on 6 and 7 September 2007 and the second on 12 and 13 September 2007. A total of 44 surface sediment samples were collected at different depths and cover the whole lagoon (Figure 6). Sampling was performed using a Van Veen type grab and the station position was acquired using a GPS radar. The fine-silty sediments were wet sieved through a mesh of 63 microns. This method allowed us to separate coarse (diameter >63 µm) from fine fraction (diameter <63 µm).

Sediment samples, whose size is greater than 63 µm, are dried at 50°C. Then, dry sieved during 20 minutes through an AFNOR type set of sieves, with mesh size varying from 2000 µm to 63 µm (2000 µm, 1400 µm, 630 µm, 500 µm, 250 µm, 180 µm, 125 µm, 100 µm and 63 µm).

Micro-granulometric analyzes were realized using a Mastersizer 2000 type LASER granulometer. Samples were drawn by agitator pump to the Mastersizer 2000. The results of fraction size (in µm and percentage) were provided in graphical and numerical forms.

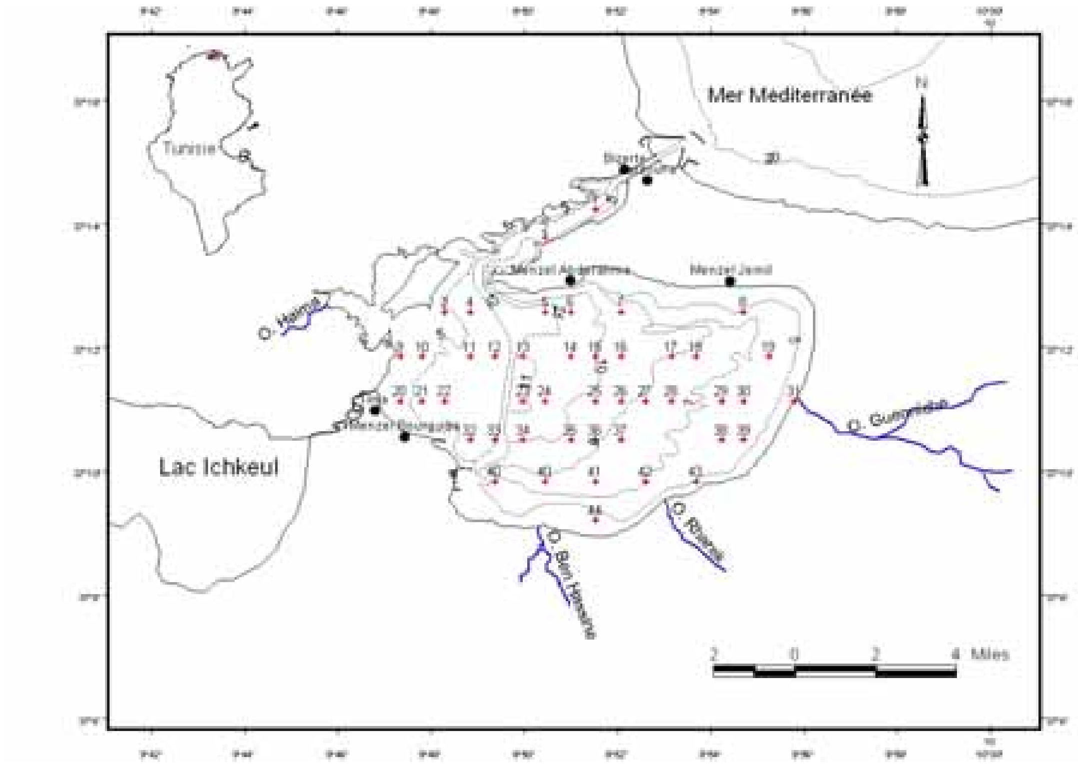


Figure 6. Localization of sediment sampling stations and bathymetry of the lagoon of Bizerte.

4. Granulometric analyses results

4.1 <u>Surface sediment distribution</u>

The percentage of coarse and fine fractions, respectively (>63 µm) and (<63 µm), was calculated. The results show that there is an important variation between the two kind of fractions. Actually, the fine fraction percentage varies from 4.6 to 100%.

The distribution of fine and coarse fractions in Bizerte lagoon, led to noticing that the sediments are essentially composed of sand, muddy sand, sandy mud or mud. Surface sediment granulometry can be distributed into four separate areas (Figure 7):

- (1) The deeper areas of the lagoon are characterized by a muddy fine fraction. This is similar in the west area and especially that affected by solid input from rivers flowing through the catchment basin surrounding the south of Tinja lake up to Menzel Jamil aquaculture station in the east.

- (2) The central area contains sandy mud sediments. It is a mixture between mud and fine sand. This area is surrounded by mud, except in the north, where there is fine sand fractions near Menzel Abderrahmen.
- (3) Along lakeshores, sediments are generally coarse (average size is about 250 µm), and sand percentage is up to 75%.
- (4) A sandy-muddy facies can be found in the eastern area. The average sand diameter is less than 120 µm and up to 250 µm, with a percentage varying between 25 and 50%.

These results are in perfect coherence with those of KAMENS *et al*. (1984); SOUSSI *et al*. (1983); ANONYME, (2002); ROMDHANE & BELKHOUJA, (2004) and OUAKAD (1993 and 2007). In fact, facies types were identified based on bottom morphology and especially the supply (input) sources. Clay facies are found in the entire central area in the west and south-west of the lagoon. These areas function as traps for the fine sediment coming from river inputs, during flood period, deposited either by overloading or by decanting. When moving toward the northern, eastern and southern coastal areas of the lagoon, the clay fraction tends to decrease and is gradually mixed with coarse fractions giving rise to a deep sandy-mud facies composition (Figure 7). The sandy facies dominated by coarse fractions characterizes all coastal areas, except for the western area, which has terrigenous fine fraction at very low depth. Nevertheless, our results highlight a change of surface sediment distribution compared to previous studies of SOUSSI *et al.* (1983 and 1985) in the northeastern area of the lagoon during the last two decades. Our results also show that mud predominates in the eastern part part, especially near the aquaculture station of Menzel Jemil (Station 19), where the fine fraction percentage is about 75%. This would be the result of filter-feeding organisms, whose action agglomerates fine particles. The microscopic analyses of the sample of station number 19 demonstrate that the mud is rich in fecal pellets. According to ROMDHANE and BELKHOUJA (2004), SRARFI *et al*. (2004) and SRARFI (2007) the highest organic levels are observed in the central part and the north and north-eastern parts of the lagoon, also in Menzel Jmil and Abderrahmen, where the mud percentage exceeds 16% (a black muddy deposits due to different releases, especially from sewage). Our results greatly exceed the values of SOUSSI *et al* (1983) work (highest values not greater than 15%). It is worth mentioning that during the last two decades, the lagoon underwent a significant organic matter enrichment.

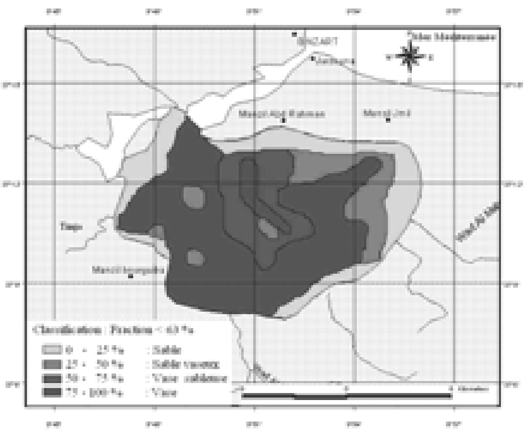


Figure 7. Spatial distribution of coase/fine ratio

4.2 Grain-size distribution of the coarse fractions (D>0,63µm)

Grain-size distribution semi-logarithmic curves were realized for each sample, where X-axis is diameter (µm) and Y-axis is cumulative percentage of refusal. Sediments of the Bizerte lagoon are characterized by different cumulative curves with several aspects:

- (1) Well-adjusted S shaped curves and regular steep slope, despite slight aspect differences (Figure 8), with parabolic facies (Figure 9). Almost all sampled sediments at depth between 8 and 10 m have this type of facies. This aspect demonstrates that there is an homogeneous sedimentary stock, with an energy suitable for carried load (DESPRAIRIES, 1974; LAFOND, 1953 and 1965; RIVIERE, 1952, 1953 and 1977).
- (2) Linear semi-logarithmic cumulative curves with low slopes and logarithmic facies for sediments sampled in stations number 33, 5, 2, 3, 11, 17 and 44 (Figure 10) at depths between 7 and 9 m. This facies indicates that the sediment is transported by current and over-loading deposit is created as current speed decreases (DESPRAIRIES, 1974; LAFOND, 1953 and 1965; RIVIERE, 1952 and 1953).
- (3) Hyperbolic facies (Figure 11), where the deposit of fine fraction sediments (<63 µm) is the result of decantation within calm area and very low hydrodynamics, at great depth (DESPRAIRIES, 1974; LAFOND, 1953 and 1965; RIVIERE, 1952, 1953 and 1977).

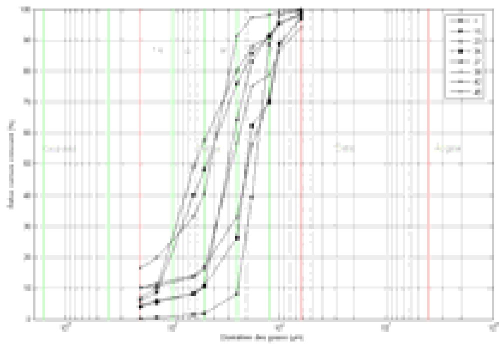


Figure 8. S shaped curves of surface sediments.

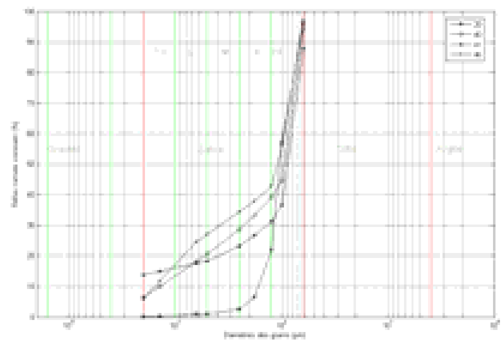


Figure 9. Parabolic facies of surface sediments.

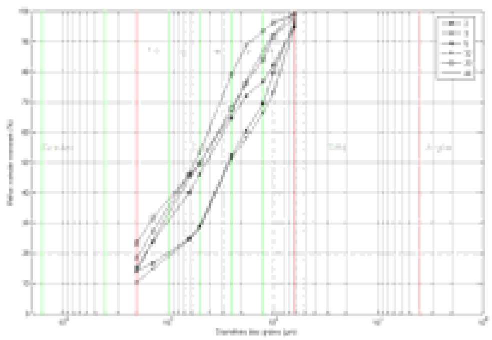


Figure 10. Logarithmic facies of surface sediments.

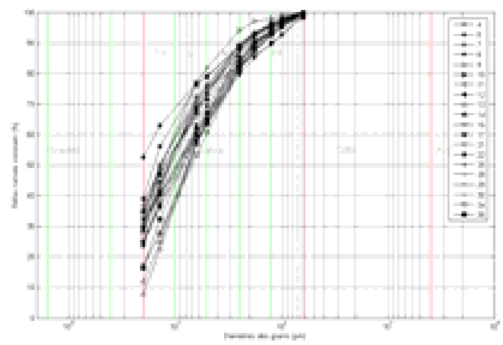


Figure 11. Hyperbolic facies of surface sediment.

4.3 <u>Spatial distribution of sand and transportation mode</u>

Coarse sand fractions cover a large area of the lagoon. While medium fractions are found in the eastern area where some places are covered with fine or very fine sand fractions (Figure 12).

4.4 <u>Transportation mode</u>

The position on Passega diagram (PASSEGA, 1957) of the points corresponding to the surface sediments in the area of study shows that the first fractile values are between 149 µm and 3391 µm; median values are between 95 µm to 2100 µm (Figure 13). According to this analysis, different transportation modes can be deduced:

- Sediments are transported through saltation mode in stations number 51 and 1. This can be seen in the segment (RQ) of Passega diagram
- Saltation plus rolling modes of some particles in stations number 26, 45, 38 and 40, are shown in segment (QP) of Passega diagram.
- Rolling and suspension transportation modes of sediments in stations number 42, 5 and 44 are represented on segment (OP) of Passega diagram.

- Only rolling transportation modes for coarse sediment fractions as shown on segment (ON). This mode is used in the majority of all the other stations.

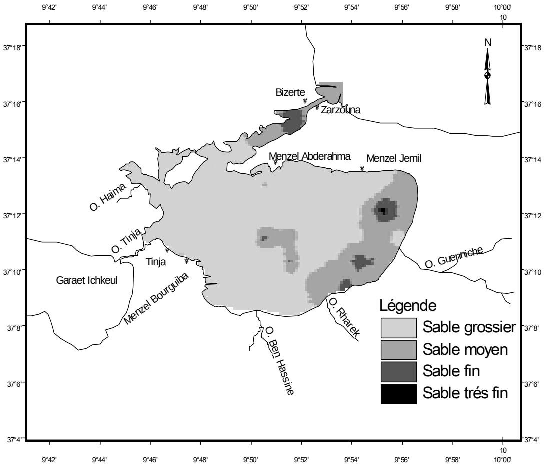


Figure 12. Spatial distribution of sand.

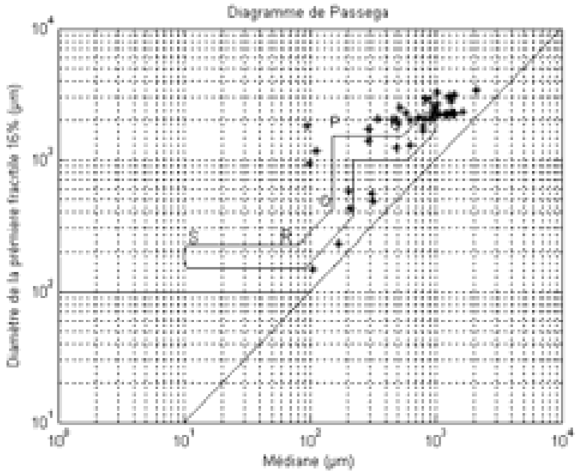


Figure 13. Position of the points representative of surface sediments on Passega diagram

4.5 <u>Fine fractions granulometry (D<0,63µm)</u>

Graphic representations of semi-logarithmic cumulative curves of diameters as function of percentage by volume of fine grain-size fraction (<63 µm) (Figure 14) have a parabolic aspect for all the analyzed samples. This aspect indicates that deposits are little to no evolved and sediment transportation is made by turbidity current (BARUSSEAU & VENEC-PEYRE, 1973).

Based on fine sediment fractions (diameter <63 µm), the table acquired from the LASER sedimentometer, silts (>4 µm) and clay (<4 µm) percentages were calculated for each sample. The percentage of clay is varying between 5 and 20% for all samples (Figure 15). Clay can be found in the discharge area of Oued Garech, located in the south of the lagoon and in the central part of the area of study. Clay can also be found in the west in the discharge area of Oued Tinja. Silts are relatively more dominant than clay and cover the navigational channel up to Menzel Bourguiba, in the south-west of the lagoon.

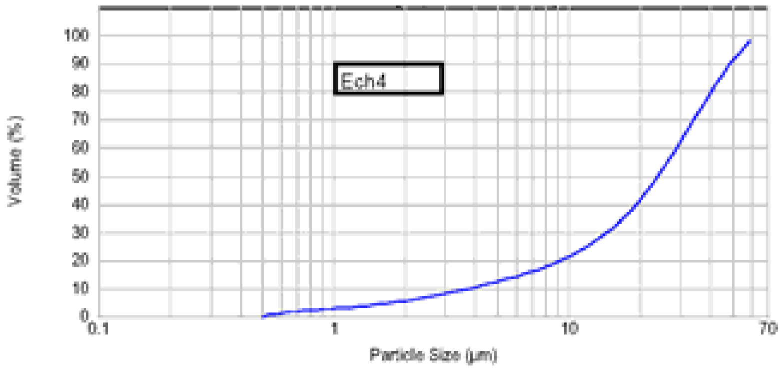


Figure 14. Grain-size parabolic curve of fine particles.

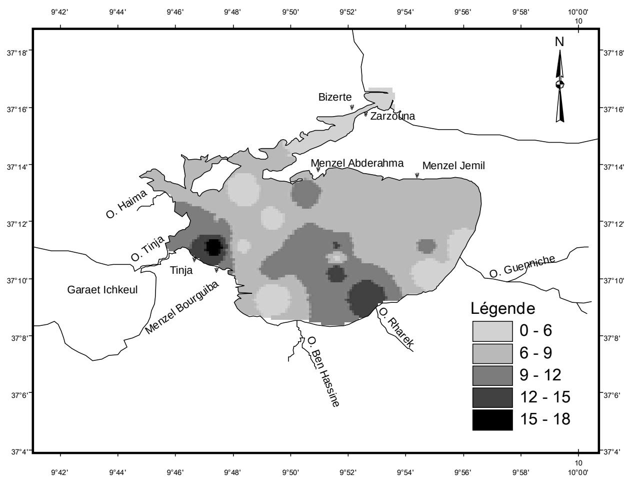


Figure 15. Spatial distribution of clay.

5. Sedimentary hydrodynamics: comparison with numerical models

Grain-size analyses have indicated the main presence of coarse sediment along coastal lagoon areas, associated with strong bottom currents. In the north, coastal areas of the lagoon are affected by erosion, resulting from the lack of terrestrial sand supply and high intensity current. In the eastern part a sand screen formation was identified. This can be due to the low wave intensity in shallow waters (depth does not exceed 6m). Moreover, the main reasons of that are the low tension stresses and bottom slope in the southeast.

We have shown that mud covers the whole eastern part of the lagoon and especially near the aquaculture station of Menzel Jemil. This study highlights the evolution of surface sediment distribution in the Bizerte lagoon as regards to previous works realized by SOUSSI *et al.* (1983 and 1985).

Sampled surface sediments are made of 75% fine sand (<63 µm). This fine fraction is due to filter-feeding organisms, whose actions agglomerate fine particles. This mud is rich in fecal pellets.

Based on this study, we can conclude that coastal lagoon areas are subject to an intense renewal while the central part is a deposit area.
An overview of grain size and fine sand percentage reveals a dominance of mud and of course of the terrestrial supply of the bordering catchment basins. The low sedimentary exchanges with sea water through the channel favor the siltation in the lagoon of Bizerte.

6. Conclusion

Grain-size distribution analyses of surface sediments of the lagoon of Bizerte reveal a high concentric organization altered by terrestrial inputs. Grain-sizes vary from mud mainly in the central lagoon, to coarse sand in the outer areas.
Our results highlight the evolution of surface sediment distribution in the Bizerte lagoon compared to previous works realized by SOUSSI *et al.* (1983 and 1985). In fact, we have noticed that mud covers the whole eastern part of the lagoon, especially near Menzel Jemil aquacultural station. Also, mud accumulation is due to filter-feeding organisms.
Grain-size cumulative curves of surface sediments of this area have different shapes. Graphic representations are: S-shaped curves regular with parabolic facies indicating an homogeneous sedimentary stock and suitable energy conditions for carried loads.
At average depths (4 and 8 m) and in the eastern areas where the bottom slope is at its lowest, sediments show linear cumulative curves; it indicates a transportation mode made by turbidity current and over-loading deposits as the current speed decreases.
In the central part of the lagoon and at the deepest depth, the samples have an hyperbolic shape. The sedimentation occurs by over-loading when current speeds are low.
According to the grain-size distribution indexes of analyzed samples, sand is mainly coming from terrestrial supply. They can be loaded by oueds (streams) of the catchment basin of the lagoon.
Fine sediment fractions are mainly composed of an important proportion of silts and a less important proportion of clay.
Sedimentary hydrodynamics of the Bizerte lagoon depends on current due to the west and northwest dominant winds and also on terrestrial inputs.

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