

# HYDROLOGICAL CHARACTERISTICS OF THE OUALIDIA AND SIDI MOUSSA LAGOON COMPLEX (MOROCCO)

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**Abstract.** As part of the hydrological monitoring of the Oualidia-Sidi Moussa lagoon complex during 2014-2015 period, a network of hydrological stations was set up in both lagoons. These stations were selected based on the needs of algaculture and shellfish farming trial facilities established within the lagoons. Monthly hydrological monitoring allowed for the characterization of their ecosystem through the seasonal variability of physicochemical parameters during low and high tide cycles. At low tide, the waters are cold, nitrate-enriched throughout the year, and experience significant warming in summer and autumn. At high tide, the waters are generally saltier from upstream to downstream, as the less dense freshwater masses remain localized in the upstream areas of the lagoons. The shallow upstream parts of both lagoons are characterized by a high percentage of organic matter due to the dominance of fine sediment, a result of weak hydrodynamics. In contrast, downstream areas are dominated by coarser sediment and have a very low organic matter content, facilitated by the presence of stronger currents, especially during spring tides.

**Key words:** Lagoon, Oualidia, Sidi Moussa, physicochemical parameters, hydrology, bathymetry, currentology, sedimentology

## 1. INTRODUCTION

Lagoons are defined as paralic environments (Guelorget & Perthuisot, 1983), participating in both marine and continental domains. They are increasingly filled with sediments brought by the flow of continental water, sea agitation (waves, tides), and air movement (Bird, 2007). The Oualidia and Sidi Moussa lagoons are characterized by rich biodiversity and a diverse avifauna (El Hamoumi *et al.*, 2000; El Hamoumi & Dakki, 2010; Somoue *et al.*, 2020), which have led to their designation as Ramsar sites, Sites of Biological and Ecological Interest (SIBE), and Important Bird Areas (IBA). This complex is located on Morocco's Atlantic coast between El Jadida and

Safi, in the Doukkala region. The lagoons communicate with the ocean through inlets located downstream. They extend upstream in the form of a channel over 4 km long, up to a dike separating the lagoon from the salt marshes. Freshwater springs are distributed along both lagoons, causing surface water dilution along a gradient of decreasing salinity from downstream to upstream. In the downstream area, meteorological and marine dynamics are influenced by sea agitation (waves, tides) and winds (FitzGerald & Miner, 2013). The Oualidia-Sidi Moussa complex is located on Morocco's Atlantic coast and has an oceanic climate: mild and rainy in winter, humid in summer, with no winter frosts and high humidity throughout the year. The region experiences typical

disturbances from the Atlantic, with west to northwest flows bringing stratiform and cumuliform clouds. Precipitation from these disturbances is usually steady, with the rainy season typically extending from October to May, with three peaks in November, December, and January. The area has four dry months from June to September (Fig. 1), a situation influenced by wind direction, which is driven by the Azores High and the region's latitudinal position (Carruesco, 1989).

The common characteristics of the various stations can be summarized as follows (Fig. 2):

- Predominance of moderate winds from the W, N, and NE sectors along the coast from Safi to Casablanca.
- Strong winds (11 to 16 m/s) always come from the W and SW sectors.

The primary objective of this study is to monitor the annual hydrological and sedimentary conditions of the Oualidia–Sidi Moussa lagoon complex, in order to characterize their ecosystem through the seasonal variability of physicochemical parameters during daily low tide (LT) and high tide (HT) cycles. This will help to understand the growth monitoring of shellfish and algal species in both lagoons. According to several authors, including Rharbi *et al.* (2001) and Rosa *et al.* (2019), a better understanding of the functioning of these ecosystems is essential for ensuring their sustainable management. The results presented in this paper are consistent with previous studies, particularly Elyaagoubi *et al.* (2022) and Hilmi *et al.* (2009).

## 2. MATERIALS AND METHODS

To achieve the objective of this study, three stations in the Oualidia lagoon and one station in the Sidi Moussa lagoon were selected for monthly monitoring during the 2014-2015 period. This network of stations was chosen based on the

locations of algaculture and shellfish farming trial facilities established in the two lagoons, as shown in figure 3. The study spans one year, with one sampling campaign conducted per month during spring tides at both high tide (HT) and low tide (LT). The first campaign took place in October 2014, and the final campaign was conducted in September 2015.

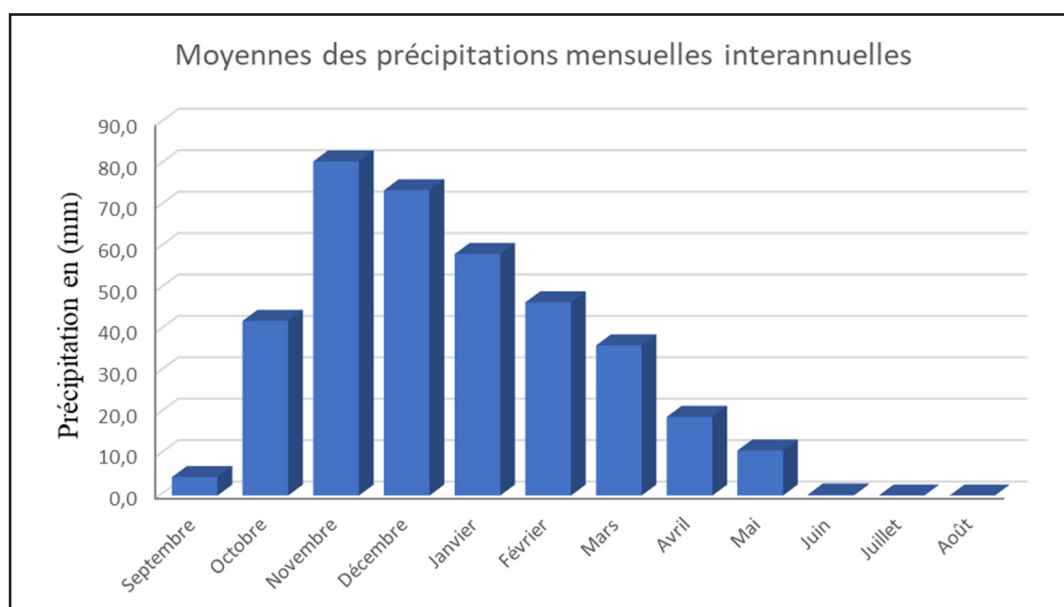
The oceanographic study at both sites focused on the hydrological variability of marine waters by assessing physicochemical parameters (temperature, salinity) using a WTW probe. At each station, water sampling at 0.5m depth was conducted with a reversing bottle for:

- Dissolved oxygen measurement, using the Winkler method (Strickland & Parsons, 1972).
- Suspended matter determination by filtration and double weighing (Strickland & Parsons, 1972).
- Nutrient analysis using the method from Aminot & K  rouel (2004) with an AA3 auto-analyzer.

All analyses were performed at the INRH-Casablanca central labs, covering both low and high tides during spring tides at the four stations across both lagoons.

The sedimentological study involved multiple campaigns (Fig. 4) with granulometry and organic matter content assessment:

- Substrate texture was evaluated by weight percentage after wet sieving (Plumb, 1981; CEAEQ, 2003), using Wentworth's classification (Foucault & Raoult, 1988). Sediment facies were determined by positioning each fraction in Folk's (1974) triangular diagram (modified).
- Organic matter was measured through sample ignition (weight loss by combustion) following CEAEQ (2003), with samples heated for 16 hours at 375°C. Organic matter percentage was calculated as: % O.M. = (dry sample weight - burned sample weight) / (dry sample weight) × 100.



**Fig. 1.** Fluctuation of average monthly precipitation between 1993 and 2017 (Source: ORMVAD OULED GHANEM 2017).

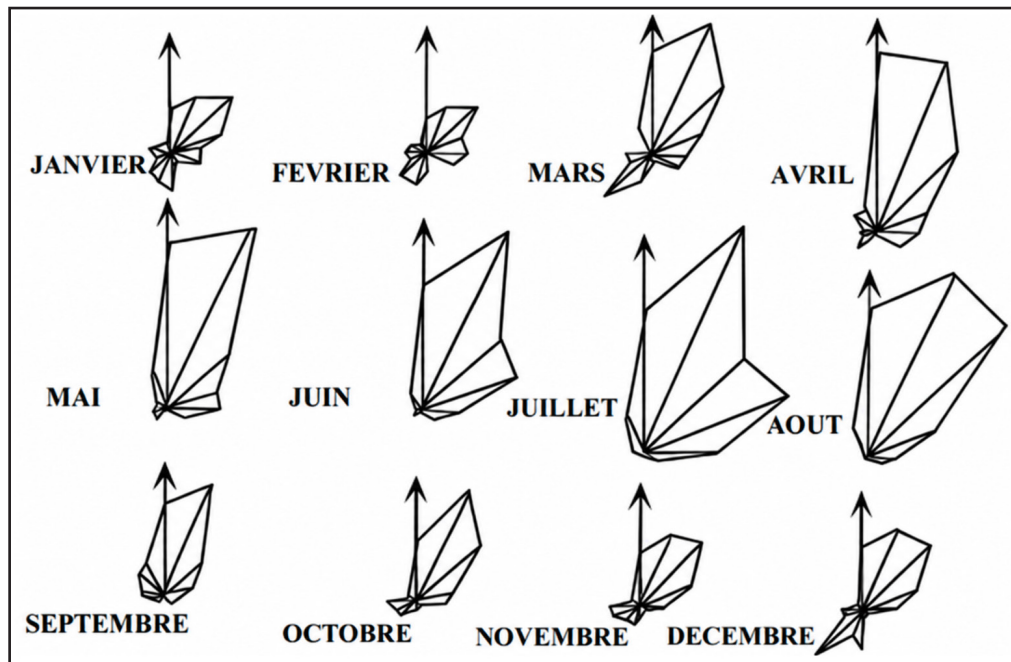


Fig. 2. Main wind directions in the OULED GHANEM area between 1931 and 1961 (Carruesco, 1989).

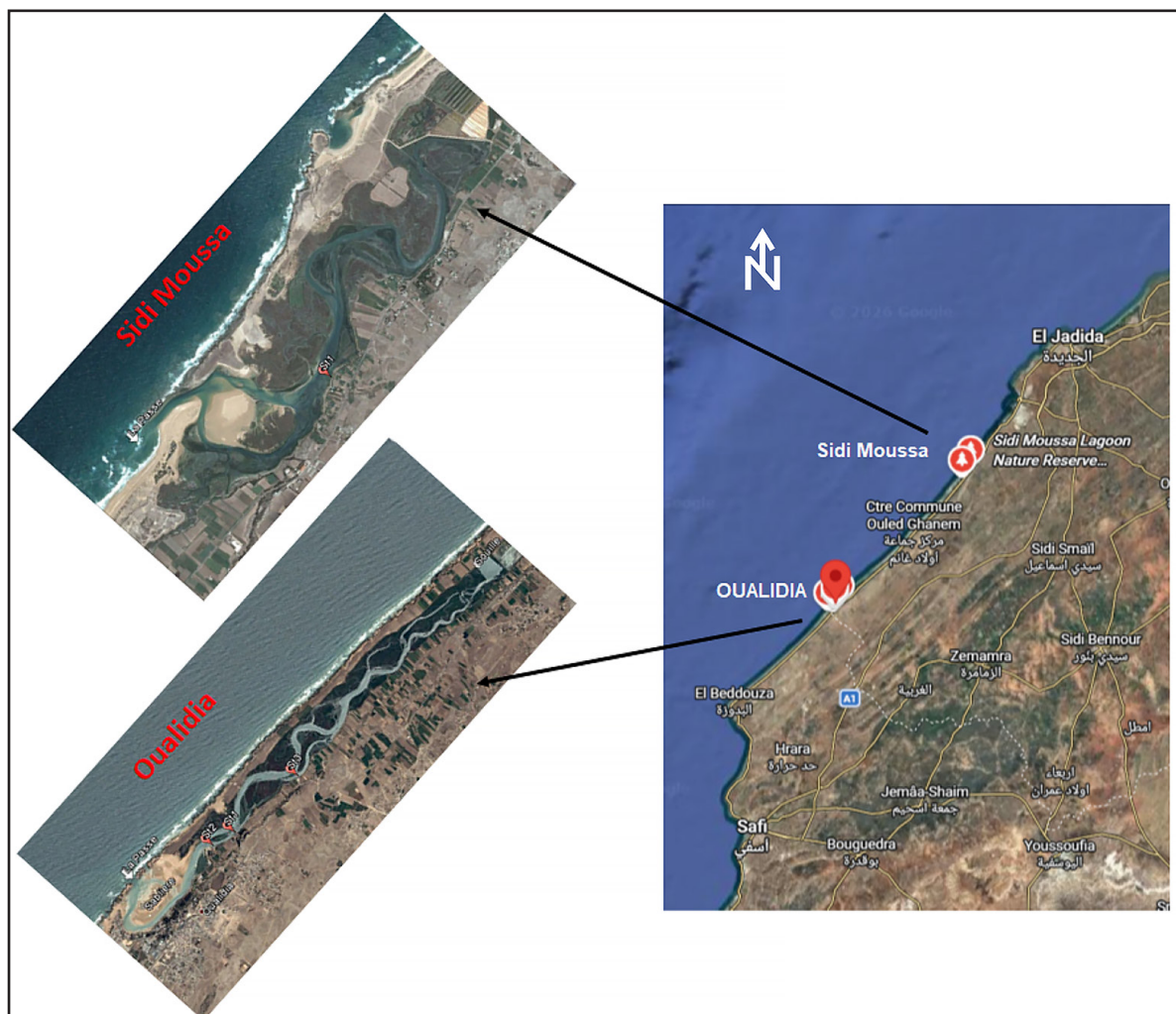


Fig. 3. Hydrological station network established in the Oualidia Lagoon and Sidi Moussa Lagoon.

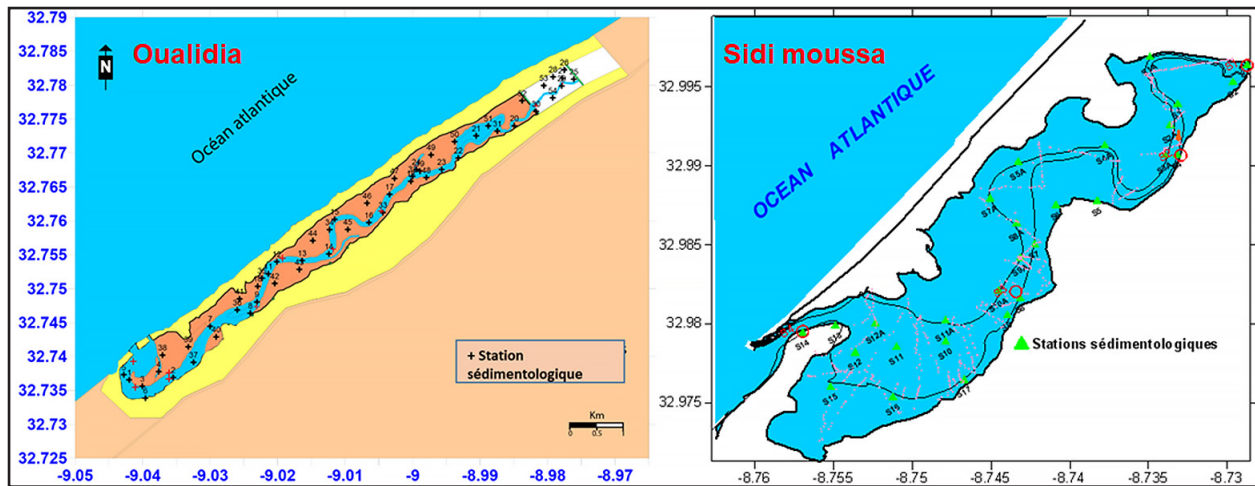


Fig. 4. Network of sedimentological stations in the Oualidia Lagoon (left) and Sidi Moussa Lagoon (right).

- The bathymetry of the two lagoons was conducted during two distinct periods during a spring tide using an integrated system mounted on a *Zodiac* boat. This system included an echo sounder to display water depth and the geographic coordinates of the points, a probe lowered into the water to measure the depth, and a GPS antenna for recording the geographic coordinates of the surveyed area. The entire system was connected to a laptop, using AMAT software to record the data.

### 3. RESULTS

#### 3.1. BATHYMETRY OF THE TWO LAGOONS

The bathymetric surveys of the Oualidia lagoon conducted in October 2017 show that the depth of the lagoon varies between the shoreline and 7 meters at high tide, while it does not exceed 5 meters at low tide (Fig. 5). The area between Parc 3 and Parc 8 is the deepest part of the lagoon, where the depth exceeds 6 meters at high tide. The upstream area is the shallowest, showing a gradual decrease in depth, except for the "souille" zone, where the depth exceeds 2 meters at high tide.

By correcting the depth according to the tidal variation, which ranged from 0.8 meters at low tide to 3.6 meters at high tide during the study period, it is observed that the depth varies between the shoreline and 5 meters, maintaining the same bathymetric structure from downstream to upstream (Fig. 5). Previous results by Bennouna *et al.* (2002) and Bidet & Carruesco (1982) suggested that the average maximum and minimum depths in the lagoon are 5 meters and 1.5 meters, respectively.

Regarding the Sidi Moussa lagoon, the bathymetric survey was conducted on October 16 and 17, 2012, during the peak of high spring tide, lasting 3 to 4 hours along radials perpendicular to both banks of the main channel. The bathymetric measurements taken during this mission (Fig. 6) reveal a subdivision of the lagoon into two zones.

The downstream zone, which includes the sand pit and the lower part of the main channel, shows depths exceeding 3 meters at high tide. In contrast, the upstream zone indicates a gradual decrease in depth, rarely exceeding 2 meters, except in the area of the former breach, where the depth surpasses 3 meters.

#### 3.2. PHYSICOCHEMICAL CHARACTERIZATION AND HYDROLOGICAL VARIABILITY OF THE LAGOONS

##### Temperature

The evolution of water temperatures in both lagoons has shown seasonal variation at both high and low tides. During full tides, the minimum temperatures (between 15 and 16°C) are observed in summer, due to the influence of upwelling waters (Makaoui *et al.*, 2018) and persist until autumn and into winter. The maximum temperatures are recorded in spring. In contrast, at low tides, higher temperatures are recorded in autumn and summer. The minimum temperatures are mainly observed during the winter season (15 and 16°C) and can reach 13°C in February at Oualidia (Fig. 7).

The water temperature in the Sidi Moussa lagoon is generally higher than that of the Oualidia lagoon throughout the year, both at high and low tides. In Oualidia, the waters are very homogeneous, with temperatures being the same at the three farming sites. However, at low tide, Station 3 experiences a more pronounced warming of the waters, which can range from 1 to 4°C (as seen in April and July).

##### Salinity

Since October 2014, during the period of intense rainfall, both lagoons have shown a noticeable decrease in salinity at low tide, with salinity values reaching approximately 25 psu at Oualidia (Station 3) and 15.5 psu at Sidi Moussa. At high tide, the waters have maintained a relatively stable salinity around 35 psu. This indicates an increase in the discharge of freshwater due to various sources of freshwater surrounding both lagoons, primarily upstream (Fig. 8).

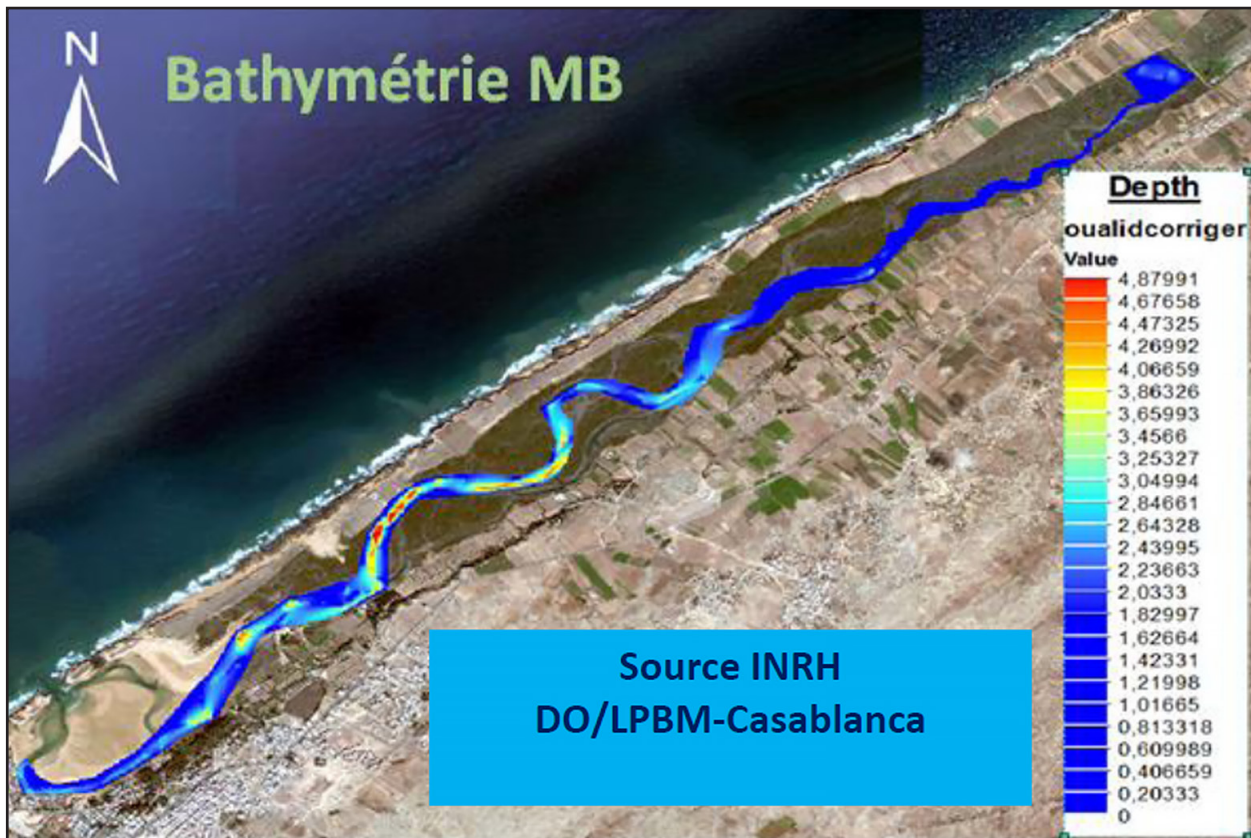


Fig. 5. Bathymetric surveys carried out at low tide in October 2017 in the Oualidia Lagoon.

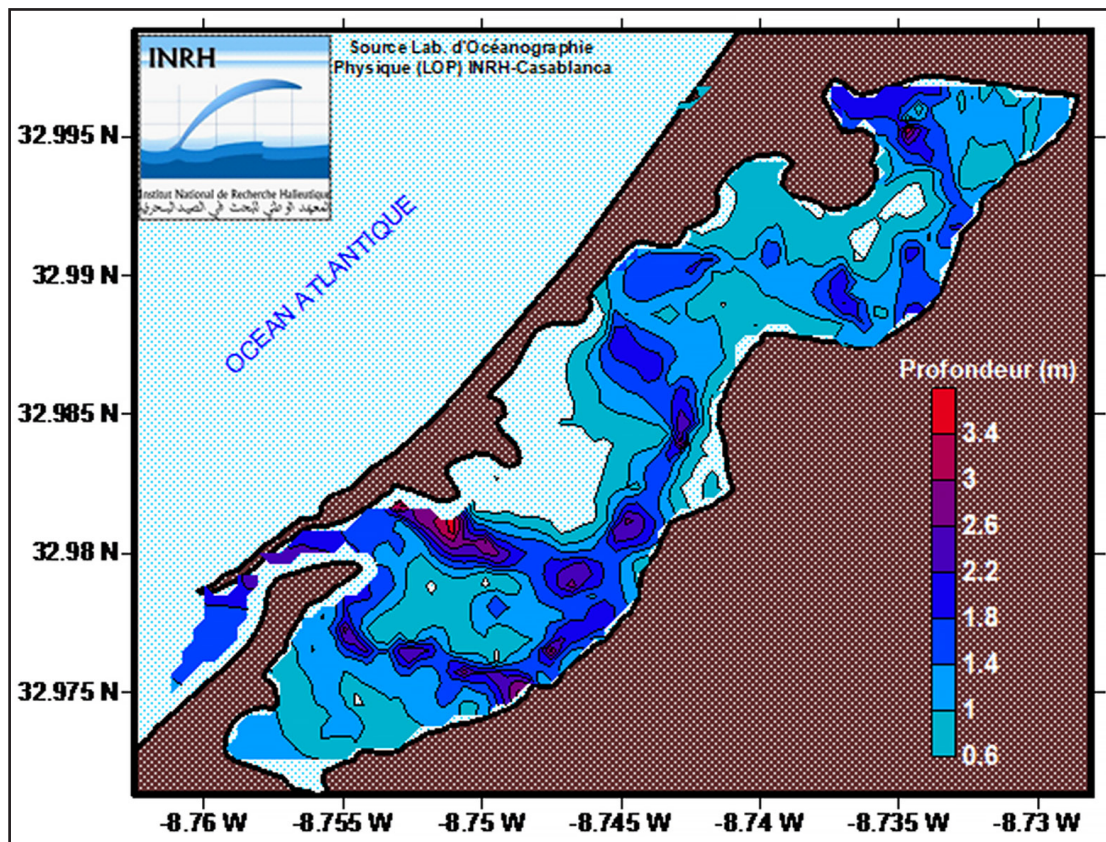
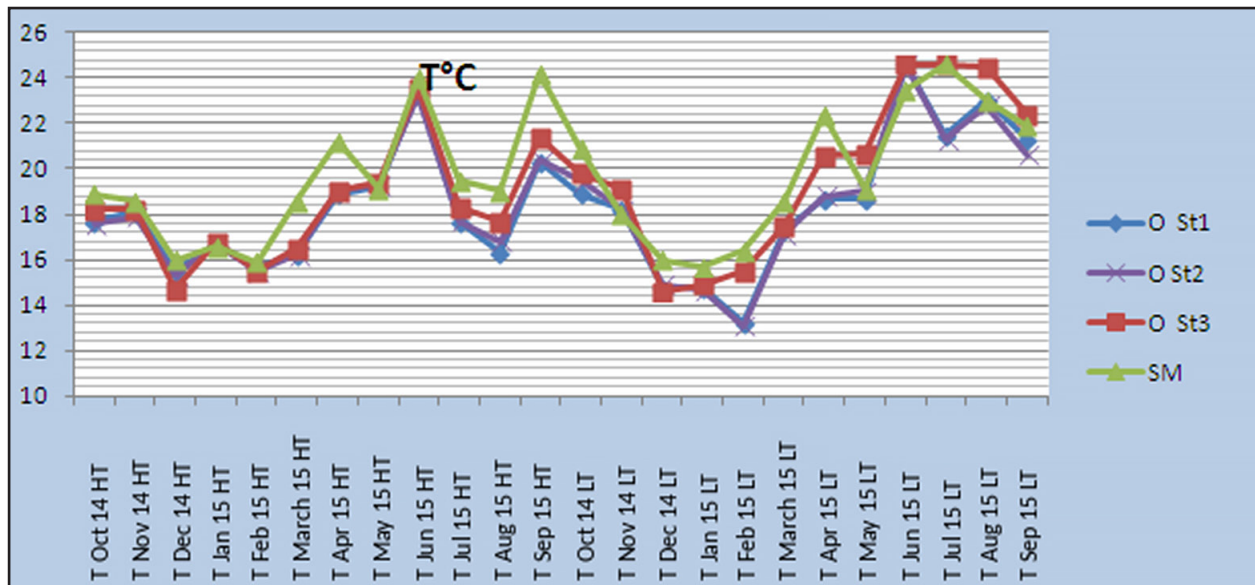
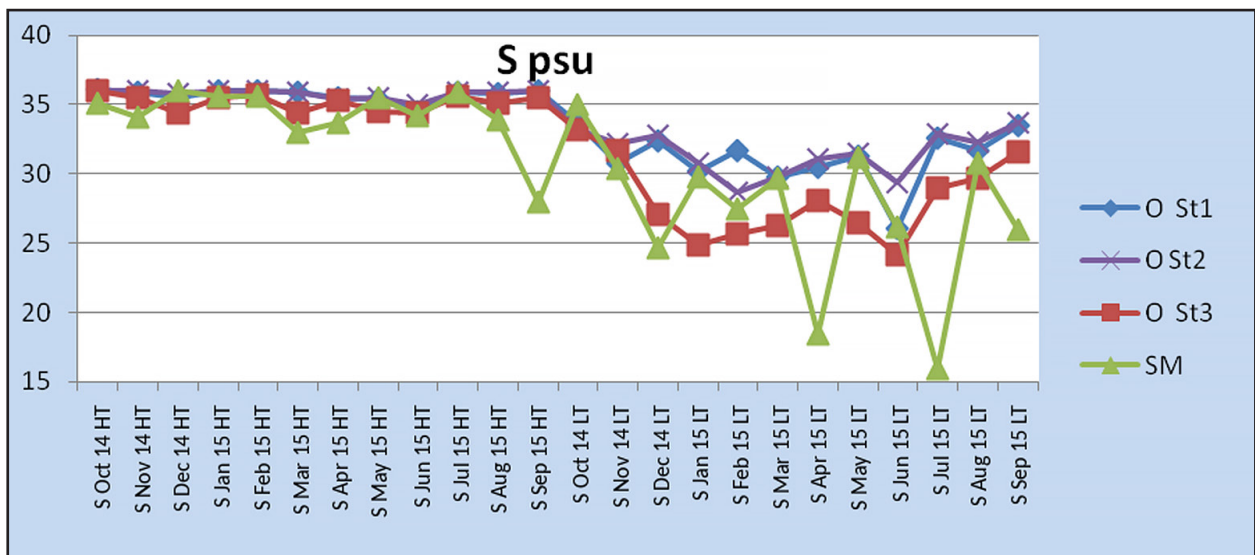


Fig. 6. Bathymetric surveys carried out in the Sidi Moussa Lagoon during the period of 16–17 October 2012.



**Fig. 7.** Evolution of temperature (°C) in the Oualidia Lagoon (O St1, O St2 and O St3) and in the Sidi Moussa Lagoon (SM) at high tide (HT) and low tide (LT) over the period October 2014 – August 2015.



**Fig. 8.** Evolution of salinity (psu) in the Oualidia Lagoon (O St1, O St2 and O St3) and in the Sidi Moussa Lagoon (SM) at high tide (HT) and low tide (LT) over the period October 2014 – August 2015.

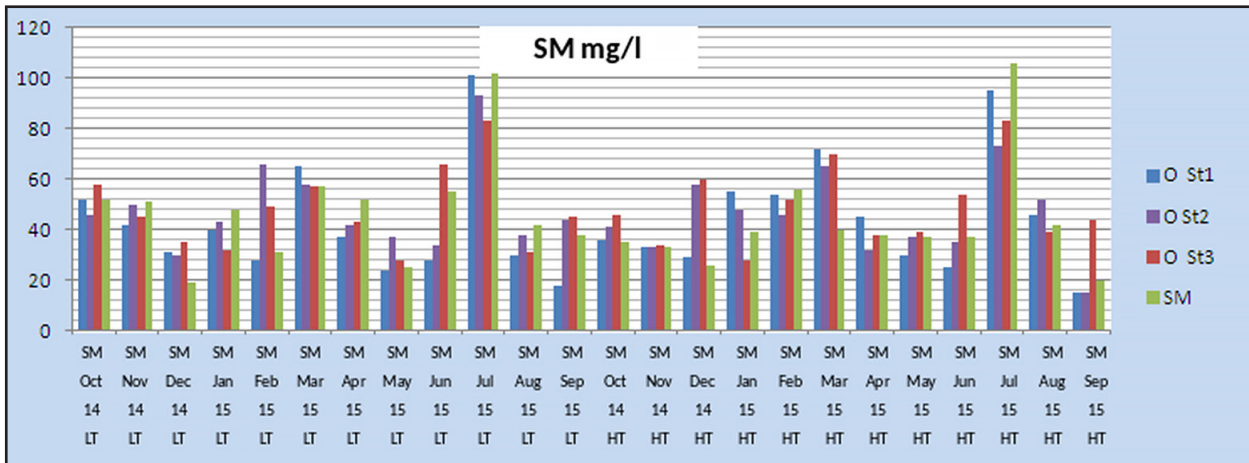
Indeed, in the Oualidia lagoon, this situation is particularly evident at Station 3, which records the lowest salinity compared to Stations 1 and 2, which are located further downstream.

#### *Suspended Matter (SM)*

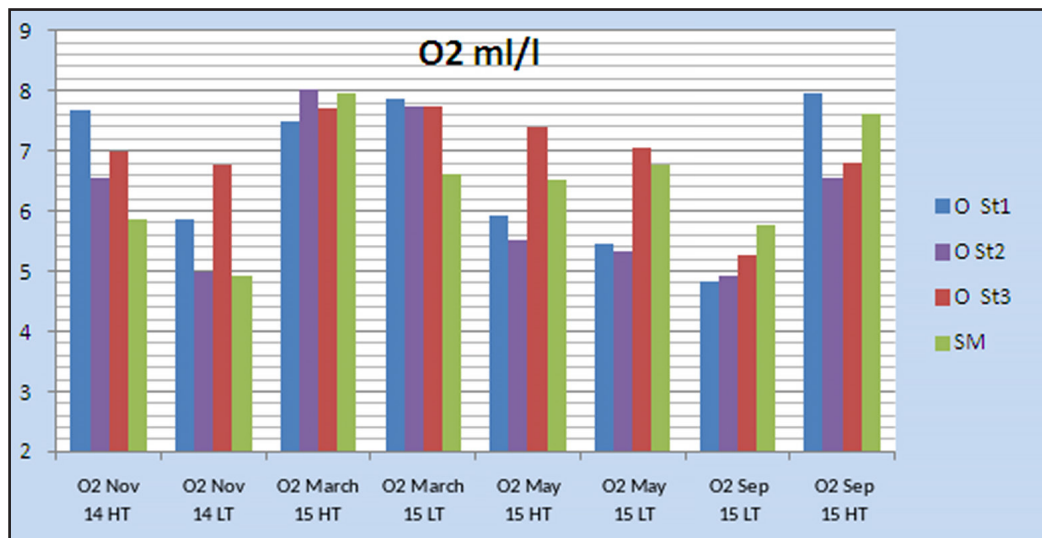
The evolution of turbidity in both lagoons is characterized by high levels in spring, exceeding 50 mg/l at both high tide (HT) and low tide (LT). During other seasons, the suspended matter is below 50 mg/l, except for the month of July, during which elevated values were observed, due to high wind velocity in summer season (Fig. 9).

#### *Dissolved oxygen*

Throughout the study period, dissolved oxygen concentrations were generally higher at high tide than at low tide in both Oualidia and Sidi Moussa lagoons. In Oualidia, the highest concentrations were observed at high tide, reaching approximately 8 ml/L in March and September, whereas lower values were recorded at low tide, including about 5 ml/L in November and 4.8 ml/L in September. In Sidi Moussa, dissolved oxygen concentrations also varied with the tidal phase, with high-tide values reaching approximately 7.9 ml/L in March and 7.6 ml/L in September, while values below 5 ml/L were observed at low tide, particularly in November (Fig. 10).



**Fig. 9.** Evolution of Suspended Matter (SM) in Oualidia (O St1, O St2, O St3) and Sidi Moussa (SM) at high tide (HT) and low tide (LT) over the period from October 2014 to September 2015.



**Fig. 10.** Evolution of dissolved oxygen saturation (ml/l) in Oualidia (O St1, O St2, O St3) and Sidi Moussa (SM) at high tide (HT) and low tide (LT) over the period from November 2014 to September 2015.

These variations may reflect the combined influence of tidal renewal, water residence time, temperature, and biological processes.

#### Nutrients

The evolution of nutrient levels in both lagoons indicates significant mineral richness at low tide. At high tide, despite the influx of marine waters from the Atlantic Ocean, phosphate levels remain elevated during February and March 2015 (Fig. 11). Nitrate concentrations are nearly diluted by 50%.

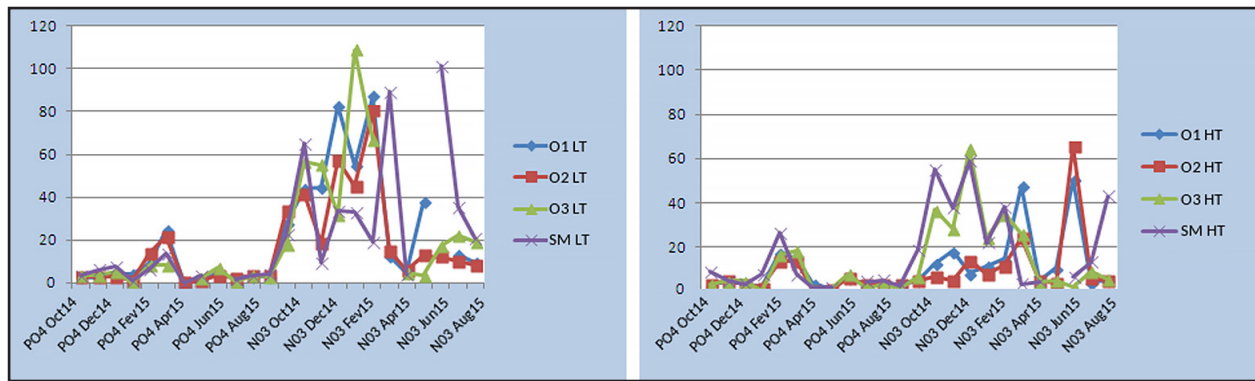
Regarding spatial variation in the Oualidia lagoon, Stations O1 and O2 are most affected by marine waters at high tide, as nutrient concentrations are more diluted there, while Station O3, located upstream, experiences less influence. Thus, it is observed that both lagoons maintain mineral richness throughout the year, which contributes to

significant organic enrichment, especially in the Oualidia lagoon (Somoue *et al.*, 2020).

#### Water Circulation

The hydrodynamic study conducted by Hilmi *et al.* (2009) in the Oualidia lagoon showed that the currents are primarily tidal currents, with a predominance of the semi-diurnal M2 component (with a period of 12 hours and 25 minutes). During spring tide periods, the maximum observed speeds are around 0.77 m/s; the filling time during the flood is 7 hours and 25 minutes, while the emptying time during the ebb is 5 hours.

In neap tide periods, the current speeds are lower, ranging from 0.1 to 0.2 m/s. The filling time is 4 hours and 25 minutes during the flood, and the emptying time is 8 hours during the ebb.



**Fig. 11.** Evolution of nitrates and phosphates ( $\mu\text{M}$ ) in Oualidia (O St1, O St2, O St3) and Sidi Moussa (SM) at low tide (LT) and high tide (HT) over the period from October 2014 to August 2015.

However, these filling and emptying times differ from downstream to upstream in the lagoon and are related to the complex topography of the lagoon, as well as the presence of secondary channels and marshes upstream (Hilmi *et al.*, 2005b).

Moreover, the circulation and water renewal times in the Oualidia lagoon are primarily driven by the tide outside the entrance passes (Koutitonsky *et al.*, 2006, 2007). According to Hilmi *et al.* (2005b), the renewal time in the Oualidia lagoon varies from a local renewal time (TRL) of about 1 day near the entrance passes to approximately 25 days upstream at the artificial downstream dam. According to Koutitonsky *et al.* (2007), the TRL at the artificial downstream dam is about 30 days.

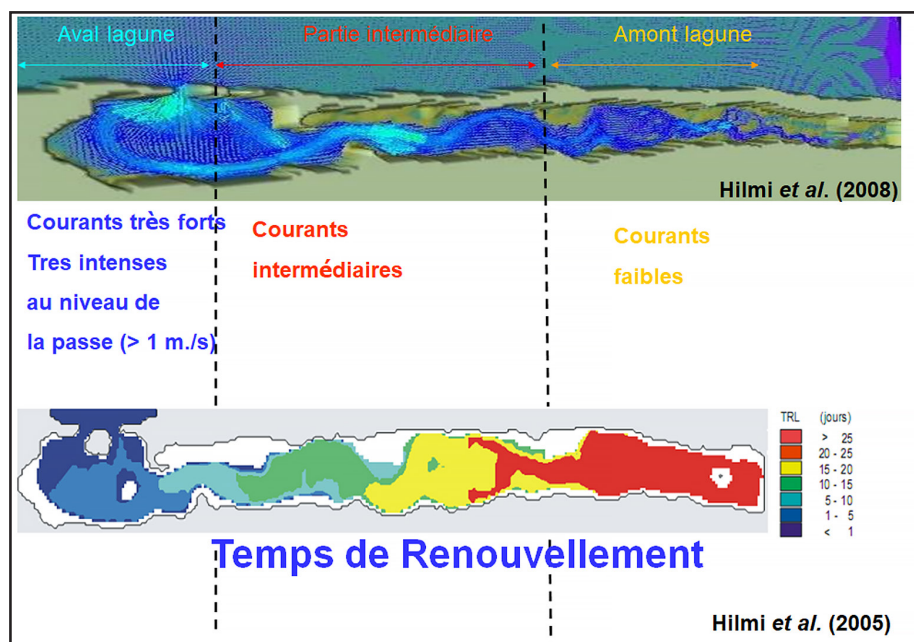
The figure 12 shows the spatial variation in current intensity, with very strong currents near the lagoon inlet ( $> 1 \text{ m s}^{-1}$ ), intermediate currents in the central sector, and

weak currents in the upstream sector. In contrast, the water renewal time (days) is shorter near the inlet and progressively increases toward the upstream part of the lagoon. The dashed lines indicate the three main hydrodynamic sectors: downstream, intermediate, and upstream lagoon (Hilmi *et al.*, 2008).

### 3.3. SEDIMENTOLOGICAL CHARACTERISTICS

#### *Granulometric Distribution*

The various analysis results are presented in the form of maps depicting the distribution of different sedimentological facies (Fig. 13). The sedimentary cover of the Oualidia lagoon consists of two types of deposits: poorly sorted bioclastic sands, which occupy the marine-origin internal tidal delta, and muddy materials located in the upstream area of the lagoon.



**Fig. 12.** Hydrodynamic zonation of Oualidia Lagoon based on spatial variations in current intensity and water renewal time.

The sandy facies, which characterizes the pass area and the sand bank, generally consists of sands that exhibit similar characteristics to beach sands. These sands can be divided into two groups:

- Medium to coarse bioclastic sands, that form the internal tidal delta. They are transported by intra-lagoon dynamics and redistributed within the lagoon to form the sand bank.
- Fine sands, that occupy the lagoon's edge and part of the upstream area. These fine sands resemble those found in dune cordons. Wind may play a significant role in supplying this type of sand to the lagoon (Bidet & Carruesco, 1982).

The intertidal zone of the lagoon is characterized by a muddy facies. This area can be regarded as depressions with low hydrodynamics, where sedimentation occurs through settling and flocculation. In the central zone towards the salt marshes, there is a marked decrease in the sediment fraction and an increase in fine sediment rates, thus indicating a decreasing energy gradient due to the diminishing competence of tidal currents.

The granulometric study of the sands collected in February 2013 (winter period) along the Sidi Moussa lagoon reveals the presence of four sedimentary facies, ranging from downstream (pass area) to upstream (salt marshes): a sandy facies, sandy-muddy facies, muddy-sandy facies, and a muddy facies (Fig. 13).

The sandy facies occupy the pass area, the sand bank, and extends nearly one kilometer. Sand accumulations have also been noted along the coastal cordon.

The sandy-muddy facies is located in the tidal channels and slikkes in the middle of the lagoon, resulting from a decrease in depth and an increase in the energy of the environment.

The muddy-sandy and muddy facies characterize the intertidal zone and the marshes; however, there is a noted enrichment of the fine fraction upstream in the lagoon. This area can be considered as depressions with low hydrodynamics, where sedimentation proceeds through settling and flocculation of the mud.

This study has highlighted two morpho-sedimentary sectors in the Sidi Moussa lagoon: a downstream sector at the pass characterized by strong marine hydrodynamics and an upstream sector characterized by weak marine hydrodynamics.

### Organic Matter Content

The evolution of organic matter in the surface sediments of the Oualidia lagoon indicates the presence of an increasing gradient from downstream to upstream (Fig. 14). The values are consistently high in the upstream area, reaching up to 16.87%, suggesting the significant influence of continental inputs (plant debris). In contrast, the stations located downstream of the lagoon exhibit lower organic matter content (1.07%), which can be explained by the combination of two factors: the sparse vegetation cover in the intertidal zone and the strength of the currents (Hilmi *et al.*, 2005a, 2009), which do not favor the sedimentation of fine particles or the trapping of organic matter.

The organic matter content along the Sidi Moussa lagoon fluctuates between 1.91% and 8.32% (Fig. 14), also demonstrating an increasing gradient from downstream to upstream. The values remain notably high upstream, reaching 8.32% (St1), which again highlights the importance of continental contributions (plant debris). The morphology of the lagoon plays a crucial role in trapping fine sediments, leading to a greater accumulation of organic matter upstream. Conversely, in the stations located downstream, the organic matter content is low at 1.91% (St14) due to the strong agitation in this area, which hinders the sedimentation of fine fractions and consequently the deposition of organic matter.

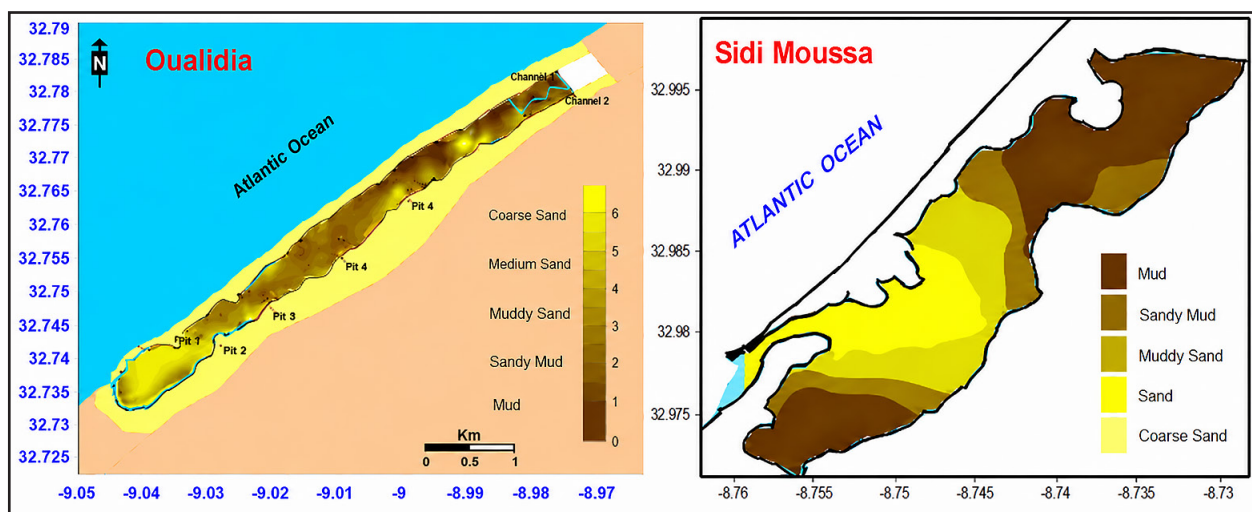


Fig. 13. Distribution of sedimentary facies in the Oualidia and Sidi Moussa lagoons.

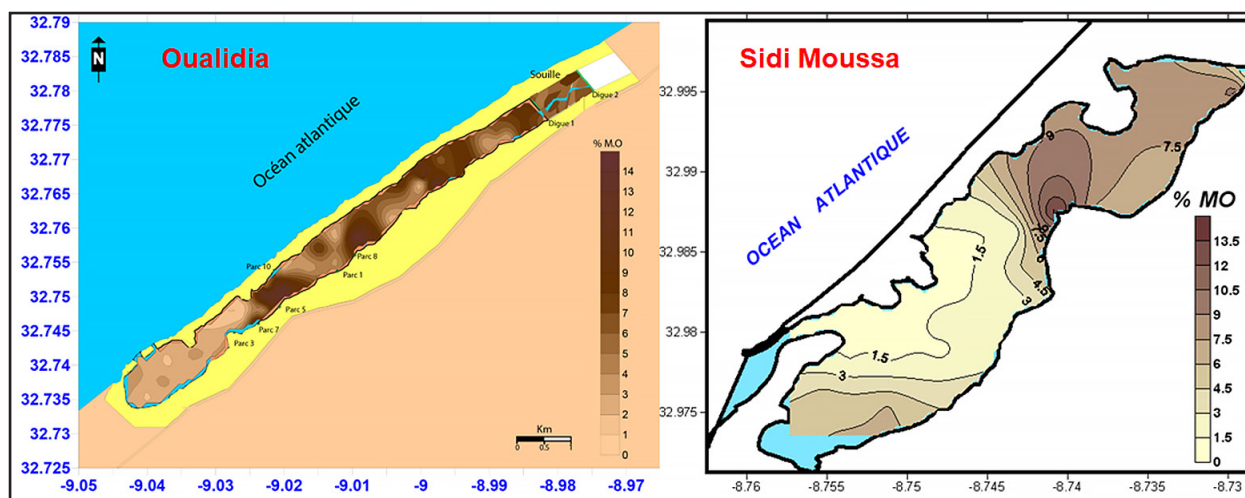


Fig. 14. Distribution of organic matter in the Oualidia Lagoon (left) and Sidi Moussa Lagoon (right).

This pattern likely reflects the same combination of factors identified for the Oualidia lagoon — sparse vegetation cover in the intertidal zone and strong currents limiting the sedimentation of fine particles and the trapping of organic matter. In the lagoon's sediments, terrigenous inputs represent an additional source of organic matter, which can become predominant in the upstream areas of the lagoon. Maanan (2003) reported a high percentage of organic matter content, ranging from 3.4% to 9.5%.

#### 4. CONCLUSIONS

The annual hydrological monitoring of the Oualidia – Sidi Moussa lagoon complex has allowed us to characterize its ecosystem through seasonal variability of the physicochemical parameters during the two daily tides, at low tide (LT) and high tide (HT). This variability can have a direct impact on the growth of shellfish and algal species in both lagoons.

Indeed, at low tides, the waters are cold and enriched with nitrates throughout the year, experiencing significant warming during the summer and autumn seasons. At high tides, the waters are generally saltier from the upstream to the downstream areas of the lagoons, as fresh water masses are located upstream of both lagoons.

The upstream regions of the lagoons are characterized by a high percentage of organic matter and the dominance of muddy fractions due to low hydrodynamics, which is favored by the shallow depth in this area. This condition has led to the deposition of organic muddy sediments. In contrast, downstream, there is a dominance of coarse fractions and a very low percentage of organic matter. This observation can be attributed to strong hydrodynamics, especially at the entrance channel, and more so in the Oualidia lagoon, which is more exposed to wave action than the Sidi Moussa lagoon.

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