EVOLUTION OF THE DOWNSTREAM REGION MORPHOLOGY OF THE OUALIDIA LAGOON

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Abstract. The Oualidia lagoon, located between El Jadid and Safi, is one of the sites in Morocco where oyster farming has developed in an artisanal manner since the 1950s. Currently, the main problem in coastal areas is that they suffer from rising sea levels which are expected to increase coastal erosion. According to the Intergovernmental Panel on Climate Studies (IPCC, 2007), this rise in sea level is mainly due to global warming. Thus, among the problems that lagoons suffer from, as being partially closed areas, is the filling of these entities following an excessive supply of sediments of marine or terrestrial origin? As a result, the downstream part of the Oualidia lagoon has moved towards the southwest and tends to close the main channel by sedimentation of the sand. In response to this closure, a secondary channel was created at the northeastern part in front of the royal palace by erosion and transport of sand by the tidal current during the period of high and low tide of the lagoon. Also, the circulation of water in the lagoon remained intense and is characterized by strong hydrodynamics despite the change in the downstream morphology of the Oualidia lagoon.

Key words: lagoon, morphology, bathymetry, hydrology, physico-chemical parameters, grain size, sedimentology, tidal currents, Morocco's Atlantic coast

1. INTRODUCTION

The Oualidia lagoon, located on Atlantic coast between El Jadida and Safi, is one of the sites in Morocco where oyster farming has developed in an artisanal manner since the 1950s. Given the importance of this lagoon on the economy and tourism, a better knowledge of its ecosystem is necessary in order to improve and rationalize the management of the aquaculture resources of this site (Rharbi *et al*., 2001). This lagoon has been the subject of numerous studies focused on biological and hydrological aspects (Beaubrun, 1976; Orbi *et al.,* 1998; Rharbi *et al.,* 2001; Makaoui *et al.,* 2018), geological and sedimentological aspects (Carruesco, 1989; Sarf, 1999), currents (Beaubrun, 1976, Carruesco, 1989; Hilmi, 2005; Hilmi *et al.,* 2017), as well as on the quality and health of the marine environment (Chafik *et al.,* 1996; El Attar, 1998; Bennouna, 1999). Also, tidal asymmetry (TA) has been suggested as a possible cause, and a sediment trap was dredged in 2011 to mitigate this condition of poor water quality in upstream region of the lagoon (Koutitonsky *et al.,* 2006, 2007, 2012 and 2024). Currently, the main problem in coastal areas is that they are suffering from a rise in sea level which is expected to increase coastal erosion. According to the Intergovernmental Panel on Climate Studies (IPCC, 2007), this rise in sea level is mainly due to global warming. Erosion materials are dispersed by waves and currents and can either be transported by littoral drift to be reworked on adjacent coasts, or reach the seabed. Thus, among the problems that lagoons suffer from, as being partially closed areas, is the filling of these entities following an excessive supply of sediments of marine or terrestrial origin.

2. METHODOLOGY

A mooring of an ADCP was carried out on January 18, 2023 at 3:30 p.m. at a depth of 5m (High Tide HT) and was recovered on February 1, 2023 at 4 p.m. at the Saidi Park next to the combined continuous measurement system of the Multi-Parameter Probe YSI EXO 2 and the GMX 501 weather station fixed since December 2021 (Fig. 1).

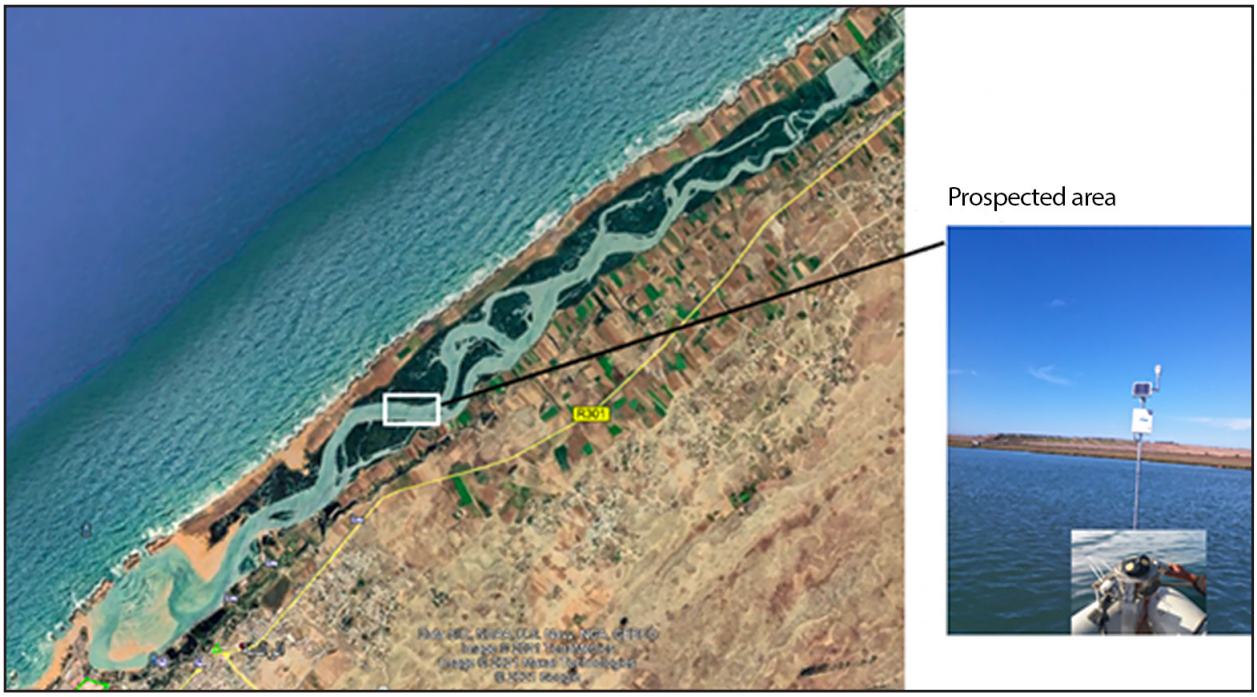

Fig. 1. ADCP and combined continuous measurement system of the Multi-Parameter Probe YSI EXO 2 and the GMX 501 weather station installation area at Park Saidi in Oualidia.

To study the evolution of the morphology of the Oualidia lagoon over time, a methodological approach was based on the use of ArcGIS software. Spatial changes occurring in the downstream part between the years 2011, 2016 and 2023 were based on satellite images from Google Earth. The images were pre-processed using ENVI to ensure optimal data quality, after which the images were converted to vector formats, followed by vector intersection analysis to identify areas of accumulation and erosion of the downstream part. Carrying out bathymetry measurements were performed using a single-beam echo sounder installed on a zodiac. The bathymetric data collected were recorded in real time using the echo sounder during high tide. After the end of the surveys, the raw data were stored on a computer for further processing. The path covered the depth variations along the main and secondary channels, thus allowing a better understanding of the underwater topography of the downstream part of the lagoon (Fig. 2).

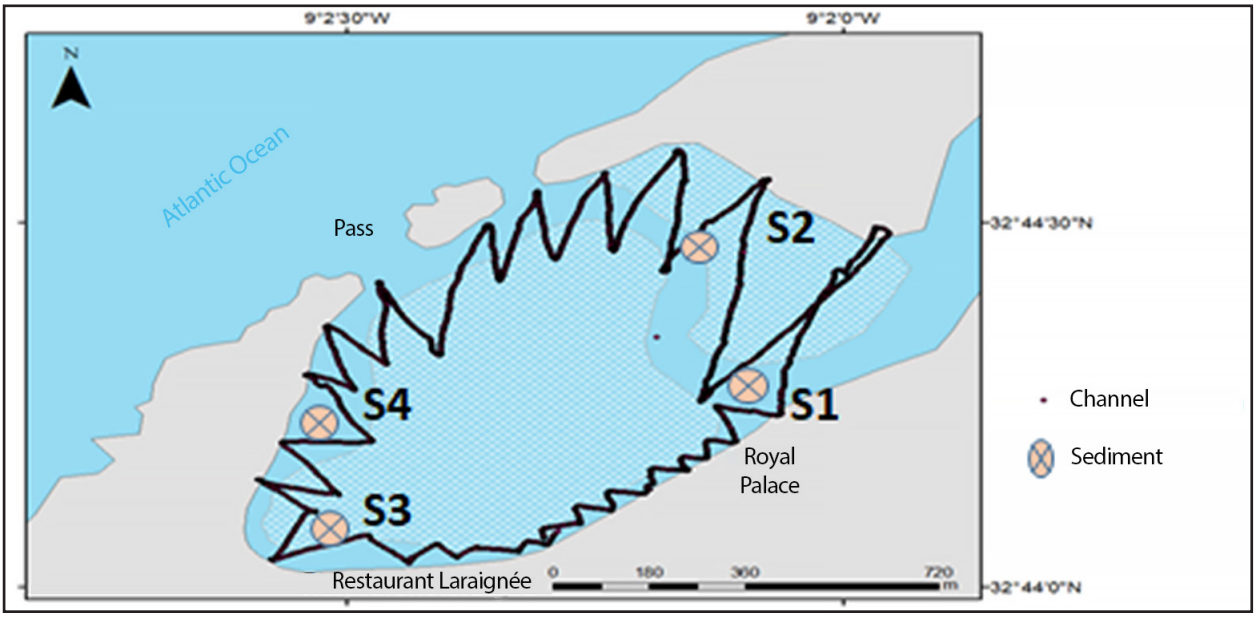

Fig. 2. Bathymetric prospecting and sedimentological stations.

The sediment samples were taken during low tide by a Van Veen type grab at 4 stations on either side: two samples (S3, S4) from the sedimentation zone next to the restaurant Laraignée and two samples (S1, S2) from the new channel located between the pass and the royal palace (Fig. 2). Each sample was carefully labeled, stored and preserved in an appropriate container for laboratory transport. The grain size analysis was carried out to determine the distribution of the different grain sizes present in the sand samples:

- Sieving method: 110g of each sample was placed on a series of sieves between 0.63 and 2.6 mm. The sieves were then shaken mechanically so that the sand particles were distributed according to their size in the different meshes.
- Weight of particle size fractions: After agitation, the sieves were removed and the weight of sand retained on each sieve was measured. These weights were used to calculate the proportion of sand in each particle size fraction.
- Grain size curve: Using the proportions obtained, we plotted the grain size curve, which graphically represents the distribution of grain sizes in the sand samples.

3. RESULTS AND DISCUSSIONS

Over the years, the downstream part of the lagoon has undergone remarkable evolution. Due to the rate of sand sedimentation, contributing to the progressive enlargement, especially towards the SW part at the main channel level, this regular deposition process favored the supply of the sand, thus increasing its volume and surface area at over time. Despite the effects of currents and waves, the general trend has been towards the increase of the sand pit. This evolution demonstrates the importance of the sand sedimentation rate in shaping the lagoon, creating a dynamic balance between erosion and accretion. Over the years, the sand pit of the lagoon has undergone significant changes (Fig. 3).

Due to the high rate of sand sedimentation, some areas were subject to significant accretion while other parts were subject to erosion. Between 2011 and 2015, the map shows that specific areas of the downstream were subject to erosion and the creation of a new secondary channel in the middle of the area (Fig. 4), probably due to strong currents entering through inlet north pass or that of the ebb coming from the lagoon during low tide. The following years revealed continued fluctuations in the evolution of the sand pit. Some areas experienced notable accretion, while others experienced erosion, indicating dynamic processes in the lagoon. Satellite images from 2022 highlighted a general trend of sand pit accretion, likely due to continued sedimentation of sand from ocean currents.

The bathymetric surveys carried out during the year 2023 in the downstream zone show that the morphology of the study area has undergone a significant modification over the last six years. On the one hand, the main channel which was unique to the south in 2017, experienced silting in the southern part between the Araignée restaurant and the royal palace. On the other hand, in parallel with the silting up of the main channel, the study area has seen through erosion the creation of a new channel to the north between the pass and the main channel at the level of the royal palace which promotes the circulation of water to the north during the emptying and the flow of the lagoon (Fig. 5).

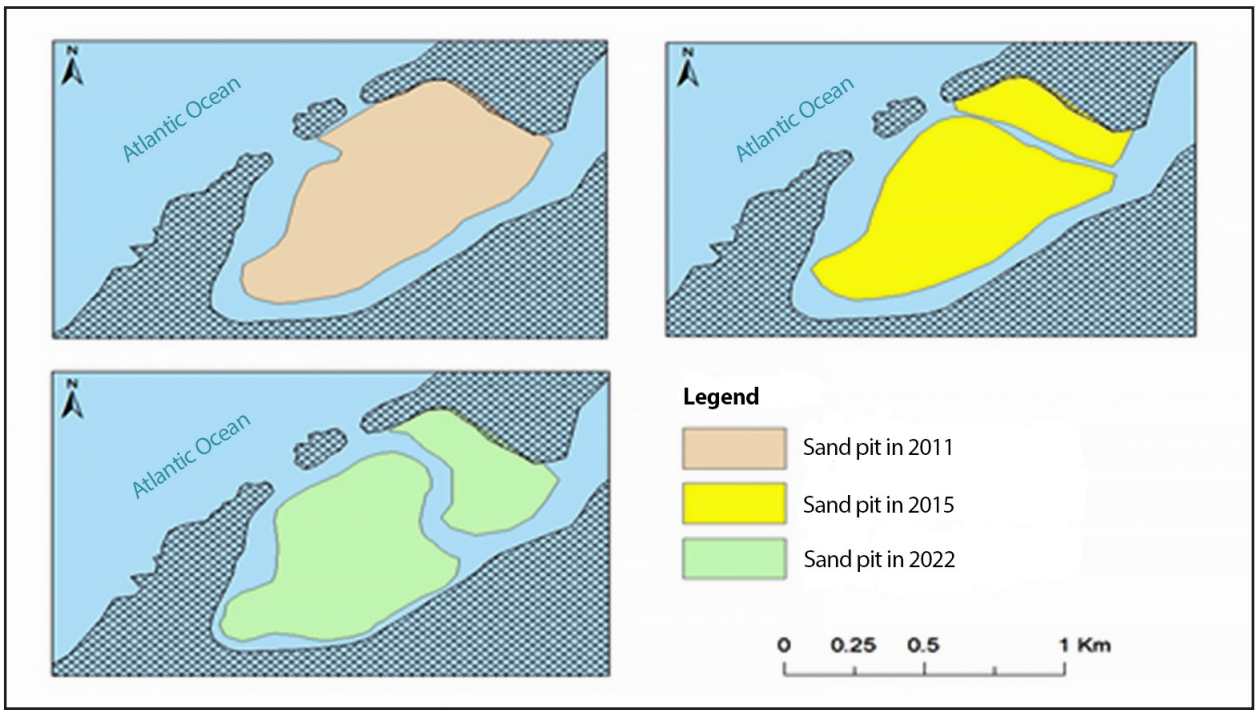

Fig. 3. State of the sand pit in 2011, 2015 and 2023.

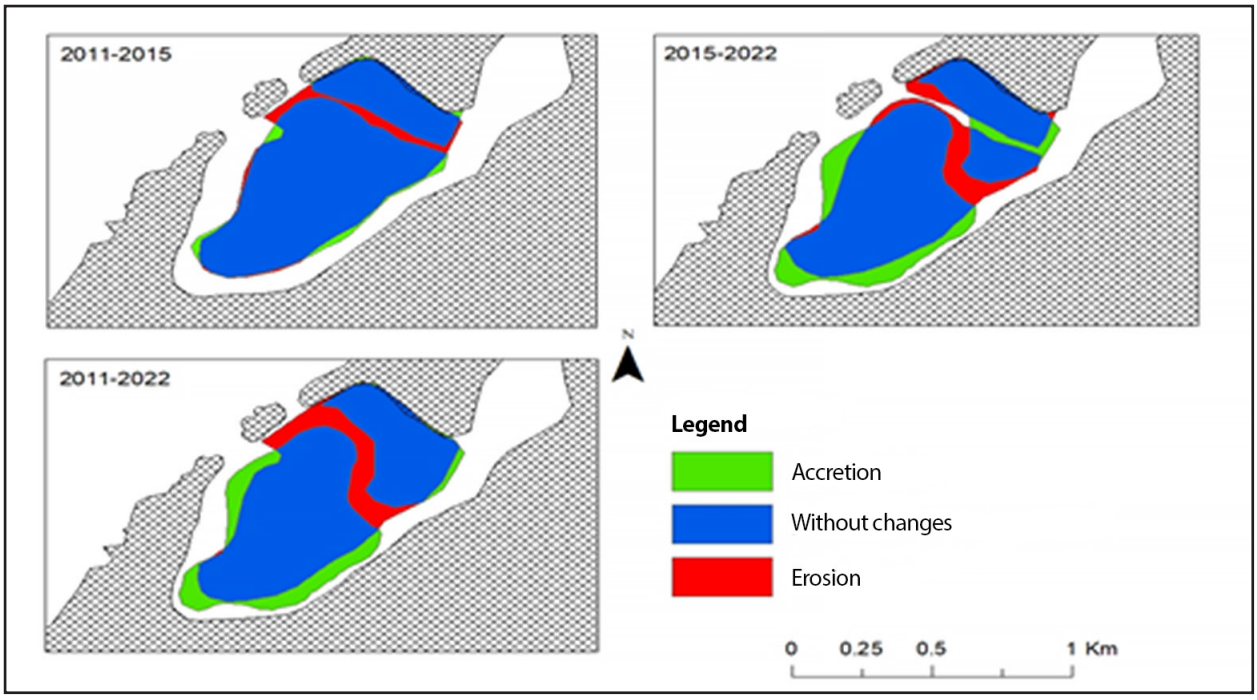

Fig. 4. Erosion and accretion zone from 2011 until 2022.

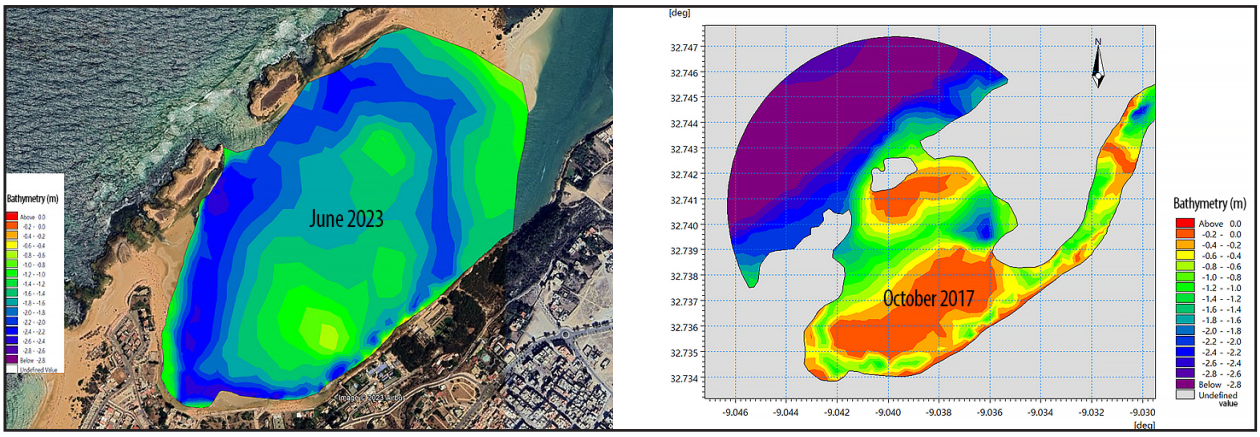

Fig. 5. Bathymetric surveys at the sand pit of the Oualidia lagoon in June 2023 and October 2017 (Source LPBM-CR INRH Casablanca).

The distribution of grain size at the sedimentological stations carried out on either side of the study area confirms that north-east has undergone erosion. Indeed, at stations 1 and 2, the dominance of medium sediment compared to fine sand and mud indicates that the area has suffered erosion in recent years. This erosion favored the creation of the channel between the pass and the main channel at the royal palace. On the other hand, at station 3, the dominance of mud indicates retention and sedimentation in the southwest zone of the lagoon which tends to close the main channel in this zone (Fig. 6).

The results obtained following the calculation of the particle size indices are illustrated in the table 1.

Following the particle size analysis and the calculation of the corresponding indexes (Table 1), the results obtained are as follows: sands S1, S2 and S4 reveal an average *Mz* less than 1 Ø, reflecting their coarse nature (Coarse sand). In parallel, the S3 sample has a fine grain size (muddy sand). Regarding the *sorting (So)*, the S1, S2 and S4 sands display values between 0.6 Ø and 0.81 Ø. These moderate figures indicate a classification in moderately sorted sands, showing deposition in environments with variable agitation. In contrast, S3 sand is distinguished by an exceptionally high *So* value, implying deficient grain size sorting. This feature could be attributed to the combined influence between freshwater and marine inputs.

Table 1. Particle size indexes

Station	Mean (*Mz*) (Ø)	Median (*Md*) µm	Sorting (*So*) (Ø)	Skewness (*Sk*)	Kurtosis (K)
S1	0.70	595	0.81	-0.26	1.53
S2	0.66	597	0.80	-0.29	1.62
S3	2.74	291	2.42	0.58	1.52
S4	0.67	602	0.60	-0.16	1.16

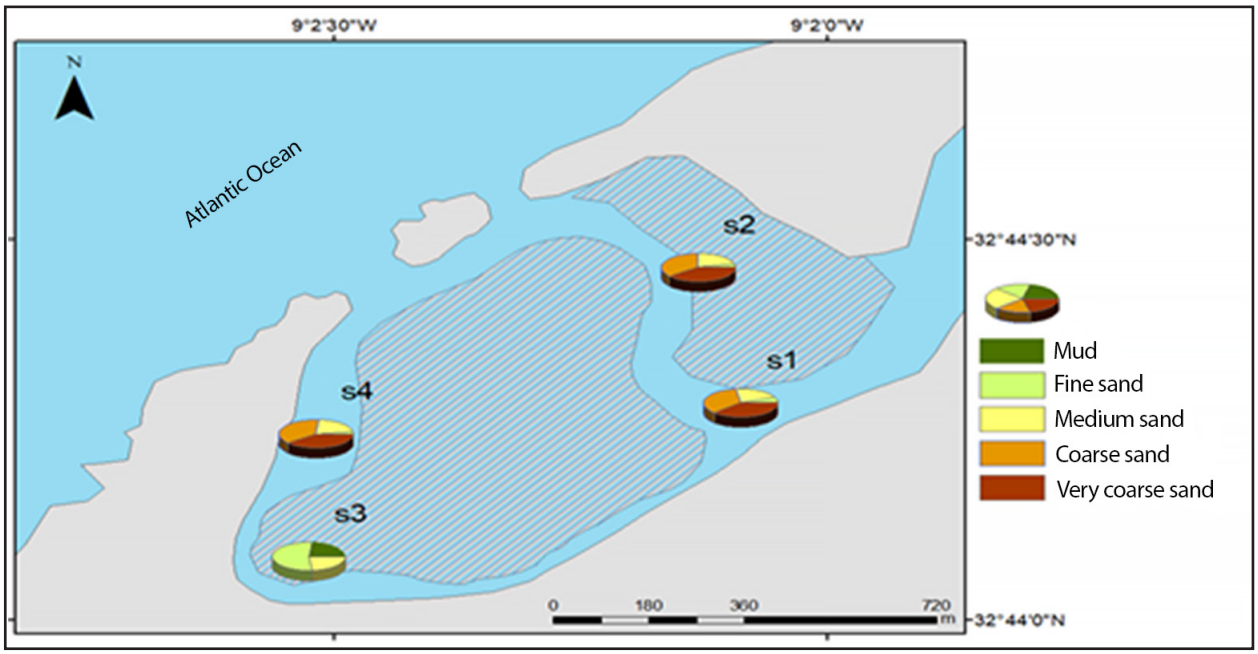

Fig. 6. Distribution of sediment types at the sand pit of the Oualidia lagoon in June 2023 (Source LPBM-CR INRH Casablanca).

During the month of June 2023 and during the cruise period, regular monitoring of the middle of the Oualidia lagoon by the CTD Exo2 multi probe, installed at the TAT Park of the Oualidia lagoon, indicated anomalies of the water *temperature* (very high values) at low tide. Indeed, temperatures exceeding 27°C from June 23 to 28, 2023 coincide with the neap tide where salinity does not vary much between low and high tide. The temperature varies with a difference of more than 7°C every day. On June 27, 2023, it recorded a very significant increase from 19°C to 29°C, due to the variation in the tidal cycle and the variation in air temperature. *Chlorophyll a* and *turbidity* were inversely proportional. Chlorophyll richness is accompanied by low turbidity at the beginning and end of the month, whereas in the middle of the month, the waters were more turbid with low chlorophyll richness (Fig. 7). *Salinity* varies with a difference of 8 PSU during periods of high tide (from 06/01/2023 to 06/05/2023), and a margin of more than 4 PSU during neap periods (from 06/06/2023 to 06/10/2023) between 31 PSU at low tide and 36 PSU at high tide.

The *pH* fluctuates similarly to the variation in salinity and is very influenced by the tides. The maximum of around 8.5 was recorded during high tide and the minimum of 8 was recorded during the low tide period, indicating a gradient of 0.5.

For meteorological conditions, the wind recorded during this period was predominantly from the North-East with generally low intensities not exceeding a maximum intensity of 6m/s (Fig. 8). The air temperature fluctuates regularly between day and night during this period, varying by a margin of over 10°C, with a maximum of 29°C during the day and a minimum of 17°C at night.

The atmospheric pressure recorded during this period varied between 1010 and 1018 Pa. Thus, during this period, and mainly during the neap tide, the lagoon experienced a warming of the waters caused by increases in air temperature, on the one hand, and by the low intensities of the winds, on the other hand, which favor the increase in the temperature of the lagoon waters during low tide and discourage upwelling activity offshore.

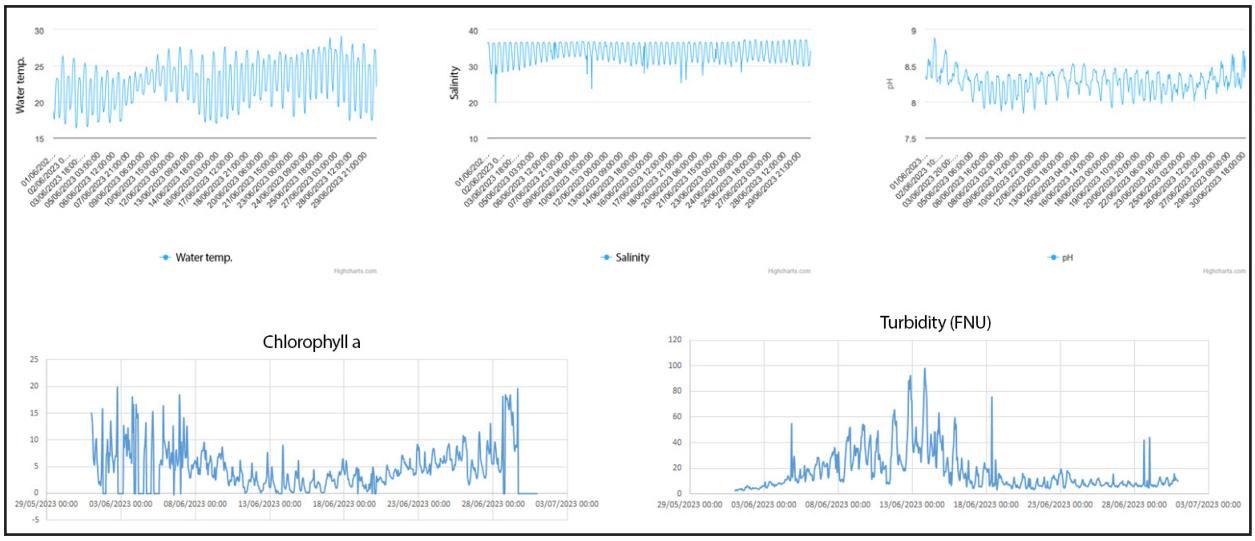

Fig. 7. Evolution of the parameters of the CTD Exo2 of Oualidia lagoon (June 2023).

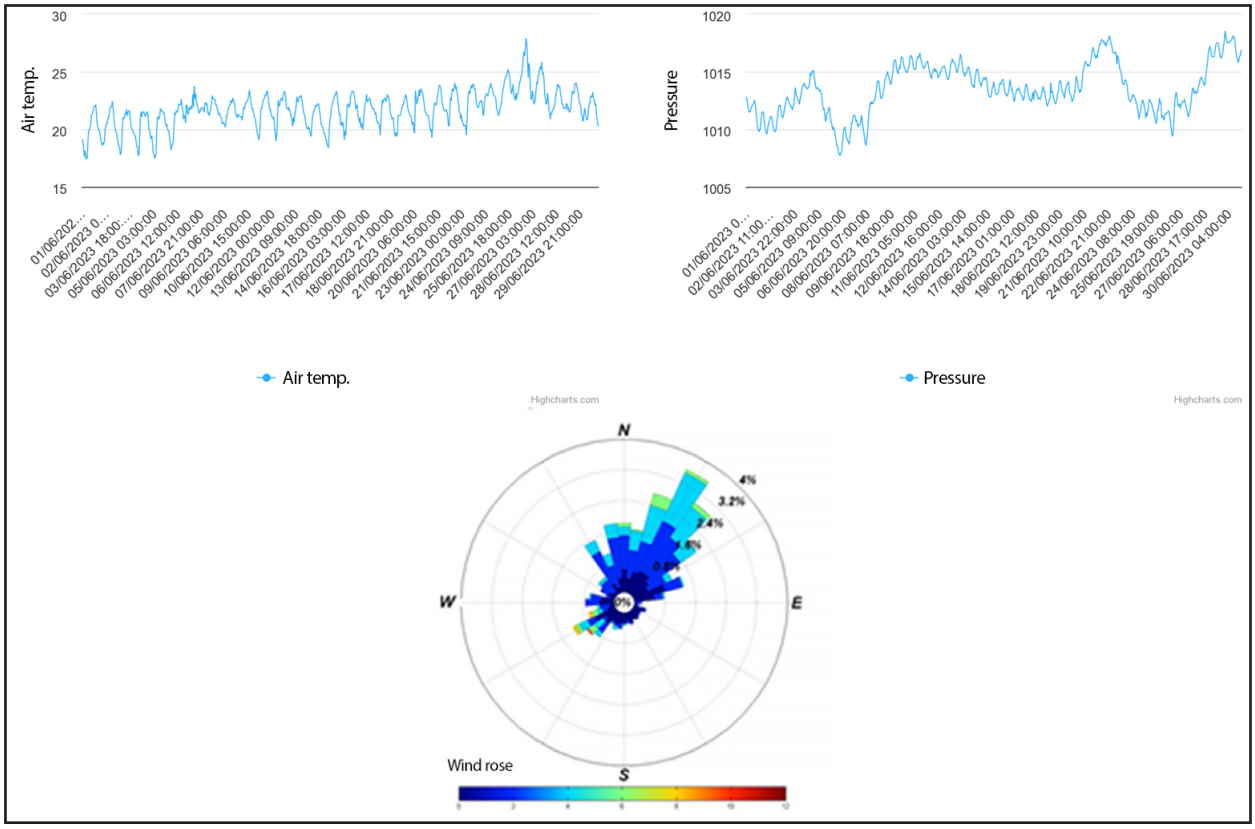

Fig. 8. Evolution of Oualidia meteorological parameters (June 2023).

As for the exchange between the ocean and the lagoon is well marked and shows that the circulation of ocean waters in the lagoon during the two tides is in good condition.

The circulation of water at the level of the lagoon records maximum current speed values, exceeding 90 cm/s, during the spring tide at Saidi Park (Fig. 9). The prevailing current in the study area is between 80 and 90 cm/s. The maximum current speed recorded can reach 1m/s. Following the tide (Fig. 10), maximum currents are observed at mid-high tide and at low tide. The current speed measured in the middle of the lagoon did not exceed 40 cm/s before the formation of the sink in 2005 (Hilmi *et al*., 2017) and around 51cm/s at Park 7 in 2020, after the construction of the pit (Source INRH 2020) which shows that changes in the morphology of the sand pit have no impact on the circulation of water in the lagoon.

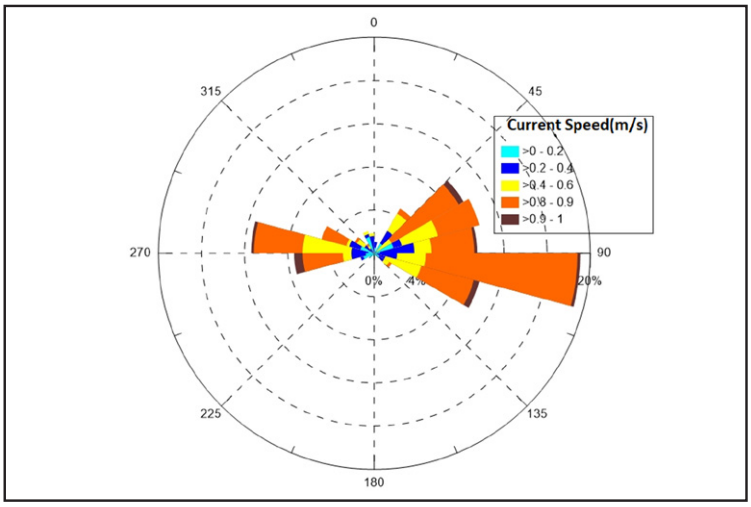

Fig. 9. Current rose recorded at Saidi Park from January 18 to 26, 2023.

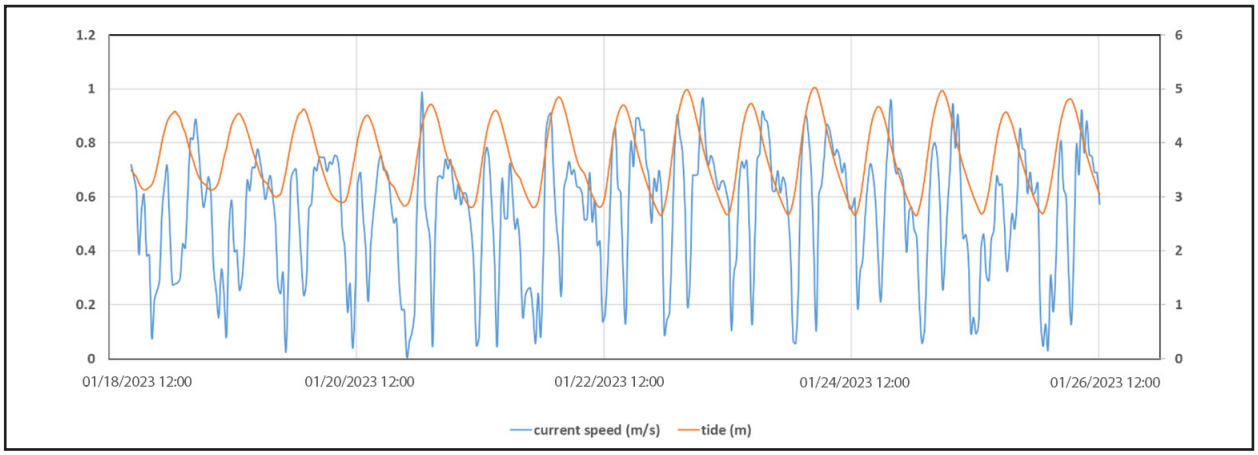

Fig. 10. Current speed recorded according to the tide measured from January 18 to 26, 2023.

4. CONCLUSIONS

The curvature of the main channel, downstream of the lagoon, is the most important and determining factor in the morphological changes of the sand pit in this area. Indeed, the curvature of the channel allows the characterization of two zones: convex zone and concave zone. In the convex zone, sedimentation takes place by lateral accretion of sandy prisms. On the contrary, the concave zone is the site of continuous erosion of the left bank. These two coupled sedimentary processes allowed the accentuation of the sinuosity and consequently the change in the location of the main flow and the advancement of the channel towards the continent through time. At the continental level, erosion decreases, however sedimentation continues at the convex zone. Over time, this unevenness of the erosion/sedimentation process will lead to clogging of the main channel. Comparison of the bathymetry of the downstream area of the Oualidia lagoon between the years 2017 and 2023 shows that the morphology has undergone a significant evolution which is manifested by the silting up of the main channel to the south on the one hand and the accompanying erosion by the creation of a new channel to the north. Over the years, the sand pit of the lagoon has undergone remarkable evolution. Due to the rate of sand sedimentation, contributing to the progressive enlargement of the sand pit especially towards the South-West part at the level of the main channel, this regular deposit favored the growth of the sand pit, thus increasing its volume and surface area over time. Despite the effects of currents and waves, the general trend was towards the increase of the sand pit and the closure of the main channel to the southwest between the royal palace and the restaurant l'Araignée. This evolution demonstrates the importance of the sedimentation rate southwest of the sand pit while creating a dynamic balance between erosion and sedimentation.

This development has so far not indicated any impact on the hydrology of the lagoon, which is manifested by good circulation of water during both ebb and flood tides. The current at the Saidi Park station showed that the circulation of water at the lagoon is intense and is characterized by strong hydrodynamics despite the change in the morphology of the sand pit.

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