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Evaluation of Hydrodynamic Conditions in the Oualidia Lagoon (Atlantic Coast of Morocco) †

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Abstract: The present study is based on the combination of field measurements with Copernicus Marine Service (CMS) data and numerical modeling approaches to assess the historical and actual variations of ocean parameters in the Oualidia lagoon in Morocco, including tides, waves, currents and winds. The lagoon of Oualidia is a site of ornithological importance; it has been classified as a site of biological and ecological interest (S.I.B.E), through the Master Plan of Protected Areas, and as a RAMSAR site since 2005. This lagoon has undergone significant anthropogenic modifications in recent years, which included the creation of a sediment trap in 2011 and a dike opening upstream in 2005. The objective of this research is to evaluate the hydrodynamic conditions of this lagoon and its open sea area (offshore) using field measurements, numerical modeling and ocean data collected from Marine Copernicus Service platform. As a result, the analysis of wind data for the year 2021 shows that the prevailing winds are generally northwest, from north to northeast, with a very strong predominance of north to northeast winds. The harmonic analysis of tides for the same period showed that the lagoon is dominated by an M2 tide component with an amplitude reaching 0.9649 m. In addition, the results of the analysis of waves in front of the lagoon of Oualidia revealed a predominance of waves of height ranging between 1 and 2.5 m, representing nearly 60% of the model outputs. Waves with a height of from 3 to 4 m represent 10% of the results, while large winter waves (>4 m) represent only 3%. In addition, the analysis of current data (in situ/modeled) indicates that the current velocities decrease from the downstream to upstream area, in relation to the variations in and the period of tides that affect the variability of tidal currents inside of the lagoon.

Keywords: hydrodynamics; tides; waves; currents; CMS; offshore; oualidia; morocco

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1. Introduction

Surface water systems are waters that are naturally open to the atmosphere, such as rivers, lakes, reservoirs, estuaries and coastal waters. Their water quality management requires three important working methods: (1) monitoring, (2) theoretical analysis, and (3) computer modelling [1].

To help decision-makers identify the extent of environmental problems in these environments, reliable measured data are essential. Monitoring is the only way to know the actual characteristics of the ecosystem and to provide a basis for theoretical analysis and numerical modelling [1]. It is only after making certain observations that theoretical analysis and numerical modelling can help to understand hydrodynamic and water quality processes and produce reliable outputs to support decision making. In many instances, these processes cannot be well described in mathematically based models until they are measurable in real water bodies [1].

Lagoons, in particular, represent 13% of the world's coastline [2–4]. These coastal ecosystems are relatively isolated from the open ocean by coastal barriers that allow for communication between channels and inlets. Some lagoons have a maximum depth of more than 30 m, although the average depth is rarely greater than 2 m [5]. Traditionally, lagoons have been very beneficial to humans, providing both high biological productivity and port and navigation facilities. However, these coastal ecosystems are actively affected by interactions between terrestrial, marine, and atmospheric processes and are most sensitive to a variety of natural processes, including global climate change and also human activities [6]. For these reasons, the permanent assessment of hydrodynamical, sedimentological and ecological states of these ecosystems is of paramount importance for understanding their natural evolution and supporting decision making in these complex coastal environments.

In this paper, we focus on the historical and actual assessment of the main hydrodynamic factors controlling the long-term and short-term trends of the sedimentological and hydrodynamic properties in Oualidia lagoon (Atlantic Coast of Morocco). This study represents a primary assessment of the hydrodynamic parameters in the Oualidia lagoon based on Copernicus forecasting systems and in situ measurements and numerical modeling approaches that will allow for modeling of the hydrodynamic and sedimentological state of the lagoon using mathematical models.

2. Materials and Methods

2.1. Study Area

The lagoon of Oualidia is located on the Moroccan Atlantic Coast in the province of Sidi Bennour city (32°44′42″ N–9°02′50″ W) and extends parallel to the coast over a distance of about 7 km long and 0.5 km wide. The communication of the lagoon with the ocean is ensured by three inlets located downstream: a permanent main inlet (150 m wide and 3 m deep, on average) and a secondary inlet (50 m wide and 2 m deep) and a third small one, which is active only during periods of high tides (Figure 1).

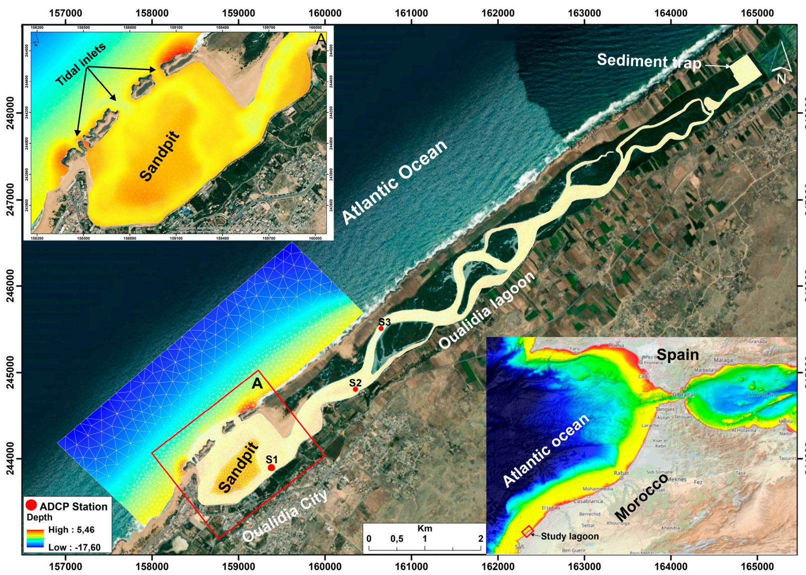

Figure 1. Location of the study area, bathymetric interpolation and ADCP measured stations.

This lagoon is among the most important coastal wetlands in Morocco. At present, in relation to its ornithological importance, this site has been classified as a site of biological and ecological interest (S.I.B.E) through the Master Plan of Protected Areas, and as an RAMSAR site since 2005. This site, of international value, constitutes a migratory stopover and a winter refuge appreciate by the various species of waterbirds.

2.2. Data Collection

Wind data were obtained as NETCDF files by the European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int, accessed on 1 March 2022).

Water levels and offshore currents data were downloaded from the IBI model product reanalysis in the Copernicus project (http://marine.copernicus/eu/services-portfolio/access-to-products/, accessed 1 January 2022).

Significant wave height, direction and period data were collected using the IBI-MFC model (https://resources.marine.copernicus.eu/product, accessed on 1 January 2022). This model provides a multi-year high-resolution wave reanalysis product for the IBI area from 1 January 1993. The model system is executed by AEMET (Spanish Meteorological Agency) in the AEMET supercomputer (NIMBUS). The configuration of the multi-year model is as similar as possible to the configuration of the model used in the IBI-MFC near-real-time forecasting system. The model application is based on the MFWAM model developed by Météo-France (MF), with the same 5 km horizontal resolution grid.

In situ measurements of currents were recorded at three different stations in the lagoon (Figure 1), which were used to calculate the characteristics of the vertical velocity profiles. Velocities were recorded at each 0.5 m layer (~10 layers deep), with layer 10 located closest to the water surface, while layer 1 occurs directly above the ADCP, from 0.5 m to 5 m above the bottom. The deployment depth was 5 m and data were recorded every 600 s. The current meter continuously records several parameters, such as current speed and direction, water temperature, and water pressure. These measurements were made over a period of 10 days, including neap and spring water coefficients.

2.3. Current Velocity Simulation

To gain a comprehensive understanding of the hydrodynamic circulation in the Oualidia lagoon, a hydrodynamic model called MIKE 21, developed by the Danish Hydraulic Institute (DHI, https://www.mikepoweredbydhi.com/, accessed 1 January 2022), has been applied. MIKE 21 is a two-dimensional depth-averaged model that employs finite differences. It has been widely applied in coastal areas, estuaries, bays, and similar water bodies to simulate water levels and flows.

The hydrodynamic model was employed for one-month simulation period (April 2021). This timeframe encompassed two spring tides and two neap tides, enabling the assessment of the simulated parameters under varying tidal conditions. By incorporating different tidal phases, the study provides a comprehensive understanding of the lagoon's hydrodynamics and their variations throughout the tidal cycle.

During the calibration phase of the model, several input parameters were adjusted to ensure accurate representation of the currents and water levels throughout the entire lagoon. These parameters included bottom friction, turbulent mixing coefficients, and bathymetry interpolation uncertainties. The calibration process aimed to match the model outputs with the measured currents and water levels at three different stations within the lagoon.

3. Results and Discussions

3.1. Wind Data Analysis

The wind rose of one year's data (2021) observed at the inlets of the lagoon of Oualidia is presented in Figure 2 (Source: https://www.ecmwf.int/en/research/climate reanalysis, accessed on 1 January 2022). The wind rose analysis shows that the prevailing winds are generally northwest, from north to northeast, with a very strong predominance of north to northeast winds, as described by [7,8]. Annual wind statistics offshore of the Oualidia lagoon indicate that the annual mean winds have speeds ranging from 2 to 10 m s^{-1}. Thus, the study of [9], showed that the annual average winds have speeds ranging between 4 and 9 m s^{-1}, with predominantly northeasterly and northerly directions.

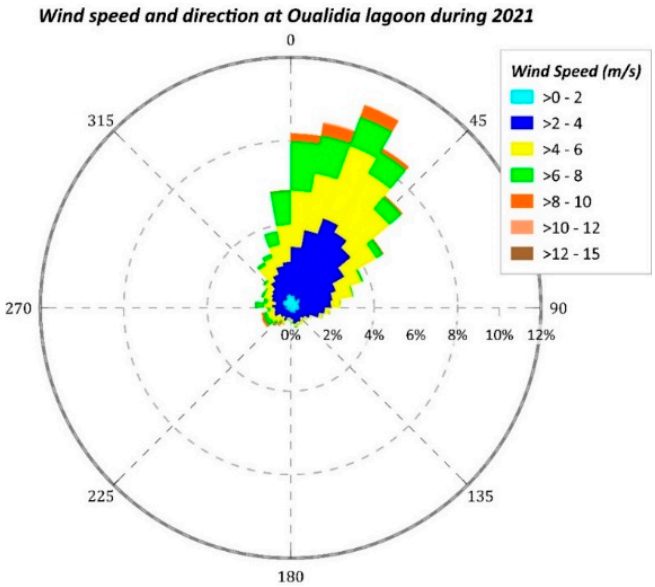

Figure 2. Wind rose of the year of 2021 at Oualidia lagoon (ECMWF, http://www.ecmwf.int, accessed on 1 January 2022).

Regardless of the season, maximum north and northeast wind intensities are often greater than 9 m s^{-1}. The percentage of the dominant wind speed shows varying frequencies of occurrence depending on the season, ranging from 2% to 4% for a wind speed varying between 2 and 4 m s^{-1}, from 4% to 8% for a maximum wind speed of up to 6 m s^{-1} and between 8% and 10% with a wind speed varying between 6 and 10 m. s^{-1}.

3.2. Water Level Analysis

The tidal data used in this analysis were mainly collected from Iberia Biscay Irish—Monitoring Forecasting Centre (IBI MFC2). The analysis of these data showed that the Oualidia lagoon is strongly influenced by semi-diurnal M2 type tides (of a 12.42 h period) [7–9].

The tide is of the semi-diurnal type, almost regular. The average tidal range is 1.30 m for the neap and 2.80 m for the spring tides. The exceptional spring tide is +3.94 m and the exceptional spring low tide is 0.41 m, for an amplitude of 3.53 m.

The tidal amplitudes and phases of the Oualidia lagoon for the water-level constituents are given in Table 1. The amplitude and phases of the tidal harmonics along the main channel reveal a regular change in the character of tides from the entrance inlets to the upstream of the lagoon. The M2, Z0 and S2 harmonics along the lagoon were particularly significant. The fourth most significant was N2, followed by K2.

It can be seen that, in the Oualidia lagoon, the semi-diurnal M2 harmonic predominates, with an amplitude of about 0.96 m. This is followed in importance by the harmonics S2 (amplitude 0.35 m), N2 (amplitude 0.20 m) and K2 (amplitude 0.09 m).

The diurnal tidal components O1, K1 and P1 show lower amplitudes, partly due to the presence of an amphidromic point offshore. An examination of the relative phases of the harmonic components indicates that the tide along the Moroccan coast propagates from south to north.

Table 1. Harmonic analysis of tides during 2021 at Oualidia lagoon.

	Oualidia Lagoon	
Tidal Component	**Amplitude (m)**	**Phase (deg)**
M2	0.9649	51.57
Z0	0.3582	180
S2	0.3511	76.7
N2	0.2069	35.07
K2	0.0946	70.72
K1	0.0659	50.79
O1	0.0596	303.51
MSM	0.0261	207.93
SSA	0.0209	26.81
P1	0.019	43.73

3.3. Wave Analysis

The primary analysis of the wave data showed that the Oualidia lagoon is characterized by a dominance of waves with heights between 1 and 2.5 m, representing nearly 60% of the model outputs. Waves of 3–4 m in height represent 10%, while large winter waves (>4 m) represent only 3% of the model results (Figure 3).

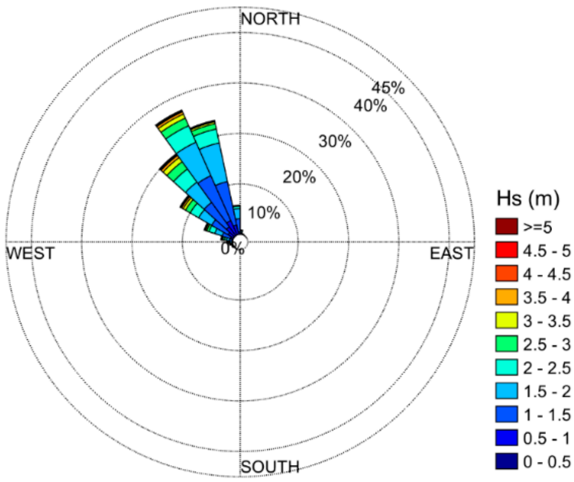

Figure 3. Rose of wave height in the offshore zone of Oualidia lagoon (https://resources.marine.copernicus.eu/product, accessed on 1 January 2022).

In terms of period, the 10–11 s interval dominates between April and September (56% to 68% of model outputs). Between the months of May and September, the period that dominates is that of 6–7 s, with a rate varying between 50% and 73%.

3.4. Current Variability

The study by Hilmi et al. [10] broadly indicates that the currents primarily respond to the tide outside the lagoon. The currents are oriented parallel to the channel axis, with maximum velocities varying between 0.56 m s^{-1}, 0.57 m s^{-1}, and 0.73 m s^{-1}. These speeds decrease to about 0.1–0.2 m s^{-1} during neap tides. Current directions oscillate by 180 degrees between ebb and flood [11].

In 2003, six measurement points were carried out by current meters distributed over the lagoon so that the different points allow for the characterization of the axial and transverse components of the current [12]. The maximum velocities recorded were about 1.2 m s^{-1} for the station near the lagoon's inlets. While moving towards the upstream zone of the lagoon, the maximum speeds were in the order of 0.7 m s^{-1}. Further upstream of the lagoon, the velocities rapidly decrease.

The current measurements conducted in 2012 [13] showed that the current velocities in the Oualidia lagoon decrease from downstream to upstream. The maximum velocities that are directed upstream are about 1 m. s^{-1} and the maximum velocities directed downstream are 0.65 m s^{-1}. The duration of the flood is shorter than that of the ebb, but the flood currents are not necessarily more intense than the ebb currents. The strongest currents occur from 1 to 2 h before and after high tide. During these periods, the surface currents are slightly greater than bottom currents; otherwise, surface and bottom currents are identical.

Flood and ebb conditions during April 2021 were simulated to determine water currents in the Oualidia lagoon. the highest current velocities during spring tides were observed near the inlets, with a maximum measured value of 0.97 m s^{-1} at station 1 and an average of approximately 0.41 m s^{-1} (Figures 4 and 5).

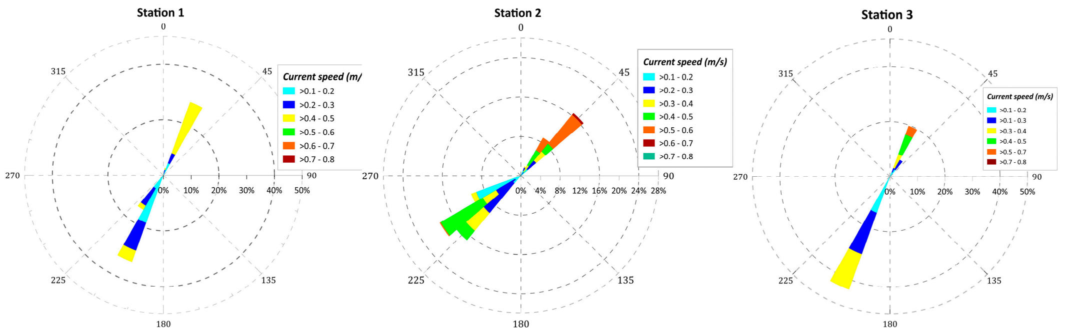

Figure 4. Rose of currents in measured stations in Oualidia lagoon.

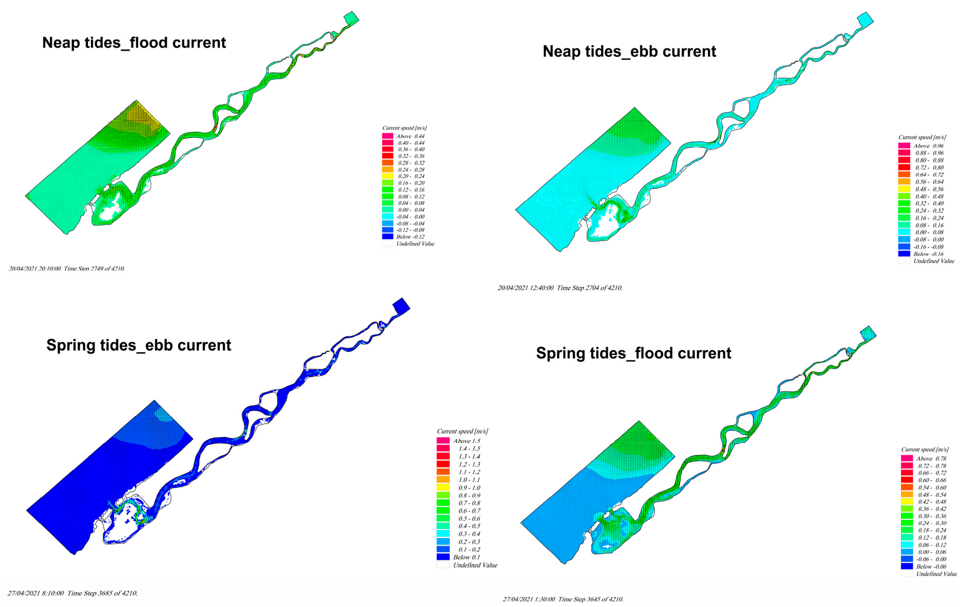

Figure 5. Maps of current velocity simulated during spring and neap tides on April 2021 (Food/ebb).

As one moves towards the upstream area, the current velocities gradually decrease. Station 2, situated in the transition zone of the main channel, experiences lower current velocities due to the presence of a small island near the measuring station. The maximum current velocity at station 2 was recorded as 0.60 m s^{-1}, with an average value of 0.31 m s^{-1}. Station 3, located in the middle of the main channel towards the upstream area, exhibited a maximum current velocity of 0.76 m s^{-1} and an average value of 0.39 m s^{-1}. The increase in current speed at station 3 compared to station 2 is primarily influenced by the period of the tides (peak spring tides), the channel morphology, which is highly constrained at this station, and the elevated depths, all contributing to the acceleration of water flow. As the water flow proceeds towards the upstream part of the channel, where the channel is divided into several secondary channels and the depth becomes shallower, the water flow gradually decreases.

It can be noted that the current speeds decrease from downstream to upstream of the lagoon, taking into account the variability and the period of the tides, which influence the variability of currents inside the lagoon (neap and spring).

4. Conclusions

The evaluation of oceanographic parameters in the lagoon of Oualidia allowed for us to describe the historical and current state of the lagoon of Oualidia in terms of hydrodynamic circulation.

Data from Copernicus Marine Service, in combination with in situ measurements, showed the significant variability in the oceanographic parameters of the study area, namely currents, tides and waves.

The lagoon system of Oualidia is mainly controlled by the interaction of tidal currents and waves in the downstream area, this interaction, in relation to the direction and speed of prevailing winds, can influence and control the circulation of water inside the lagoon and, consequently, the distribution of sediments and changes in the morphology of the main channel of the lagoon.

This investigation has allowed for us to extract preliminary conclusions on the oceanographic state of the lagoon and its offshore part in order to proceed to a multidate modeling of the hydrodynamic and morphosedimentary processes based on a well-developed mathematical modeling.

Author Contributions: M.B. downloaded and processed data and wrote the paper. M.B., K.E.K., N.E.C., I.J., A.B. and B.Z. designed and carried out the study. M.B., K.E.K., N.E.C. and I.J. collected and processed the in situ data used in this research. V.K. and A.M. read and improved the content of the article. The study was supervised by K.E.K., A.B. and B.Z. All authors have read and agreed to the published version of the manuscript.

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