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EFFECT OF SUBMARINE MORPHOLOGY ON ENVIRONMENT QUALITY: CASE OF MONASTIR BAY (EASTERN TUNISIA)

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Abstract: The Monastir Bay is characterized by high organic pollution (up to 6% TOC), along the coastal zone and significant eutrophication. Such degradation seems to be strongly related to both characteristics of the supplied water which is rich in organic particles and the submarine morphology showing a flat extending between Khniss and Lamta and a series of shoals and sand bars between Ras Dimass and Kuriates Islands. Results of the hydrodynamics modeling have shown that the submarine morphology of the bay is responsible for the transformation of the waves coming from the open sea (N, E, SE) to the coastal zone, where reduced energy contributes to the concentration of pollution. Wave modeling has also shown that such concentration prevails in low-depth (0 to -3m depth) areas where both surf and breaking zones are almost absent. This case illustrates an example of the Mediterranean coasts vulnerability to pollution under moderate energy conditions.

Key Words: Pollution, shallow water, shoals, hydrodynamics, SMC modeling.

1. INTRODUCTION

Coastal areas have an important effect on economic, social and ecological issues worldwide. They are among the most complex and variable marine systems because their dynamics are subject to the effects deriving from a complex geometry and where the bathymetry plays a crucial role in wave propagation. Moreover, the wide range of processes affecting coastal hydrodynamics such as waves, currents, and tides, among others, interact at different spatial and temporal scales, thus making of these zones highly variable environments (Alvarez-Ellacuria et al., 2010). Coastal areas with shallow water are strategic locations, providing shelter to many organisms.

However, the diversity of anthropogenic activities, displays environmental impacts on the coast, particularly in terms of pollution and exploitation of natural resources. The coastline appears as a fragile area, specifically where hydrodynamics is reduced, which is the case at the Bay of Monastir. Previous studies on this bay were based only on a geochemical, sedimentological and biological analysis (Sassi et al., 1998a and b; Sahnoun, 2000, Sahnoun et al., 2003; Nouira et al., 2013, Jebali et al., 2011; El Asmi-Jellouli et al., 2001).

The geochemical studies have shown that this littoral is affected by metallic and organic pollution (Sassi et al., 1998b; Sahnoun, 2000, Sahnoun et al., 2003; Nouira et al., 2013). As a consequence of the weak hydrodynamics prevailing in the bay, nutrient-rich wastewaters discharged in several points along the shoreline, have progressively led to eutrophication and are directly responsible for the reducing character of surface sediments (Sassi et al., 1998a).

Although these studies have identified the environmental quality of the coastal areas under consideration, the use of numerical models can provide information on the hydrodynamics of these areas and allow a comparison with the results obtained by other techniques. A hydrodynamic study is developed to determine the reasons that had led to the concentration of pollution in areas with low bathymetry at the Bay of Monastir (Khniss-Ksibet El Mediouni coastline). The objective of this study is to validate the results of the previous geochemical studies, by using for the first time, the hydrodynamic modeling based on the use of the results of a recent topo-bathymetric campaign and waves data.

2. STUDY AREA

2.1. Description of the site

The region of Monastir, located 150km south of Tunis, is marked by the extension of lands having low topography, but with a slight variation in local topography, represented mainly by the Mio-Plio-Quaternary cliff of Monastir and the Tyrrhenian hills of Ksibet el Mediouni, on the one hand, and by collapsed areas represented mainly by the Sebkha of Monastir, on the other hand (Amari & Bedir,1988; Kamoun, 1981; Paskoff & Sanlaville, 1983).

The bay of Monastir is characterized by a very low-water depth (Fig. 1). The 3m isobath is at 2km from the coastline of Khniss-Ksibet El Mediouni and at 900m from the coast of Lamta-Sayada. But the 5m isobath is at 2.5km from Khniss-Ksibet El Mediouni and at more than 8 km from the coast of Teboulba-RasDimass. This bay is also characterized by the presence of several sandy shoals (the Ras Dimas-Kuriates islands beside Teboulba-Bekalta) substantially aligned NW-SE, making physical barriers between the shore and the open sea, while being separated by different passes.

We report also that the south-of-Monastir peninsula; the El Enf sand spit circumscribes the Lagoon of Monastir which has sheltered the fish-farming station between the 1970s and the 1990s. This lagoon, in which maximum water depth is 1.5m, has two passes, water enters from the northern pass and is discharged from the southern pass, loaded with organic matters from the former aquaculture station. South of the El Enf sand spit, a few hundred meters wide flat sea floor extends from Khniss to Teboulba, where sediments are composed of very fine sands rich in decaying organic matters (Sassi et al., 1998a), that are indicative of highly anoxic conditions.

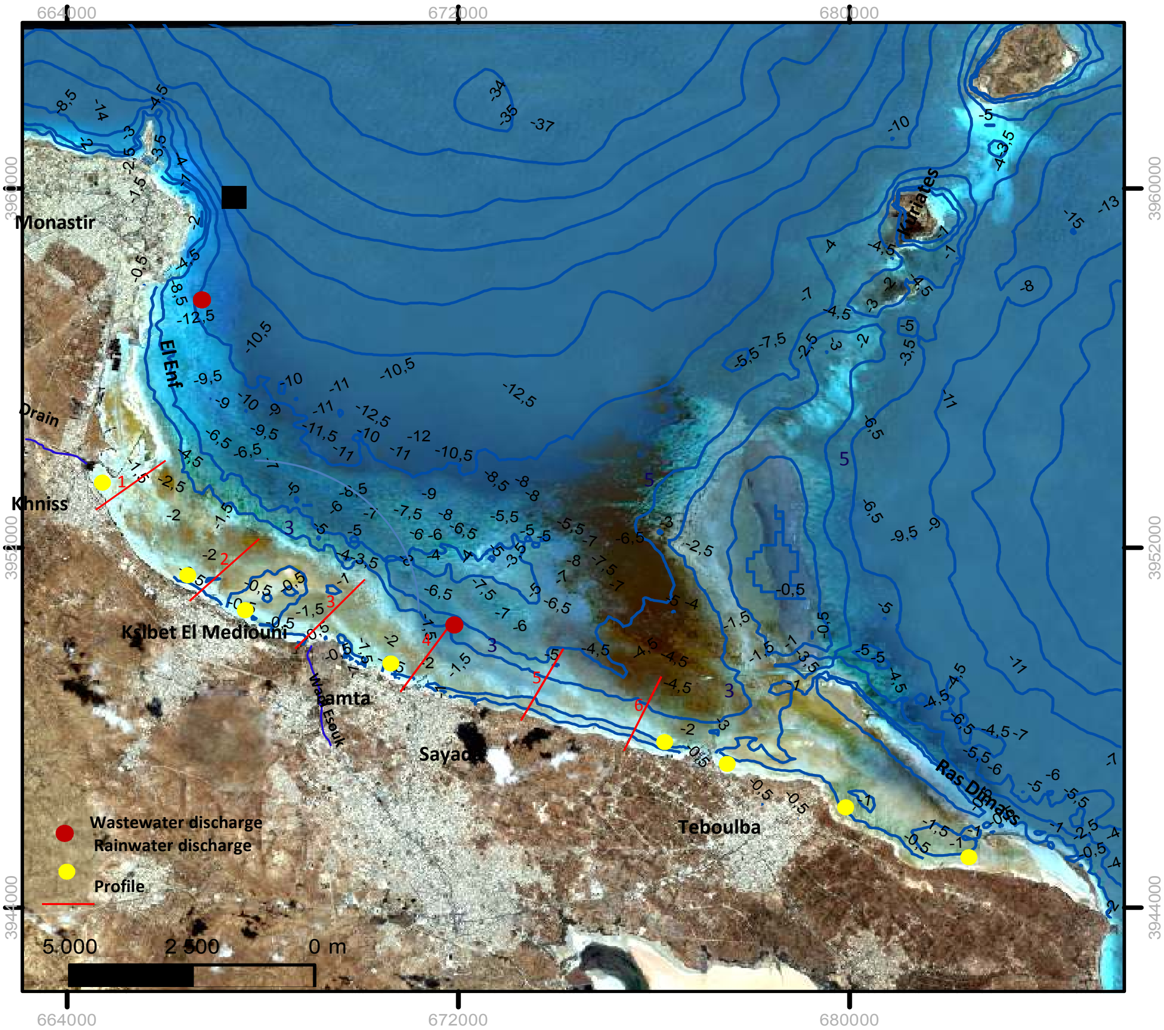

Figure 1. Map of bathymetry in the Bay of Monastir and location of wastewater and rainwater discharge.

The overall rainfall in the region is not significant with a 20-year annual average of 316mm, during the period 1970-1990. However, exceptional events are probably responsible for a large contribution of water and sediment on the coast.

2.2. Wind

Statistical analysis of local winds (INM, Fig. 2) shows that the prevailing winds are characterized by a speed between 1 and 5 m/s, and come from three main directions of W, NNE and E with an occurrence probability of 10.7%, 8.5% and 7.6%, respectively.

2.3. Tide

Astronomic tides cause the water levels to rise and fall and yield large scale current patterns, sometimes with high velocities. Tides directly affect coastal morphology, navigation, fisheries habitat and recreational activities (Kamphuis, 2002).

The average annual level of the tide on the eastern coast of Tunisia is 35cm, while the maximum level of the extraordinary vivid waters is 50 cm. The total tide is of semi-diurnal type, resulting from astronomical and meteorological tides, showing that the sea level is determined by the effect of the meteorological tide (Fig. 3).

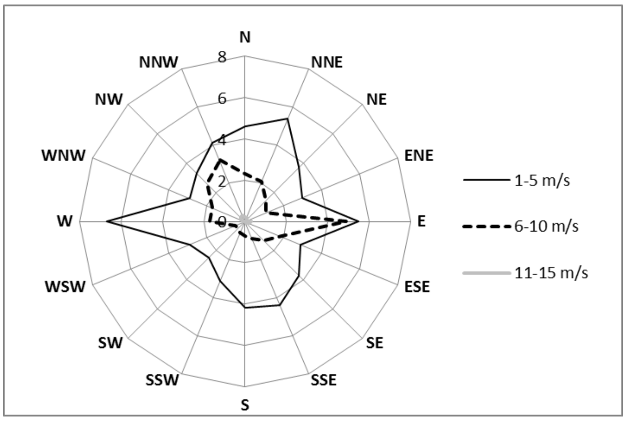

Figure 2. Wind rose (direction and frequency), (1997-2006) (INM).

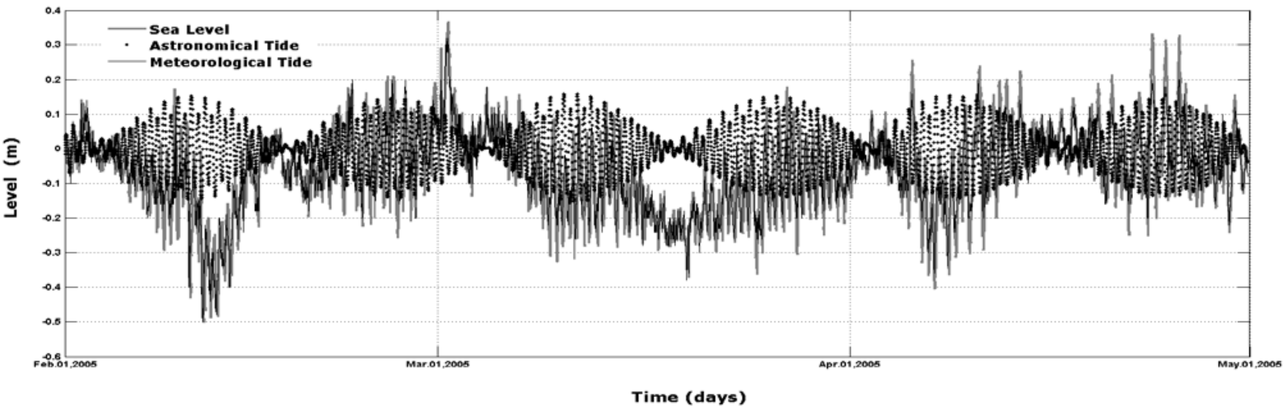

Figure 3. Astronomical and meteorological tides in the study

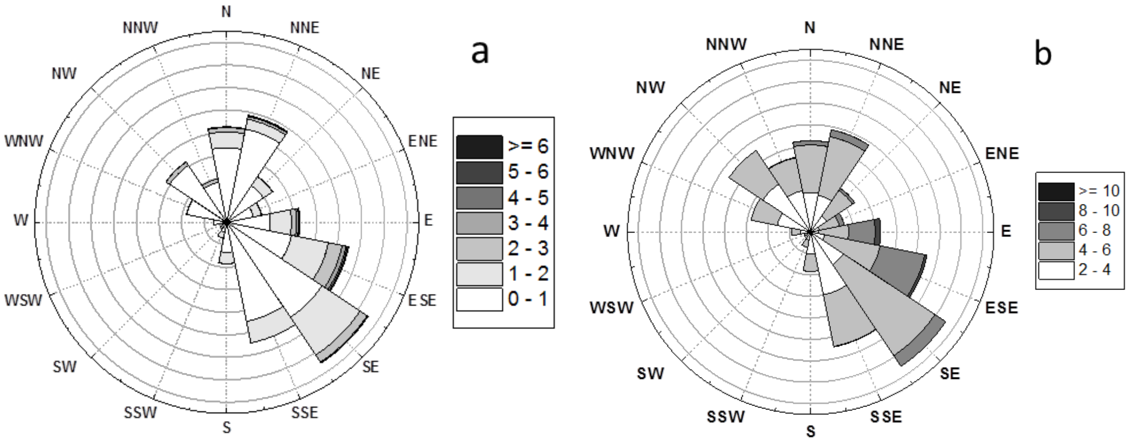

Figure 4. Wave rose ((a: wave height, direction and frequency) and (b: wave period, direction and frequency)) in the Bay of Hammamet.

2.4. Wave climate

Wave rose (Fig. 4a and b) shows that the predominant waves are the ones coming from ESE to SSE. The occurence frequency of these waves is 45.5%. The mean and stormy wave height takes a value of 1 m and 2 m, respectively. The mean peak period is 7 seconds and the stormy peak period is 10 seconds.The significant wave-height probability distribution function (Fig. 5), obtained from a hindcast analysis for the 1991-2008 time interval, shows that the significant wave-height (Hs) is lower than 1m for 50% of the time, and of approximately 3m, for 10% of the time. Extreme values of Hs are 3.8 m and 4 m for quintiles 95% and 99%, respectively.

2.5.Anthropogenic conditions

At the Socio-economic level, the Monastir-Teboulba coast has experienced, in the recent decades, a marked increase in urban density and industrial activities (agri-business industry, textile, oil mills, etc.). The Bay receives both wastewaters and rainwater. Wastewaters are discharged via two sea outfalls, from the treatment stations of El Frina-Monastir and Lamta-Sayada (Fig. 1). Wastewater-discharge averages 6500 m^3/day at El Frina station and 3000 m^3/day at Lamta-Sayada station.

Stormwater come to the shore from a catchment of 340 km^2 primarily via the drain of Khniss, implanted in the early 1970s and designed for the disposal of rainwater in urban and industrial areas bordering the Bay (Fig. 1).

The drain of Khniss is the most important work to be executed. Since its inception, the work has had a very negative role on the bay, not only due to the fine sediments carried to the Bay, but also to the introduction of huge freshwater quantities, polluted by significant organic and metallic loads.

2.6. Geochemical characteristics

Geochemical analyses of surface sediments in the bay have showed that this coastline is affected by organic pollution, with a high (2 to 6%) total organic carbon (TOC) content. The C/N ratio is always below 6 beyond -3m water depth, reflecting the fully marine character of the organic matter (Debyser, 1961; Premuzic et al., 1982).

In addition, and on the Khniss-Ksibet El Mediouni coastline, the C/N ratio ranges from 5 to 10, indicating the dominance of marine origin (algae, seagrass, phytoplankton, etc.) of the organic matter (OM). However, it should be noted that locally (outlet of the Drain and Monastir Lagoon), the C/N ratio is larger than 10. This reflects the dual nature, marine and continental, of the OM (Sassi et al., 1998a). Also, much of the organic matter in the sediment is carried by the discharged wastewaters from either household or fishing wastewaters (Sassi et al., 1998a).

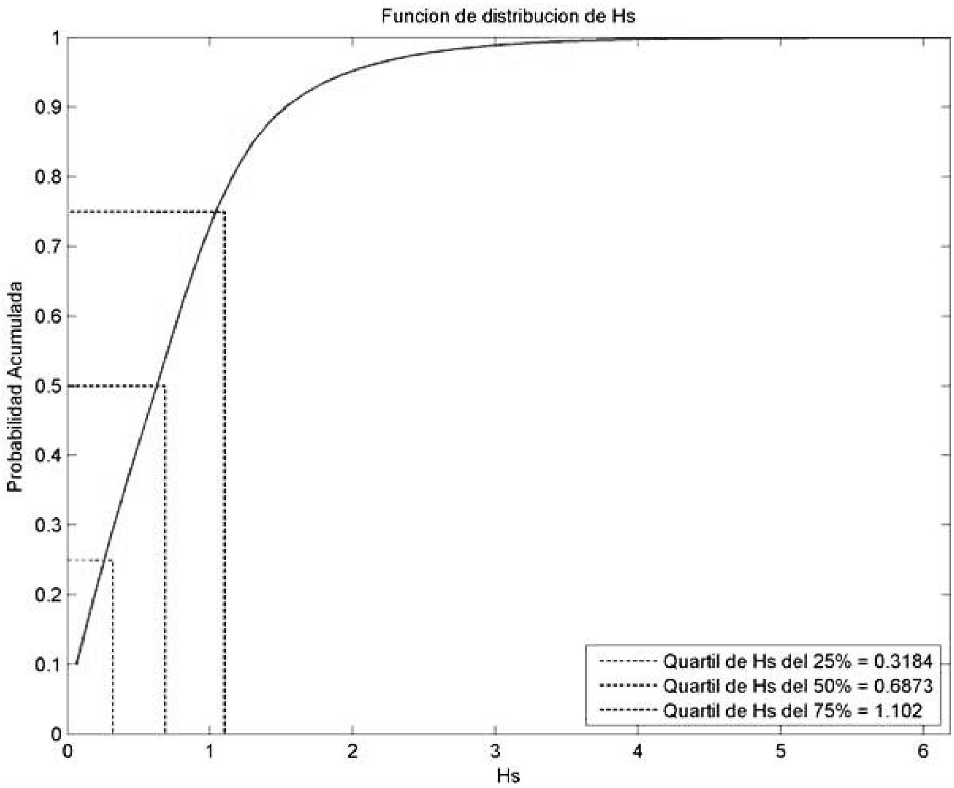

Figure 5. Statistical analysis of the wave height.

Nouira et al., (2013) have stated that the highest concentrations of additive in pesticides (polychlorinated biphenyl (PCBs)) were detected in front of the Drain of Khniss and near Teboulba city, which has known rapid industrialization and socio-economic development for the last 20 years.

Metal analyses performed on surface sediments (Sassi et al., 1998b; Sahnoun et al., 2003) have shown that higher levels of Pb were detected in front of the port of Monastir and in front of the Lamta-Sayada agglomeration. The distribution of Cr contents in sediments indicated that this element is mainly concentrated in front of Khniss City and between the port of Monastir and the El Enf sand spit. Lower concentrations of this element were detected in front of the Lamta-Sayada agglomeration. The highest concentrations of Zn were detected near the port of Monastir, in front of the Drain Khniss and in front of the wadi Souk (Lamta - Sayada agglomeration). Ni is highly concentrated in the sediments of the Drain outlet. These deductions indicate that, like organic pollutants, heavy metals are particularly concentrated in front of urban agglomerations as well as at the mouths of the wadis.

3. METHODOLOGY

Offshore wave climate (Hs, Dir, Tp) was used together with the bathymetry conditions for wave modeling from deep to shallow water. Such conditions were extracted from a detailed bathymetry survey achieved in 2009 by IHE-APAL (2009). The depth was obtained by employing a Raytheon 200kHz echosounder and the vessel positioned by differential global positioning system (DGPS). Bathymetric data were post-processed and corrected to the Datum Plane for the area using information from the tidal gauge operated at the Monastir harbor.

In terms of marine conditions, wave climate was obtained from a retroanalysis data base for the period 1991-2008 (Reguero et al., 2012). The hindcast wave database has a temporal resolution of 1 hour and provides spectral sea state parameters in deep water including significant wave height, Hs, mean period, Tm, peak period, Tp, and mean direction with respect to the North, Dir. A detailed description of this analysis is available Reguero et al., (2012).

In this study, coastal dynamics was studied by using the Coastal Modeling System (SMC), which was used for the Brazilian coasts (Hsu et al., 2008); Spanish coasts (Tintoré et al., 2009, Raabe et al., 2010, González et al., 2010) and Tunisian coasts (Saidi et al., 2012). This numerical model represents a Coastal Management System developed by the Coast General Director (DGC) and the Coastal Research Group (GIOC) of the University of Cantabria (Gonzalez et al., 2007). The SMC consists of five models. MOPLA is an element integrated in the SMC, allowing the morphological evolution modeling for coastal areas. MOPLA consists of three coupled modules: the wave transformation module (Oluca), the depth-averaged currents module (Copla), and the sediment transport and morphological evolution module (Eros). Offshore wave conditions were transformed into conditions at breaking by means of numerical model SP-Oluca. This model solves the parabolic approximation of the Mild Slope equation, simulates the random sea over irregular bottom bathymetry and takes into account spectral multidirectional waves (refraction, shoaling, diffraction, breaking and reflection). The current field was computed by using a 2D hydrodynamic model (Copla) where the forcing terms were the gradients in the radiation stresses of the incident waves. As a result, a stationary solution was obtained where rips and longshore currents are identified (Gonzalez and Medina, 1997).

4. RESULTS

4.1. Morphology of the bay

The submarine morphology, drawn from cross-sectional profiles, shows the presence of a 1 to 2m deep basin, extending over 100 to 1500m between Khniss and Lamta (Fig. 6). This depression is relayed by a shoal structure as the continuity of the El Enf sand spit disappearing on the way to Teboulba. It can promote the settling of fine particles coming from the continent. The submarine slope between Lamta and Teboulba depresses continuously without displaying any irregularities, and where the -3m is located 900m off shore. Around Teboulba-Ras Dimass, the bathymetry is yet less important, with a water column that does not exceed 1.5 m at about 2000 m off coast.

Changes in morphology and low-water depth seem to be responsible for a very complex water circulation, thus increasing an accumulation of particles in the quieter areas.

4.2. Wave modeling

To assess the hydrodynamic characteristic of the study area in shallow water, we have selected three wave directions that have a significant influence were chosen: N, E and SE. Propagations were performed with extreme wave data (Hs_{12}) (Table 1).

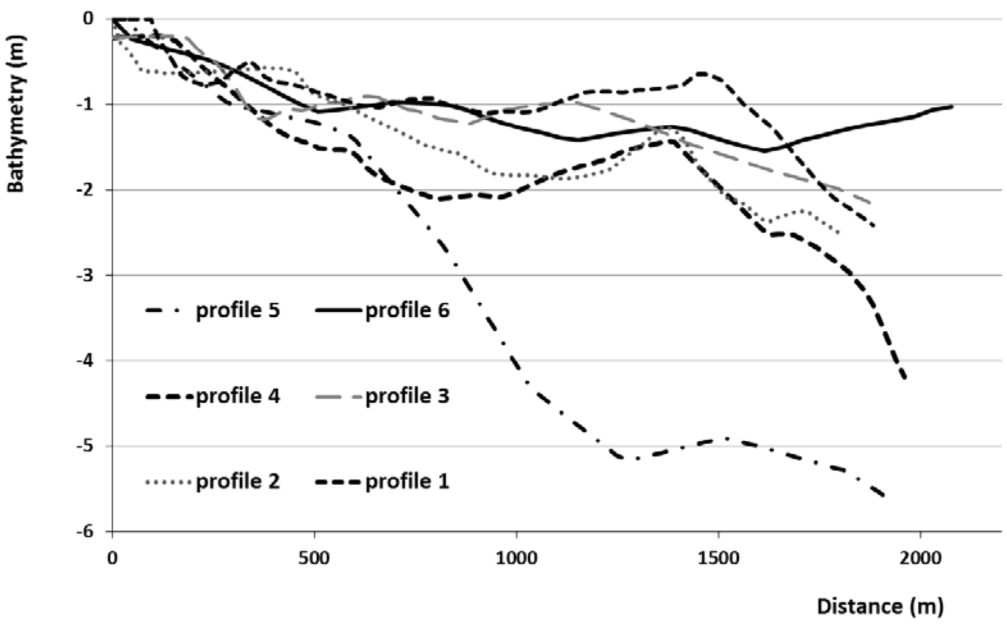

Figure 6. Transverse profiles of the sheltered zone between the shoreline and the submerged shoal in the Bay of Monastir.

Table 1: Wave data used for SMC propagation

Direction of wave	Hs_{12}	Tp(s)
N	4.09	10
E	4.98	8
SE	4.14	6.2

The wave from the North comes to the Bay with high intensity and undergoes many modifications near the coast. These waves tend to be concentrated at Cap Monastir, at El Enf sand spit and at the level of the shoals present between the Kuriates Islands and the coast of Teboulba-Ras Dimass (Fig. 7a).

The concentration of energy on these barriers leads to the mitigation of the effect of the waves on the coast, and notably along the Khniss- Lamta flat (Fig. 7a) where coast-reaching waves are very attenuated only in highly-deep zones. Also, the propagation of N-waves on the coast generates a very limited surf zone only.

Consequently, the currents, induced by these waves coming from the north, are alongshore current at the El Enf sand spit, between Lamta and Teboulba. This currentis reoriented towards the coast of Khnis-Lamta, at shoals providing an energy concentration. With regards to the Khniss-Lamta coastline, the nature of the sea bottom seems to be responsible for the non-uniform distribution of wave energy which increases at the Khniss-Lamta shoal (Fig. 7b).

The wave from the East is intense at the East of the Teboulba-Kuriates shoal series and tends to be attenuated in the bay. These waves, which are refracted in the East of the study area, undergo a NS to NE-SW diffraction in the Bay. These waves are very limited on the shoals and on the Khniss-Lamta flat (Fig. 7c).

The generated currents are intense at the East of the Teboulba-Kuriates shoal series. Furthermore, the El Enf sand spit promotes longshore current generation which is oriented and focussed on the Khniss-Lamta. In this area, the currents are oriented towards the coast, while between Lamta and Teboulba the current is almost non-existent (Fig. 7d).

Waves coming from the SE undergo refraction and diffraction on the Teboulba-Kuriates shoal series. In the North, these waves bypass the Kuriates Islands, and then propagate first in the NE-SW direction and then in the NS direction in the middle of the bay.

The intensity of the waves decreases along the El Enf-Teboulba shoals. The intensity is also reduced in the sheltered area of Ras Dimass. The surf zone is very small, especially near the shoals of Khniss and Ras Dimass (Fig. 7e).

The currents, generated by these waves, are similar to those produced by the waves coming from the East. The hydrodynamics is attenuated with a total absence of longshore drift. The only current directed towards the coast is located at the Khniss-Lamta coastline (Fig. 7f).

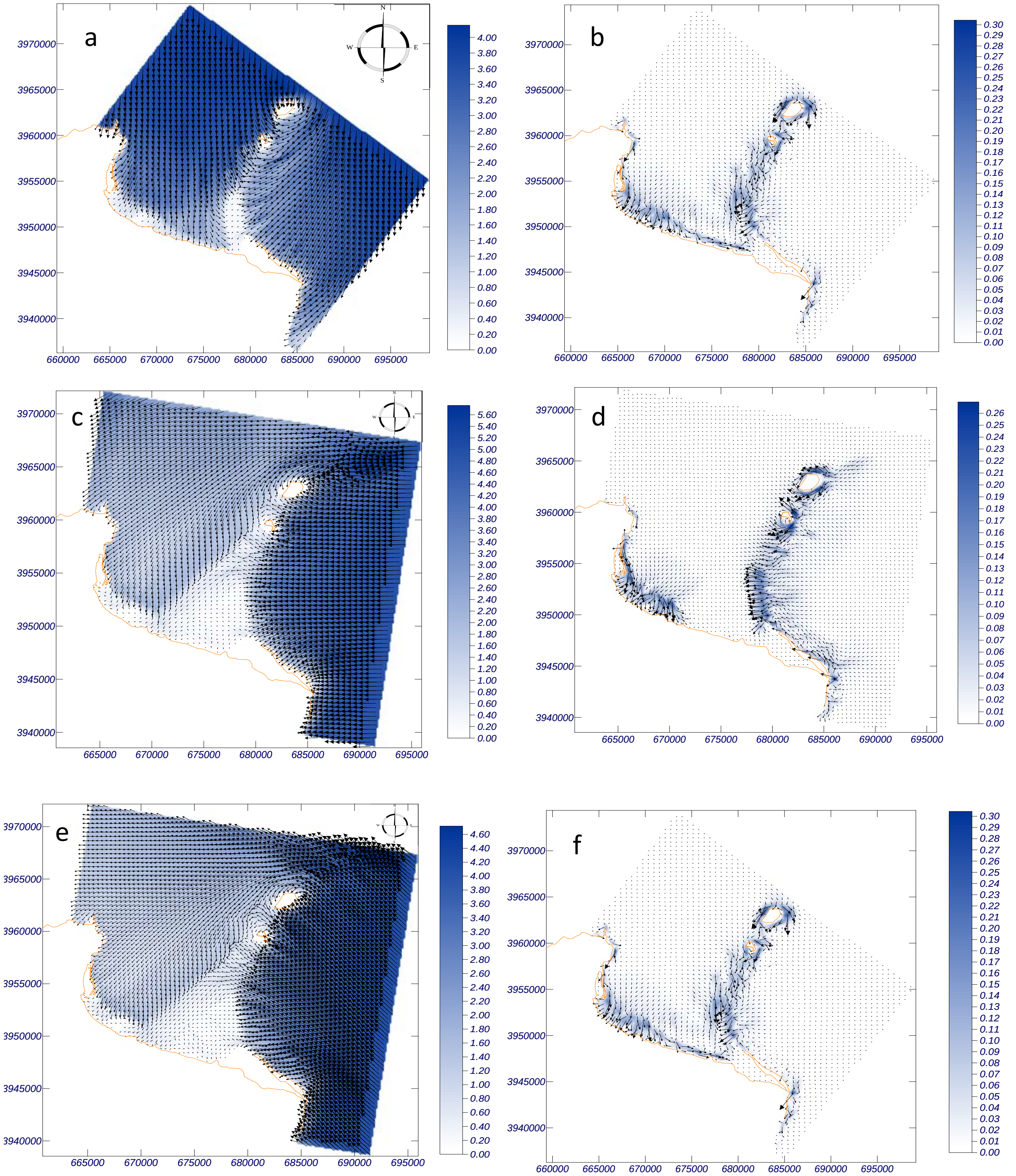

Figure 7. Plot of the wave distribution and the wave-induced phase average current field for the North (a, b), East (c, d) and South-East (e, f) directions.

5. DISCUSSIONS

The results of the wave propagation at the Bay of Monastir show that the coastline can be divided into two relatively independent sections:

(1) Khniss-Lamta, for which the wave breaking occurs at the -3m depth for the three wave directions (N, E, SE). The presence of the El Enf-Lamta shoal causes a gradient of energy, thus promoting the emergence of cross-currents directed towards the coast. This phenomenon is responsible for the sediments transport from the northern coast of the Bay to Khniss-Lamta. Such behavioris observed from the three modeled cases.

(2) Lamta-Teboulba, which is not affected by East to South-East waves. Regarding waves coming from North, the breaking occurs at the isobath-3m, inducing alongshore transport of sediments at Lamta that propagates up to Ras Dimass.

The intensity of currents seems to be higher for waves coming from North with a maximum speed is 0.3 m/s. Flow velocity is less than 0.26 m/s waves from SE to E. Moreover, the trend of the alongshore transport is interrupted between Khniss and Lamta where cross-current systems become more important.

Furthermore, the complex configuration of the bathymetry in the study area is responsible for the significant transformation of waves. In addition, the presence of shoals constituting the extension of the El Enf sand spit, especially between Khniss and Lamta, leads to the concentration of the wave energy and, consequently, an increase in wave height, which leads to their considerable attenuation on the coast. Indeed, according to Hequette & Aernouts (2010) the distribution of wave energy along shorelines strongly depends on wave refraction over the inner shelf and shoreface, any change in bathymetry in the shallow depths of the coastal zone is expected to induce modifications in wave propagation patterns and, therefore, in longshore variations in wave height.

These findings confirm the results of the geochemical studies performed on the sediments of the study area. Indeed, anoxic environment is mainly due to the morphology of the Bay. The first series of shoals (Teboulba-Kuriates) reduces significantly the effect of the wave. This attenuated wave is again concentrated at the first section (Khniss-Lamta).

Wastewaters arriving at the coast are obstructed, especially through the extended flat between Khniss and Lamta. Consequently, currents can no more transport the suspended particles carried by the Drain of Khniss and other effluents to evacuate them seaward, beyond the -3m depth (surf zone). Thus, these fine particles are sequestrated along the Khniss-Lamta flat, collecting various organic compounds in suspension. Sediments are then very polluted by organic matter(4 to 6% TOC; Sassi et al., 1998a; Souissi et al., 2001), preventing any diffusion of oxygen through the water/sediment interface and, thereby, promoting anoxia in the sediment.

The situation is less alarming for the Lamta-Teboulba section, where the submarine flat is less extended, and thus allowing alongshore sediment transport up to Ras Dimass.

6. CONCLUSIONS

For several decades, the coastline of the Bay of Monastir has suffered from the deterioration in the quality of sediments and waters, which led to the eutrophication of the coastal fringe. The deterioration of this environment is mainly due to the discharge of waters (waste-water of household use, rainwater draining an industrialized watershed) rich in nutrients and pollutants and the configuration of the bay, which is characterized by its low bathymetry and the presence of several shoals that reduce the wave effect and control its direction.

This littoral is influenced by three dominating wave directions coming from the North, East and South-East. The wave propagation, in relation to the afore-mentioned wave directions, has shown a different behavior between the coast of Khniss-Lamta and that of Lamta-Teboulba. Between Khniss and Lamta, the presence of the shoal south of El Enf sand spit leads to the concentration of energy of waves coming from all directions and its dissipation to enhance a transverse transport of sediments to the coast.

The Lamta-Teboulba coastline is sheltered from the effect of waves coming from the East and South-East, but influenced by waves coming from North, a phenomenon that creates a sedimentary transit between Lamta and Ras Dimass.

These statements indicate the presence of a weak coastal hydrodynamics, throughout the whole area, and give rise to a more pronounced eutrophication which is more pronounced between Khniss and Lamta.

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