



# Coastal erosion in the south-eastern Mediterranean: case of beaches in North Tunisia

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## Abstract

This research is conducted as part of a Spanish International Cooperation Agency project with the aim to investigate the sustainable protection of Tunisian coastal zones, as in the case of Beni Khiar and Dar Chaabane coasts (Hammamet Gulf) separated by Oued El Kebir river. The sedimentary dynamic of these beaches is studied in order to identify the main causes responsible for their erosion by the use of different approaches of in situ measurements and numerical methods. Geophysical surveys and sedimentary analyses have demonstrated that sediments are finer and less carbonated from Beni Khiar to Dar Chaabane. Then, the shoreline mapping of several missions of aerial photos has illustrated a mean shoreline retreat between 3 and 4 m/year. In terms of sand volume, a sediment loss more than 30,000 m<sup>3</sup>/year at Dar Chaabane has been observed since the hill lake structures were built within Oued El Kebir river in 1996. Finally, modelled hydrodynamic and sedimentary patterns have illustrated the refraction of waves in deep water close to shoals and a high-energy concentration along Dar Chaabane coast. The sediment transport direction is mainly of NE-SW induced by ESE-SE wave-driven alongshore current. Results provided by these approaches have shown the importance of Oued El Kebir sediment yield in supplying the neighbouring beaches. Changes in sedimentary dynamics are affected by the modification of hydrodynamic patterns caused by the presence of hydrological dams and the implementations of hotels close to the shoreline. This finding underlines the key role of Oued El Kebir fluvial activity in controlling the equilibrium of beaches and their sensitivity to coastal managements induced by man activities, as in the case of the most Mediterranean beaches.

**Keywords** Beach erosion · Sedimentary budget · Hill lake structures · Coastal management

## Introduction

Coastal erosion is one of the most important socioeconomic problems that challenge the capabilities of states and local authorities. This chronic problem is increasing in coasts where the man-induced activities are important. In the case of south Mediterranean coast, having a high economic interest of tourism, huge efforts have been driven by many countries to

preserve or re-create beaches. Such projects, coupled with other developments in coastal zones such as harbours and marinas, are increasing since the beginning of the twentieth century leading to several problems of beach erosion and degradation (Poulos and Collins 2002). The flash and catchment disequilibrium in the last centuries resulted from the development of alluvial managements in rivers contributing also in coastal degradation since the channelisation of flow for protection against flooding can reduce the sediment supply to the coastal areas in more recent times (e.g. Antony 2014). In the case of Tunisian beaches, erosion problems in coasts and their impact on the socioeconomic activity have been considered as the major interest of some consulting and scientific works with the aim to diagnostic changes in the coastal structures and the shoreline recession. Paskoff (1985, 1998) has investigated the causes and mitigation of Tunisian beach erosion. Then, the works of Oueslati (1994, 2004) have interested in the morphological changes of Tunisian beaches caused by coastal management. The case of the northern side of Tunisia has been studied in terms of sedimentary dynamics.

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Saidi et al. (2013) have analysed the different sedimentary textures in Tunis Gulf (NE Tunisia) and their relation with energy conditions. In NW of Tunisia, Halouani et al. (2012) have studied the morphodynamic changes and the shoreline stability; they have shown an altering variability of erosion and accretion caused by changes in wave direction and sediment grain size. The works of Souissi et al. (2014) have demonstrated the effect of waste water discharges in the sedimentary dynamic of Monastir Bay (East of Tunisia) using in situ and modelling data.

This research focuses on the understanding the hydro-sedimentary dynamic of the NE Tunisian beaches, as in the case of Beni Khiair-Dar Chaabane, in terms of functional relationship between sediment movement and energy patterns with the aim to identify the principal factor responsible for beach erosion and the interruption of the natural balance disturbance. A special attention has been given to the diversity of the sediment sources contributing in the supply of the studied beaches and their dynamics. To do it, a series of field measurements and modelled data have been used to understand the beach dynamics. Such analyses have been driven before 2006 when the problem of erosion was of major interest for the local authorities.

## Study area

### Geographic and geologic settings

Dar Chaabane-Beni Khiair beach is located on the northern side of Hammamet Gulf (NE Tunisia), with  $36^{\circ} 41' 26''$  of latitude and  $10^{\circ} 36' 51''$  of longitude; it has 4 km of length, from Beni Khiair fishing harbour in the north-eastern side to Dar Chaabane pier in the south-western side. The coastline is mainly shaped by rocky formations that can be also observed at the bottom of the nearshore zone. These formations are of Tyrrhenian deposits, with a high content of biological materials and siliceous sediments. The large carbonated platform covering the sea bottom dates from Miocene, the end of the tertiary period (Enabli 1980; Ben Salem 1995).

Dar Chaabane beach is separated from Beni Khiair one by the mouth of Oued El Kebir river (Fig. 1). This latter represents the main discharge of a small hydrological basin with a mean slope of 2.8% and a total area of 20 km<sup>2</sup>. The fluvial system is modest and depends strongly on the rainfall regime and flooding periods when the sediment supply increases. The basin of Oued El Kebir is characterised by two main lithological deposits (Fig. 2a): (1) deposits of Oued El Kebir, dating from Tyrrhenian period and rich in foraminiferous fossils and (2) deposits of Beni Khiair, dating from Miocene period and containing a large fraction of quartz poorly carbonated (Ben Salem 1995).

### Socioeconomic setting

Dar Chaabane-Beni Khiair is recognised as an important socio-economic sector since it offers an attractive place with a high touristic activity. Many man-made structures covering the coastline have been built, in particular, the three hotels Lido, Ramses and Riadh (Fig. 1b).

In terms of water resources, Oued El Kebir supply is of high importance. The expected water demand is driven by population increases and could reach its maximum around the next years. Since 1996, two hill lakes have been built in El Kebir basin with the aim to provide water supplies for agriculture irrigation as well as industrial and tourism sectors. Then, two dams (Tnitin and Zamou) were built in 2001–2002 (Fig. 2a).

### Materials and methods

A series of field surveys and laboratory analyses were performed to provide a better understanding of the sedimentary dynamic at Beni Khiair-Dar Chaabane beach. The detailed descriptions of these approaches are given in this section.

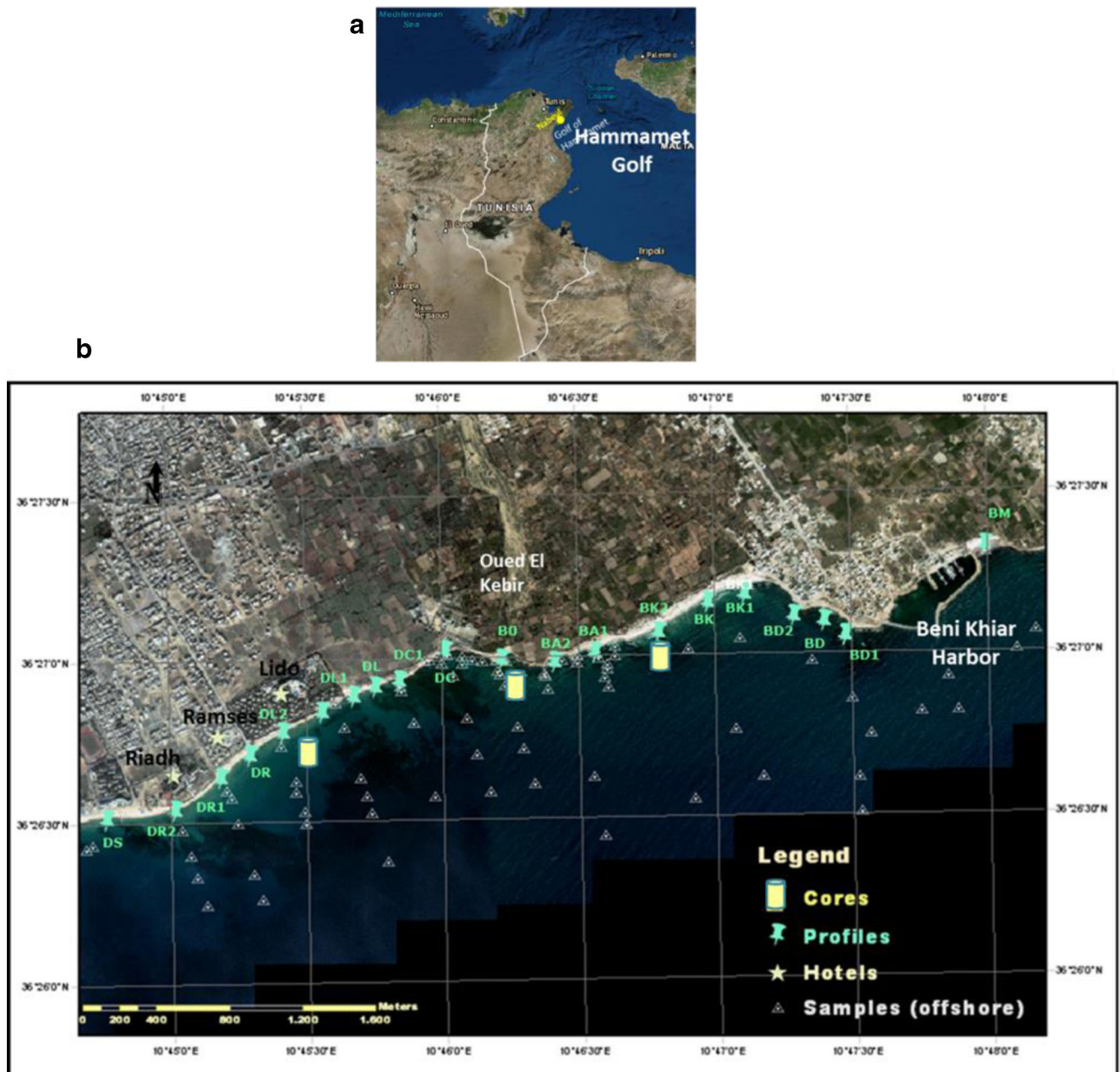
### Geophysical and sedimentary surveys

A geophysical survey was carried out between 1 and 15 m of depth. It was achieved by using the Ortech Pipeliner system of 3.5 kHz and an echosounder established over the bark platform. During this survey, 64 sediment samples from 1 to 10 m of depth were collected (Fig. 1b).

A field survey of superficial sediments, from the backshore to the shore-breaker zone, was undertaken in the two principal seasons of summer and winter. Samples covered a series of 20 profiles, orthogonal to the coastline and spaced at 200 m approximately (Fig. 1b): 'BM, BD1, BD, BD2, BK1, BK, BK2, BA1 and BA2' at Beni Khiair and 'DC, DC1, DL, DL1, DL2, DR, DR1, DR2 and DS' at Dar Chaabane.

With the aim to investigate the temporal evolution of sedimentary dynamic, three cylinder-shaped cores of sediment were extracted close to Beni Khiair (core A), Oued El Kebir mouth (Core B) and Dar Chaabane (core C).

In laboratory, samples were washed and heated at 85 °C. Once heating, a sedimentary analysis was implemented. First, samples were homogenised, dried to constant weight (100 g of beach sand) and sorted into fractions by mechanically shaking a column of sieves of different mesh sizes (2, 1.4, 1, 0.6, 0.5, 0.25, 0.3, 0.125, 0.90 and 0.063 mm) for 20 min using a Ro-Tap shaker. The results were converted into wt.% and used to determine statistical parameters (mean (Mz), sorting index (So), skewness (Sk) and kurtosis (Ku)) using graphical methods (Folk 1959; Friedman and Sanders 1978). Then, the carbonate rate was extracted from the different samples.



**Fig. 1** a Study area: Gulf of Hammamet. b Dar Chaabane-Beni Khiair coast separated by Oued El Kebir stream. The offshore and beach sediment samples are also shown

Finally, a compositional analysis was performed by a diffraction operation. Likewise, a point counting of grain in thin sections was analysed under a binocular microscope. Both geophysical and sedimentary surveys were gathered to investigate the dynamic of the study area.

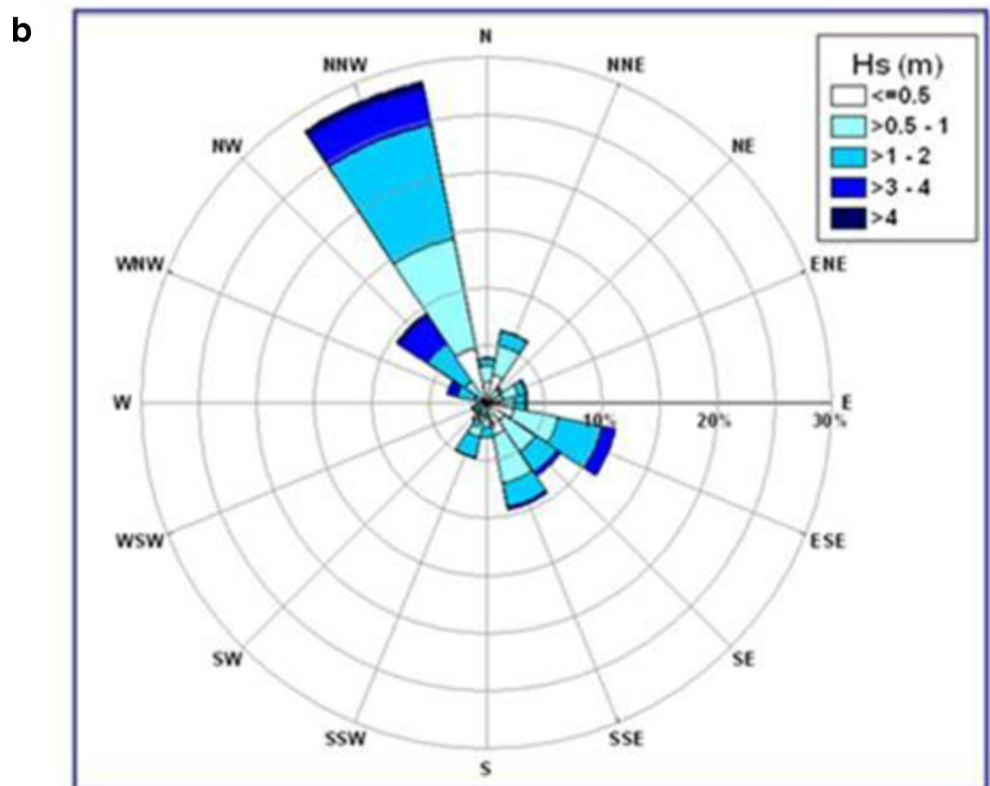
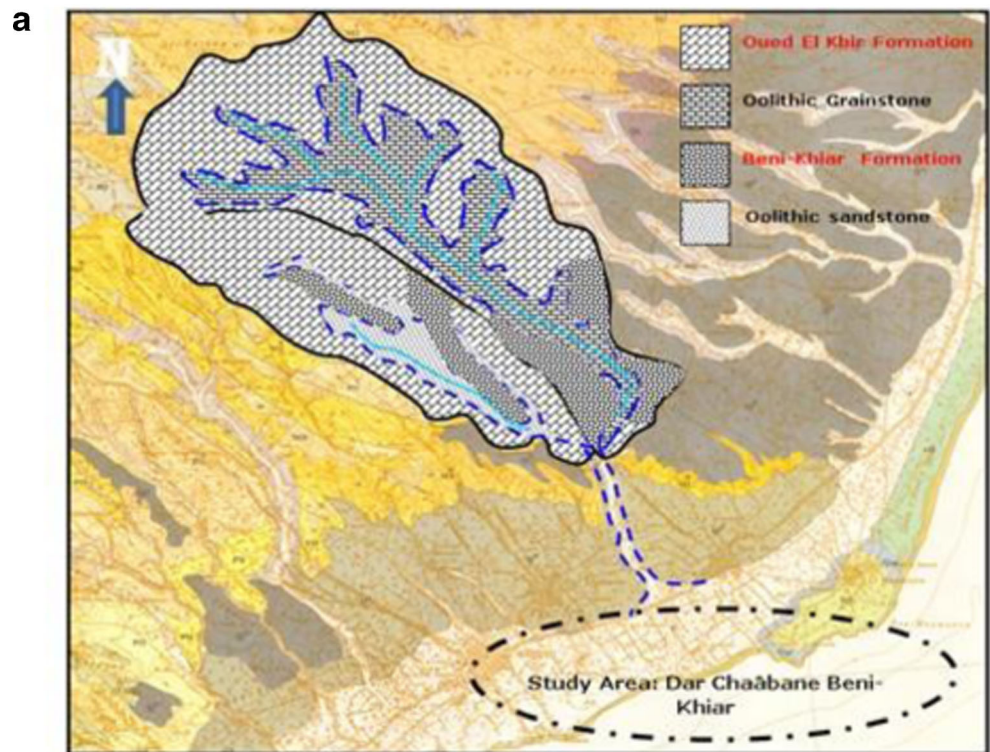
**Shoreline mapping**

Long-term changes in shoreline evolution were determined using different aerial and satellite surveys providing a good spatial coverage of the coast. Extracted data are valuable and

present an important information useful to distinguish the different trends of sediment movement.

Seven periods of surveys 1947, 1962, 1974, 1985, 1996, 2002 and 2003 were selected for building a composite map of the shoreline evolution. Using a geographic information system (GIS), the temporal changes at Dar Chaabane-Beni Khiair coast were analysed. First, the digital maps were georeferenced to a common projection UTM. A set of prominent landmarks on the maps (lighthouses and maritime constructions as Beni Khiair harbour and the groin of the western limit of Dar Chaabane) were used as control points in the process that

**Fig. 2** **a** Hydrological watershed of Oued El Kebir stream. **b** Wave rose in deep water at Gulf of Hammamet



aligned from different time. Then, maps were overlaid by GIS tool and the erosion rates were estimated. By the use of this method, the root mean square error (RMSE) varies between 2 and 10 cm.

Once shoreline changes were determined at orthogonal profiles (from BM to DS), sediment transport rate was calculated by evaluating changes in the bulk volume using the well-known method proposed by Dean and Dalrymple (2002). This

method consists in measuring the sediment volume variation between successive mapped shorelines. Then, the sediment volume can be quantified by multiplying the distance of change by the alongshore distance and the closure depth of the beach profile (taken as the depth beyond which the action of wave is negligible).

### Bathymetry survey and hydrodynamic modelling

Bathymetry data and offshore wave climate (wave height ( $H_s$ ), mean direction with respect to the North (Dir) and peak period ( $T_p$ )) were used together for wave modelling from deep to shallow water.

Bathymetry data were extracted from a detailed survey achieved in March 2007 during high tide. Data covered the study area from Beni Khair to Dar Chaabane; they were gathered in a series of transversal profiles settled every 10 m in the alongshore direction. The depth value was obtained employing a Raytheon 200-kHz echosounder and the vessel positioned by differential global positioning system (DGPS). Bathymetry data were post-processed and corrected with the Datum Plane for the area using information from the tidal gauge operated by Beni Khair harbour.

In terms of marine conditions, wave climate was obtained from a retro-analysis database (Reguero et al. 2012) providing spectral sea state parameters with a temporal resolution of 1 h. Wave rose in deep water shows that waves coming from ESE-SSE are predominant (Fig. 2b). The mean and the stormy wave height take a value of 1 and 2 m, respectively. The mean and the stormy  $T_p$  is of 7 and 10 s, respectively. Astronomical tide is semi-diurnal with a mean range of 0.15 m. The total sea level can reach a value of 0.4 m due to the meteorological tide effect caused to the atmospheric pressure.

Deepwater wave climate was transferred to shallow water and breaking conditions for different tide levels (high, low and middle tide using the numerical model MOPLA which is part of the coastal management system (SMC), a system developed by the Environmental Hydraulics Institute IH Cantabria (González et al. 2007)).

MOPLA is 2DH, a short-term process-based numerical model. It is composed of three coupled modules: (1) the wave transformation module (Oluca) which represents a weekly nonlinear combined refraction and diffraction model simulating the behaviour of monochromatic and a random sea waves—it is based on the parabolic approximation solution to the mild slope equation (MSP); (2) the deep-averaged current module (Copla) which solves the vertically integrated equations of conservation of mass and momentum in two horizontal dimensions and uses the Oluca as input—it is capable of operating with a wave-current space and time-varying hydraulic roughness and turbulent fluctuations (eddy viscosity); and (3) the sediment transport and morphological evolution module (Eros) which includes a deterministic intra-wave

period model for non-cohesive sediment—it solves the sediment flux equation in the surf zone and the bathymetry changes associated to the spatial variations of the sediment transport. The input conditions are used by the SMC system as an output of the Oluca and Copla models. The sediment transport is calculated using (Soulsby 1997).

## Results

### Sedimentary dynamic

Results obtained from the geophysical survey are illustrated in Fig. 3 where the texture of marine materials varies with depth. The bed between 2 and 15 m is characterised by coarse sands and irregular Tyrrhenian rocky structures fully covered by *Posidonia oceanica* seagrass; these structures are more regular with depth. Sediments are not homogenous between 15 and 25 m; they are coarser in Beni Khair and finer in Dar Chaabane and close to Oued El Kebir mouth. Beyond 25 m of depth, the sea platform was wrapped by fine sandy layers.

The distribution of the grain size and the calcium carbonate content of sediment samples, taken between 1 and 10 m of depth, displays high changes from the north (Beni Khair) to the (Dar Chaabane) as presented in Figs. 4a and 3b. Significant differences between both sectors are clearly observed: coarse-grained sediments (between  $-0.23$  and  $0.80 \Phi$ ) with a high percentage of carbonate at Beni Khair and fine sediments less carbonated (5–10%) at Dar Chaabane.

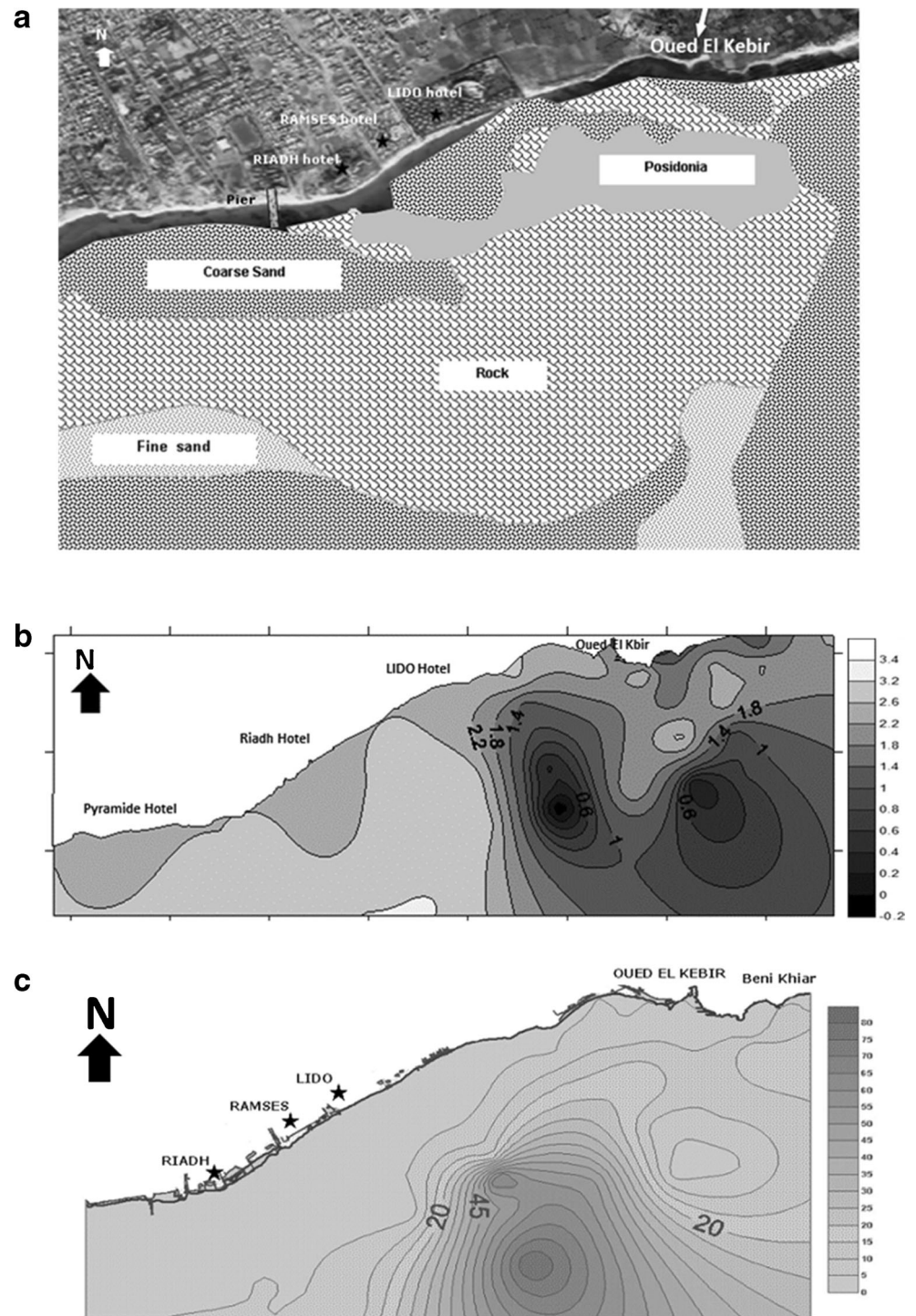
At deep water, coarse-grained and carbonated sediments of Beni Khair should be the result of crumbling processes of rocky beds. This activity is less important at Dar Chaabane where sediments are fine and poorly carbonated. Such differences between both sectors suggest the diversity of the sediment sources and the hydrodynamic conditions.

Grain size statistical parameters of superficial sediments (from the backshore to the shore-breaker zone at the orthogonal profiles) have been also determined. According to the Folk (1959) classification scheme, the sand size fraction is fine, medium to coarse-grained. Cumulative percentage bins have shown that sediments are fine with high sorting index, moderately to well sorted and symmetrically to asymmetrically skewed with negative or positive tail.

Generally, the mean grain size increases slightly from the backshore to the shore-breaker zone; it tends to be coarser and less sorted far from the shoreline. The skewness index is much larger in the shore-breaker zone.

At Beni Khair, the mean grain size distribution of sediment samples (from BM to BA2) shows that lowest values (0.3 mm) are observed at BA1 and the highest ones (0.5 mm) at BK close to the harbour. The variation of skewness index emphasises that sediments tend to be symmetrical in the direction of transport NE-SW. The

**Fig. 3** Sedimentary characteristics of the study area. **a** Distribution of sediment textures extracted from offshore geophysical survey. **b** Map of sediment mean grain size (Mz) distribution. **c** Map of carbonate percentage distribution



tendency of sediments to be finer, more sorted and positively skewed from the east to the west is broken in some small bay structures (the case of BA2 profile for example) where the poorly sorted sediments are protected from the wave action. Therefore, changes in sediment properties from NE to SW should be related to a progressive drift direction affected by the strength of driven waves.

The sediments of Oued El Kebir mouth (BO profile) are coarse-grained, well sorted and negatively skewed. Such properties are associated to the fluvial sediment supply rich with well-selected materials.

In Dar Chaabane, the grain size distribution presents many irregularities. Sediments are medium- to fine-grained with a moderate selection and a symmetrical skewness. They are coarser, less sorted and positively skewed at

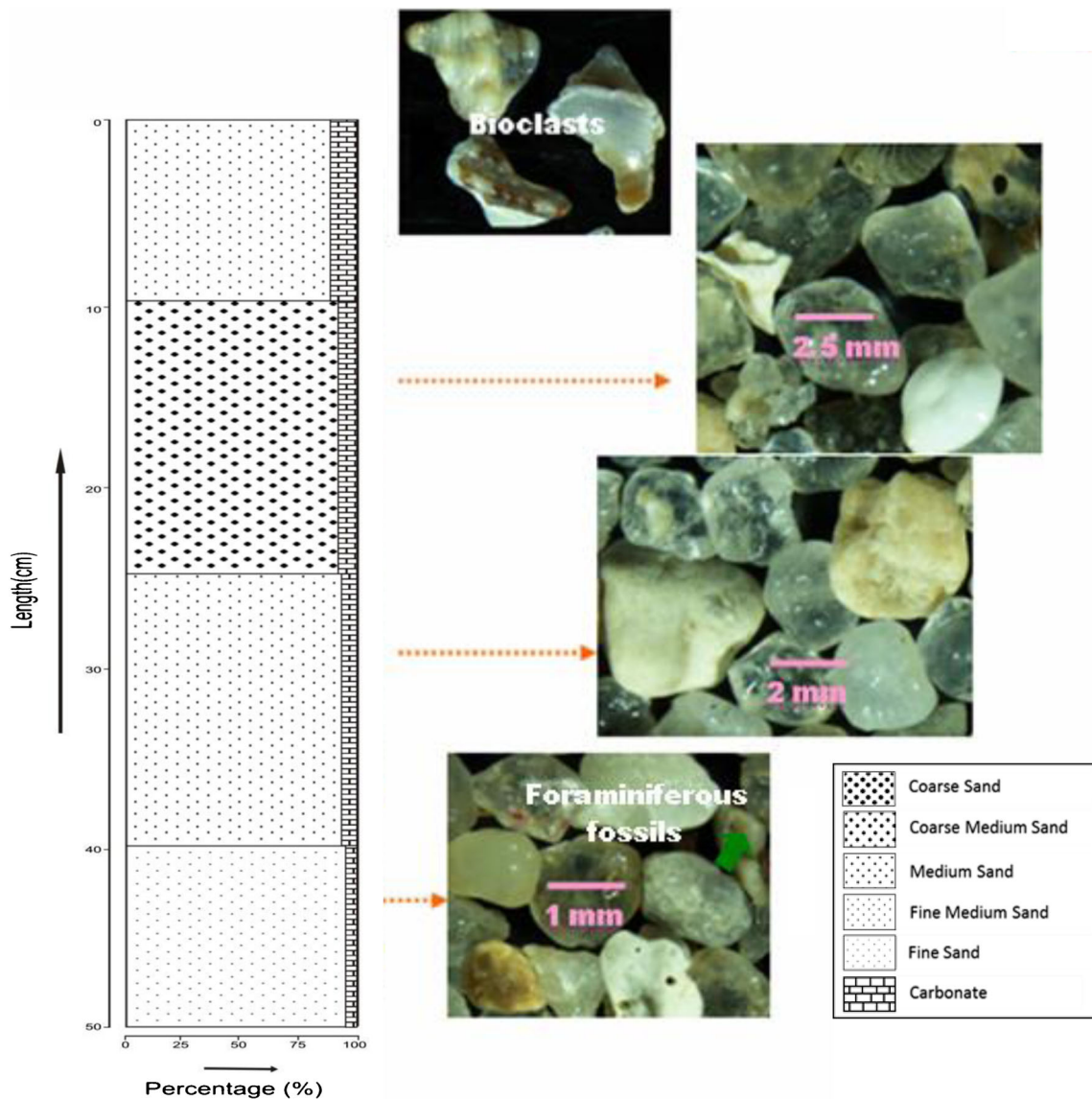


Fig. 4 Petrography of the sediment materials in core A

DC and DC1 profiles. In return, grains are finer and more sorted with a positive skewness index away from DC1 (between DC2 and DS).

Accordingly, the spatial evolution of sediments from Beni Khiar to Dar Chaabane is controlled by an increasing hydrodynamic activity in NE-SW direction responsible for a grain size reduction and a better selection of the sediments.

Similarly, to the space, the time represents an important dimension to understand the sedimentary dynamic. Seasonal surveys have shown large differences in sediment properties. Under winter conditions, fine-grained and well-selected materials have been observed in Oued El Kebir mouth; they are generated by an important fluvial activity during the strong events of flooding. In summer, sediments are coarse-grained and poorly sorted since the fluvial activity is less significant

close to Oued El Kebir river and the selection of sediment materials is limited.

Of the total number of grains counted under the binocular microscope, an average roundness was accounted 20% at Dar Chaabane and 60% at Beni Khiar. Proportionality between the roundness and the shining character of sediment can be explained by a significant hydrodynamic activity at Beni Khiar.

Petrography analysis was applied to three cores (A, B and C), collected from the study area in order to determine the evolution of the sedimentary texture during the last periods of time. Results provided by this analysis are presented subsequently. Generally, sediments provided by cores are fine-, medium- to coarse-grained and poorly to richly carbonated between the different layers of cores.

Core A (Fig. 5) shows an increasing rate of carbonate from the base to the upper layer. This content consists mainly in bioclastic fragments having similar textures to those observed in the rocky formations of Beni Khier where biologic fraction is important with a large percentage of shell mollusc composition (45%). The bottom layer of core A presents medium- and fine-grained sediments with large quantities of foraminiferous fossils derived from different geological sources (Fig. 5). Then, the carbonated character of Beni Khier sediments can be explained by a biologic activity provided by an alteration phenomenon of the unconsolidated bed-rocks contributing in the beach nourishment.

The composition of core B (Fig. 6) shows that sediments are fine and shining rich in benthic foraminiferous fossils in the base; they are coarse, less shining and poorly carbonated in

the top of the core. The grain size and the content of carbonate in core C are slightly similar to the core A of Oued El Kebir mouth: the base is rich in fine sediments and metamorphosed foraminiferous fossils consolidated with quartz materials (Fig. 7) while the top layer is characterised by sponges and *Posidonia oceanica* seagrass.

The different sediment compositions, shown by sedimentary analyses, suggest the contribution.

Oued El Kebir system in the supply of Dar Chaabane beach. Modelling foraminiferous result from a metamorphosis induced probably by a sediment transport under high-energy conditions. The origin of current-day foraminiferous, sponges and *Posidonia oceanica* seagrass, observed in the top layer of core C, can be associated to the sea bottom of the offshore zone. They have been potentially transported from the

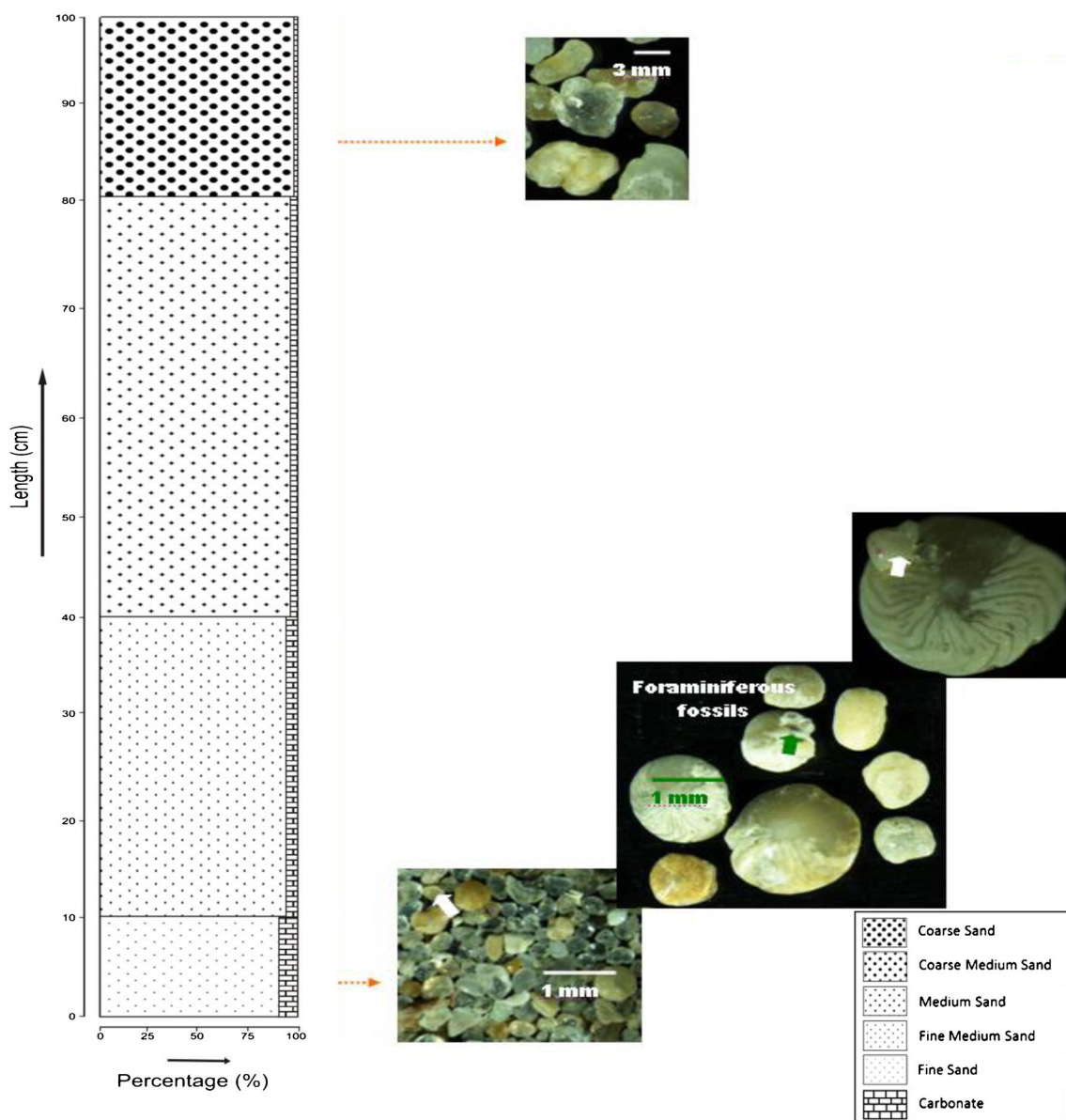


Fig. 5 Petrography of the sediment materials in core B



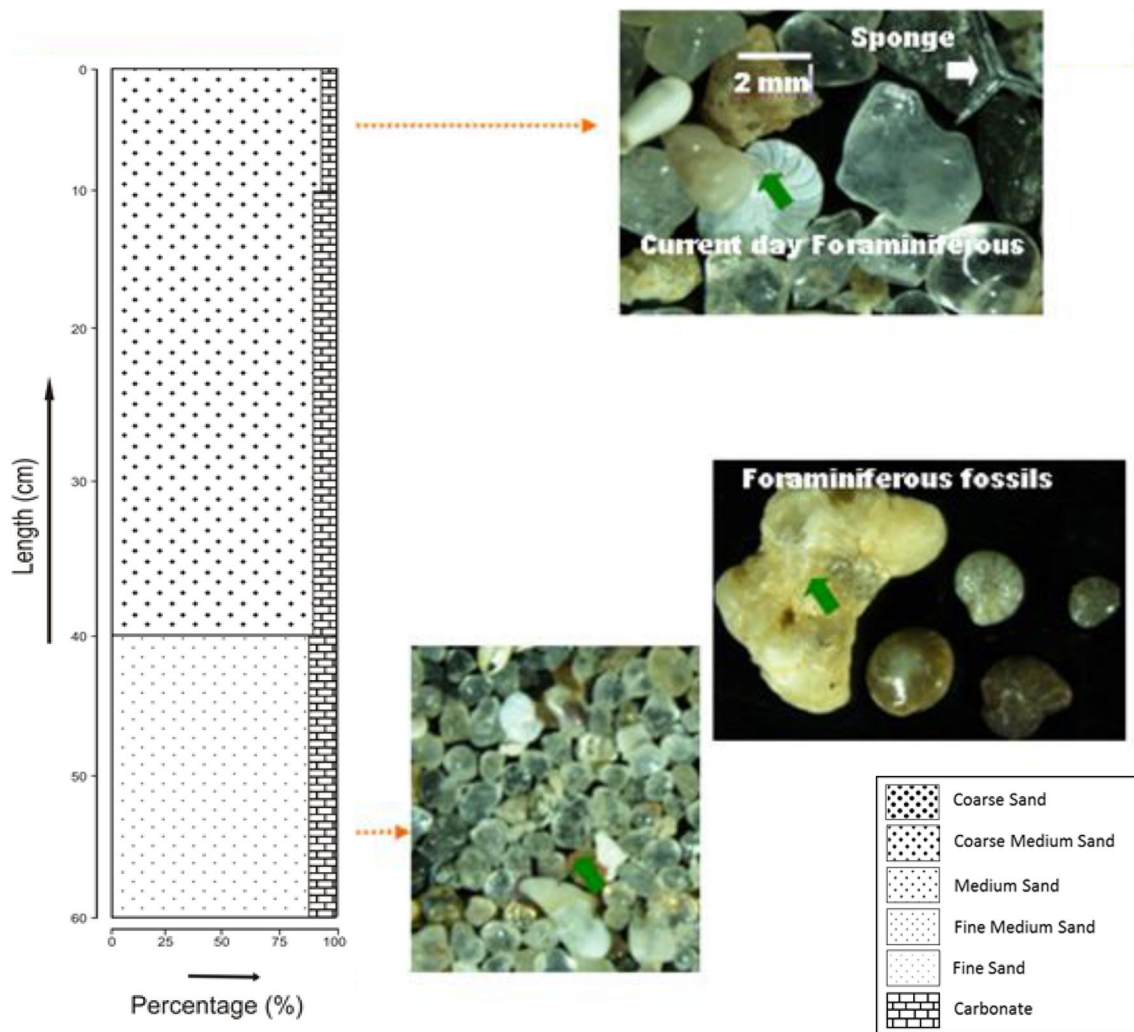


Fig. 6 Petrography of the sediment materials in core C

offshore to the beach by a transversal hydrodynamic activity at Dar Chaabane.

The fluvial activity of Oued El Kebir river supplies both Beni Khair and Dar Chaabane beaches. This activity is responsible for the sediment transport from Oued El Kebir formations (upper basin) before the construction of Tnitin and Zamou dams. This transport is alimented only by Beni Khair formations (lower basin) after dam's construction. Form Beni Khair to Dar Chaabane, sediments are finer and more shining in the direction of the alongshore sediment transport NE-SW.

### Shoreline evolution

Shoreline surveys were used to determine the time evolution of the shoreline position in time (from 1947 to 2003) and in space (from MB to DS). In this part, only 13 transects are presented (BD, BK1, BK2, DC, DC1, DL, DL1, DL2, DR, DR1, DR2, DS) as shown in Fig. 7.

The shoreline mapping shows that the 1962 position is advanced compared to the 1947 one. This is evidenced by

an accretion at Dar Chaabane between DC and DR profiles (section DCLR in Fig. 7) with a rate of +3.5 m/year and decreases to +0.2 m/year in the south of the sector between DR1 and DS. In this period, the advance at Beni Khair is limited to 0.1 m/year (section BK in Fig. 7). This prosperous period of sand accumulation between 1947 and 1962 can be explained by large deposits of sediments provided by a high fluvial activity of Oued El Kebir. Since 1962, negative changes in the shoreline position have been observed at the most studied profiles. Between 1974 and 1996, the mean retreat was quantified as -4 m/year at DC-DC1 and -3 m/year at DL-DL1-DL2-DR-DR1-DR2. The loss of sediment during this period reduces the quantity of sand available in this zone and increases the erosion problems. Since 1996, a large retreat has been largely observed at Dar Chaabane and particularly close to hotels Lido, Ramses and Riadh hotels while the shoreline maintains the same position approximately close to rocky parts (BD profile in Fig. 7).

In terms of volume change, results have shown a loss of sediments at DCLR section with an amount of 37,500 m<sup>3</sup>/year

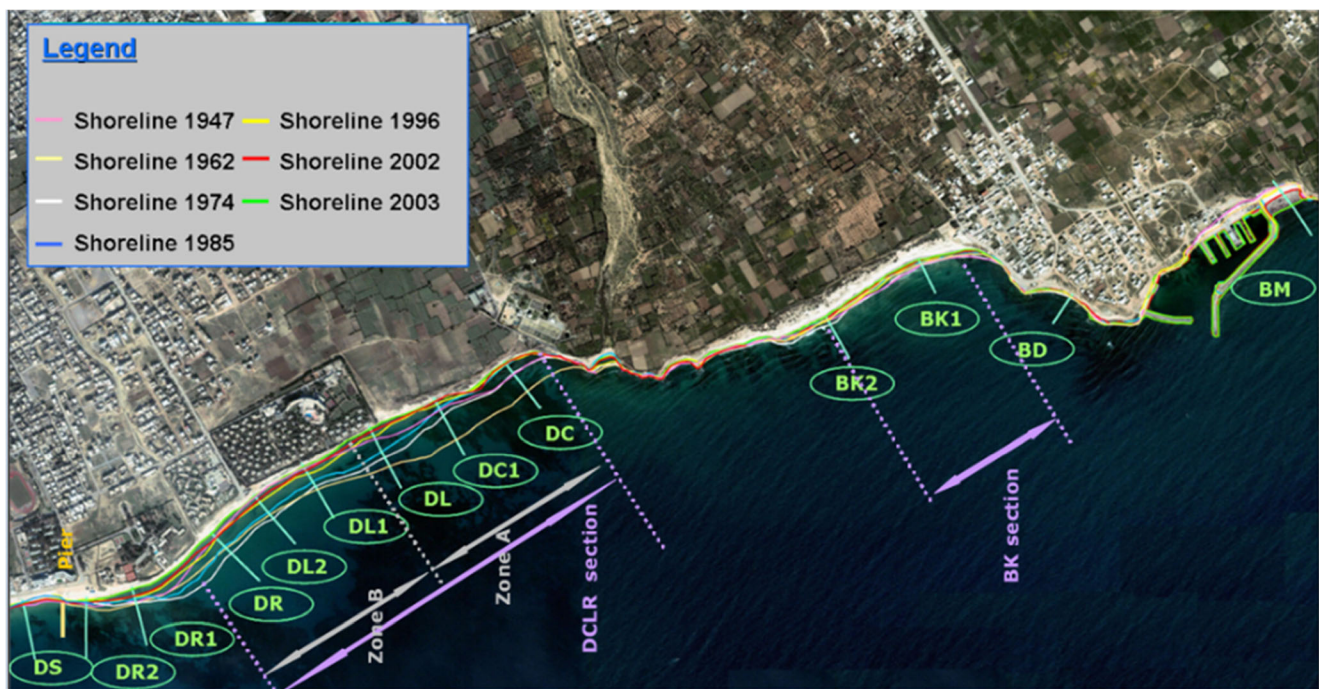


Fig. 7 Shoreline mapping at Beni Khiaar-Dar Chaabane during seven missions: 1947, 1962, 1974, 1985, 1996, 2002 and 2003

in 1962–1996 and  $36,500 \text{ m}^3/\text{year}$  in 1996–2003. This loss is limited to 2000 and  $1500 \text{ m}^3/\text{year}$  in 1962–1996 and 1996–2003, respectively.

Detailed analyses of sand volume changes at DCLR was implemented in order to quantify the sediment distribution between the two zones A (DC, DC1 and DL profiles) and B (DL1, DL2 and DR profiles). The loss of the bulk volume rate in B is of  $27,500 \text{ m}^3/\text{year}$  in 1962–1996 and increases to  $29,000 \text{ m}^3/\text{year}$  in 1996–2003. This loss is less important in A where the rate is quantified as  $10,000 \text{ m}^3/\text{year}$  in 1962–1996 and decreases to  $7500 \text{ m}^3/\text{year}$  in 1996–2003. Such results can be explained by a shortage of materials coming from the Oued El Kebir mouth, which is responsible for the reduction of the sediment supply, required for the nourishment of the zone B.

### Hydrodynamic patterns

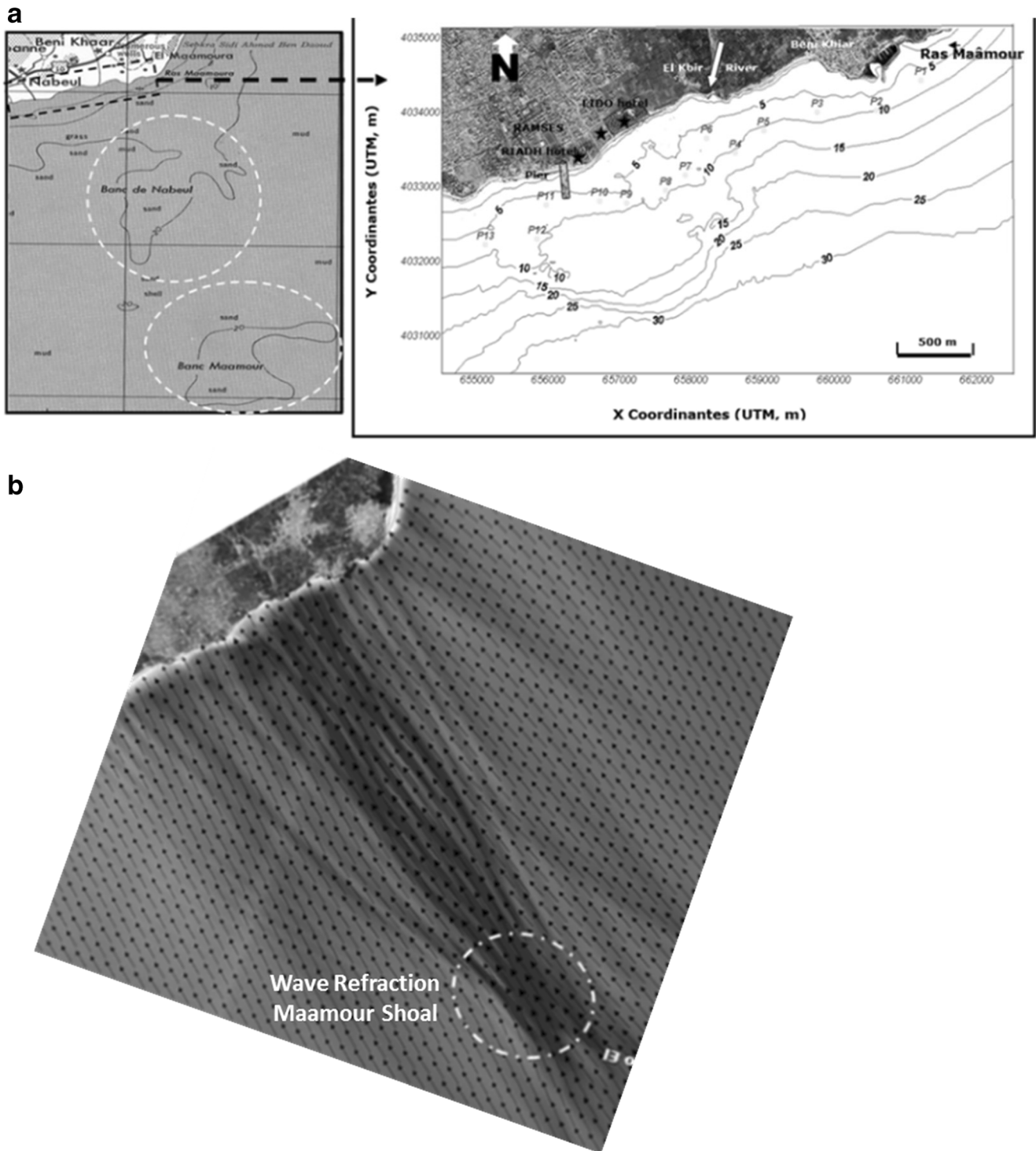
Hydrodynamic modelling was carried out using the bathymetry data and the wave climate.

The bathymetry is uniform between 75 and 100 m of depth and identifies two shoals ('El Maamour shoal' and 'Nabeul shoal') close to 40–50 m of depth as shown in Fig. 8a. The detailed bathymetry covering the nearshore zone has 20 m of resolution. It illustrates some complexities especially close to Dar Chaabane sector.

Simulated spectral waves have illustrated changes in wave patterns along both sectors Dar Chaabane and Beni Khiaar. Results have shown that waves coming from SE-SSE maintain the same direction from the deep to the shallow water. In

return, waves coming from ESE-SE suffer from changes in direction to the SE. SSE waves are refracted close to El Maamour shoal (Fig. 8b), such transformation leads to an energy divergence (convergence) and a decreasing (increasing) of wave height gradient. The energy concentration is less important in Beni Khiaar sector since it is contained by rocky structures. The complexity of the bathymetry configuration and the presence of rocky plateau in the nearshore bottom of Dar Chaabane, between 15 and 10 m, are responsible for a significant transformation of waves and an increasing of energy close Lido and Riadh hotels. An example is shown in Fig. 9 where the distribution of wave energy in shallow water is non-uniform with changes in wave direction from ESE to SE.

Current patterns, modelled by Copla module of SMC system, show a system of rips at Dar Chaabane close to hotels and an alongshore current from NE to SW. The wave-induced phase average current field of waves coming from ESE and SSE is displayed in Fig. 9c, d, respectively. ESE and SE waves present a high obliquity respect to the shoreline with an angle of  $45^\circ$  leading to an increasing transport of sediment; modelled results have shown alongshore currents of 45–50 cm/s and sediment transport rate of  $30\text{--}35 \text{ cm}^3/\text{s}$  for waves with 2 m of height and 10 s of period. In return, SSE waves are orthogonal to the shoreline with a mean velocity of 10 cm/s and a mean sediment rate of  $5 \text{ cm}^3/\text{s}$ . The trend of the alongshore currents seems to be broken at Dar Chaabane close to hotels (Lido and Riadh) where the systems of rips, caused by high wave gradients, are significantly pronounced.



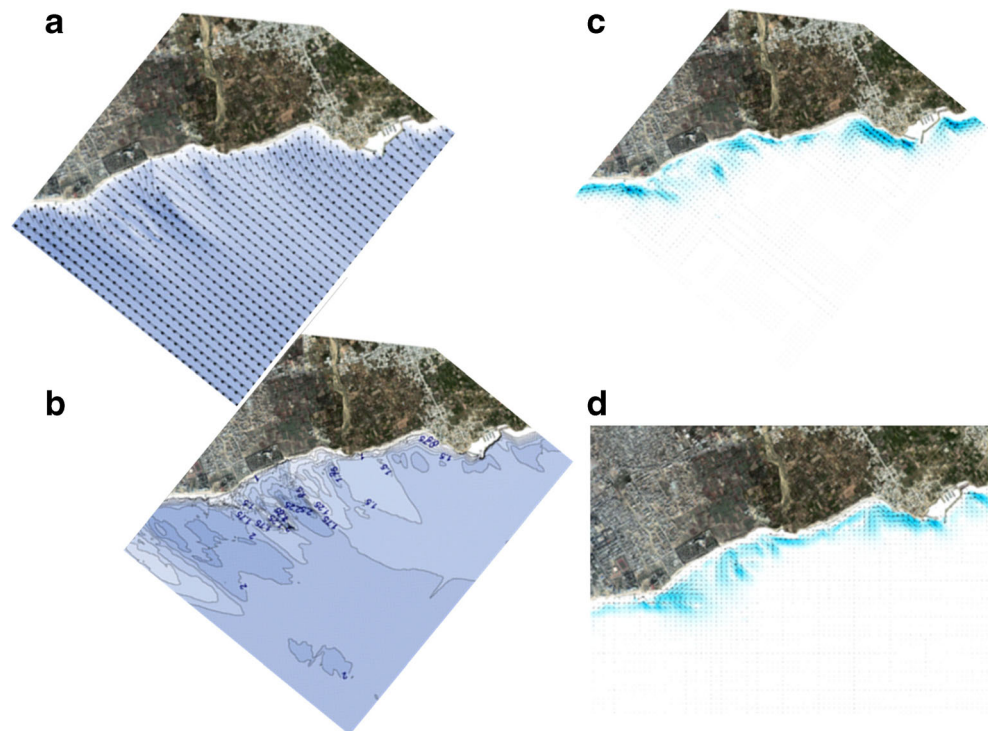
**Fig. 8** a Offshore bathymetry showing the two shoal of Nabeul and Maamour (left panel). The detailed bathymetry close to the beach is also shown (right panel). b Offshore wave refraction close to Maamour shoal

According to the hydrodynamic results, the sedimentary system of Beni Khiar-Dar Chaabane is characterised by the following: (1) transport patterns from NE to SW; (2) presence of the rocky structures in Beni Khiar responsible for an energy containment and material retention; and (3) circulatory systems of rip currents at Dar Chaabane close to LIDO and RIADH hotels.

### Discussion and conclusion

In this paper, the dynamic of Beni Khiar-Dar Chaabane has been investigated using different approaches of sedimentary and hydrodynamic analyses in order to identify the origins of erosion problems in Dar Chaabane and Beni

**Fig. 9** A plot of the wave vectors (a) and height distribution (b) for waves coming from ESE ( $H = 2$  m,  $T = 10$  s). The wave-induced phase average current field for waves coming from ESE (c) and SSE (d) with  $H = 2$  m and  $T = 10$  s



Khiar beaches considered as wave dominated with a low tidal range.

Results have shown changes in sand volume distribution and a high retreat of the shoreline position in the last years since 1996. Sedimentary analyses have emphasised similarities in the sediment texture between Oued El Kebir catchment and Dar Chaabane beaches and between rocky structures and Beni Khiar beaches.

The importance of the alongshore current from NE to SW responsible for a sediment transport and the circulatory systems of rip currents at Dar Chaabane beaches close to Lido and Riadh hotels are evidenced by the hydrodynamic analyses.

Changes in beach dynamic are explained by both directly and indirectly human interventions. In fact, the modifications of Oued El Kebir river supply by the presence of hydrological dams and the implementations of hotels close to the shoreline have contributed in the degradation of beaches.

Compared to Pacific and Atlantic open coasts, energy conditions of waves and wind in the Mediterranean basin are generally much lower; the tidal range is less than 1 m defining a micro-tidal context. Therefore, coastline evolution and shoreline features result from the sediment yield of fluvial activity. The importance of sediment supply by rivers from the sediment deposition in Mediterranean coasts, the progradation of deltas and the Holocene coastal deposits of fluvial origin have been investigated in several researches (e.g. Antony et al. 2014). In particular, it was demonstrated that small rivers with catchments less than  $50 \times 10^3$  km<sup>2</sup> of

superficies can contribute largely in sediment yields to coastal zones (Poulos and Collins 2002; Vanmaecke et al. 2011).

Over the twentieth century, the increasing population living on southern shores of Mediterranean and the socioeconomic development have exacerbated coastal erosion and perturbed the ecosystems. The problems of coastal destabilisation and erosion have been due to long-term decay of fluvial sediment. Anthropogenic modifications of sedimentary patterns affect the different systems articulated around man-made structures. For example, coastal erosion is mainly a product of river damming established to affront problems of increasing water demand and control flooding caused by extreme events. According to Antony et al. (2014), the construction of hundreds of dams around the Mediterranean Sea, especially over the last 50 years, has led to a dramatic reduction to approximately 50% of the potential sediment supply.

Furthermore, the high pressure of port and touristic development is responsible for a massive exploitation of beaches and a deep alteration of the physical processes controlling the natural coastal system. The combination of both man interventions and touristic activities has contributed in the loss of sediment and the shoreline retreat, which is the case for example of Tangiers (Sedrati and Anthony 2007) and Tetouan coasts (Anfuso et al. 2007; Elmrini et al. 2012a, 2012b) of Morocco, the north-eastern coast, the Nile delta, the Rhône and the Ebro.

During the 1800s, the two modern branches of the Nile delta have prograded by 3 to 4 km in response to the large quantities of fluvial sediments delivered to the coast (Frihy and Lawrence 2004). This accretion regime switched to an erosion

at the beginning of the twentieth century, which is mainly explained by the construction of two dams on the upper river in Aswan and barrages on both the upper and lower Nile River that cut off almost all water discharge and the delivery of fluvial sediments to the coast (Frihy and Khafagy 1991). This extensive erosion is also attributed to an abrupt decrease in water discharge and fluvial sediment yield during the twentieth century resulting from low rainfall in the Nile catchment in Ethiopia and central Africa, sea level rise and local deltaic subsidence (El Banna and Frihy 2009). The effects of sediment budget perturbations in the Rhone delta have been studied by many works where the deltaic material is reduced by a factor of 3.7, from 12.63 to  $3.41 \times 10^6 \text{ m}^3/\text{s}$  (Sabatier et al. 2006). This evolution has been explained by a decrease in river sediment input related to a natural decreasing frequency of major floods at the end of the Little Ice Age (Arnaud-Fassetta and Provansal 1999; Arnaud-Fassetta 2003), reforestation of the catchment and, since the 1950s, dam construction and dredging activities. In the case of Ebro delta, it was demonstrated that the growth of the delta was shifted a few decades ago to an erosional evolution as a result of the nearly total reduction of river sediment discharge due to dam construction in the lower reaches (Palanques et al. 1990).

According to the results demonstrated in the present research, the extensive erosion of sediments and the shoreline retreat in Beni Khiar-Dar Chaabane are mainly explained by man interventions. The presence of dams since 1996 within Beni Khiar catchment is responsible for a decrease in water discharge and fluvial activity. This reduction is responsible for a perturbation of sediment budget in the coastal area and beach erosion. Then, the touristic activities concentrated in LIDO and RIADH hotels have deeply increased the degradation of Dar Chaabane beach and abrupt changes of water depth between the shoreline and the closure depth. These irregularities have induced hydrodynamic complexities and high gradients of energy responsible for transversal systems of rip currents that increase under extreme conditions. Moreover, the hydrodynamic conditions and the wave transformation from the offshore to the shallow water close to shoals offer a favourable environment for the sediment transport and the beach erosion in micro-tidal marine context where wave energy has a key role in the hydrodynamic conditions. In such environments, the dynamic is highly dependent on the river supply because the longshore sediment transport is not the first forcing but represents an important parameter in modelling and reshaping the coast. The impact of hydrodynamic conditions to induce sediment transport and the morphology changes in Tunisian coasts has been investigated in some works. Louati and Zargouni (2009) have studied the sediment transport in the sandy beach of Tunis bay (NE Tunisia) using the numerical model UNIBEST. Some studies have been carried out in Medjerda and Miliane river and have shown that the dominant NE and NW waves generate longshore currents providing a

sediment transport N-S. In the case of Beni Khiar-Dar Chaabane, the dominant waves coming from SSE and SE are responsible for the littoral derive with a velocity of 48 cm/s. Similar results were demonstrated by the works of Brahim et al. (2014) where current velocities at coastal areas of Tunis Gulf (Ghar El Melh) was quantified as 20 and 10 cm/s in winter and summer, respectively. The seasonal variability of hydrodynamic conditions is largely observed in the beach responses to winter and summer sceneries, as in the case of the most Mediterranean shores. Turki et al. (2012) have investigated the seasonal responses of Barcelona beaches to energy conditions using statistical techniques. They have demonstrated that shoreline changes take different positions under two hydrodynamic regimes in winter and summer. According to the present research, Beni Khiar-Dar Chaabane, like most zones in the Mediterranean, experience a discontinuity in the catchment-river-coast system induced by a disequilibrium of the sedimentary budget.

This work has been driven before 2006 when the problem of erosion was of major interest for the local authorities. After this period, sustainable solutions to coastal problems have been taken. Since 2009, Tunisian government has established a series of breakwaters in Dar Chaabane with the aim to accelerate the accretion. This solution has been responsible for the modification of the shoreline dynamic of the physical system in Beni Khiar-Dar Chaabane.

The present work represents an excellent example where the understanding of the combination of hydrodynamic and sedimentary processes driving beach changes is important for coastal managers. An integrated approach is required for the best management of the conflicts in coastal zones.

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## References

- Anfuso G, Martinez del Pozo A, Nachite D, Benavente J, Macias A (2007) Morphological characteristics and medium-term evolution of the beaches between Ceuta and Cabo Negro (Morocco). *Environ Geol* 52:933–946
- Antony, E., J., 2014. The human influence on the Mediterranean coast over the last 200 years: a brief appraisal from a geomorphological perspective. *J Geomorphol*, 219–226, 20
- Arnaud-Fassetta G (2003) River channel changes in the Rhone Delta (France) since the end of the Little Ice Age: geomorphological adjustment to hydroclimatic change and natural resource management. *Catena* 51:141–172
- Arnaud-Fassetta G, Provansal M (1999) High frequency variations of water flux and sediment discharge during the Little Ice Age

- (1586–1725 AD) in the Rhone Delta (Mediterranean France). *Hydrobiologia* 410:241–250
- Ben Salem H (1995) Evolution de la peninsule du cap Bon (Tunisieorientale) au cours du Neogene. *Notes Serv Geol Tunisie* 61:73–84
- Brahim M, Abdelfattah A, Sammari C, Aleya L (2014) Surface sediment dynamics along with hydrodynamics along the shores of Tunis Gulf (north-eastern Mediterranean). *J African Earth Sci* 103:30–41
- Dean, R.G., Dalrymple, R.A., 2002. Coastal processes with engineering applications, Cambridge University Press, ISBN 0521495350
- El Banna M, Frihy OE (2009) Human-induced changes in the geomorphology of the northeastern coast of the Nile delta, Egypt. *Geomorphology* 107:72–78
- Elmrini A, Maanan M, Anthony EJ, Taouati M (2012a) An integrated approach to characterize the interaction between coastal morphodynamics, geomorphological setting and human interventions on the Mediterranean beaches of North-Western Morocco. *Appl Geogr* 35:334–344
- Elmrini A, Anthony EJ, Maanan M, Taouati M, Nachite D (2012b) Beach-dune degradation in a Mediterranean context of strong development pressures, and the missing integrated management perspective. *Ocean Coast Manag* 69:299–306
- Ennabli, M., 1980. Etude hydrogeologique des aquiferes du Nord-Estde la Tunisie pour une gestion integree des ressources en eau, These 3eme cycle. Université de Nice
- Folk RL (1959) Practical petrographic classification of limestones, vol 43. American Association of Petroleum Geologists Bulletin, pp 1–38
- Friedman, G. M., Sanders, F. E., 1978. Principles of sedimentology, Wiley, New York, 1978. No of pages: 792
- Frihy OE, Khafagy AA (1991) Climatic and human induced changes in relation to shoreline migration trends in the Nile delta promontories. *Catena* 18:197–211
- Frihy O, Lawrence D (2004) Evolution of the modern Nile delta promontories: development of accretional features during shoreline retreat. *Environ Geol* 46:914–931
- González M, Medina R, Gonzalez-Ondina J, Osorio A, Méndez FJ, García E (2007) An integrated coastal modeling system for analyzing beach processes and beach restoration projects, SMC. *Comput Geol* 33(7):916–931
- Halouani N, Fathallah S, Gueddari M (2012) Beach and nearshore morphodynamic changes of the Tabarka coast, Northwest of Tunisia. *Environ Earth Sci* 66:1059–1069. <https://doi.org/10.1007/s2665-011-1312-5>
- Louati M, Zargouni F (2009) Topo-bathymetric modeling and longshore sediment transport. The example of the sandy beaches of Tunis Bay, Northeast Tunisia. *J Geomorphol*:220–221
- Palanques A, Plana F, Maldonado A (1990) Recent influence of man on the Ebro margin sedimentation system, northwestern Mediterranean Sea. *Mar Geol* 95:247–263
- Paskoff R (1985) Les littoraux—impact des aménagements sur leur évolution, Col. Géo-graphie. Masson, Paris, p 185
- Paskoff R (1998) Les littoraux. Impact des aménagements sur leur évolution. 3e édition, coll. “ U ”, Armand Colin, Paris, p 264
- Poulos SE, Collins MB (2002) Fluvial sediment fluxes to the Mediterranean Sea: a quantitative approach and the influence of dams. In: Jones SJ, Frostick LE (eds) *Sediment Flux to Basins: Causes, Controls and Consequences*, vol 191. Special Publications Geological Society, London, pp 227–245
- Oueslati A (1994) Les côtes de la Tunisie: recherches sur leur évolution au Quaternaire, Volume 2. Ed. Faculté des Sciences Humaines et Sociales, p 402
- Oueslati A (2004) Littoral e aménagement en Tunisie. Ed. Faculté des Sciences Humaines et Sociales, p 534
- Reguero BG, Menéndez M, Méndez FJ, Mínguez R, Losada IJ (2012) A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards. *Coast Eng* 65:38–55. <https://doi.org/10.1016/j.coastaleng.2012.03.003>
- Sabatier F, Maillot G, Fleury J, Provansal M, Antonelli C, Suarez S, Vella C (2006) Sediment budget of the Rhône delta shoreface since the middle of the 19th century. *Mar Geol* 234:143–157
- Saidi H, Souissi R, Zargouni F (2013) Grain size characteristics of superficial sediments of the Gulf of Tunis (NE Tunisia). *Arab J Geosci* 3365–3387. <https://doi.org/10.1007/s12517-013-1008-0>
- Sedrati M, Anthony EJ (2007) A brief overview of plan-shape disequilibrium in embayed beaches: Tangier Bay, Morocco, revisited. *Méditerranée* 108:125–130
- Souissi R, Turki I, Souissi F (2014) Effect of submarine morphology on environmental quality: case of Moanastir bay (Eastern Tunisia). *Carpathian J Earth Environ Sci* 9(3):231–239
- Soulsby, R., 1997. Dynamics of marine sands. H.R. Wallingford
- Turki I, Medina R, Gonzalez M, Coco G (2012) Natural variability of shoreline position: observations at three pocket beaches. *Mar Geol* 338:76–89. <https://doi.org/10.1016/j.margeo.2012.10.007>
- Vanmaercke M, Poesen J, Verstraeten G, de Vente J, Ocakoglu F (2011) Sediment yield in Europe: spatial patterns and scale dependency. *Geomorphology* 130:142–161