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ORIGINAL ARTICLE

Morphological characteristics and medium-term evolution of the beaches between Ceuta and Cabo Negro (Morocco)

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Abstract This work presents the results of a combined study on the beach morphology and the evolution at short- and medium-term of the littoral between Ceuta and Cabo Negro (Morocco). It is an interesting sector showing a great increase of human occupation and coastal structures. The monitoring program allowed for the reconstruction of the beach morphological behavior and the seasonal changes. The studied beaches presented reflective profiles recording little seasonality, with the most notable morphological changes being strictly related to storms. Surf Similarity and Surf Scaling parameters highlighted the existence of intermediate and reflective beach states, characterized by plunging breakers. Aerial photographs and a satellite image have been geo-referenced and elaborated with GIS tools to reconstruct the short- and medium-term evolution of the littoral and the sediment transport pathways. The littoral showed important erosion at short- and medium-term related to a negative sedimentary budget because of offshore transport. Sand accumulation was recorded close to the main ports, i.e., Marina Smir and Marina Kabila. These port structures constituted impermeable, fixed limits, which divided the studied area into littoral cells. Other free, transit limits were also observed.

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Introduction

Shoreline position fluctuates in a variety of time scales, a behavior that introduces many difficulties when reconstructing coastal trends (Carter 1988; Crowell et al. 1993; Jiménez et al. 1997; Short 1999). Variability in coastline position may be the response to a single factor or a combination of them (Bird 1993; Forbes et al. 2004). Principal causes of coastal erosion or accretion are individual large storm events (Stone et al. 1996, 1997; Donnelly et al. 2001; Stone and Orford 2004), seasonal variability in wave energy and/or circulation in the nearshore zone (Sonu and James 1973; Masselink and Pattiaratchi 2001), multiyear to decadal-scale variations in storminess, wave energy, and coastal morphodynamics (Thom and Hall 1991; Forbes et al. 1997; Zhang et al. 1997; Shand et al. 2001), long-term variations in the relationship between wave climate and sediment supply and diminution of fluvial supplies (Orford et al. 2001, 2002).

Coastal changes are surveyed using a wide variety of methods and data sets according to the study time spans (Smith and Zarillo 1990; Crowell et al. 1991, 1993; Dolan et al. 1991; Jiménez and Sánchez-Arcilla 1993; Jiménez et al. 1997; Gorman et al. 1998;

El-Asmar 2002). Studies on short-term shoreline dynamics are usually carried out at small spatial scales, in a time span less than 10 years (Crowell et al. 1993). The most common technique used is beach topographic profiling or 3D surveying, repeated at regular intervals, in order to measure daily to annual variations in shoreline position and beach volume (Morton 1979; Carter 1988; Komar 1998; Corbau et al. 1999; Short 1999).

Vertical aerial photographs, satellite images, maps, and charts represent a very useful tool to reconstruct coastline changes at medium (between 10 and 60 years) and long (> 60 years) temporal and spatial scales (Crowell et al. 1993) and, further, they display coastal type distribution, land uses and dune field evolution (Taney 1961; Dolan et al. 1980; Leatherman 1983; McBride et al. 1991; Fisher and Overton 1994; Jiménez et al. 1997; Forbes et al. 2004). The precision and accuracy of aerial photogrammetric measurements depend on their own characteristics (Dolan et al. 1980; Andres and Byrnes 1991; Crowell et al. 1991; Moore 2000) and on the difficulties of locating shoreline position, typically taken as the high-water line (especially in microtidal environments, Dolan et al. 1979, 1980; Leatherman 1983; Pajak and Leatherman 2002), or identified in mesotidal environments as the seaward vegetation limit, dune foot or cliff top (Crowell et al. 1993; Fisher and Overton 1994; Boak and Turner 2005).

Several authors studied coastal behavior at different time scales. Morton (1979) analyzed coastal evolution at geological and recent time scales. The former was related to natural processes and the latter was principally linked to human actions. Smith and Zarillo (1990) used two vertical aerial photographs to reconstruct medium-term coastline trend, and the Emery (1961) methodology of beach profiling to measure short-term shoreline position changes over a period of 13 months. They concluded that short-term changes in shoreline position may be quite important and may represent the single largest source of error in quantitative calculations of medium- and long-term shoreline changes.

In Spain, Jiménez and Sánchez-Arcilla (1993) and Jiménez et al. (1997) analyzed the Ebro delta evolution. The former authors obtained similar trends using shoreline position data from three sets of aerial photographs, covering a period of 32 years, and from beach profiling techniques, carried out with a seasonal periodicity during 4 years. The latter authors studied the short-term evolution (namely 2 years) of the Ebro delta, with seven sets of aerial photos with a time span of 4 months, and beach profiling techniques. They obtained a perfect agreement from a qualitative point of view, i.e., erosion and accretion zones always coincided, but recorded small differences in measured values, especially in very flat coastal sectors.

This work presents the results of a combined study on the beach morphology and the short- and medium-term evolution of the littoral between Ceuta and Cabo Negro (Morocco). It is an interesting sector showing a great increase of human occupation and coastal structures.

Beach morphology has been reconstructed with a topographic monitoring program over a period of 2 years, the obtained data being representative of beach morphodynamics and seasonal behavior. The analysis of coastal evolution for a period of 17 years (medium-term trend, according to Crowell et al. 1993) was carried out using well temporally spaced photogrammetric flights and a satellite image.

Obtained data has been very useful to improve the general knowledge on the morphological characteristics, the erosion problems, the broad sediment circulation patterns and the distribution of cells in the studied littoral which is characterized by a great lack of data. In this way, the results of this study constitute basic, useful information that may be employed by local government planning staff as a preliminary approach to the integrated coastal erosion management of the littoral.

Studied area

The studied area consists of a 24-km long coastal sector between the Moroccan cities of Fnideq and M'Diq (Fig. 1). The coastline, N–S oriented, is open on the east side but restricted to the North and the South because of the headlands of Ceuta and Cabo Negro. The beaches consist of sand sediments, mainly composed of quartz (Nachite et al. 2005). Dune ridges, fossil cliffs and a small, rocky shore platform (in Restinga zone) are also present along the studied littoral (Anfuso et al. 2004; Nachite et al. 2004).

Cliffs are cut in sandstone, marl, limestone, and micaschist. Significant sedimentary inputs are not derived from cliff retreat because they are poorly eroded only during most important storms.

Most important watercourses flowing into the studied coast are the Rio Negro and the Smir rivers and the Fnideq Stream which basins, respectively, are 16, 73, and 10 km^2. Their fluvial inputs, according to Nachite et al. (2005), are not significant especially after 1991, when a dam was emplaced in the Smir River (the most important source). Further, there is no evidence of sediment supply from offshore.

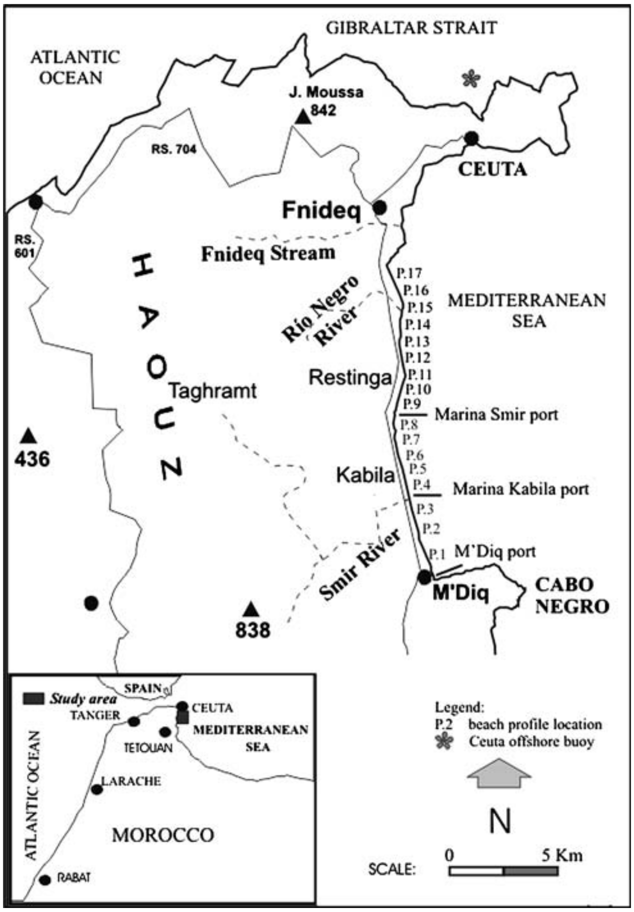

Fig. 1 Location map of the studied area. Position of beach profiles, offshore buoy and ports' structures are also indicated

The studied area is a semidiurnal, microtidal environment, ranging tidal variations from a few centimeters in neap tides, to 80–100 cm in spring tides. The tidal wave, coming from the Atlantic, penetrates into the Mediterranean and spreads out toward the east, progressively decreasing in intensity. In certain cases, the sea level variation produced by barometric tides, reaches a magnitude comparable to that one related with the astronomic tides. From May to October there is a predominant easterly wind ''Chergui,'' whereas from October to February, westerly ''Gharbi'' winds prevail. During the months of April and May a certain equilibrium can be observed between the winds from ENE and WSW (LPEE 1987; B. El Moutchou 1995, unpublished data).

As a result of the orientation of the littoral, waves approach the coast from the first and second quadrants. Waves associated with storm conditions come from the E and ENE. In M'Diq, the highest registered height for a wave from these approaching directions is 5.5 m with a period of 5 s and a recurrence period of 20 years (LPEE 1987). The main currents flow northwards and, during the summer season, toward the SSE, with a maximum velocity of 0.68 m/s (Lakhdar Idrissi et al. 2001).

Concerning coastal occupation, it has been growing up over recent years because of increasing tourist demand. These have mainly consisted of the construction of two tourist ports (Marina Smir and Marina Kabila), summer houses, hotels and a motorway which runs parallel to the coast (Fig. 2), affecting the dune ridges and two lagoons which are of great ecological interest (Castro et al. 2006).

Methodology

Wave climate

As for the wave characteristics, data has been obtained from the offshore, scalar buoy ''Ceuta,'' which belongs to the Spanish measures network ''REMRO'' (Ministry of Environment). Unfortunately, because of its location (Fig. 1), the buoy may not adequately record waves, which approach from the S and SE. Additionally, direct measurements of wave height (by means of a metric pole), period (counting the number of waves arriving in a lapse time of 2 min) and visual observations of breaking type have been carried out during the field surveys and have been used to calculate the Surf Scaling and Surf Similarity parameters.

Beach profiles and seasonal changes

In order to characterize beach morphology, 84 topographic profiles have been taken using a theodolite over the space of five surveys (July 2003, January and February 2004, and April and June 2005). Beach profiles carried out in July 2003 and June 2005, and in January 2004, corresponded theoretically and, respectively, to summer and winter conditions; the surveys from February 2004 and April 2005 corresponded to erosive conditions because they were carried out after significant easterly windstorms.

In each survey, 17 normal topographic profiles were taken along the coastline (Fig. 1), measured from fixed points on the backshore and extended to a depth of ~1 m below the mean sea level. The processing of the topographic data allowed for the reconstruction of the beach morphology and foreshore slope (Anfuso et al. 2006). Beach slope has been calculated for the portion of the beach profile falling within the foreshore zone, i.e., the area between the high and low water level positions. Furthermore, beach profiles have been normalized in correspondence with the mean sea level,

Fig. 2 The northward oriented Kabila port entrance (**a**), the southward oriented Marina Smir port entrance (**b**); human constructions on the backshore at M'Diq (**c**) and Al Amine urbanization (**d**, close to profile 15 in Fig. 1)

defined as 0 level, and beach volumes determined for each profile. Volumetric changes per unit of beach length (m^3/m) have been calculated using a Windows program, by considering the volumetric differences recorded at each transect between consecutive field surveys (in the specific, the used transform integrates under curves using the trapezoidal rule).

As for the sediment characteristics, surface samples have been gathered in the foreshore. The samples have been sieved in the laboratory through 18 sieves, with 0.5 phi intervals, obtaining the statistical parameters described by Folk and Ward (1957), i.e., the mean, the sorting, the skewnees and the kurtosis of the sediments. Carbonates' concentrations have also been analyzed. Two classic morphodynamic parameters, based on wave height and period and beach slope, have been employed in order to characterize the studied beaches. The type of breaker has been calculated by the Surf Similarity index (Battjes 1974), which differentiates between spilling, plunging, collapsing, and surging breakers. The expression of the previous index is the following:

$$\xi = \tan \beta / (H_{\mathrm{b}}/L_0)^{0.5}, \tag{1}$$

where tan β is the average beach slope in the foreshore area, H_{b} is the height of the breaking wave and L_0 is the wave length in deep water.

The morphodynamic state was expressed through the Surf Scaling parameter (Guza and Inman 1975), which differentiates between dissipative, intermediate and reflective beach states. The expression of the aforementioned parameter is:

$$\varepsilon = \sigma^2 H_{\mathrm{b}} / 2g\, tan^2\, \beta, \tag{2}$$

where σ is the wave frequency in radians, g is the acceleration of gravity and β is the beach slope.

Coastline evolution

Concerning coastal evolution, according to Dolan et al. (1980, 1991), Leatherman (1983), Jiménez et al. (1997), and Pajak and Leatherman (2002), two sets of aerial photographs (dated 1986 and 1994) and a pan-sharpened, Quickbird satellite image (dated 2003) have been used to reconstruct and quantify shoreline evolution and littoral cell distribution. Adjacent zones of opposing characteristics, i.e., zones corresponding to discontinuities in the rate and/or the direction of sediment transport, have been chosen as cell limits. According to the terminology proposed by Carter (1988) and Bray et al. (1995), limits have been classified as "fixed," if they are stable in correspondence to human or natural structures, and as "free," if their position changed with time. Following Lowry and Carter (1982), further distinction has been made between "divergent" limits, observed when sediment transport spreads into two opposite directions in correspondence to the limit, "convergent" limits, when sediment transport converges to the limit, and "pulse" limits, when transport produces accumulation on one side and erosion on the other side of the limit.

Aerial photographs have been scanned, geo-referenced and computer rectified to eliminate effects of scale and distortion (Lillesand and Kiefer 1987; Crowell et al. 1991; Moore 2000). Ground Control Points

(GCP^s) for photo registration and geo-referencing have been obtained from the geo-referenced satellite image and all the information has been presented as UTM coordinates, Zone 30N and datum WGS84.

The error related to the distortion of the photographs (Dolan et al. 1980; Anders and Byrnes 1991; Crowell et al. 1991; Moore 2000) has been greatly solved and controlled in the geo-referenced documents through the root mean square error (RMSE). The mean geometrical error of the photographs was less than 5 m, but it was much lower in correspondence to the shoreline. The error introduced by the operator because of the difficulties of locating the precise position of the water/sand contact due to the spatial resolution of photographs, was less than 1 m.

The precision and accuracy of aerial photogrammetric measurements depend also on the difficulties of locating shoreline position, which has been defined as ‘‘the water line at the time of the photo’’. In order to determine the potential error in shoreline mapping because of the microtidal range of the area, the intertidal slope of the studied beaches has been used to calculate the foreshore width oscillations (Dolan et al. 1980). Shoreline variations due to erosion/accretion processes have also been considered. Wave height effects were not considered because no storm conditions have been observed in anyone of the photographs.

The distance (along 42 transects) between the shoreline positions from each date and the beach surface area (with the script tool provided for ArchGIS), have been calculated for different time spans, i.e., 1986–1994 and 1994–2003 periods, in this study referred as short-term changes according to the terminology of Crowell et al. (1993). Lastly, the 1986 and 2003 coastlines have also been compared to have a view on the overall evolution of the littoral (i.e., a time span of 17 years, referred as medium-term frame, Crowell et al. 1993): it is equivalent to the ‘‘end-point method’’ which considers the amount of shoreline movement by selecting two shorelines, usually the earliest and the most recent. It helps to reduce seasonal effects and/or the influence of a single storm on the medium-term trend (Dolan et al. 1991).

Results and discussion

Waves characteristics

Despite the problems related to the position of the offshore buoy, the data presented is useful in order to have a broad characterization of the studied area. The littoral is a low-energy environment, with almost 70% of the data corresponding to wave height lower than 0.5 m (Fig. 3).

Wave height presented significant seasonal variations (Fig. 4): higher values were usually recorded during February and March and second in November and December; lower values prevailed during summer months but minor storms were sometimes also observed. Furthermore, it is possible to note that 2004 was the most energetic of the studied years.

Lastly, it is important to note that the storm recorded a few days before the beach surveys carried in February 2004 (Fig. 4), presented wave height values with a recurrence period of 6 months, and it was the most important in 2004. It was related to important easterly winds (wind speed 22 m/s), which generated maximum significant wave heights of 2.6 m with 9.1-s period (Benavente et al. in press).

Beach morphology and behavior

Dealing with grain size, the beaches are made up of coarse and very coarse sand (Fig. 5), moderately and poorly sorted, and being for the most part very negatively skewed (Nachite et al. 2005).

On considering beach morphology, all the beaches showed clear reflective conditions in the sense of Wright and Short (1984) and Carter (1988). Beaches presented a well-developed berm, which gave rise to elevated foreshore slope values (mean value $\tan \beta = 0.09$; Figs. 5, 6).

It is also interesting to note that grain size and beach foreshore slope presented quite constant longshore values (Fig. 5). Local variations in beach slope were

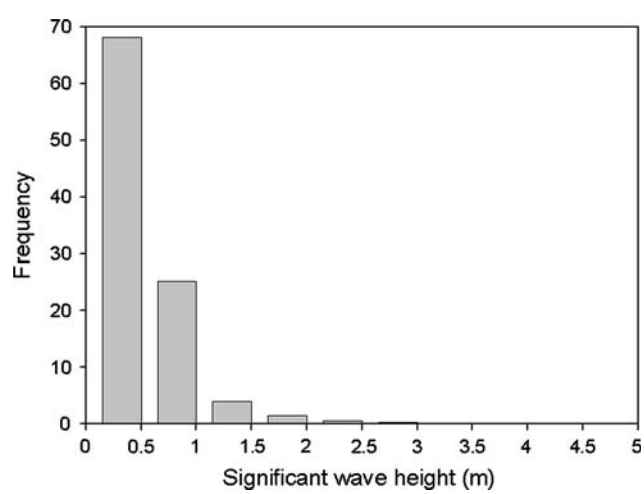

Fig. 3 Frequency of wave height obtained from the ‘‘Ceuta’’ offshore, scalar buoy (REMRO network, Ministry of Environment). Data referred to the 1985–2005 period

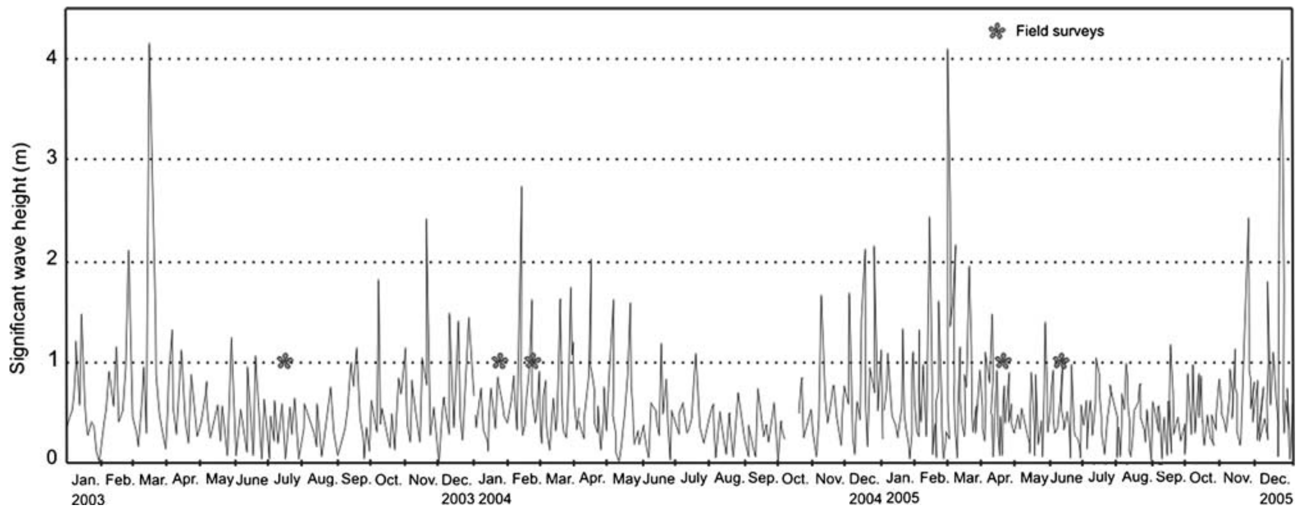

Fig. 4 Wave height distribution during the 2003–2005. Temporal location of the field surveys carried out within this study has also been indicated

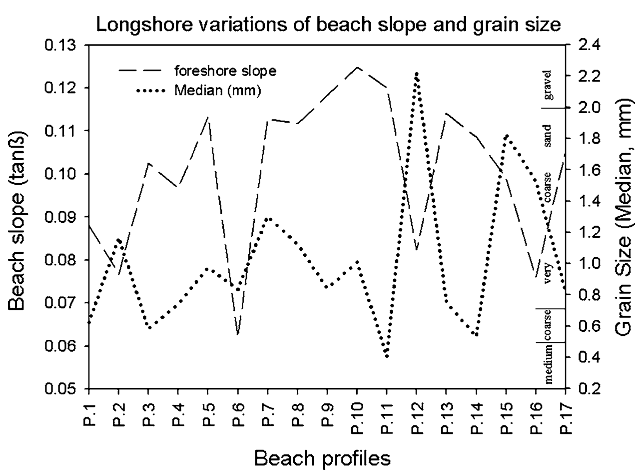

Fig. 5 Longshore distribution of grain size and beach foreshore slope values. Data obtained from topographic surveys and sediment sampling carried out in July 2003

related to the contouring conditions because of the presence of human and natural structures. Variations in grain size were linked to the presence of shell fragments, coarser sediments being related to elevated percentages of shell fragments. Considering the relation between grain size and beach slope, data from the studied littoral corresponds well the general, classic relation proposed by Bascom (1951), in this way evidencing the "natural" behavior of the studied beaches, i.e., the absence of important contouring conditions which only at certain places achieve some importance, altering the relation between grain size and beach slope.

To define the observed morphological states from a quantitative point of view, the Surf Similarity index and the Surf Scaling parameter have been calculated for the July 2003 and February 2004 surveys (Fig. 7 a, b). During the survey of July, the Surf Similarity index showed more or less constant values, corresponding to plunging breakers, in accordance with the field observations. Values which were closer to spilling breakers have been observed in correspondence to P.6, in summer conditions, due to this area's low-slope value, which was linked to the presence of a small groin. The curve, corresponding to the February survey, showed breakers on the limit between plunging and spilling (Fig. 7a). As for the Surf Scaling parameter, reflective conditions were shown in the month of July, in accordance with the higher slope measured values. In February, the values reflected an intermediate state localizing in some profiles values, which were clearly dissipative (Fig. 7b).

The volumetric variations of the beach volumes during the studied period, calculated from the backshore to the mean sea level, are presented in Table 1.

Regarding beach evolution during the monitored period, the vast majority of the studied beaches recorded an accentuated accretion in January 2004 because of the fair weather conditions observed in the month before the surveys (Fig. 4), and erosion after the storm which affected the studied littoral only a number of days before the surveys carried out in February (Fig. 4), Benavente et al. (in press). In February, almost all the beaches underwent erosion in the dry beach, recording at places small increases at mean sea level position (Fig. 6, P. 5). The highest erosion values, namely 13–16 m^3/m, were recorded in profiles P.2, P.5 and P.6 (Fig. 6 and Table 1), accretion values generally being small.

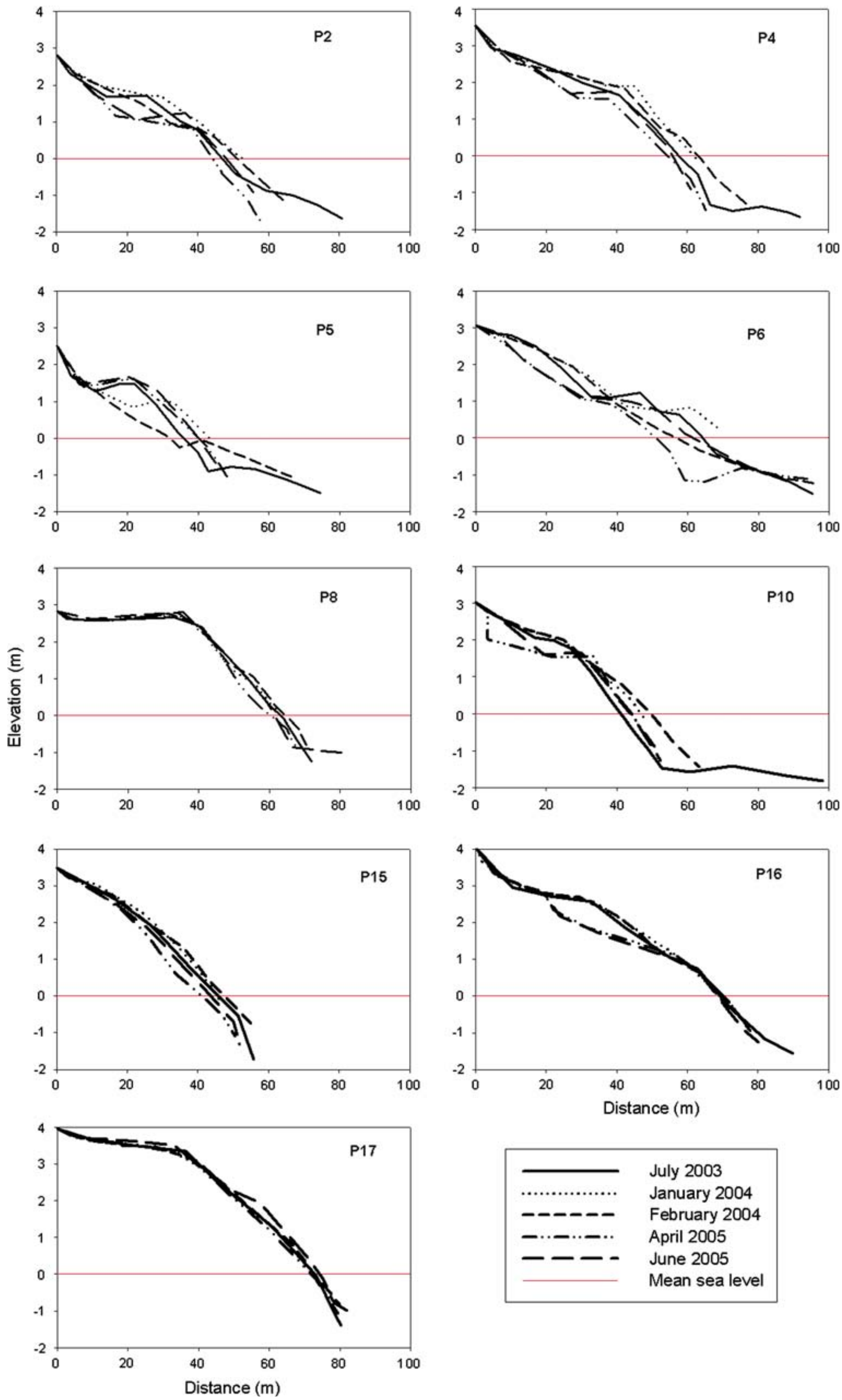

Fig. 6 Topographic profiles of the studied beaches. Field surveys of July 2003, January and February 2004, April and June 2005

On comparing the surveys of February 2004 and April 2005 (Fig. 6 and Table 1), the majority of the beaches experienced erosion (Fig. 6, P.2, P.4, P.6, P.10, P.15, and P.16), the maximum recorded values being around 13–20 m^3/m. Lastly, the values calculated for June 2005 showed accretion in the majority of the

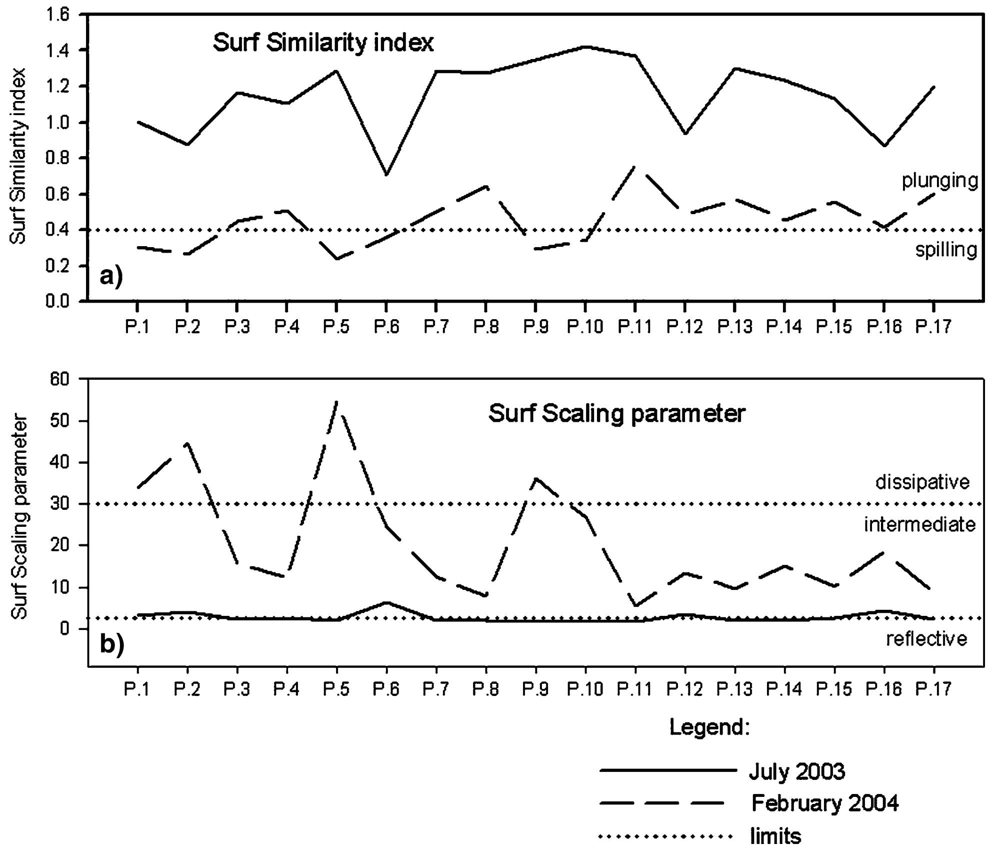

Fig. 7 Variations of the Surf Similarity index (**a**) and the Surf Scaling parameter (**b**). Limits, respectively, according to Fredsoe and Deigaard (1992) and Guza and Inman (1975)

Table 1 Beach volumes (m^3/m)

Profile	July 2003	January 2004	February 2004	April 2005	June 2005
P.1	29.5	31.5	32.2	34.7	20.5
P.2	69.8	84.1	70.9	57.3	71.4
P.3	82.7	77.2	72.9	68.0	60.7
P.4	113.1	123.8	119.4	98.6	106.2
P.5	36.2	48.9	32.4	51.6	54.3
P.6	92.9	96.5	81.3	66.7	80.8
P.7	61.1	64.2	59.3	68.7	72.7
P.8	136.2	137.7	138.6	131.7	136.1
P.9	34.4	34.8	28.7	–	39.8
P.10	81.9	90.5	94.0	73.3	73.1
P.11	135.8	135.8	127.0	127.5	118.6
P.12	63.4	69.2	75.7	69.4	74.8
P.13	62.8	59.2	63.4	64.7	67.8
P.14	96.8	100.0	101.1	101.5	105.5
P.15	90.0	94.7	94.5	77.9	84.5
P.16	146.2	148.9	152.8	135.2	131.2
P.17	197.1	197.6	194.3	195.1	202.0

studied beaches, which demonstrates their great capacity of recovery, related to the prevalence of fair weather conditions (Fig. 4).

According to the previous results, the beaches of the studied littoral did not follow the seasonal behavior described in the classic models of Shepard (1950), Bascom (1951), and Shih and Komar (1994) which beaches presented a winter profile with low, erosive slope and a summer, constructive profile with a higher slope. Similar behavior was also observed by Medina et al. (1994) and Larson and Kraus (1994) in very energetic beaches, which registered seasonal transfer from the berm to the bar of around 100 m^3/m.

In the studied littoral, the most important morphological and volumetric changes were related to the frequency and intensity of storms as Owens and Frobel (1977), Davis and Fox (1972), Carr et al. (1982), Martínez (1986), Donnelly et al. (2001), and Morton and Sallenger (2003) observed in other littorals.

In general, dealing with beach change modalities, the morphological changes were quite uniform along the foreshore or the entire beach and only very small or no slope changes arose (Fig. 6, P.8, P.16, and P.17), this mode of change is very similar to the parallel retreat described by Nordstrom and Jackson (1992) and Jackson et al. (2002).

In other cases, the movement of sand, from the upper part of the beach to the mean sea level position, gave rise to lower-slope values, mainly during erosive conditions, especially in February 2004 (Fig. 6, P.5). This is a typical behavior for the beaches with an intermediate to high-slope values (Wright and Short 1984), quite similar to the beach pivoting mechanism described by CERC (1984), Hardisty (1986), Hughes and Cowell (1987), Thom and Hall (1991), and Benavente and Reyes (1999). Lastly, in other cases, the longshore transport eroded in certain beaches and deposited in other beaches (profiles 2, 6, 7, 11, and 12, Fig. 6), depending on the contouring conditions of the beaches, which are difficult to determine from a littoral that is apparently homogeneous.

During the 2-year studied period, the beaches reported a great variability and no one of them showed a clear tendency, being apparently stable. The profiles which presented significant variation were located close to human structures. Profiles 3 and 4, and 5 and 6, were located south and north of Marina Kabila port, and of a small groin, respectively, profile 9 was to the north of Marina Smir port.

The collected data cannot be strictly used to reconstruct beach evolution over the two monitored years because of two main reasons. First, they are too scattered in time, this way it is not possible to calculate a best-fit line (Dolan et al. 1991). Secondarily, it is not possible to approach them with the end point rate method proposed by Dolan et al. (1991). This latter, usually based on the comparison between the earliest and the latest dates, could be used to compare corresponding profiles (e.g., profiles related to summer or winter conditions), in low changing beach environments (Anfuso and Gracia 2005). Unfortunately, it was not the case for the studied beaches, which presented rapid and time located changes.

Coastal evolution at short- and medium-term

Data on the coastal evolution at short- and medium-term have been incorporated into a GIS project in conjunction with the distribution of natural and human coastal structures, in order to give a preliminary approximation to the sediment circulation patterns and, hence, to the coastal compartmentalization (i.e., littoral cells' distribution).

Concerning error in shoreline mapping, it is important to stress that the position of the shoreline mapped in the aerial photographs is related to two main problems: (1) the shoreline variations because of astronomical tide; (2) the daily, weekly, monthly and seasonal variations (erosion/accretion cycles) of the shoreline that in some cases may be larger than the annual and decadal variations measured on the aerial photographs (this represents the largest source of error, Smith and Zarillo 1990). Concerning tidal variations, as it was not always possible to determine tide conditions at the moment of the photo, the maximum and minimum foreshore widths (respectively, referred to spring and neap tide conditions), have been calculated using the surveyed topographic profiles. The foreshore width ranged from 2.5 m, in neap tide conditions, to 5.0 m, in spring tide conditions. Dealing with erosion/accretion shoreline variations, the maximum shoreline variation recorded during the studied period at mean sea level position was 5.0 m, and the minimum shoreline variation was 2.1 m. From the previous data a mean value of 3.66 m has been obtained and considered representative for the tide and erosion/accretion shoreline movements. In this way, shoreline variations obtained with the use of aerial photographs lower then 3.66 m were not considered as significant. The aforementioned value was much smaller than the shoreline variations measured on the aerial photographs. This is because the studied beaches show few morphological changes and they present an important slope, which minimizes the effects of tidal variations (Smith and Zarillo 1990). Lastly, considering the magnitude of the studied intervals (i.e., 8 and 17 years), coastline variations lower than ± 0.40 and ± 0.21 m/year were not considered as representative, respectively, for the short- and the medium-term trends and were not represented in Fig. 8. Linear values (m/year) of erosion/accretion are represented for the short-term periods and beach surface variations (m^2) for the medium-term period (Fig. 8).

Concerning the first studied short-term time frame (1986–1994, Fig. 8), important erosion was observed along the littoral, accretion only being recorded along two small coastal sectors, i.e., at Bahia Smir and at Restinga areas. In the former zone exists a free, pulse limit and in the latter, a fixed, pulse limit, constituted by the rocky shore platform. The Marina Smir and Marina Kabila ports had an affect the littoral drift as soon as they were built but no evidence of this is noted on the 1994 coastline trend, probably because the construction of the ports is quite recent, the former being finished in 1989 and the latter in 1991.

In the following short-term time frame (1994–2003, Fig. 8), erosion processes predominated again along most of the littoral. Accretion was observed close to Almina area, because of the existence of a free, pulse limit, and close to Marina Smir and Marina Kabila ports. The ports' structures actuated as fixed, pulse limits because of their forms and orientations: Marina Smir port constituted an impermeable obstacle to the northward directed transport, producing accretion south of the structure and erosion in the northern side. The opposite situation was observed in correspondence to Marina Kabila port.

The sediments accumulated close to the ports, were not removed by the littoral transport, which produced

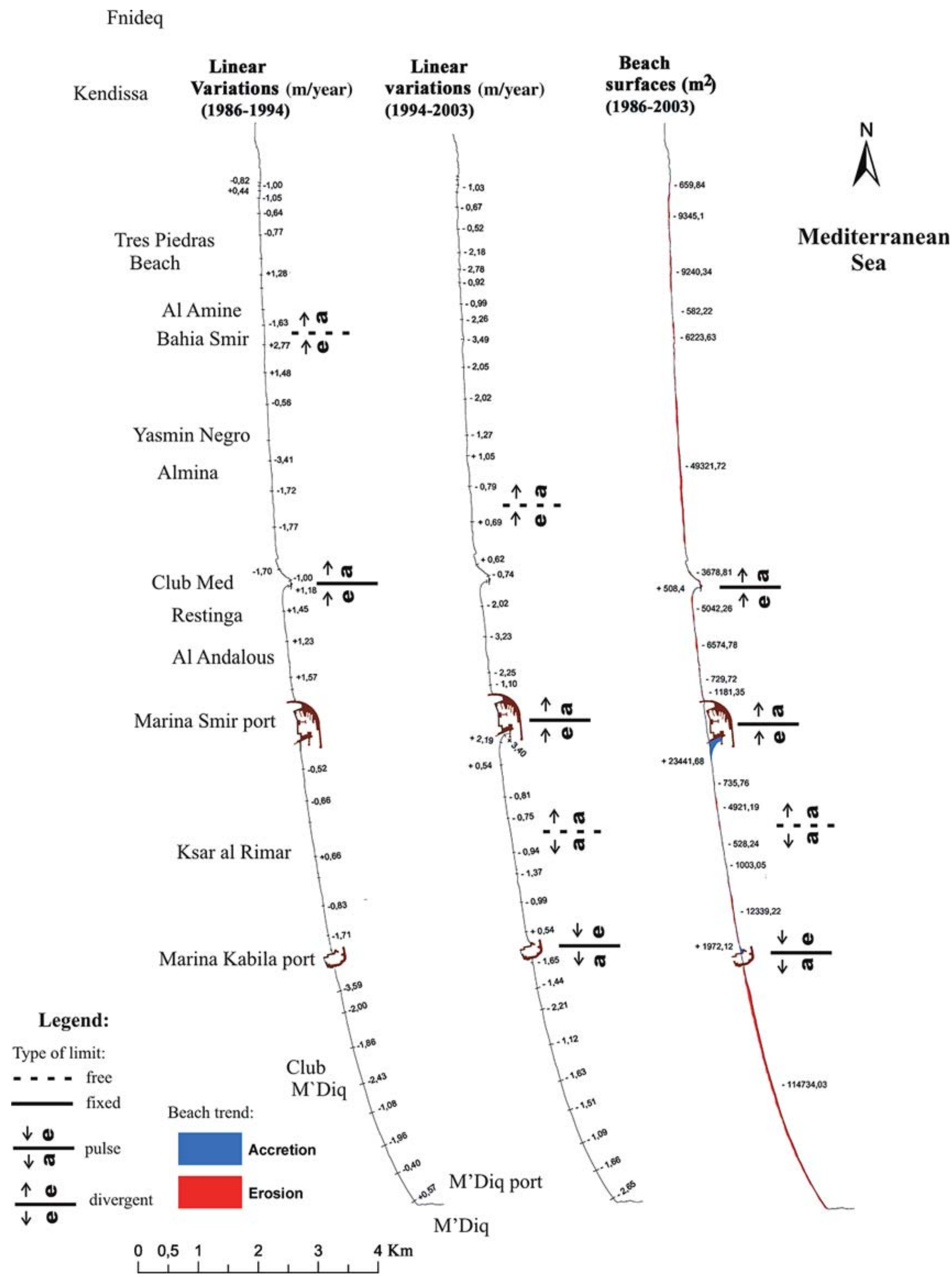

Fig. 8 Short- and medium-term coastal evolution of the studied littoral

progressive erosion in the central zone. This zone was characterized by the existence of a free, divergent limit that changed its position according to wave height and the specific wave approaching direction.

Concerning the beach surfaces evolution for the medium-term time frame (the 1986–2003 period, Fig. 8), general, important retreat has been observed especially in the southern part of the studied littoral and secondarily at Almina area.

It is probably because the beaches located on the southern part of the littoral are more exposed to the easterly and northeasterly waves than ones located in the northern part of the littoral, according to field observations of February 2004. The northerly beaches are likely to be partially protected by the Ceuta headland and by a rocky platform located in the submerged zone. Further studies are needed to reconstruct the submerged morphology, which also controls the formation of free limits.

Dealing with cell distribution for the medium-term period, it was quite close to the one previously described. Differences can be observed at Restinga, where small accretion was recorded southward of the rocky shore platform, which constituted a fixed, pulse limit. It is important to highlight the good correspondence between beach morphology and the existence of the aforementioned fixed limits, following to Carter (1988). Beach profiles located south of Marina Smir port and Restinga rocky shore platform, and north of Marina Kabila port, i.e., in the accretion (updrift) areas, respectively, P.8, P.11, and P.4, presented bigger slopes than the profiles located in the erosion (downdrift) areas, respectively, P.9, P.12, and P.3.

On taking into account the distribution of the erosion/accretion areas, it is possible to identify in either qualitative or quantitative terms, the transport pathways (Cooper and Pethick 2005), which in the studied area are closely related to the existence of cell limits, i.e., essentially natural and human structures. The influence of a limit on the longshore transport is evidently mostly controlled by the form and dimensions of the limit. In the studied littoral, waves from the S and SE generate a northward directed transport which interacts with natural and human structures producing accumulation to the south of Marina Smir port and Restinga rocky shore platform. A small amount of accumulation to the north of Marina Smir port is related to the interaction between an opposite transport associated with waves approaching from the N and NE, and the port structure.

Considerations for coastal erosion management

The results of the present study show that beach profiling and aerial images analyzed by means of GIS, can be used as very useful and appropriate tools for the detection of beach morphodynamic behavior and shoreline changes over the studied time scales, and the impacts of human structures.

In fact, the applied methodology allowed the quantification of the main erosion/accretion areas, and the characterization of coastal compartmentalization and sedimentary transport. This information is indispensable to define effective and efficient protection methods (Komar and McDougal 1998), according to the natural beach behavior and sediment transport pathways (Healy et al. 2002).

At seasonal and annual time scales, the littoral was more or less stable. In this way, human constructions are not actually affected by significant erosive problems, being only reached by storm waves few days per year (Fig. 9).

At short- and medium-term, the littoral recorded an important erosive trend. It is possible to state that in a few years most human structures will be severely threatened by coastal retreat processes.

The observed, negative sedimentary budget is linked to the transport of sediment out of the studied area as well as to the decrease of rivers' sediment supplies and dune's sediment availability.

Fig. 9 Beach erosion at different locations because of a storm approaching from the East, which affected the littoral from 23 to 27 of May 2006. At M'Diq, wave erosion affects the deposits, accumulated in the dry beach, related to construction of a promenade and an hotel on the dune ridges (**a**); swash processes north of Marina Kabila port arrive at the base of a building under construction (**b**), undermine a wall limiting an urbanized zone (**c**) and reach a zone where dunes have been removed because of building purposes (**d**)

Dealing with the sediment transport, at short- and medium-term, offshore transport prevails on longshore one, which achieves a certain importance only in the sector between Marina Smir and Marina Kabila ports. This coastal sector shows the formation of about 24,000 m^2 of beach surface south of Marina Smir port and it is the only one which presents a positive budget corresponding to an accretion of beach surface of around 6,000 m^2 (this value was obtained by summing erosion and accretion areas). The sediment accumulated south of the Marina Smir port gave rise to a wide dry beach area, whereas only a narrow strip, close to the shoreline, is used for bathing purposes. According to this, beach surface area could be reduced of about 15,000 m^2 (Fig. 10) and the remaining 50 m wide beach would be enough for local tourist purposes. Dredged sediments may be used to nourish the erosive, central part of this sector.

Probably, massive nourishment works should be carried out in a near future in the zones, which record the more significant erosion rates, i.e., the zone between Marina Kabila and M'Diq ports and at Yasmin Negro and Almina areas. In this case the information gathered through the monitoring program will be very useful to properly design the nourishment works, i.e., the artificial beach profile, the volumes to fill and grain size characteristics (Fucella and Dolan 1996; Anfuso and Gracia 2005).

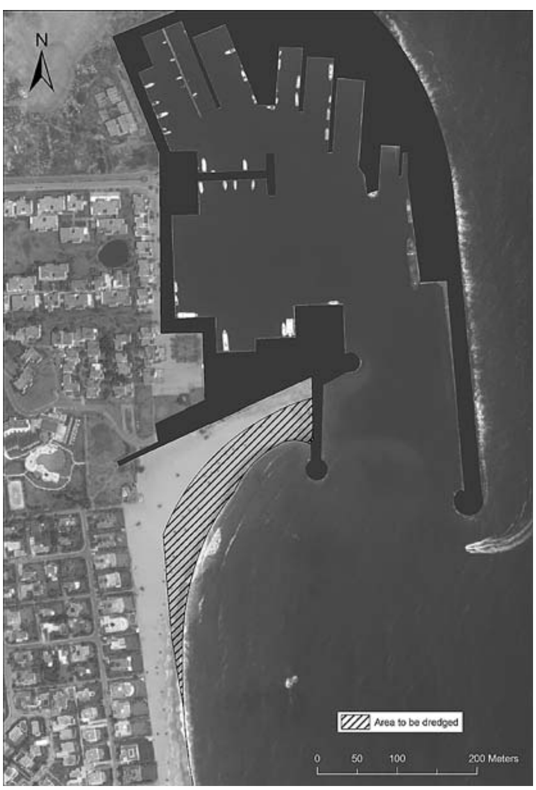

Fig. 10 Proposed actuations at Marina Smir port

Concerning rivers' supplies, it is important to highlight that important volumes of sediments have been retained over recent years by dams and reservoirs. At present the most important dam, on the Smir River, is totally filled up.

Lastly, concerning dunes' sediments, it is important to note that nowadays they are totally excluded to the littoral budget because dunes are deeply urbanized or in process of urbanization (Fig. 9). This is because the great urban chaos related to the present Coastal Act that predicts a very narrow respect zone including the seashore and a coastal belt extended 6 m landward from the maximum limit, which the water reaches. Actually, a new Coastal Act, which predicts a 100 m wide respect zone, has been waiting to be approved since 1996. Unfortunately, the approbation of the aforementioned law was delayed several times and it will arrive too late in the studied zone, which is almost completely urbanized.

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