

Seasonal changes and morphodynamic behavior of a high-energy mesotidal beach: case study of Charf el Akab beach on the North Atlantic coast of Morocco

Mohammed Taaouati · Driss Nachite ·
Javier Benavente · Abdelmounim Elmrini

Received: 25 June 2009 / Accepted: 18 January 2011 / Published online: 4 February 2011
© Springer-Verlag 2011

Abstract The morphodynamic behavior of a mesotidal sandy beach was monitored during both calm and energetic conditions. Two years of seasonal surveys were carried out on Charf el Akab, a gently sloped beach in the North Atlantic coast of Morocco. The method of survey consisted of a 3D study of the beach morphological changes and provided 2 cm vertical accuracy. During the surveyed period, Charf el Akab beach underwent very energetic wave conditions, and the breaking wave height was of $H_b \geq 1.5$ m. The beach is characterized by a nonpermanent swash bar and composed of well-sorted medium sand. The application of environmental parameters revealed a dissipative state with very low beach gradient which did not vary significantly over the studied period. Morphological changes consist of beach erosion and bar decay under high-energy waves, whereas the intertidal bar re-established and the beach recorded an accentuated accretion due to relatively fair weather conditions. The beach volume reveals a seasonal behavior; the sand accumulated during summer is dramatically removed during winter season. The range in beach sand volume from the most accreted to the most eroded conditions observed is about $-5,493$ m³. The average sand volume flux between surveys reaches -1 and 0.4 m²/day during peak erosion and accretion periods. The relationships between the wave forcing and the sand volume adjustments were examined. The sand volume change was found to be highly correlated (0.91) with the

wave energy flux. The highest correspondence (0.95) was found between the sand flux rate and the wave energy flux. The wave forcing is expected to be the main factor governing beach morphodynamics at Charf el Akab site.

Keywords Moroccan coast · Beach morphology · Seasonal change · High wave energy · Net beach change

Introduction

The dynamic interaction between environmental forcing and coastal morphology occurs over a wide range of time and space scales (e.g. Larson and Kraus 1995; Ruggiero et al. 2005). Changes to which beaches are subjected may be seasonal or longer in duration; they may be weekly, daily or as short as a single tidal cycle or even occur from one crashing wave to the next (Davis 1985). Morphological changes are surveyed using a wide variety of methods and data sets according to the study time intervals (Crowell et al. 1993; Larson and Kraus 1995; Anfuso et al. 2007). On a seasonal time scale, studies on shoreline dynamics are usually carried out at small spatial scale, from meters to a kilometer (Larson and Kraus 1995). The most common technique used is beach topographic profiling or 3D surveying (Anfuso et al. 2007), which is the case of the present work. The technique is repeated at regular intervals, in order to measure daily to annual variations in shoreline position and beach volume (e.g. Carter 1988; Komar 1998; Short 1999).

In fact, beach evolution can be related to various processes such as wave properties (wave height and wave period), sediment availability and characteristics, tidal variations, beach morphology (average beach slope), and coastal configuration. Many attempts have been made to

M. Taaouati (✉) · D. Nachite · A. Elmrini
Department of Geology, Faculty of Sciences,
Abdelmalek Essaâdi University,
BP 2121-93002 Tétouan, Morocco
e-mail: mtaaouati@gmail.com

J. Benavente
Department of Geology, Faculty of Marine Sciences,
University of Cadiz, 11510 Puerto Real, Cadiz, Spain

correlate beach morphology and environmental forcing. In this way, several conceptual models and classifications have been proposed to investigate the beach profile evolution as a function of wave and sediment parameters (Short 1979; Wright and Short 1984). Short (1991) and Masselink and Short (1993) introduced the tidal range as a discriminating parameter. Moreover, the beach itself exhibits a distinct cyclic response to the seasons, individual storms, tidal cycles, and even to higher frequency forcing (Greenwood et al. 2004).

Among the different types of beaches existing in the coastal zones, the sandy ones are the most widely studied. In the literature, microtidal and secondarily macrotidal environments received more attention when studying beach morphodynamics. However, high-energy mesotidal beaches remain the least studied and have scarcely received mention in few recent works (e.g. Brander and Short 2000; Haxel and Holman 2004).

In this paper, morphological changes were examined at Charf el Akab, a high wave energy beach on the north Atlantic coast of Morocco. It is an interesting sector showing a progressive increase in human activities during the past few years, and well-known for energetic events during the winter months (Duplantier and Lesueur 1983; Cirac et al. 1989), especially the ones that approach the coast from west-northwest direction. Not surprisingly, the impact of these high energetic events on the flat sandy beaches in the region is considerable.

The main aim of this work was to investigate if quantitative measures of beach changes can be related to the wave forcing for a high-energy mesotidal beach such as Charf el Akab. Beach changes were investigated by using a 3D topographic monitoring program over a period of 2 years. The obtained data were very useful to describe the beach morphodynamic behavior at seasonal time scale.

In this article, different data and methods designed to evaluate the beach morphodynamics will be described. Afterwards, the dominant pattern of erosion and accretion and the different quantitative measures of the beach such as net volume and sand fluxes will be examined. Finally, the relationship between the wave forcing and the beach change will be determined by using the net sand volume and sand flux rates obtained from consecutive survey maps. A significant statistical relationship was found between the wave energy flux and the beach change. The wave forcing was considered therefore as a discriminating factor in the morphodynamic evolution of the studied beach.

Field site description

The studied beach is located on the Moroccan north Atlantic coast between Spartel Cape and Tahaddart sandy

spit (Fig. 1). The coastline, NNE–SSW aligned, is dominated by long and wide sandy beaches, such as Charf el Akab, Sidi Kacem and Haouara (Fig. 1); it is characterized by vegetated dunes which protect tidal marsh. Last, the coastal zone between Spartel Cape and Tahaddart is drained by rivers (Tahaddart, Mharhar, Boukhalef, etc.) which carry terrigenous sediments towards the continental shelf (Duplantier and Lesueur 1983).

Growing human pressure negatively influences the coast evolution and breaks the dynamic equilibrium of the coastline causing an increase in erosion of beaches. Aerial photographs indicate that the coastline of this littoral sector has retreated by approximately 70 m between 1985 and 1992 (D. Nachite, personal communication), presumably due in part to sand extraction and dam construction (Lahlou 2004).

Charf el Akab is an approximately 2-km long and 200-m wide beach where Quaternary calcarenites outcrops are present in the backbeach. It is backed by vegetated dunes that are few meters high and some decameters wide (Fig. 2a). In fact, vegetated dunes can be observed along this coastal zone between Spartel Cape and Tahaddart spit except of some few sectors such as Tahaddart spit characterized by not-vegetated dunes. Sediments consist of fine to medium well-sorted sands. Mean grain sizes in the foreshore and backshore zones are 0.266 and 0.2 mm, respectively. The beach is characterized by many surficial structures formed by wind, tide and wave processes. On the backbeach area, these features are formed primarily by the wind, particularly when a well-developed berm is present. Sand shadows (Davis 1985) are usually found on the backshore of Charf el Akab beach, especially when strong offshore winds prevail in the studied area. They are associated with pebbles, shells and considerable heavy minerals fractions. The foreshore zone exhibits a wide variety of surficial features such as swash marks, antidunes, ripples, etc. The most usual are the rill marks which are formed by water drainage in the rip channels. During the surveyed period, the beach exhibited one intertidal straight bar with a well-defined landward-facing slip-face (Wijnberg and Kroon 2002). The bar is backed by a landward runnel and dissected by one or more rip channels (Fig. 2b). The water in the depressed area eventually flows back to sea through the rip channels. This intertidal bar may include the Group II bars defined by Greenwood and Davidson-Arnott (1979), which were named “swash bars” by Carter (1988). Wijnberg and Kroon (2002) abandoned this terminology and used the term, “slip-face ridges”.

The beach is exposed predominantly to wind waves generated by west to northwesterly winds, and the wave height can reach 7–9 m during large storm events (Jaaidi and Cirac 1987). Significant wave height (H_s) for this experiment ranged from 0.8 to 3.4 m (Fig. 3a). The tides are semi-diurnal and can be classified as mesotidal with a maximum tide range of about 3 m. During the measurements period, the

Fig. 1 Location map of the study site, showing the continental shelf morphology. Depth contours are almost parallel to the coastline and are constantly spaced. The offshore WANA node location is also indicated

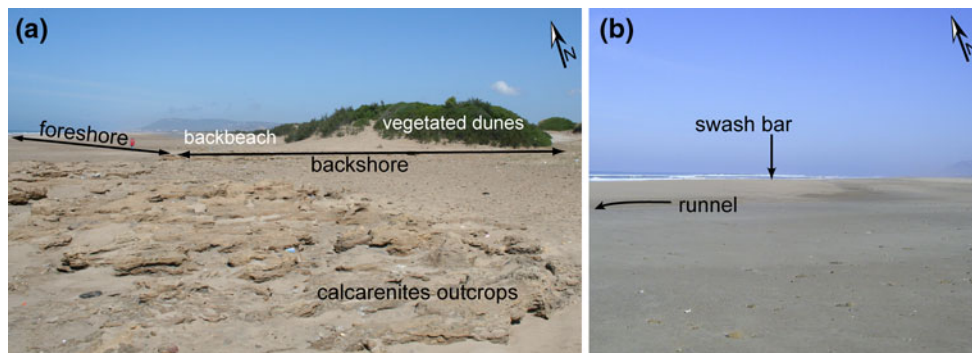
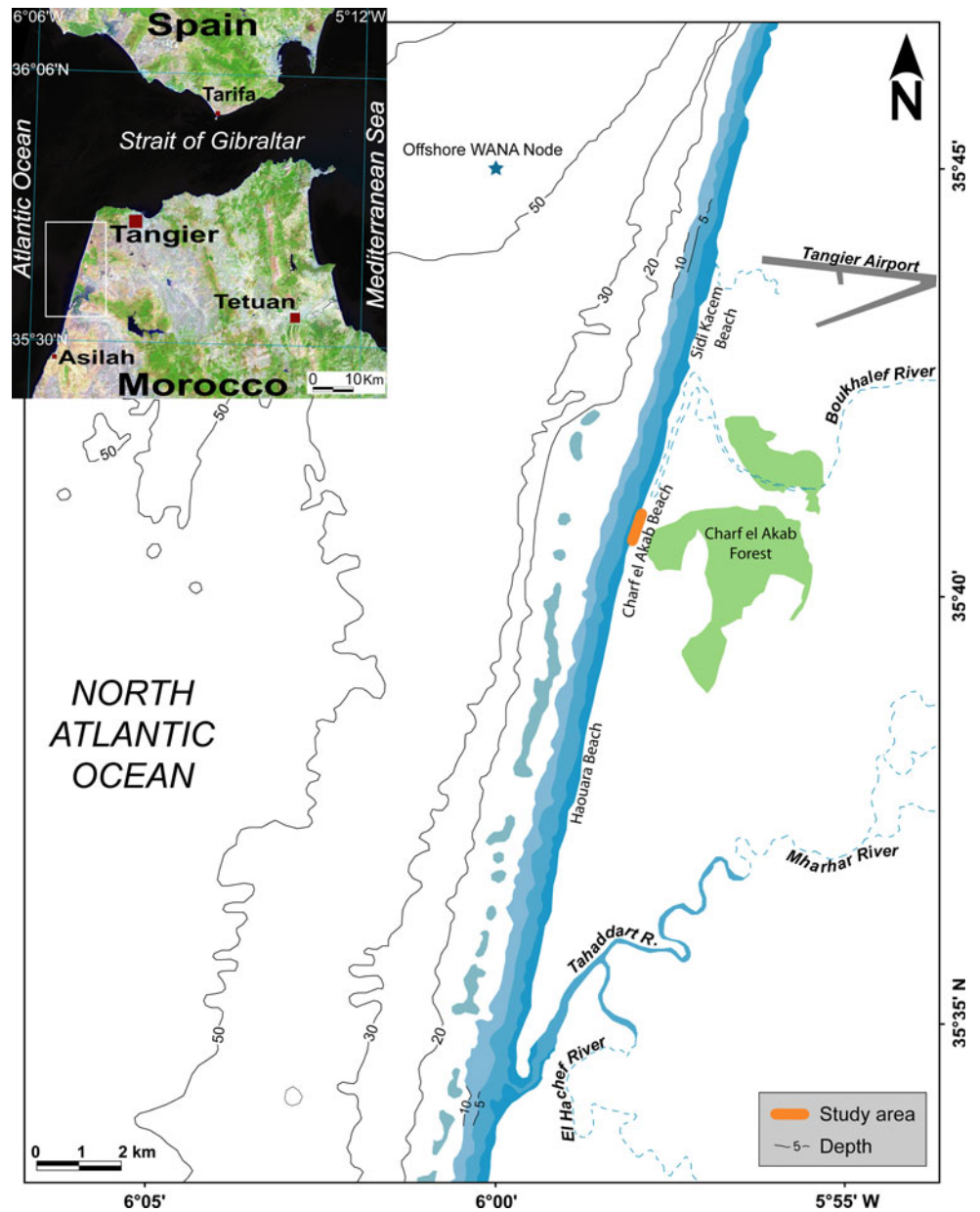
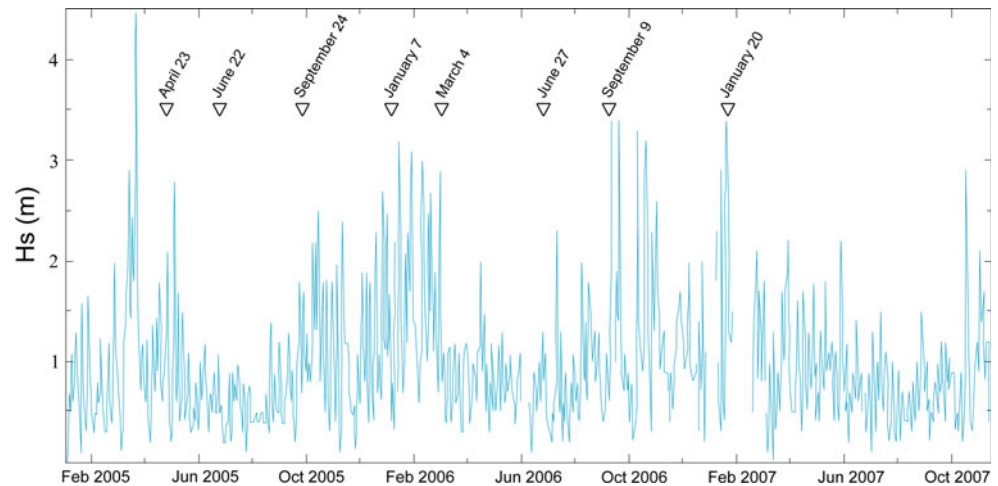


Fig. 2 Ground photographs of the studied coastal zone with **a** beach morphology of Charf el Akab and **b** swash bar and runnel morphology

Fig. 3 Significant wave height distribution during the study period. Temporal locations of the beach surveys carried out within this work are marked by triangles



beach had an intertidal slope ranging from 0.016 to 0.021. Ratio between tidal range and intertidal slope is in the order of 140–190 m, which provides a large horizontal translation of the shoreline during tidal cycles.

Data and methodology

Wave data

Wave data were collected from an offshore node (35°45'N, 6°W) (Fig. 1) which belongs to the Spanish prediction system “WANA” (Ministry of Public Works). They are output data and do not come from direct measurements. However, those data are useful and reliable in order to have a morphodynamic characterization of the studied beach at seasonal time scale. Deep water wave height H_0 is used to estimate the breaking wave height H_b , which depends on the subtidal zone morphology and its variation alongshore (Larson and Kraus 1994). In fact, applying H_b/H_0 conversion requires homogeneous shoreface slopes with little or no longitudinal variations (Benavente et al. 2000). Since the subtidal zone exhibits a broadly constant slope along Charf el Akab beach (Fig. 1), the breaking wave height has been calculated by using the approximation proposed by Komar and Gaughan (1972), which is expressed as

$$H_b = 0.39 g^{0.2} (TH_0^2)^{0.4}$$

where H_b is the breaking wave height, g is the gravitational constant, T is the wave period and H_0 is the wave height in deep water.

Three-dimensional beach surveys and sediments sampling

In order to characterize beach morphology, eight field experiments were conducted at either two-monthly or

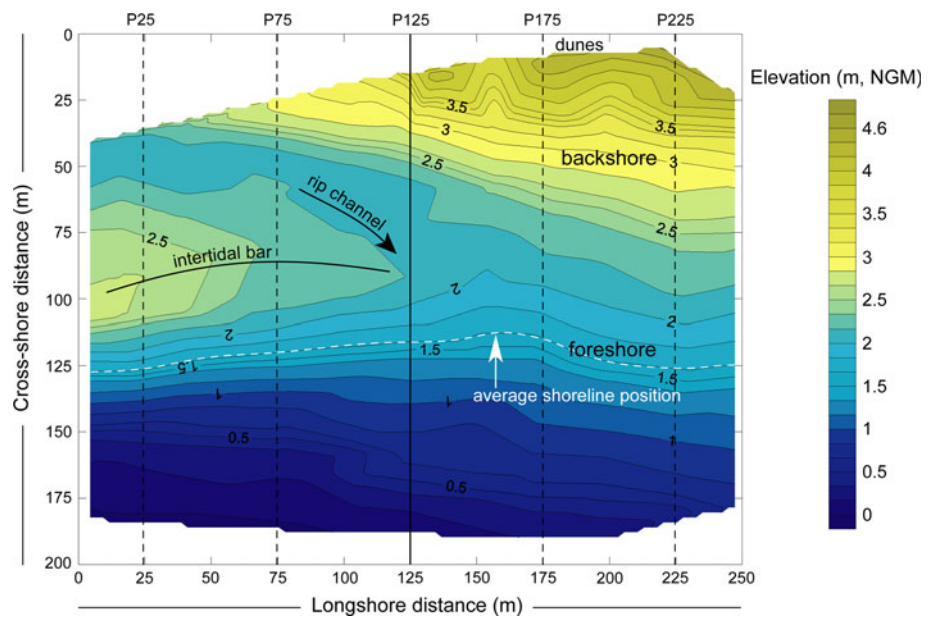
seasonal intervals from April 2005 to January 2007 (Fig. 3), using a total station (TOPCON GTS-225). Beach surveys were made at low tide and consisted of 3D topographic profiles, which started in the edge of the dune at a permanent benchmark and extended to the seaward limit. The long-shore and cross-shore distances of the area covered by the topographic surveys were of approximately 250 and 200 m, respectively. Altimetry precision was estimated from the measurements of topographic points located on fixed terminals established on the backshore. Vertical and horizontal accuracy were estimated to be within 2 and 5 cm, respectively. Elevation data are relative to the Moroccan General Leveling (NGM). Digital elevation models and contour maps were elaborated from the topographic data using a terrain modeling program.

The beach map for January 07, 2006 illustrates the nature of the surveys (Fig. 4). Morphological beach change is assessed by studying the evolution of a transversal profile (2D) located at the middle of the studied area (Fig. 4). This central profile is regarded as representative of the overall evolution of the beach at seasonal time scale, although longitudinal morphological changes can affect locally the beach topography. In order to characterize cross-shore and longshore variations in the beach slope, five profiles were made across the foreshore zone, from 40 to 200 m cross-shore distance, with 50-m intervals (Fig. 4).

In addition to beach profiles, the total sand volume was calculated to provide an indicator of net beach erosion and accretion. In order to estimate sand transport between sequential surveys, the difference in sand volume between surveys divided by the time between surveys and the longshore distance of the beach was calculated to obtain a sand flux in m^2/day . These changes are considered to be primarily associated with cross-shore transport.

Two sediment samplings were carried out during the summer and the winter of 2006. Each of them consisted of three transversals, and five sediment samples gathered

Fig. 4 Beach topography map from January 7, 2006 beach survey. Elevation is in meters relative to the Moroccan General Leveling (NGM). The shoreline is defined as the position of the average mid-tide level, and beach features (*bar*, *runnel*) encountered during this survey are also shown on the map



throughout each transversal in the foreshore, backshore and dune. These were dried and sieved in the laboratory through 11 sieves, with 0.5 phi intervals. Graphics were elaborated and statistical parameters (mean, sorting, skewness and kurtosis) were calculated according to the Folk and Ward (1957) method.

Environmental parameters

Most studies dealing with beach morphodynamics use different parameters which provide a prediction of beach characteristics (e.g. beach state, bar occurrence, bar type). Two environmental parameters, based on wave height, period and steepness and beach slope, were employed in order to characterize the studied beach.

The breaker type was estimated by the surf similarity index (Galvin 1968; Battjes 1974), defined as

$$\zeta_b = \frac{\tan \beta}{(H_b/L_0)^{0.5}}$$

where $\tan \beta$ is the beach slope and L_0 is the wave length ($L_0 = gT^2/2\pi$). On a uniformly sloping beach, breaker type is estimated by spilling ($\zeta_b < 0.4$), plunging ($0.4 < \zeta_b < 2$) and surging ($\zeta_b > 2$) (Galvin 1968; Battjes 1974).

The morphodynamic state was determined through the surf scaling parameter (Guza and Inman 1975):

$$\varepsilon = \frac{H_b \sigma^2}{2g \tan^2 \beta}$$

where σ is the radian frequency ($\sigma = 2\pi/T$). This parameter is used to predict beach state and to distinguish

between reflective ($\varepsilon < 2.5$), intermediate ($2.5 < \varepsilon < 30$) and dissipative ($\varepsilon > 30$) beach states (Wright and Short 1984).

A widely used parameter is the dimensionless fall velocity (Ω) proposed by Gourlay (1968) and Dean (1973), which provides a prediction for beach state based on the breaking wave height and the sediment size (Wright and Short 1984), and is expressed as

$$\Omega = \frac{H_b}{w_s T}$$

where w_s is the sediment fall velocity. Previous studies had used this parameter to predict the beach state (Wright and Short 1984; Masselink and Short 1993; Short and Aagaard 1993) and the occurrence of bar morphology which provides a distinction between barred and non-barred beaches (Dean 1973; Wright and Short 1984; Allen 1985; Sunamura 1989; among others). According to the Wright and Short (1984) model, the dimensionless fall velocity can be applied to differentiate between non-barred, reflective beaches ($\Omega < 1.5$), single-barred, intermediate beaches ($1.5 < \Omega < 5.5$) and multi-barred, dissipative beaches ($\Omega > 5.5$). Masselink and Short (1993) proposed a classification of beaches based on the dimensionless fall velocity and the relative tide range (RTR) (Davis and Hayes 1984). The latter index is expressed as the ratio between mean spring tidal range (MSR) and breaking wave height:

$$RTR = \frac{MSR}{H_b}$$

Hence, since Charf el Akab is a high-energy tidal beach where wave and tide act together on its morphology, the

model of Masselink and Short (1993) can be a good predictor the studied beach state.

A significant environmental parameter is the wave energy flux which is a good predictor of beach erosion and accretion. This parameter, called “wave power (P)”, is used to assess the effect of the incident energy level on beach morphology and indicate accreting and erosive conditions in the studied beach. Assuming linear theory holds, the average energy flux is expressed as (USACE 2008)

$$P = \frac{\rho g^2 H^2 T}{32\pi}$$

with, ρ is the sea water density $1,025 \text{ kg/m}^3$) and H is the offshore wave height.

Results and discussion

Wave data analysis

Wave data from the offshore WANA node indicate general high-energy conditions (Fig. 3). The highest waves are related to westerly storm winds, which commonly act in winter months. During the studied period, high-energy events occur mainly in the months of January, February and March and secondarily, in October, November and December (Fig. 3). During the 2005–2006 winter season, at least six events occurred with over 2.5 m breaking wave heights. On the whole, maximum offshore wave height reached 4.5 m.

Figure 5 illustrates the offshore wave conditions (H_0 , T). Roses show a direction of incidence from NW to WSW, with a notable predominance of the waves approaching mainly from the WNW sector (50–60%) and secondarily from W direction with a frequency of about 20–25%, whereas waves coming from NW and WSW directions remain less frequent with almost 5% each one. As shown in Fig. 5, both wave heights lower than 0.5 m and higher than 2 m are less frequent (<20%) while wave heights ranging from 0.5 to 2 m are observed in more than 60% of the total. The most frequent wave periods are ranging from 4 to 12 s (>60%), whereas those of more than 12 s and less than 4 s are the less frequent ones, recording a small percentage of about 20%.

There are no commonly accepted thresholds which delineate “high” from “low” energy conditions (Brander and Short 2000). In order to define high-energy coast, Eliot (1973) and Short (1986) used a breaking wave height (H_b) of >1.5 and >2.5 m, respectively. During the surveyed period, the average breaker height at Charf el Akab beach was approximately of 2.7 m; this way, the studied site can be considered as a high-energy environment.

Beach morphodynamics and behavior

Granulometric analyses reveal small differences in sediment size and sorting between winter and summer, and sediments correspond to well-sorted medium sands. Thus, the mean sediment size D_{50} was considered as a constant, with $D_{50} = 0.25 \text{ mm}$. This value was used in the calculation of the sediment fall velocity w_s , which depends mainly on the grain size (Gibbs et al. 1971), and the obtained value was $w_s = 0.055 \text{ m/s}$. During the studied period, slight changes in beach gradient were observed. The beach was gently sloped and the average beach gradient was $\tan \beta = 0.019$ (Table 1).

In order to define the observed morphological states from a quantitative point of view, the surf similarity index ξ_0 , the Dean number Ω and the surf scaling parameter ε were calculated for each survey. Mean value of these parameters was also estimated and the results are summarized in Table 1. During the surveyed period, the surf similarity index showed more or less constant values, corresponding to spilling breakers under both calm and energetic conditions, in accordance with field observations. As for the surf scaling parameter, high values were obtained, in accordance with the lower slope values, indicating dissipative conditions in Charf el Akab beach during all surveys. Based on Masselink and Short (1993) model, Charf el Akab is expected to be a barred dissipative beach. In addition to the environmental parameters, the dissipative state of Charf el Akab beach is confirmed by both lower slope values and visual field observations during the surveys.

Despite the extremely energetic conditions, the gently sloped beach did not change markedly (Fig. 6). In high-energy environments, beaches tend to be in equilibrium with the extremely energetic conditions by maintaining a low constant beach gradient which allows the dissipation of the incident energy. In his study on western Ireland coast, Cooper et al. (2004) argued that beaches subject to modally high-energy regimes require extreme storms to cause significant morphological impact. This dissipative trend was announced by Aagaard et al. (2005), who had noticed that in spite of the extremely energetic wave conditions, the relatively gentle slope of Egmond beach (Netherlands) did not change significantly. Therefore, the beach slope will not be used as an indicator of beach changes at Charf el Akab site.

Accretion/erosion events

The evolution of the beach profile is illustrated in Fig. 7, showing the significant change in beach morphology related to the accretion and decay of an intertidal bar due to the variations in the incident wave energy. The beach profile

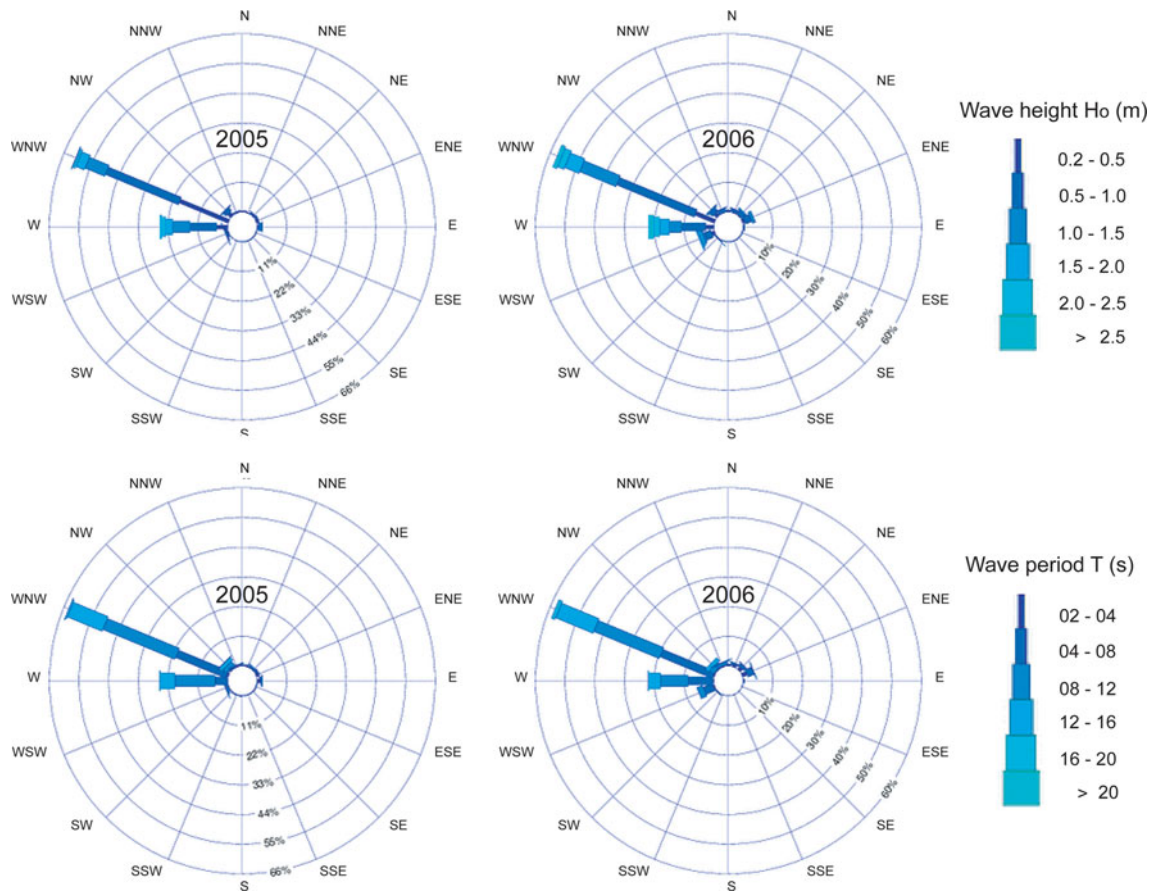


Fig. 5 Roses of the deep water wave height and period during the 2-year survey period

Table 1 Beach environmental parameters

Date	H_b (m)	$\tan \beta$	ζ_b	ε	Ω	RTR
23/04/2005	2.78	0.02	0.2	77.8	3.77	0.82
22/06/2005	1.84	0.02	0.14	113.74	5.09	0.72
24/09/2005	1.68	0.017	0.1	294.41	4.85	1.30
07/01/2006	3.5	0.019	0.16	128.82	5.17	0.66
04/03/2006	4.55	0.019	0.16	120.5	5.7	0.57
27/06/2006	1.48	0.018	0.1	326.88	5.08	1.30
09/09/2006	2.27	0.016	0.09	421.87	6.35	1.04
20/01/2007	2.87	0.021	0.12	232.56	6.96	0.77
Mean	2.72	0.019	0.13	214.6	5.4	0.9
Breaker type	–	–	Spilling	–	–	–
Beach state	–	–	–	Dissipative	Barred	dissipative

recorded an accentuated accretion in summer 2005 because of the fair weather conditions prevailing during this season (Fig. 3), resulting in formation and growth of an intertidal bar. This bar reached the maximum height and width in September 2005. In January 2006, the lower beach underwent important erosion, whereas the upper beach recorded an accretion producing a well-developed berm.

This configuration, which can be called the accretion profile, was altered during high-energy conditions, which prevail usually from January to March, to an erosion profile with a planar configuration with no intertidal features. Following large wave events, the bar began to re-built, during summer 2006, and migrated to the upper beach to form a well-developed berm encountered in January 2007 survey. It is interesting to state that the intertidal bar was less pronounced in the summer of 2006 as compared with summer 2005. This is mainly due to the prevalence of relatively high-energy conditions in the months before the June survey, and even during the summer of 2006 (Fig. 3).

Net beach change

In order to illustrate morphological changes and a typical cycle of erosion and accretion of the beach, four contour maps (Fig. 8) were made for the studied period, producing surfaces indicating net accretion (positive values) and net erosion (negative values). The difference between sequential surveys showed two contrasting morphodynamic phases. The accretion phase happened during the summer season due to the prevalence of relatively calm

Fig. 6 Temporal variation of the beach slope values during the studied period

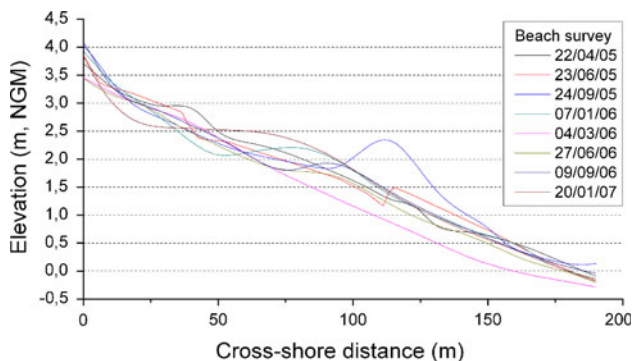
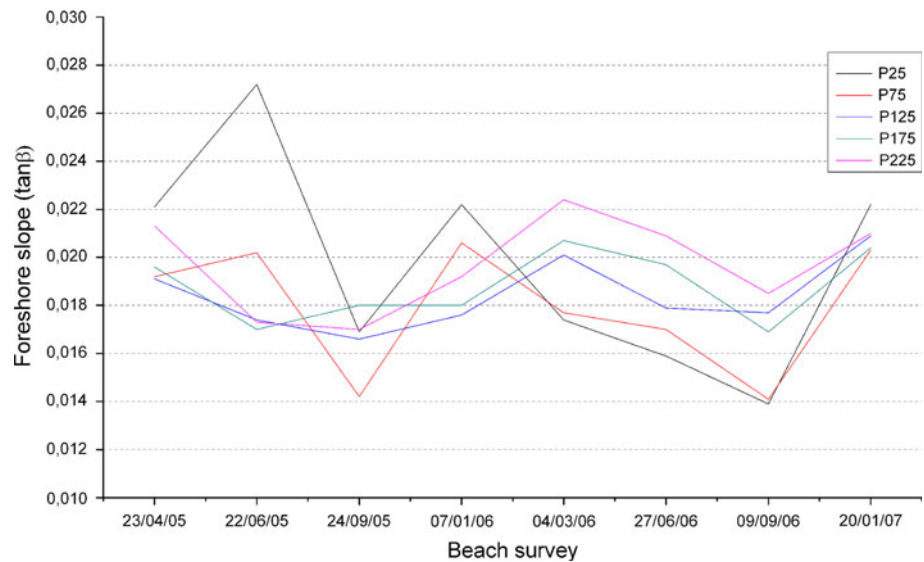


Fig. 7 Average beach profiles evolution during the study period. The profiles show the maximum accreted conditions (from June 23 to September 24, 2005), and the maximum eroded conditions (from January 07 to March 04, 2006). Minimum variation occurred from April 22 to June 23, 2005, which can be considered as a recovery period

conditions, especially of the intertidal zone (Fig. 8a, c). The accretion consisted in a re-establishment of the bar which evolved in a well-developed berm; the backbeach underwent, however, high erosive conditions induced by eastern strong winds. This behavior was proved by visual field observations during the summer. The strong winds affected the backbeach by eroding and transporting dry sediments in the offshore direction. The erosion phase occurred during the winter months, when the high-energy events caused great erosion across the foreshore (Fig. 8b, d), especially in the intertidal zone, where the erosion coincided with bar destruction. The backbeach was filled in during the high-energy events indicating an onshore transport due to swash of the greatest waves.

Net sand volume and sand volume rate are showed in Table 2. Estimated error, around ± 0.02 m, on the surveys corresponded to an uncertainty of ± 808 m³ in the

computed volumes. The net sand volume adjustments revealed a seasonal signal in accordance with the wave forcing; the entire beach lost approximately 6,500–14,000 m³ of sediments during the winter season. On the other hand, during accreting conditions in summer, beach gained around 4,000–9,000 m³. Then, sand beach range volume from the most accreted to the most eroded conditions observed was about $-5,493$ m³, which indicated that high energetic events (e.g. January–March 2006) caused a dramatic erosion of the beach.

In order to show erosion and accretion rate, sand flux was estimated (Table 2). Maximum erosion and accretion fluxes were -1 and 0.4 m²/day, respectively. It is interesting to note that these differences were calculated between seasonal surveys; however, much higher instantaneous rates could be expected.

On the whole, both beach volume and sand flux were relatively small during the summer and large and highly variable during the winter. Therefore, Charf el Akab beach is expected to undergo significant erosion over the period of study.

A comparison between the beach change maps and the sand volume adjustments showed that greatest morphological and volumetric changes were strongly associated with the accretion and erosion of an intertidal bar. This result coincides with the findings of Masselink and Hegge (1995) who demonstrated that changes in Nine Mile Beach morphology, on the Australian coasts, were mainly associated with the formation and evolution of secondary morphological features, in particular, swash bars in the intertidal zone.

Seasonal beach change and hydrodynamic forcing

Because Charf el Akab beach presented a nearly constant slope during the period of investigation, beach volume

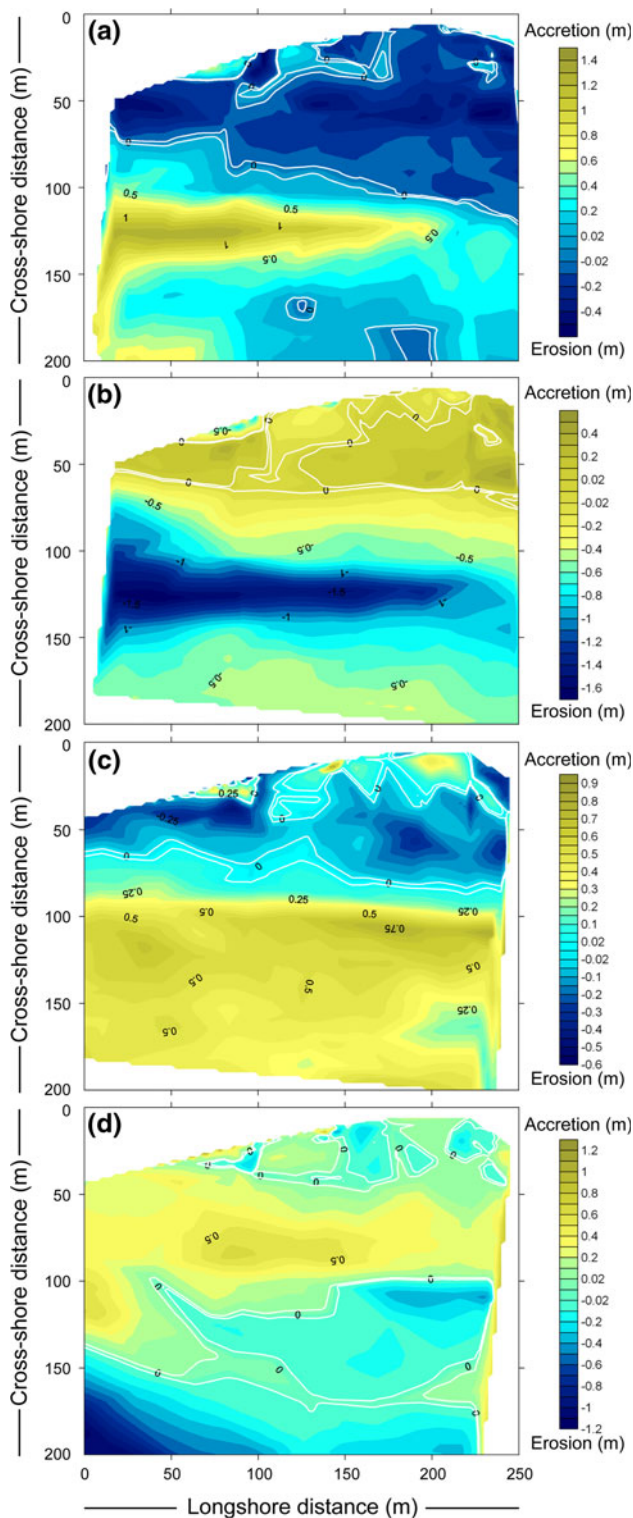


Fig. 8 Beach change maps for **a** 23/04/05 to 24/09/05, **b** 24/09/05 to 04/03/06, **c** 04/03/06 to 09/09/06 and **d** 09/09/06 to 20/01/07. High values (green) indicate accretion and low values (dark blue) indicate erosion. The area between white lines represents the -0.02 to 0.02 m elevation trench considered as a negligible variation

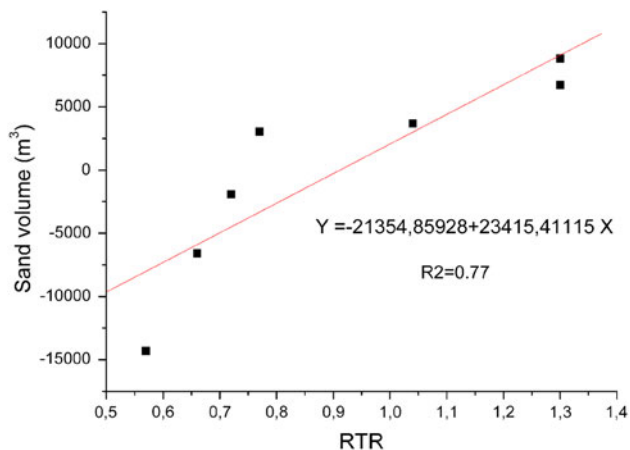
variations can be employed as an indicator of beach changes (Allen 1981; Carr et al. 1982; Thom and Hall 1991; among others). In this sense, relationships between sand volume and various morphodynamic parameters (Ω , ε , ζ_b and RTR) were evaluated, and a good correspondence (0.77) was obtained when considering RTR. Figure 9 shows the significant impact of the Relative Tide Range on beach volume resulting in sand accumulation for high values of RTR (low values of incident wave), whereas sand erosion coincides with low values of RTR. The tide range could have therefore an important effect on beach change at Charf el Akab. Many authors (e.g. Davis et al. 1972; Wright et al. 1982; Jago and Hardisty 1984; Masselink and Turner 1999) stated that water fluctuations govern the frequency, roughness and localization of various hydrodynamic processes (shoaling, swash) acting on beaches. It can be deduced that on Charf el Akab beach, high tide ranges tend to slow down the rates of beach changes.

The relationship between wave forcing and beach change was evaluated at Charf el Akab by comparing the sand volume and sand flux rate obtained from the surveys with the wave energy flux. The resulting curves appear in Fig. 10 with a linear relationship fitted to the data. Correlation coefficient between the beach volume and the wave energy flux was 0.91 (Fig. 10a), which revealed the good correspondence between the wave forcing and the beach volume in the monitored beach. This relation was stated by Dail et al. (2000), who found a correlation coefficient of 0.88 between the total beach volume and wave energy flux at Waimea Bay, Hawaii. The best correspondence was found between the sand fluxes and the wave energy flux with a significant coefficient of 0.95 (Fig. 10b). Graphs could be considered as morphodynamic equilibrium curves with two trends. First trend shows that an increase in the wave energy level produces a significant erosion (the beach loses important volume of sediment) and the sand flux would be towards offshore, which could be considered as the “erosive” profile. The second trend indicates that, when the energy tends to zero, the beach is increasingly accreted and the sediment moves onshore, which could be considered as the “accreted” profile. The high correspondence between the wave forcing and the beach change demonstrates that waves are the main factor governing beach morphodynamics at Charf el Akab site.

This result indicates that this beach is in critical equilibrium with the energetic conditions. Human activities, that introduce changes in this system, are responsible for the erosion trend.

Table 2 Sand volume adjustments and sand flux rates

Date	Accretion (m ³)	Erosion (m ³)	Sand volume change (m ³)	Sand flux rate (m ² /day)
23/04/2005	–	–	–	–
22/06/2005	4,320	6,228	–1,908	–0.13
24/09/2005	10,723	1,914	+8,809	+0.38
07/01/2006	1,936	8,529	–6,593	–0.26
04/03/2006	1,164	15,466	–14,302	–1.05
27/06/2006	7,498	752	+6,746	+0.24
09/09/2006	4,765	1,099	+3,666	+0.2
20/01/2007	5,395	2,375	+3,020	+0.1

**Fig. 9** Relationship between sand volume and Relative Tide Range

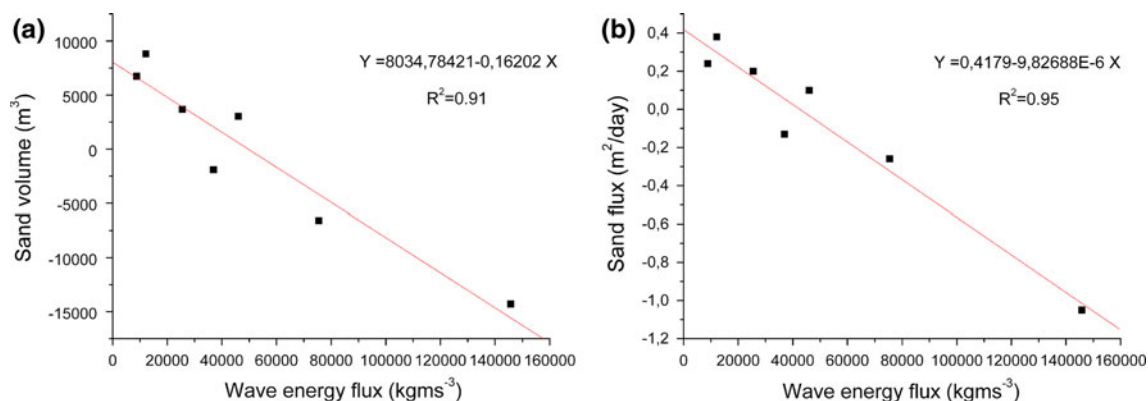
Conclusions

This study has shown that Charf el Akab is expected to be a single-barred dissipative beach. Morphological changes showed that Charf el Akab is a gently sloped beach that exhibits almost a cyclic evolution with two contrasting phases: the accretion phase during calm conditions (summer) and the erosion phase during high-energy events (winter).

Based on the changes in the sequential surveys, the net beach volume and the average sand flux are estimated to provide an indication of the rate of erosion and accretion. Range in beach sand volume between the most accreted and the most eroded conditions observed was approximately $-5,493 \text{ m}^3$. Sand volume flux estimation showed maximum erosion and accretion rates of -1 and $0.4 \text{ m}^2/\text{day}$, respectively. This indicates that Charf el Akab beach underwent significant erosion during the monitoring period.

Changes in beach morphology as well as sand volume were mainly induced by a formation/destruction cycle of an intertidal bar occurring essentially in the swash zone. In fact, quantifying and modeling swash zone processes is critical for understanding the morphodynamic beach behavior. Unfortunately, both the extremely energetic conditions and the difficulty of obtaining and maintaining sophisticated instruments over a long time on the swash and surf zones (required in this type of study) prevented us from carrying out such approach in this study.

The relationships between the net beach volume and the different environmental parameters were evaluated. A good correspondence was found between volume and RTR, which reveals that the tide fluctuation is a

**Fig. 10** Relationships between **a** sand volume and wave energy flux and **b** sand flux rate and wave energy flux with, ρ is the sea water density $1,025 \text{ kg/m}^3$ and H is the offshore wave height

significant variable that controls beach morphology at Charf el Akab site.

An examination of the beach volume and sand flux rates at Charf el Akab in relation with various wave forcing parameters revealed that net sand volume and sand fluxes were well correlated with the wave energy conditions. The best correspondence was found when considering the wave energy flux. Beach tended towards an “erosive” profile under high-energy level, whereas an “accreted” profile was developed during low-energy conditions. The beach is expected to be in equilibrium with the wave forcing but human activities interrupt this equilibrium resulting, therefore, in beach erosion.

Further studies must be made, like beach survey from neap to spring tide, in order to study tidal influence in bar development during fair weather conditions. In addition, a quantification of the long-term (annually to decadal) beach behavior at this site would be a valuable extension of the present study.

Acknowledgments This research was funded by the Moroccan PROTARS III D16/07 and the French-Moroccan AI MA/06/159 (Programme Volubilis). The principal author was sponsored by a PhD studentship provided by the National Center for Scientific and Technical Research of Morocco. We would like to thank J.A. Martinez del Pozo and Emma Bello (University of Cadiz) for field assistance during the first and second surveys. Thanks to M’fedal M’rabet for revising the English of an earlier version of this manuscript. We appreciate the comments by the journal’s reviewers which significantly improved the paper.

References

- Aagaard T, Kroon A, Andersen S, Møller Sørensen R, Quartel S, Vinther N (2005) Intertidal beach change during storm conditions; Egmond, The Netherlands. *Mar Geol* 218:65–80
- Allen JR (1981) Beach erosion as a function of variations in the sediment budget, Sandy Hook, New Jersey, USA. *Earth Surf Process Landf* 6:139–150
- Allen JR (1985) Field evaluation of beach profile response to wave steepness as predicted by the Dean model. *Coast Eng* 9:71–80
- Anfuso G, Martínez del Pozo JA, 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
- Battjes JA (1974) Surf similarity. In: Proceedings of the 14th international conference on coastal engineering, ASCE, pp 466–480
- Benavente J, Gracia FJ, López-Aguayo F (2000) Empirical model of morphodynamic beachface behaviour for low-energy mesotidal environments. *Mar Geol* 167:375–390
- Brander RW, Short AD (2000) Morphodynamics of a large-scale rip current system at Muriwai Beach, New Zealand. *Mar Geol* 165:27–39
- Carr AP, Blackley MWL, King HL (1982) Spatial and seasonal aspects of beach stability. *Earth Surf Process Landf* 7:267–282
- Carter RWG (1988) Coastal environments. Academic Press, London, p 617
- Cirac P, De Resseguier A, Weber O (1989) Situation courantologique et hydrologique sur le plateau continental atlantique nord-marocain: Mission Géomar II [Hydrological structure on the North Atlantic Moroccan Shelf: Cruises Géomar II]. *Bull Inst Géol Bassin d’Aquitaine* 46:81–95
- Cooper JAG, Jackson DWT, Navas F, McKenna J, Malvarez G (2004) Identifying storm impacts on an embayed, high-energy coastline: examples from western Ireland. *Mar Geol* 210:261–280
- Crowell M, Leatherman SP, Buckley M (1993) Shore-line change rate analysis: long term versus short term data. *Shore Beach* 61(2):13–20
- Dail HJ, Merrifield MA, Bevis M (2000) Steep beach morphology changes due to energetic wave forcing. *Mar Geol* 162:443–458
- Davis RA (1985) Beach and nearshore zone. In: Davis RA (ed) *Coastal sedimentary environments*. Springer, New York, pp 379–444
- Davis RA, Hayes MO (1984) What is a wave-dominated coast? *Mar Geol* 60:313–329
- Davis RA, Fox WT, Hayes MO, Boothroyd JC (1972) Comparison of ridge and runnel systems in tidal and non-tidal environments. *J Sediment Petrol* 42(2):413–421
- Dean RG (1973) Heuristic models of sand transport in the surf zone. In: proceedings of engineering dynamics in the surf zone, Sydney, pp 208–214
- Duplantier F, Lesueur P (1983) Les sables du littoral atlantique nord-marocain: origines et mode de mise en place [Sand on the North-Moroccan Atlantic coast: origins and depositional modes]. *Bull Inst Géol Bassin d’Aquitaine* 33:5–24
- Eliot I (1973) The persistence of rip current patterns on sandy beaches. In: Proceedings of the first Australian conference on coastal engineering, pp 29–34
- Folk RL, Ward WC (1957) Brazos River bar: a study in the significance of grain size parameters. *J Sediment Petrol* 27:3–26
- Galvin CJ (1968) Breaker type classification on three laboratory beaches. *J Geophys Res* 73:3651–3659
- Gibbs RJ, Matthews MD, Link DA (1971) The relationship between sphere size and settling velocity. *J Sediment Petrol* 41(1):7–18
- Gourlay MR (1968) Beach and dune erosion tests. Delft Hydraulics Laboratory, report no M935/M936
- Greenwood B, Davidson-Arnott RGD (1979) Sedimentation and equilibrium in wave-formed bars: a review and case study. *Can J Earth Sci* 16:312–332
- Greenwood B, Aagaard T, Nielsen J (2004) Swash bar morphodynamics in the Danish Wadden Sea: sand bed oscillations and suspended sediment flux during an accretionary phase of the foreshore cycle. *Dan J Geogr* 104(1):15–30
- Guza RT, Inman DL (1975) Edge waves and beach cusps. *J Geophys Res* 80:2997–3012
- Haxel JH, Holman RA (2004) The sediment response of a dissipative beach to variations in wave climate. *Mar Geol* 206:73–99
- Jaaidi EB, Cirac P (1987) La couverture sédimentaire meuble du plateau continental atlantique marocain entre Larache et Agadir [The soft sedimentary cover of the Moroccan Atlantic continental shelf between Larache and Agadir]. *Bull Inst Géol Bassin d’Aquitaine* 42:33–51
- Jago CF, Hardisty J (1984) Sedimentology and morphodynamics of a macrotidal beach, Pendine Sands, SW Wales. *Mar Geol* 60:123–154
- Komar PD (1998) Beaches processes and sedimentation, 2nd edn. Prentice-Hall, Englewood Cliffs, p 545
- Komar PD, Gaughan MK (1972) Airy wave theory and breaker height prediction. In: Proceedings of the 13th international conference on coastal engineering, ASCE, pp 405–418
- Lahlou A (2004) Water and wastewater purification in North Africa. Paper presented at the International Demand Management Conference, pp 51–63
- Larson M, Kraus NC (1994) Temporal and spatial scales of beach profile change, Duck, North Carolina. *Mar Geol* 117:75–94

- Larson M, Kraus NC (1995) Prediction of cross-shore sediment transport at different spatial and temporal scales. *Mar Geol* 126:111–127
- Masselink G, Hegge B (1995) Morphodynamics of meso- and macrotidal beaches: examples from central Queensland, Australia. *Mar Geol* 129:1–23
- Masselink G, Short AD (1993) The effect of tide range on beach morphodynamics and morphology: a conceptual beach model. *J Coastal Res* 9:785–800
- Masselink G, Turner IL (1999) The effect of tides on beach Morphodynamics. In: Short AD (ed) *Handbook of beach and shoreface morphodynamics*. Wiley, Chichester, pp 204–229
- Ruggiero P, Kaminsky MG, Gelfenbaum G, Voigt B (2005) Seasonal to interannual morphodynamics along a high-energy dissipative littoral cell. *J Coastal Res* 21(3):553–578
- Short AD (1979) Three dimensional beach-stage model. *J Geol* 87:553–571
- Short AD (1986) A note on the controls of beach state and change, with examples from south-east Australia. *J Coastal Res* 3(3):387–395
- Short AD (1991) Macro-meso tidal beach morphodynamics—an overview. *J Coastal Res* 7(2):417–436
- Short AD (1999) *Handbook of beach and shoreface morphodynamics*. Chichester, Wiley, p 379
- Short AD, Aagaard T (1993) Single and multi-bar beach change models (special issue). *J Coastal Res* 15:141–157
- Sunamura T (1989) Sandy beach geomorphology elucidated by laboratory modelling. In: Lathan VC, Trenhaile AS (eds) *Applications in coastal modelling*. Elsevier, Amsterdam, pp 159–213
- Thom BG, Hall W (1991) Behaviour of beach profiles during accretion and erosion dominated periods. *Earth Surf Process Landf* 16:113–127
- USACE (2008) *Coastal hydrodynamics*. Coastal engineering manual, no. 1110-2-1100 (part II), United States Army Corps of Engineers, Mississippi, 608 p
- Wijnberg KM, Kroon A (2002) Barred beaches. *Geomorphology* 48:103–120
- Wright LD, Short AD (1984) Morphodynamic variability of surf zones and beaches: a synthesis. *Mar Geol* 56:93–118
- Wright LD, Nielsen P, Short AD, Green MO (1982) Morphodynamics of a macrotidal beach. *Mar Geol* 50:97–128