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Article

Influence of a Reef Flat on Beach Profiles Along the Atlantic Coast of Morocco

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Received: 7 February 2020; Accepted: 11 March 2020; Published: 12 March 2020

Abstract: The North Atlantic coast of Morocco is characterised by a flat rocky outcrop in the south (Asilah Beach) and a sandy beach free of rocky outcrops in the north (Charf el-Akab). These natural beaches were monitored for a period of two years (April 2005–January 2007) and two different profiles (one for each beach) were analysed based on differences in the substrate. Topographic data were analysed using statistics and empirical orthogonal functions (EOFs) to determine beach slope and volumetric changes over time. Several morphologic phenomena were identified (accretion/erosion and seasonal tilting of beach profiles around different hinge points), attesting to their importance in explaining variability in the data. Periods of accretion were similar in both profiles, but the volumetric rate of change was faster in the sand-rich (SR) profile than in the reef flat (RF) profile. Moreover, the erosion rate for the SR profile was greater than the RF profile (135.18 m^3/year vs. 55.39 m^3/year). Therefore, the RF acted as a geological control on the evolution of its profile because of wave energy attenuation. Thus, special attention should be given to the RF profile, which has larger slopes, less amounts of mobilised sand, and slower erosion/accretion rates than the SR profile.

Keywords: EOF; beach profiles; reef flat; coastal dynamics; sand rich; accretion; erosion rate

1. Introduction

The presence of rocky platforms on beaches is found worldwide. An RF beach is the name for beaches that are perched on hard landforms. The US Army Corps of Engineers [1] and Larson and Kraus [2] define this as a hard-bottom beach. Morphological changes on beaches due to the existence of an RF are not well studied. A few investigations have focused on shape changes, such as Black and Andrews [3] in New Zealand and New South Wales, and Sanderson and Eliot [4] in Australia. Other authors have studied temporal changes, reporting winter erosion and summer accretion rates over a limestone platform near Perth in south-west Australia [5]. Rock and coral landforms on beaches can dissipate wave energy, as confirmed by researchers in Galicia (north-west Spain [6]), St. Martin's Island (Bangladesh [7]), and the fringing reef along Kaanapali Beach in Maui [8].

Sea level rise and other anthropic phenomena induce coastal recession worldwide [9], and coastal researchers and engineers are interested in studying coastal evolution to properly design mitigation and/or remediation measures [10]. Short-term and long-term morphological variability must be considered in the design and evaluation of beach nourishments [11]. Evaluation over seasonal time scales (months or years) is important to determine the rate of erosion and therefore determine future land use in areas adjacent to beaches. Medium-term responses, such as seasonal oscillations in winter–summer profiles, provide information about the across-shore dimension of the berm and may play an important role in the location of beach services such as showers, litter bins, toilets, as well as ramps and bridges for wheelchair accessibility [12].

Levelling of beach profiles is a widely-used tool to monitor the evolution of the coast, and various formulae have been proposed to calculate a general expression (e.g., Dean's formula [13]), although some authors have questioned their validity when an underlying shoreface geology exists [14]. Thus, several researchers have presented results of the influence of coastal reefs on the spatial and temporal variability of beach morphology [15–19]. Other characteristics, such as wave attenuation over reef platforms [20], wave-setup and water-level fluctuations [21], interannual changes in beach morphology [22], modification of the A parameter of Dean's formula [23,24] or sediment flux [25] along reef-protected profiles, have also been discussed.

Nevertheless, few comparisons can be found between the behaviour of profiles on adjacent beaches subject to the same wave conditions but with different geological substrates or boundary conditions. It is worth noting that Muñoz-Perez and Medina [12] compared the behaviour of two beach profiles from Victoria Beach (Cadiz, Spain) over a five-year period where one profile was perched on a rock platform. The northernmost zone presented a rocky platform that emerged during low tide and acted as a geological boundary for profile development, whereas the southern zone had no such platform. Some differences in erosion and subsequent accretion rates were observed.

Thus, the aim of this paper is to compare how beach profiles change (volume and slope) over time on two adjacent beaches (under the same climatic conditions), one of which is a sand-rich beach (Charf el-Akab, SR) and the other beach is supported by a reef flat (Asilah, RF). Monitoring by beach profiling was performed to analyse their morphological differences over a period of two years (April 2005–January 2007) to observe seasonal changes between summer and winter in order to draw useful conclusions regarding the behaviour of beach morphology as it relates to differences in the seabed.

2. Study Area

Beach Location

The sites investigated in this paper are located along the North Atlantic coast of Morocco (Figure 1). Two adjacent beaches were chosen. The northern beach is Charf el-Akab (35°46′ N, 5°48′ W), close to Tanger. Immediately to the south is Asilah Beach, which takes its name from the homonymous city (35°28′ N, 6°2′ W). Both beaches have an NNE–SSW orientation and are composed of the same quartz sand. The main difference between the two sites is that Asilah presents an almost horizontal rocky platform situated around the low tide level, which influences the dynamics of the coast, while Charf el-Akab is a completely sandy beach.

(a)

(b)

(c)

Figure 1. (**a**) Location of Charf el-Akab and Asilah beaches on the north-west coast of Morocco facing the Atlantic Ocean. Wave and climate data were collected from a virtual SIMAR buoy in front of Asilah (www.puertos.es); (**b**) view of Charf el-Akab sandy beach; (**c**) view of the Asilah beach supported by a reef flat. Photographs taken by the authors.

3. Methods

3.1. Meteorological Data

Meteorological data were collected from a wave prediction point (SIMAR point 5,041,003 from www.puertos.es) located in front of the monitored stretch of coast (Figure 1a). The area is mesotidal, with a tidal range of 2.7 m and a semidiurnal periodicity [26]. The hydrodynamic conditions are principally controlled by storms approaching from occidental quadrants [27]. The predominant winds, named "Chergui", blow from the east (i.e., from land) 27% of the time and are especially abundant in spring and summer, reaching maximum velocities of 130 km/h. Secondary winds ("Rharbi") blow from the west (i.e., from the Atlantic Ocean) 16% of the time. Rharbi winds are wet and prevail in winter and autumn [26].

The SIMAR database is obtained through numerical wave modelling from wind time series by solving the equation of energy balance. This virtual database does not come from direct measurements. However, it has been validated by numerous studies and used in practical applications along the Spanish coast [28].

Both beaches are subject to the same wave and wind climatic regimes because of their proximity to each other. The nearshore areas are uniform, and both beaches face the same direction. Figure 2 reports temporal series of wave height and period, wind speed, and wind direction from April 2005 to January 2007.

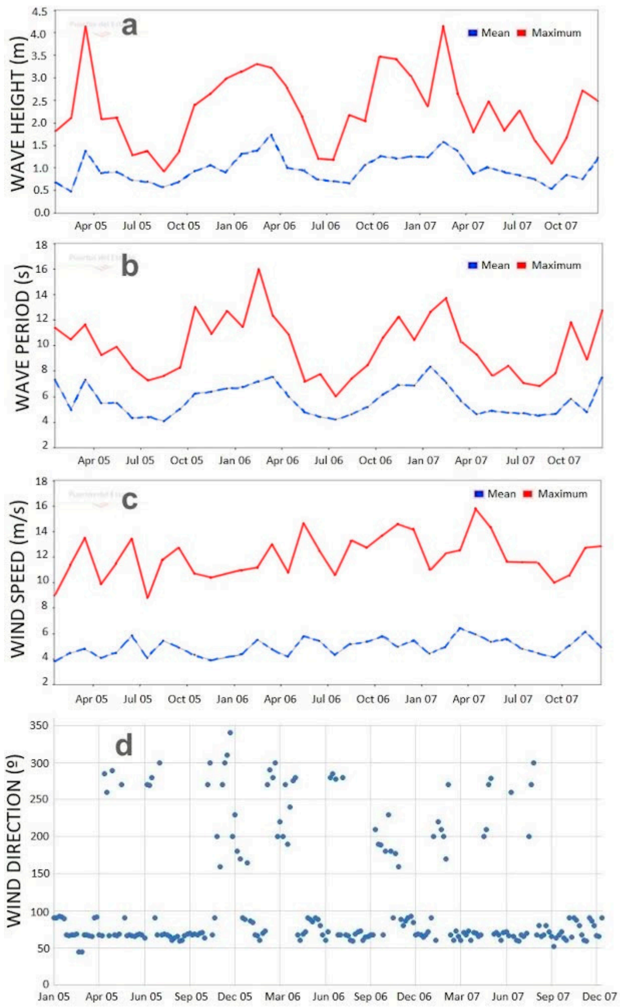

Figure 2. Temporal series of (**a**) wave height (m); (**b**) wave period (s); (**c**) wind speed (m/s); (**d**) most frequent wind direction: N = 0°, E = 90°, S = 180°, W = 270° (adapted from www.puertos.es). The dotted blue line refers to the average value, while the red one is the maximum value registered.

3.2. Field Data Surveying

The morphological changes of Charf el-Akab and Asilah beaches were studied through a topographic monitoring program carried out every two months during a two-year period, from April 2005 to January 2007. Data were collected on emerged beaches at low tide with a total station. The vertical datum (or zero elevation surface) matches the lowest low-water level (LLWL). Some fixed positions were selected and monitored at both beaches. Five profiles were taken in Charf el-Akab (Figure 1b) and seven in Asilah (Figure 1c). The beach profile spacing was 50 m, following recommendations found in the literature [29–32], whereas the distance between adjacent points along one profile was 5 m. However, because there were no appreciable differences between the profiles of the same beach (the variance ranges from 0.015 for Asilah to 0.061 for Charf el-Akab), only two mean profiles (one from each beach) were studied. Afterwards, analyses of the data collected were performed by statistical way (Statgraphics Centurion software) and EOF (multivariate statistical analysis package (MVSP)).

3.3. Statistics

Following Jimenez and Sanchez-Arcilla [33], a previous study by Anfuso et al. [34] chose to use least-squares linear regression to analyse the evolution of the profile. Similar methodologies to the one used by Anfuso et al. [34] were carried out to obtain the accretion/erosion volumes in this study. The analysis of the mean profiles was carried out using the statistical software to find differences between the behaviour of the RF and the SR profiles. The beach face slope and accretion/erosion volumes of sand per unit of beach length were calculated. The area between two profiles of adjacent dates is the accretion/erosion rate volume (m^3/m). The slope was obtained as the mean of slopes calculated at 5 m intervals along each profile. The use of EOFs enabled the identification of morphological changes [35] and allowed us to obtain additional results from the data that better explained the spatial and temporal variability of the beach profiles.

3.4. Empirical Orthogonal Functions (EOFs)

EOFs are a mathematical method and have been widely used in coastal geomorphology since Winant et al. [36] studied variability in beach profiles. Other researchers have applied this technique to different aspects of coastal morphology; for example, longitudinal variations in contour lines [37–39], sand transport in a transverse direction [40], or the distribution of sediment grain size along a transverse profile [41]. In addition, other phenomena have also been investigated using EOFs: responses to beach nourishment at different times and spatial scales [11], behavioural changes in profiles over a fortnightly tidal cycle [42], the capacity of this technique to identify modes of shoreline variability [38,39], and changes in coastal dune profiles [43].

EOFs, also known as principal components analysis (PCA), provide a technique for separating the spatial and temporal variability of beach-profile data; a detailed description of the method can be found in statistics textbooks [44]. In brief, if a function h = (x,t) represents the profile elevation at a particular position and time, such a function may then be defined as a linear combination of a few spatial, Xn (x) and temporal, Tn (t), eigenfunctions (and their associated eigenvalues) as follows:

$$h_{ij} = h\left(x_i, t_j\right) = \sum_{l=1}^{N} X_l(x_i) * T_l\left(t_j\right) * a_l = a_1 * X_1(x_i) * T_1\left(t_j\right) + a_2 * X_2(x_i) * T_2\left(t_j\right) + \ldots \quad (1)$$

Eigenfunctions are ranked according to the percentage of variability they explain, defined as the mean squared value (MSV) of the data. In some cases [36], the mean value is of such importance in explaining the variability that it must be removed from the original data to allow for the better and clearer identification of other smaller, but important, changes. Then, the MSV becomes part of the variance. The first eigenfunction explains most of the MSV in the data, the second eigenfunction explains the greater part of the remaining MSV, and so on. The MVSP software was used to calculate the EOFs. Furthermore, according to Aubrey [45], assuming that a physical process provides most of the variability, the corresponding eigenfunction would be related to that physical process.

4. Results and Discussion

4.1. Topographic Profile Analysis

Topographic mean profiles carried out from April 2005 to January 2007 at the RF beach at Asilah and the SR beach at Charf el-Akab were investigated in order to assess how the profiles change over time and to compare the two types of beaches. A representation of the mean profiles over time is shown in Figure 3. Since it is not easy to see a rational behaviour or trend, as previously mentioned in Section 2, a statistical analysis was carried out with Statgraphics software to obtain the results presented in Table 1 (i.e., net sand volume variations and rates of accretion represented by positive values and erosion by negative values).

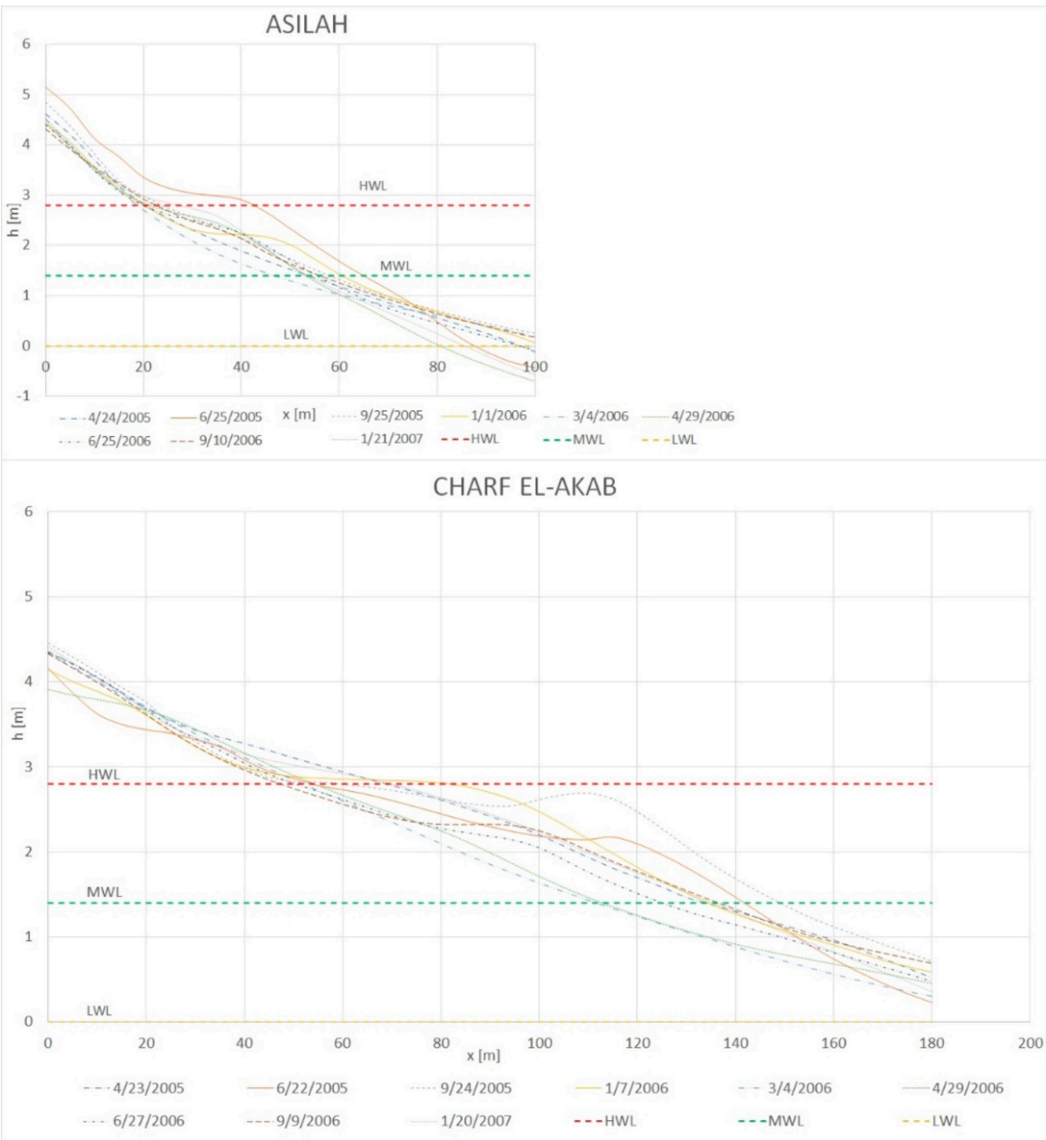

Figure 3. Topographic profiles. These are the mean profile of each beach over time from data collected in the field. The profiles are used to perform the statistical calculations and the complementary empirical orthogonal function (EOF) analyses. Profile dates are reported in the legend. High, mean, and low water levels are represented as HWL, MWL, and LWL, respectively. Levellings of the mean profile (h) are presented on the vertical axis.

Table 1. Volume rates of the Asilah (reef flat (RF)) and Charf el-Akab (sand-rich (SR)) beaches' mean profiles. The accretion volume between dates is represented as positive values (m^3/m) and the volume eroded as negative values (m^3/m). Cross-shore transport speed (m^3/m per day) has been calculated as the net value of accretion less erosion (m^3/m) divided by the time increment in days.

Date of Topographic Profile	Beach Slope (%)		Time (months)	Accretion (m^3/m)		Erosion (m^3/m)		Net (m^3/m)		Cross-Shore Transport Speed (m^3/m per day)	
	RF	SR		RF	SR	RF	SR	RF	SR	RF	SR
24 April 2005	3.6	2.1	2.00	46.04	27.31	−6.14	−11.29	39.91	16.02	0.67	0.27
23 June 2005	6.2	2.0	3.00	11.12	1.51	−32.56	−47.13	−21.44	−45.62	−0.24	−0.51
25 September 2005	3.2	1.8	3.20	4.55	5.70	−10.09	−36.18	−5.54	−30.48	−0.06	−0.32
3 January 2006	3.4	2.0	2.00	0.69	5.54	−23.11	−64.62	−22.42	−59.08	−0.37	−0.98
4 March 2006	3.1	1.8	2.00	15.33	12.04	−21.32	−4.34	−5.99	7.70	−0.10	0.13
29 April 2006	4.7	1.7	2.00	17.91	24.85	−1.46	−4.14	16.44	20.71	0.27	0.35
26 June 2006	3.6	1.8	2.50	9.74	18.33	−2.29	−4.38	7.45	13.95	0.10	0.19
10 September 2006	3.3	1.5	4.30	5.51	18.78	−18.20	−6.63	−12.69	12.15	−0.10	0.09
20 January 2007	4.8	2.2									

The results presented in Table 1 show the typical erosion/accretion cycle for both the SR and RF beaches. The accretion phase took place during the "summer" season (usually from April to September) due to the prevalence of relatively calm conditions. The erosion phase occurred during "winter" months (from October to March), when high-energy events caused erosion along the foreshore.

The erosion rate (m^3/m per year) was calculated as, first of all, the sum of the net volume eroded (negative values) in the 21 months of study. Then, the erosion rate was multiplied by the correction factor of 12/21 to compute the annual rate. Similarly, the accretion rate (m^3/m per year) was also estimated as the sum of the net accretion volume (positive values) across the entire time interval. The erosion rate for Asilah (RF) resulted in 38.90 m^3/m per year; this value was 77.25 m^3/m per year for Charf el-Akab (SR). The accretion rate was 36.46 m^3/m per year for Asilah (RF), and a similar value (40.30 m^3/m per year) was recorded for Charf el-Akab (SR). Therefore, cross-shore transport for Asilah (RF) ranged from −0.37 to 0.67 m^3/m per day and from −0.98 to 0.35 m^3/m per day for the SR beach. The slopes ranged from 3.1 to 6.2% for Asilah (RF) and from 1.5 to 2.2% for Charf el-Akab (SR).

Charf el-Akab (SR) lost twice the volume of sand per year than that for Asilah (RF). The RF dissipates the wave energy due to friction, causing less beach erosion. Nevertheless, Charf el-Akab recorded higher accretion rates than Asilah, but the erosion rate at Asilah was faster than its accretion speed; this favoured a negative sediment budget trend. Moreover, the slope of the RF beach was double (and sometimes triple) that of the SR beach (Figure 4). Once again, wave energy reduction (due to the friction on the RF) is the cause of the higher slope of the beach.

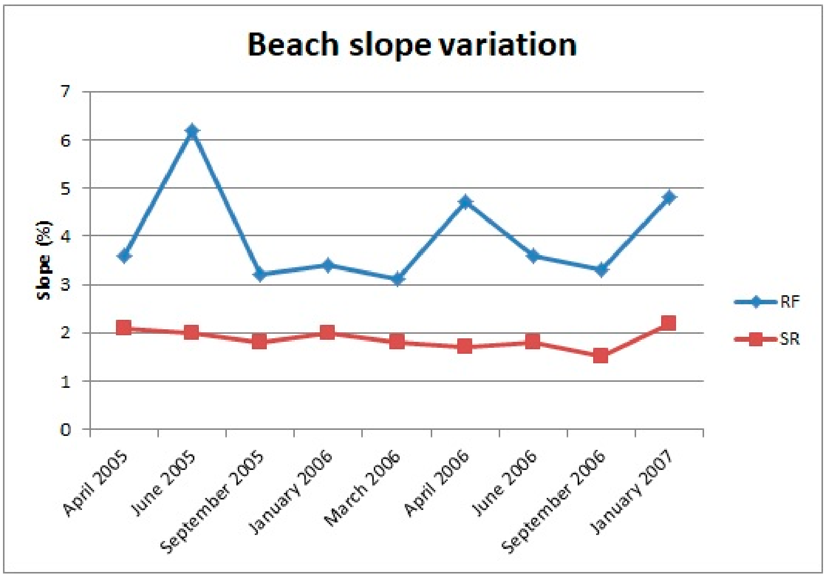

Figure 4. Slope (%) of the two kinds of beaches (reef flat, RF, is blue and sand-rich, SR, is red) during the April 2005–January 2007 period.

On the other hand, the slope of the regression line ("m") estimates the volumetric rate of change during the surveyed period. Therefore, the "m" values in Figure 5 express the erosion/accretion per month (m^3/month). The higher the slope of the fitted line, the clearer the profile trend. In this way, the SR beach presented high values of "m"; that is, clear tendencies. Both the SR and RF beaches have low R-squared values due to seasonal variability and episodes of erosion and accretion (Figure 5). The seasonal variability is clearly distinctive for the SR beach when summer periods have positive volumetric changes (accretion) and winter periods have negative trends (erosion). Even though the seasonal behaviour is similar for the RF beach, there were smaller changes in volume. The volume changes over time for the SR beach presented a more marked tendency. Anfuso et al. [34] stated that low correlation coefficients between volume changes and time indicate a high degree of beach variability.

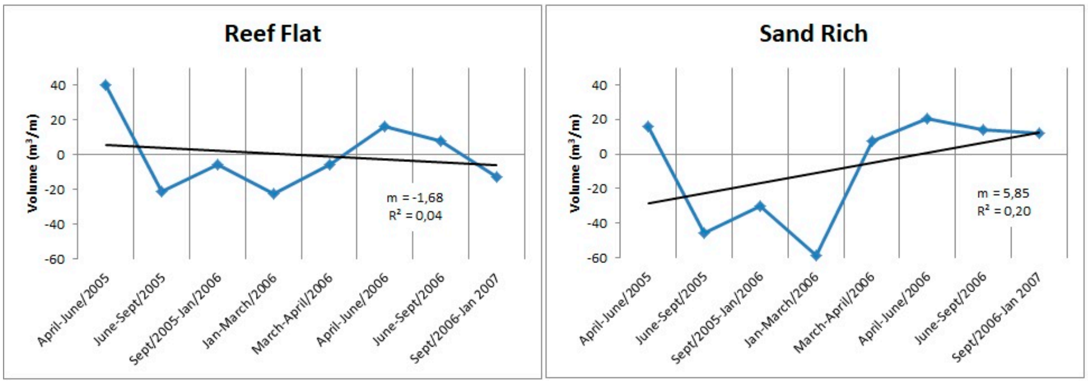

Figure 5. Evolution of sand volume of two types of beaches (reef flat, RF, and sand-rich, SR) during the April 2005–January 2007 period. Units of the linear regression slope (m) are in m^3/m per month.

Comparisons between SR and RF beaches from another country (Spain) were also carried out by Muñoz-Perez and Medina [12] using EOF methodology. The values are similar between RF and SR beaches from two different countries (Victoria Beach in southern Spain vs. Asilah and Charf el-Akab beaches in Morocco). The results are shown in Table 2 in order to verify that both countries present a similar behaviour depending on the kind of beach. The sand-rich profile of Victoria beach shows losses of less volume per year than Charf el-Akab. Nevertheless, the reef flat part of Victoria beach loses less volume per year than Asilah. Therefore, the rocky platform from Asilah experiences less change in volume because it is wider than the one at Victoria. Wide rocky platforms offer more friction, resulting in more wave energy dissipation. In the case of a sandy beach, the absence of a reef flat causes even more erosion because it is not protected from wave energy on the bottom. Significant differences between SR beaches and RF beaches indicate the importance of the presence and typology of the rock platform

Table 2. Comparison of erosion and accretion volume rates between reef flat and sand-rich profiles. The beaches are Victoria (Cadiz, Spain), Asilah and Charf el-Akab (Morocco).

		Slope Variation (%)	Erosion Rate (m^3/year)	Accretion Speed (m^3/day)
Reef flat profile	Victoria	3.8–7.8	29	0.33
	Asilah	3.1–6.2	55.4	−0.37 to 0.67
Sand-rich profile	Victoria	1.2–2.8	121	1.01
	Charf el-Akab	1.5–2.2	135.2	−0.98 to 0.35

4.2. EOF Analysis

To date, the analyses of the mean profiles have been statistically performed simply to identify differences between the RF and SR profiles on slope and accretion/erosion rates. As mentioned in Section 2, the EOF analysis allowed us to obtain more information from the data; in this way, it helped explain the variability in temporal and spatial profiles. The following results were obtained using EOFs applied to the profiles by subtracting the mean profile.

The first and second spatial components from the EOFs are plotted in Figure 6a (Asilah) and Figure 6c (Charf el-Akab), and the mean profile is presented with levelling on the right axis. Temporal components from EOFs are shown in Figure 6b,d. The variance described by the first component was bigger in the sand-rich profile than in the reef-protected profile, at 77.3% vs. 57.9%. Therefore, the second spatial component explained the greater weight in the variance for Asilah (33.6%) as compared to Charf el-Akab (9.6%). Each spatial component described how the data collected changed along the profile. Thus, the maximum and minimum points mark where either the accumulation or erosion of the beach was observed. Taking this into account, zero means there was no transport of material at that point, which is called the "rotation point." The temporal components describe the beach erosion/accumulation cycle.

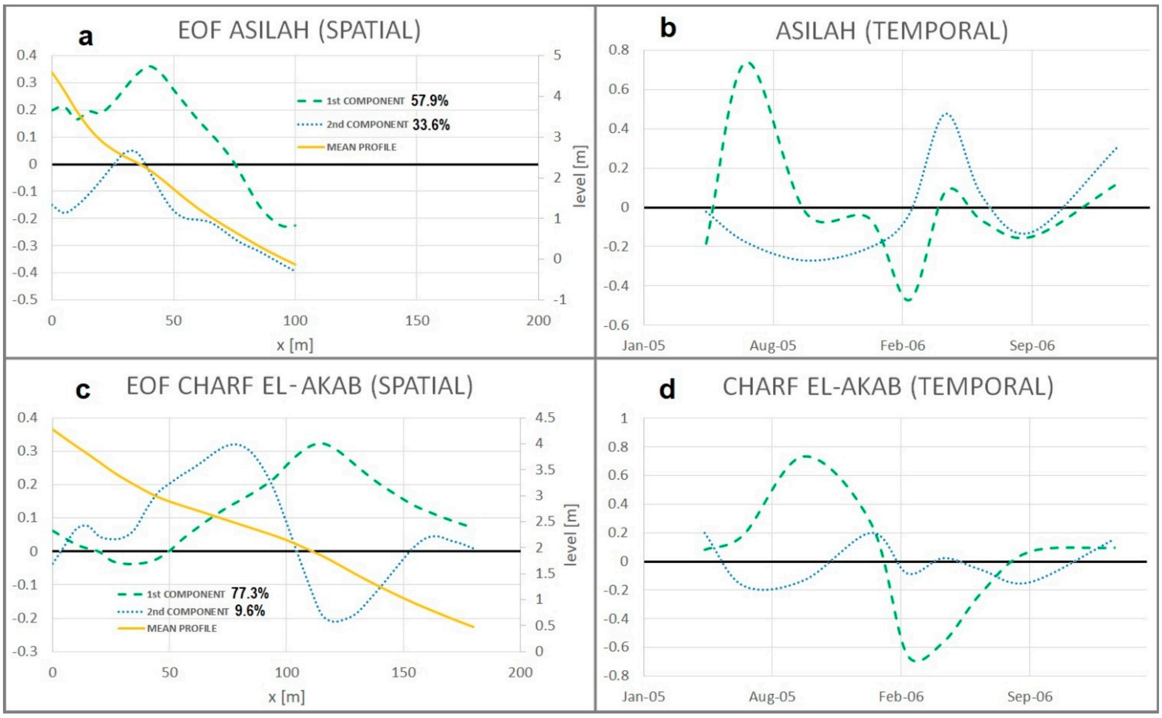

Figure 6. (**a**) Spatial EOF in Asilah (RF); (**b**) temporal EOF in Asilah (RF); (**c**) spatial EOF in Charf el-Akab (SR); (**d**) temporal EOF in Charf el-Akab (SR). The height of the mean profile is reported on the vertical axes. The percentages of variance described by the components are reported in the legends.

The first spatial component in Asilah beach (RF) crossed the rotation point at x = 75 m, which corresponded to h = 0.67 m in the mean profile. The second component was always negative except for a small part between x = 25 m and x = 40 m, which corresponded to h = 2.68 m and h = 2.18 m in the mean profile, respectively.

The first spatial component in the Charf el-Akab beach (SR) presented a small part where it changes sign between x = 20 m and x = 50 m and which corresponded to h = 3.64 m and h = 2.88 m in the mean profile, respectively. The second component presented two points that passed through the zero point: the first one at x = 105 m corresponded to h = 2.05 m in the mean profile, while the second one at x = 155 m corresponded to h = 0.93 m.

Oscillations around null axes can be observed in the temporal graphs and cannot be associated with seasonal variations. Indeed, two relative maximums and minimums were observed over the period of two years, indicating that the beach profiles changed only once every year. The peaks of the first component were observed in June 2005 and March 2006 for Asilah Beach, while the most important peak in the second component occurred in April 2006. The peaks of the first component in Charf el-Akab were recorded in September 2005 and March 2006, while the second component presented an oscillation without relevant peaks.

4.3. Physical Interpretation of the Changes

The first spatial component was associated with the general seasonal change in beach profiles as observed at Asilah; that is, typical of "storm" and "calm" conditions [13]. Similar characteristics were observed at beaches in Cadiz [12,46]. The accretion/erosion periods and the portion of the profile that reflected such changes were identified by the combined analysis of the spatial and temporal components. Therefore, if the rotation point for the first component in Asilah Beach (RF) was x = 75 m, which corresponded to h = 0.67 m in the mean profile, the accretion periods were above h = 0.67 m in summer and below this level in winter (Figure 7a). Moreover, Charf el-Akab Beach (SR) presented a small part in which the trend changed, between x = 20 m and x = 50 m, which corresponded to h = 3.64 m and h = 2.88 m, respectively. Therefore, great volumetric changes observed at Charf el-Akab took place from h = 2.88 m to the submerged zone, which corresponded with a period of accretion during 2005 and erosion during the first half of 2006. After that, the beach seemed to acquire equilibrium (Figure 7b).

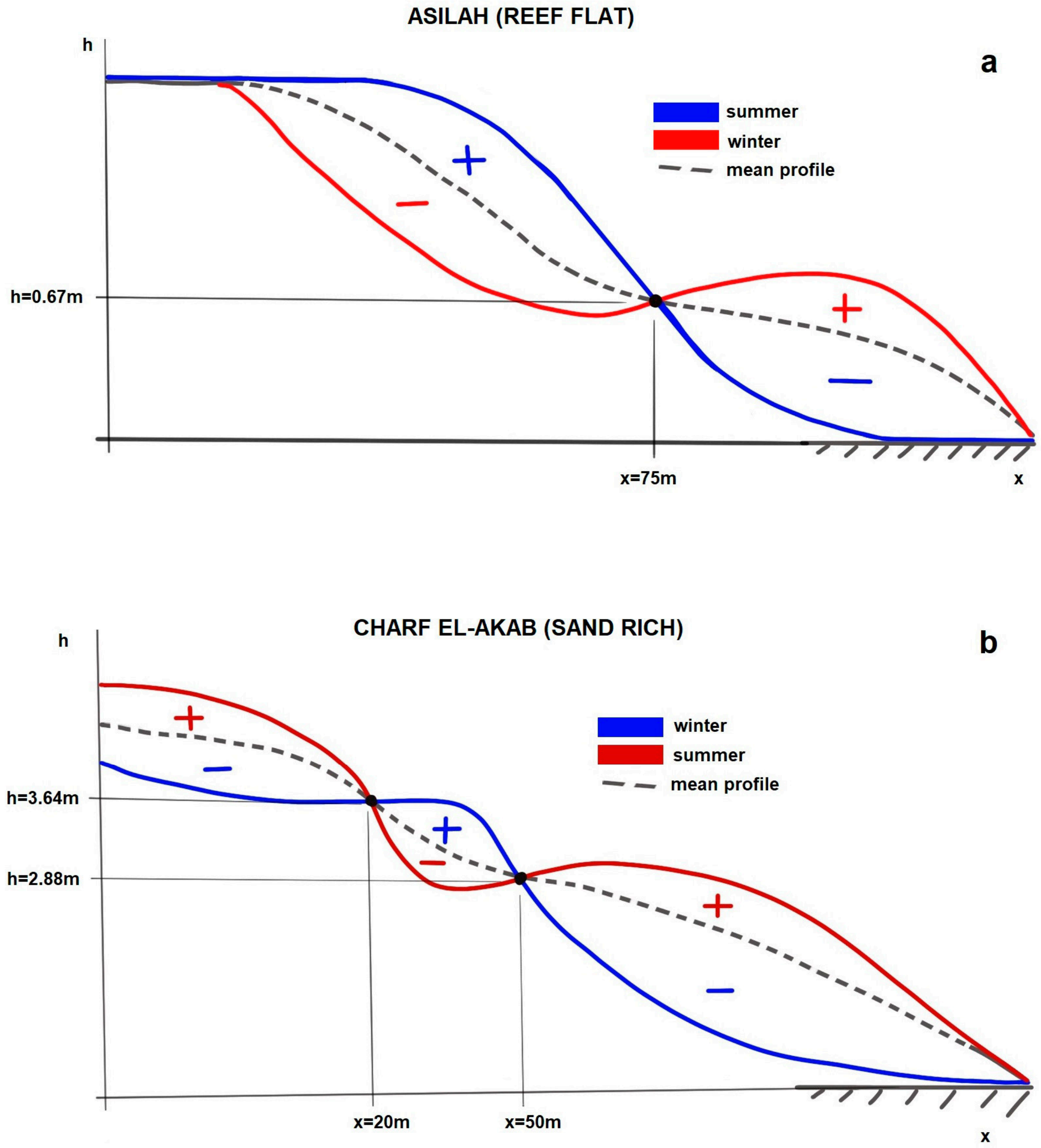

Figure 7. Sketch of seasonal changes in beach profiles at (**a**) Asilah and (**b**) Charf el-Akab beaches.

The behaviour of the second component was completely different. The increments of this component were associated, as for the first component, with a change in the significant wave height, but also with the prevalence of winds from the east. This condition produced aeolian transport on the beach, but not a large wave regime because the fetch was small and did not allow wave formation [47]. Thus, it is clear that the second component was affected by different variables and not solely controlled by sea and wave conditions. Hence, the second component was responsible for the shape of the profile and was related to different interactions among several variables, essentially sea regime and wind conditions. Thus, this component influenced the morphology of the profiles under the combined effects of wave and aeolian transport. Taking this into account, it is possible to state that the wind in Charf el-Akab did not produce notable changes in the beach profile because of the shield of topography and presence of some edification. Meanwhile, that was not the case for Asilah beach, which was affected by sand transport when east winds were strong. The presence of tall buildings in Victoria Beach is probably the reason why this behaviour was not observed in the Spanish coast. Beach morphological changes have been described in other papers [48], but more detailed knowledge about the interactions between wave transport and aeolian transport is less well described. Nickling and Davidson-Arnott [40] associated the shape of beach profiles with usable sand volume.

5. Conclusions

The aim of this paper is to assess differences in profile morphology (volume changes and slope variations of two beaches), taking into account the influence of the nature of the seabed (i.e., the presence or absence of a reef flat). Two kinds of beaches along the north-west coast of Morocco were studied; one is a sandy beach, and the other one is supported by a hard-bottom reef flat. The comparison of the profiles over time helps us to understand the importance and influence on the beach behaviour of the presence of a hard, rocky substrate. EOFs were used to determine the components that describe the behaviour of the beach profiles. The first component was associated with seasonal changes: erosion in winter months, when high-energy events cause significant erosion across the foreshore, and accretion in summer months because of calm conditions. This was particularly evident in the RF beach. On the other hand, the second component was associated with combined wave and wind sediment transport, as observed in many cases in which increments and movement of sand are associated with high winds and low wave heights. These results are similar to other studies based on the use of EOFs. In addition, the behaviour of the beaches is comparable with a previous study of Victoria Beach in the Gulf of Cadiz.

A typical yearly cycle of erosion and accretion can be observed at both beaches. Charf el-Akab (SR) beach lost twice as much sand per year as Asilah (RF) beach. When a beach has a reef flat, the beach profile suffers less erosion than a sand-rich beach where wave energy is not reduced by friction when in contact with a rocky bottom. For the same reason, the slope of the RF beach is twice that of the slope of the SR beach. Despite this, Charf el-Akab has higher yearly accretion rates than Asilah, but the erosion rate for Asilah was faster than the accretion rate, producing an erosional trend, whilst the Charf el-Akab beach seems to have reached a state of equilibrium.

Author Contributions: Conceptualization, G.P. and J.J.M.-P.; Data curation, M.T., P.P., P.L.-G. and J.R.-C.; Formal analysis, M.T., P.P., P.L.-G., J.R.-C. and J.V.; Funding acquisition, G.A.; Investigation, G.A.; Methodology, M.T., P.P., G.A. and J.J.M.-P.; Project administration, M.T. and G.A.; Resources, G.P.; Software, P.L.-G. and J.V.; Supervision, G.P. and G.A.; Writing—original draft, P.L.-G. and J.J.M.-P.; Writing—review & editing, G.P., J.R.-C., G.A, J.V. and J.J.M.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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