Morphological vulnerability index:
A simple way of determining beach behaviour

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Abstract

A simple morphological based index to determine beach vulnerability is proposed in this paper. The presented morphological vulnerability index (I_V) relates maximum annual volumetric difference and average beach volume for each particular site. High index values are representative of coastlines vulnerable to erosion.

After the index application to 15 Portuguese sites it was possible to determine empirical threshold values, defining limits between beach stages. Based on these limits the beaches can be classified as: robust beaches, for $I_V < 0.35$; fragile beaches, for $0.35 < I_V \leq 0.9$; and extremely fragile beaches, for $I_V > 0.9$. The index validation tests against field observations and recent shoreline evolution gave good results, indicating that the I_V has a strong potential application to characterise medium to long-term beach evolution.

Introduction

A successful approach to characterise large-scale sediment transport, including cross-shore rates, must use information on the principles underlying key features of the larger scale morphology (Larson and Kraus, 1995). However, to our knowledge there are no simple morphological based indexes available in literature describing beach behaviour at macro and megascale timescales (year to decades).

The main goal of this study was to develop an index capable of determining the morphological vulnerability of a given beach or coastal stretch. For the purpose of this study a beach with high morphological vulnerability is defined as having a small ability to support high energy conditions without strong morphological changes. Thus, a

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beach with high vulnerability can also be referred as a fragile beach, due to the possibility of effective shoreline or dune retreat to occur. Conversely, a low vulnerability beach can also be referred as a robust one, meaning that even facing some erosion during high energy conditions the beach will not show effective shoreline or dune retreat. It is meant by effective shoreline or dune retreat the total remotion of the upper beach (foreshore and backshore) sedimentary stock with erosion of the dune or cliff.

In order to introduce an index of this kind studies were carried out on 15 Portuguese beaches. Two different coastal sectors were surveyed including; 10 sites from Aveiro - Cape Mondego (figure 1), Northwest of Portugal (surveys from September 1992 until June 1993) and 5 sites from Praia de Faro (figure 2), Algarve (surveys from May 1995 until May 1997). The 10 sites of the Northwest coast belong to a coastal stretch with about 50km length and include beaches updrift and downdrift of groins as well as beaches without human intervention. On the Algarve coast three of the surveyed beaches are backed by human occupation (sites A to C) and two of them by a dune ridge (sites D and E). The surveys were made during low spring tides, once a month in Praia de Faro and every two months at Aveiro - Cape Mondego. All these sites were intermediate to reflective Atlantic facing sandy beaches with moderate (Algarve) to high wave (Aveiro - Cape Mondego) energy. Both coastal areas are mesotidal with maximum tidal ranges reaching about 3.6m-3.8m.

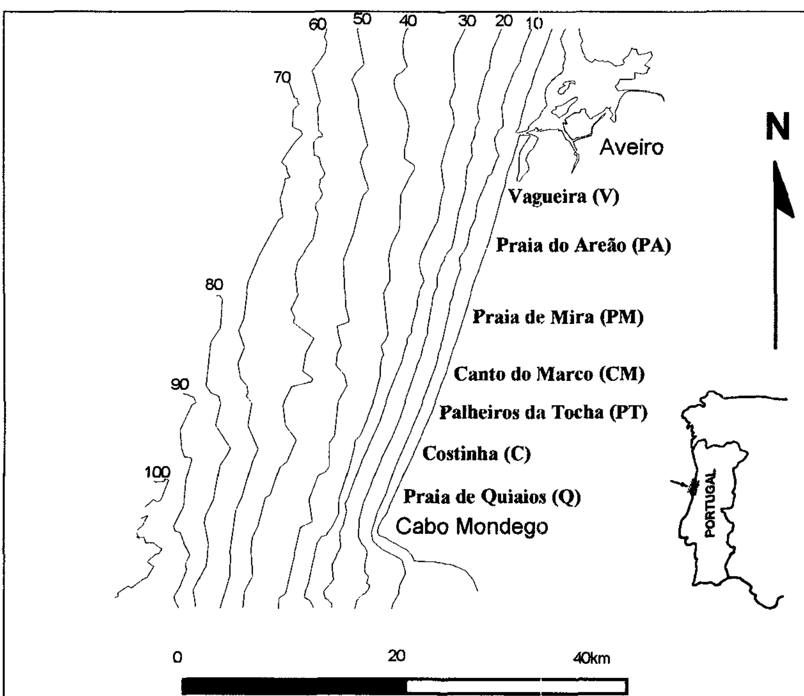

Figure 1. Location of the study sites from Aveiro - Cape Mondego coastal stretch.

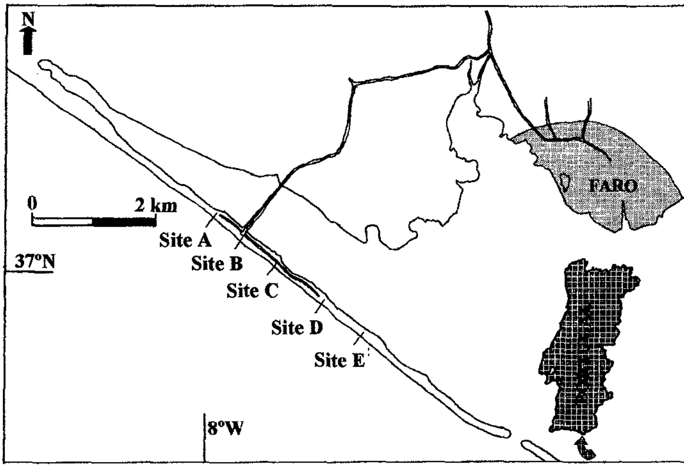

Figure 2. Location of the study sites at Praia de Faro coastal stretch.

Vulnerability index

Concepts

The main concept underlying the proposed vulnerability index is that the annual beach variability can be an indicator of its future evolution. The index application assumes that the beach variability is mainly dependent on cross-shore exchanges and that after an annual cycle the upper beach morphology becomes similar to the initial one, even if there was effective dune or shoreline retreat. Thus, this index can only be used in beaches where a seasonal behaviour exists.

To obtain the morphological vulnerability index (I_V) it was necessary to compute the beach volume above mean sea level for each obtained profile (figure 3). The landward limit for these calculations was taken to be the "non - mobility point" of the site (the inland point at which no sand movement due to wave action was observed). Using the obtained volumes, mean profile volumes (V_{mean}) were calculated for each beach and for the desired periods.

The morphological vulnerability index (I_V) is then given by the relationship,

$$I_V = (V_{max} - V_{min})/V_{mean} \tag{1}$$

where V_{max} and V_{min} are the maximum and the minimum volumes computed for the chosen survey period. A high index indicates a high range in beach volume (a dynamic site) and low mean values. Thus, high indexes will be indicative of coastlines vulnerable to erosion while low index values will be representative of shorelines without evident retreat.

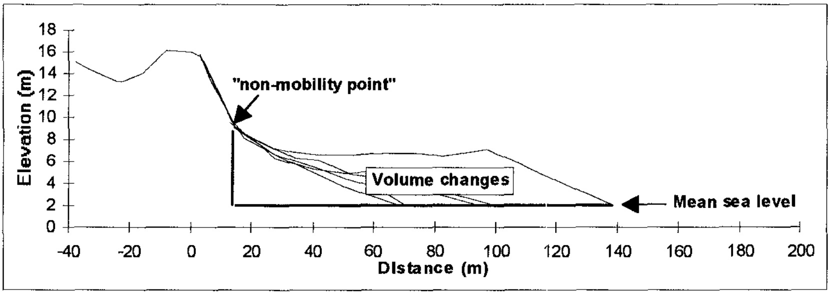

Figure 3. Schematic representation of the limits used for beach volume computation.

From the available data and after some application tests, it was found that the index only shows stable results if survey data is included for a full seasonal (Summer/Winter) cycle, with a period between successive surveys no longer than 2 months. Figure 4 illustrates the index evolution (I_{Vni}/I_{Vni-1}) with an increasing number of profiles (ni) used in the calculation of I_V. This figure shows that the index variation tends to be small or nule ($I_{Vni}/I_{Vni-1} \approx 1$) when the number of used profiles (ni) is higher than 12/13 (one year of monthly observations). On the basis of these results I_V is computed at each site using one full year of survey data, and thus indicating the beach behaviour of that period.

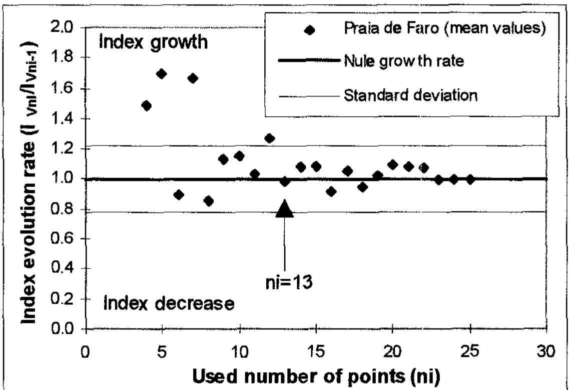

Figure 4. Index variation with the number of points used in the computation.

Application to Praia de Faro

By the application of equation (1) to the Praia de Faro data set 13 indexes were obtained for each site, from months 1-13 (first year of surveys) until months 13-25 (last year of surveys). The minimum, maximum and mean values, obtained to each site, are expressed in Table I. It is apparent from Table I that site B (parking place at Praia de Faro) is the most vulnerable to erosion or overwash. This is in agreement with field observations of frequent overwashes at this site. Dune erosion is impossible to occur at this site since the parking area was built over the former dunes, destroying them. From field observations it is also evident that sites A and C are less robust than sites D and E, since the dune at site A and the seawall at site C have been eroded and damaged by the sea. Conversely, at sites D and E the dunes remained unaffected by the swash. The conclusions obtained by the analysis of Table I agree with those reached by previous studies at Praia de Faro (Martins *et al.*, 1996; Ferreira *et al.*, 1997), using different evaluation methods.

Table I - Computed I_V values for Praia de Faro.

I_V	Site A	Site B	Site C	Site D	Site E
Mean	0.38	0.62	0.36	0.29	0.27
Max	0.41	0.69	0.44	0.34	0.34
Min	0.34	0.54	0.23	0.22	0.17

Figure 5 shows the mean values and the index variability at sites B and E, for the observed period. The difference between sites is evident, with site B having a significantly higher vulnerability index than E. With the knowledge that the dunes at sites D and E did not experienced erosion or overwash, which occurred on sites A to C, it is possible to infer a robustness limit of approximately 0.35. Above this limit coastal erosion will be frequent. Figure 6 shows the relationship between the computed index values at the different sites together with this empirical limit.

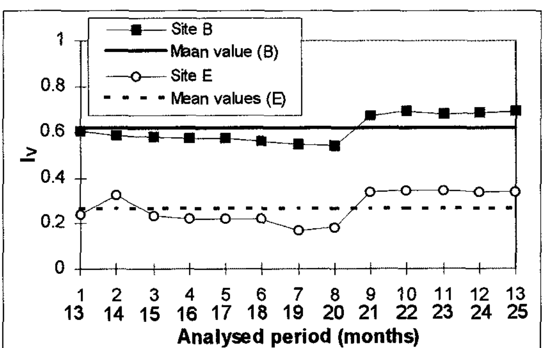

Figure 5. Index variation for sites B and E, along the surveyed period.

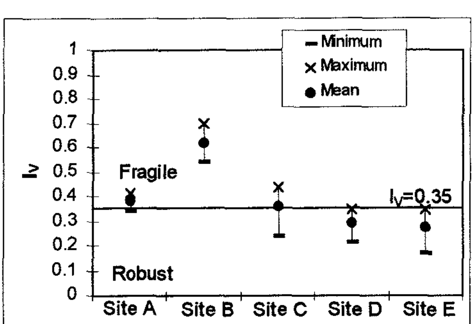

Figure 6. Determined index variability for the studied period, at each site, and its relation with the empirical limit.

Application to the Aveiro - Cape Mondego data

By the application of this index to the data resulting from the Aveiro - Cape Mondego monitoring program, it was only possible to obtain one set of I_V values, since the survey period was only 10 months in duration. From these observations two distinct groups of beaches were identified (figure 7). Three of the surveyed sites (white symbols) exhibited very high index values, and thus may be classified as extremely fragile (prone to overwash and erosion). These 3 sites (PMS, PA and VS) are placed downdrift of groins, facing strong dune retreat.

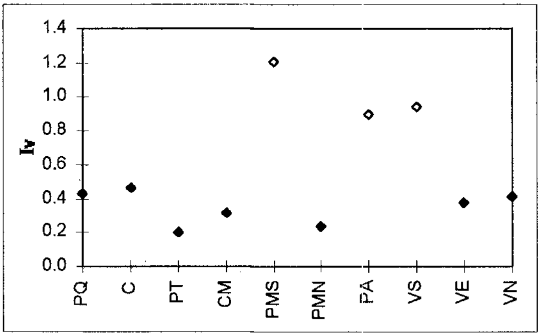

Figure 7. I_V values for the Aveiro - Cape Mondego coastal stretch.

In figure 8 the observed beach/dune retreat or accretion, for the 1980/90 period, was plotted against the computed I_V for each site. A strong correlation was observed between I_V and beach/dune evolution. These data indicate that I_V values greater than 0.9 denote extreme beach vulnerability (effective shoreline retreat higher than 2m/year).

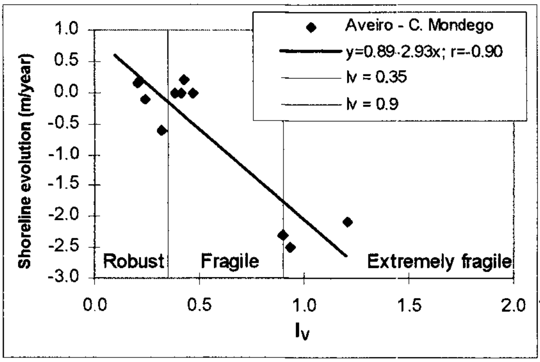

Figure 8. Relation between I_V and beach/dune evolution at Aveiro - Cape Mondego (negative values represent erosion).

Combining the results obtained by the analysis of the two coastal sectors, the following limits are proposed: $I_V < 0.35$, Robust beach; $0.35 \leq I_V < 0.9$ Fragile beach; $I_V \geq 0.9$ Extremely fragile beach.

The obtained limits are based on a restrict number of data, being necessary a future confirmation of the thresholds for other coastal areas with different wave energy and morphodynamic conditions.

Index validation

In order to confirm the results obtained by the application of the morphological vulnerability index, a validation test was performed. For this test nine beach profiles, obtained in April 1995 on the same sites of the 1992/93 surveys for the Aveiro - Cape Mondego coastal stretch, were used. The new profiles were compared with the previous ones, by measuring the observed dune retreat and computing the volumetric difference between each new profile and the corresponding average volume for the 1992/93 surveys. Table II shows the volumetric differences and the maximum observed dune retreat at each site.

Table II. Computed volumetric differences and maximum observed dune retreats between the average profiles of the 1992/93 surveys and the April 95 profiles.

Site	Volumetric difference (m^3/m)	Maximum dune retreat (m)
Praia de Quiaios (PQ)	+111.0	0
Palheiros da Tocha (PT)	+38.5	0
Canto do Marco (CM)	-38.3	0
Praia de Mira South (PMS)	-105.5	-5.1
Praia de Mira North (PMN)	-182.6	0
Praia do Areão (PA)	-141.6	-11.3
Vagueira South (VS)	-226.4	-1.6
Vagueira Central (VE)	-82.3	0
Vagueira North (VN)	-144.1	-4.1[a]

[a] Retreat due to seawall reconstruction.

A high volumetric difference occurred at most sites, showing a global erosional trend from 1992/93 to April 1995. However, an effective dune retreat only occurred at beaches where the I_V value was higher than 0.9 (PMS, PA and VS). At the other sites the dune was not reached by the sea, even if the volumetric difference was very high (e.g. PMN, where a volume change of -182.6 m^3/m was measured). This observation confirms that the robustness of a beach is not only given by the sedimentary volume exchange but mainly by the relationship between that volume and the available sand stock. Two examples of profiles from the same coastal stretch (Aveiro - Cape Mondego) showing high volumetric changes, with and without dune retreat, are presented in figure 9.

According with the obtained results, the index proved to give a good discrimination of the fragile sites, being able to point out the beaches where an effective retreat could occur.

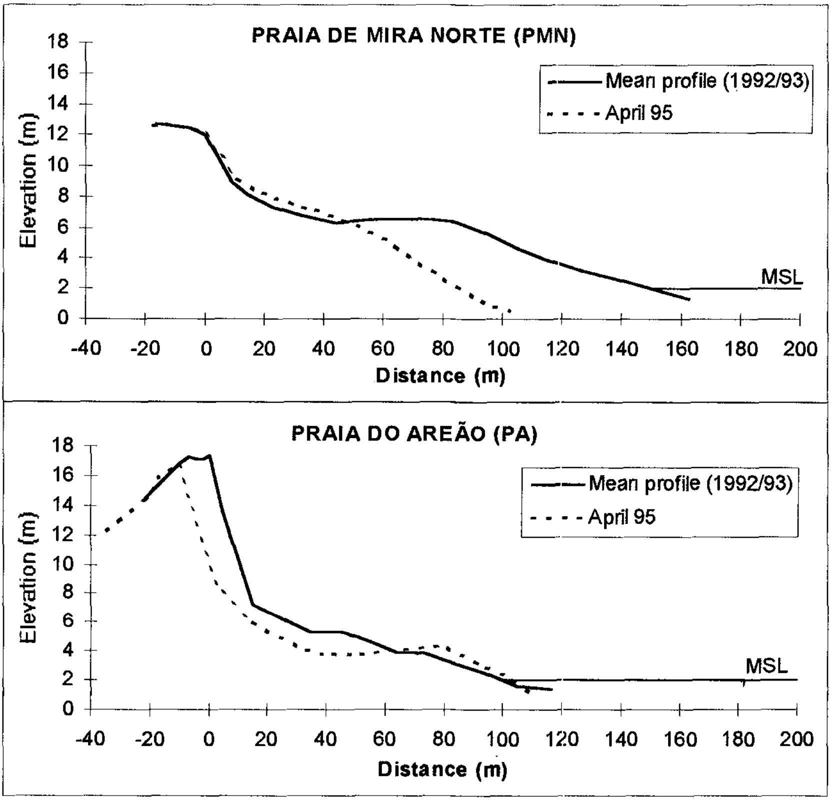

Figure 9. Comparison of behaviour between a robust (PMN) and an extremely fragile site (PA) for the same observation periods.

Conclusions

In this paper a new and simple index to determine morphological vulnerability of sandy beaches is proposed. This index was applied to 15 different Portuguese sites showing that it is possible to use simple morphological parameters to characterise the beach behaviour as well as the medium to large-scale beach evolution. For the available data sets three classes of beach behaviour are proposed: robust, fragile and extremely fragile. The morphological vulnerability index can be easily applied on beach monitoring programs, providing coastal managers a clear and simple indicator of beach stability. However, future work is required, namely in the determination of the I_V limits with larger data sets and testing the index validation to different beach types (dissipative and extremely dissipative beaches, pocket beaches, shingle beaches, etc.).

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