COASTAL DUNES VULNERABILITY INDEXES: A NEW PROPOSAL AND APLICATION TO RIA FORMOSA COAST (PORTUGAL)

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In the present work it is proposed a new coastal dune vulnerability index based on its exposure (and resistance) to overwashing and erosion under storm events, focusing solely on the short-term events. The methodology is applied and validated against the available data for the Ria Formosa (Algarve, Portugal) coastal beaches. The overwash index is determined as a function of the dune crest height in relation with the maxima water levels for different return periods, and the storm-erosion index is computed as function of the remaining beach/dune volume after the impact of the 10-year return period extreme-wave conditions in relation to the pre-storm volume. It is discussed the results of this application, enhancing the necessity of further validation.

Keywords: barrier island; maritime-storm; short-term; dune-erosion; overwashing; Ancão spit

1. INTRODUCTION

Coastal communities can be subject to losses due coastal erosion and flooding. Hence, where those communities are developed at the back of coastal dunes, it is of uttermost importance to assess the erosion and flooding risks, for which it is necessary to quantify the coastal dunes vulnerability.

In the present scope, vulnerability is understood as the characteristics of a beach/dune system that make it susceptible to the damaging effects of a hazard, in this case, from high waters and incoming waves. Hence, vulnerability here is taken as a system's fragility to the hazards, and thus will be expressed by a combination of variables, that in one hand, reveal (at least, partially) the physical robustness of a beach/dune system, and on the other hand, reflect the intensity of the hazard. It should be noted that often vulnerability is also denoted as susceptibility.

Several coastal erosion and inundation (and overwashing) vulnerability indexes have been proposed, accounting for more or less variables, depending also on the elements at risk. These can account, amongst others, for the incident wave energy, tide and surge levels, coastal geomorphology, and dune resilience. In terms of actions, one can also consider short-term effects and long-term effects. A mixture of both is used by Ferreira *et al.* (2006) to compute coastal erosion set-back lines. Another recent coastal hazard and vulnerability assessment has been presented by Garcia *et al.* (2010), focusing on overwashing intrusion. Despite all the assessments previously developed and applied at the case study site, there is the need to objectively identify and quantify the coastal vulnerability at this coast, using some of the most up-to-date predicting tools/models.

In the present work it is proposed a new coastal dune vulnerability index based on its exposure (and resistance) to overwashing and erosion under storm events, focusing solely on the short-term events. The methodology is applied and validated against the available data for the Ria Formosa (Algarve, Portugal) coastal beaches.

2. CASE STUDY DESCRIPTION

Ria formosa barrier island system is located on the south Portuguese coast (Figure 1). This multi-inlet barrier system includes a discontinuous sandy barrier, currently formed by two peninsulas and six islands, and an extensive lagoon area composed by salt marsh and sandy islands incised by a complex system of tidal channels and creeks. The barrier chain extends for 56 km alongshore and the total system covers an area of about $84\text{x}10^6$ m^2. Dias (1988) and Pilkey *et al.* (1989) associate the origin of this barrier system to changes in sea level during and after the glacial period.

The sandy barrier is highly dynamic, showing a complex evolution due to the natural longitudinal and transversal migration of the islands and peninsulas and to the human interventions in the inlets: two inlets were opened artificially and stabilized with structures (Faro-Olhão and Tavira); two were artificially relocated a number of times (Ancão and Fuzeta) and another was recently artificially opened (Cacela inlet). Due to the above, the costal strip is very fragile at several stretches, with frequent washovers at a number of locations (Matias *et al.*, 2008). In particular, it has been identified that dunes

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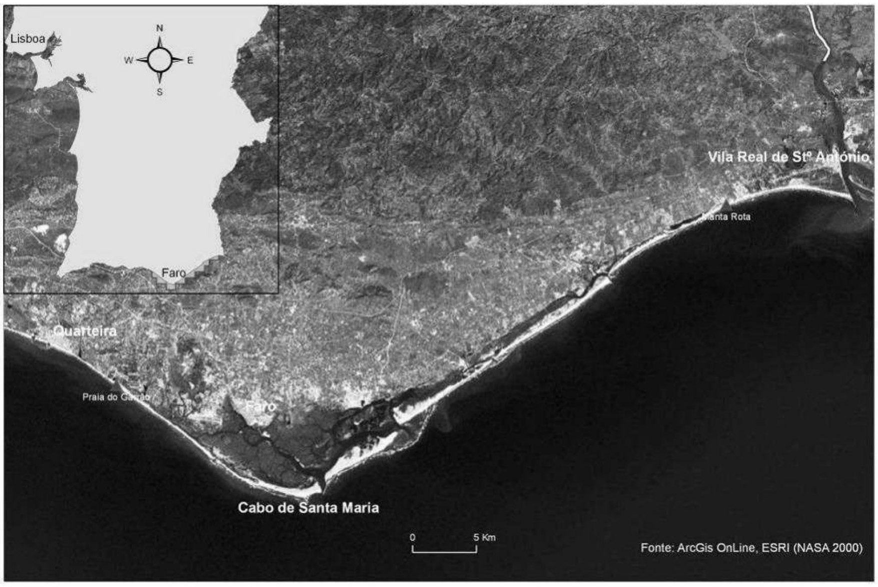
play an important role in mitigating marine erosion and submergence risks. Hence, some management actions have focused on dune rehabilitation (Matias *et al.*, 2005).

With a great importance in the local and regional economy, Ria Formosa supports several economic activities (fishing, aquaculture, tourism), and its environmental value (Natural Park since 1987) is internationally recognized (is part of the Natura 2000 network). Further, the area is subject to high real-estate and tourism development pressures.

The cuspate morphology of Ria Formosa promotes two sea fronts with differences to wave action exposure: the western area exposed to the more energetic and dominant SW wave conditions; the eastern front exposed to the SE waves. Predominant wave directions are from the W-SW (71%), with 23% coming from E-SE; 68% of the observations have significant wave heights less than 1.0 m and significant wave heights over 3.0 m (coming from SW) accounts for 2% of the observations (Costa *et al.*, 2001).

The system is mesotidal with a semidiurnal tidal regime. The tidal range varies between 2.8 m and 1.2 m for spring and neap tides respectively (Seabra de Melo, 1989). The net longshore sediment transport is directed to the east, estimated from 30 to 300 thousands $m^3 year^{-1}$ (Consulmar *et al.*, 1989).



Fonte: ArcGis OnLine, ESRI (NASA 2000)

Figure 1. Ria Formosa (Portugal) location (region within triangle markers).

3. METHODOLOGY

As identified in the introduction it is proposed a coastal dune vulnerability index accounting for dune overwashing and resilience against wave action under sea-storm conditions.

It is important to refer that the system vulnerability to long-term erosion (defined as decadal beach retreat not due to seasonal or cyclic coastal processes) and barrier-island (partial) flooding due to breaching and inlet formation was on purpose excluded from the present analysis. A specific quantification of inlet formation and mobility related hazards, for this system, is presented in Vila-Concejo *et al.* (2006). Following that work, Garcia *et al.* (2010) proposes a vulnerability index related mainly with overwashing extensions. Later, Freire *et al.* (2011) proposed a new vulnerability index accounting for dune overwashing, dune breaching and back-barrier inundation, and long-term shoreline retreat, excluding therefore the hazard related to short-term dune erosion under storm waves. The latter, however, has been earlier addressed by Ferreira *et al.* (2006), who presented set-back lines accounting both for long-term shoreline evolution and short-term (storm waves) vulnerability.

Although for general, long-term, shoreline management the methodology of Freire *et al.* (2011) is quite adequate, allowing to develop management strategies to reduce the vulnerability of hot-spots, from a predictive or operational stand-point, it is desirable to evaluate the back-beach resilience under stormy waves, which ultimately erodes and can be breached and overwashed in the most vulnerable sections of the barrier island, potentially originating a path to coastal flooding. Hence, here we combine long-term overwashing vulnerability (from Freire *et al.*, 2011) with storm-erosion vulnerability (inspired by the work of Ferreira *et al.*, 2006), using a predictive short-term beach numerical model.

The following synthesizes the methodology applied in the present work:

1. Identification of the most important coastal hazards for this specific site (the same could be extended for other sites, likely to produce different results). The outcome of this appraisal for this site is that storm wave action and high water levels are the most important hazards.
2. Evaluation of the hazard-related data in order to provide input data to the functions defined below. Particularly, as a result of the previous step, this phase involves obtaining extreme values (projections) for given return-periods using standard extreme-value analysis techniques (e.g., fitting an extreme-value probability distribution function to the yearly-maxima water levels).
3. Based on the results of steps one and two, it is proposed simple, heuristic, dune overwash vulnerability index, based on the work of Sallenger (2000), comparing the dune crest height with the water level predictions corresponding to a certain return-period. This index thus evaluates the vulnerability of the system (the dune) to one of the two hazards, namely, the high water levels.
4. Finally, in order to account for the above-identified second hazard, i.e., the wave action under storm events (that can cause main and rapid dune erosion), it is proposed here a storm-erosion vulnerability index, based on the (predicted) morphological response of the beach and dune system under a wave attack corresponding to a given return-period. This response is evaluated by means of a simple dune-resilience descriptor, such as the remaining dune volume or dune width.

The two sub-indexes which results from steps 3 and 4 above are thus adapted from previous works and developed herein. A description of them is detailed later on this section. They are both set on a scale of 1 to 4, the lower and upper bounds corresponding to low and extreme vulnerabilities, respectively, as follows:

$$I = \begin{cases} 1 & : \text{ low} \\ 2 & : \text{ moderate} \\ 3 & : \text{ high} \\ 4 & : \text{ extreme} \end{cases} \tag{1}$$

It is worth mentioning that other scales have been used by other authors, often with a broader range of classification (e.g., Williams *et al.*, 2001, Coelho *et al.*, 2006). Here, however, we choose a simple 1 to 4 scale, adapting the recommendation for susceptibility classification suggested by the Portuguese National Civil Protection Authority (Julião *et al.*, 2009).

3.1. Overwash vulnerability index

As in Freire *et al.* (2011), it is proposed here an overwash vulnerability index based on the works of Sallenger (2000). Defining this vulnerability index as Ig, it describes the susceptibility of the beach and dunar system of being overwashed through the comparison of total water level heights (including run-up) with the dune crest height. This simple approach does not account for the geological, morphological and biological aspects of the dune that influence the overwashing process (e.g., vegetation cover), by modifying the resistance of the dune crest to the erosion process caused by the incoming flow, which drives the sediment downwards along the back face of the primary dune, but captures the most important factor that controls overwash on a geo-morphologically uniform coastal sector (as in this case study), that is, the difference between dune crest height and maxima water levels.

The total water level associated with a given t (year) return period, N_t, is defined as:

$$N_t = SWL_t + R_t \tag{2}$$

where SWL_t and R_t are the mean water level and run-up height associated to the same return period t (Figure 2). In this study, the return period takes the values 5, 10, 25 and 50 years.

Eq. (2) assumes dependency of the run-up heights and water levels. If that was not assumed, one would need to have measured total water level maxima, including wave run-up, which did not occur for this site. In fact, such measurements are hardly available for any site, being common to measure separately wave-averaged water levels and wave run-up. The latter is also often estimated, instead of measured. This methodology is applied here to determine the total water levels N_t.

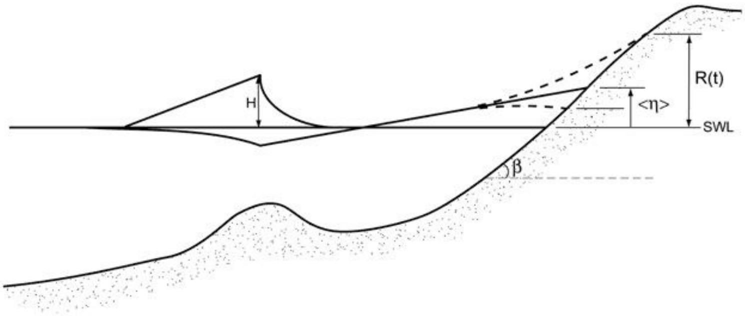


Figure 2. Definition of variables for total water calculation.

Field data from port of Huelva tidal station (*Puertos del Estado*, 2006, tidal gauge number 3326), located at about 90km away, provided time series of wave-averaged mean water levels (including tidal and storm-surge induced water levels). Despite its distance to the study site, this is the nearest tidal station with the longest record of available quality-assured data. This data has been used here to estimate the storm-surge elevations associated to the different return periods. Table 1 shows the storm-surge setup at Huelva (column 2), estimated from adjusting a Weibull distribution to the residuals (obtained by the difference between the measured levels and the predicted tidal levels) evaluated in the period January 1997 until December 2003 (7 years). Correlating the estimated residuals for two months (1st December 2009 until 31st January 2010) with the corresponding data obtained at Faro inlet (location in Figure 1), Teixeira (2010) observed a high correlation ($r^2 = 0.82$) and concluded of the validity of the following relationship:

$$S_{Faro} = 0.72\, S_{Huelva} + 9.13 \quad \text{(cm)} \qquad (3)$$

where a 15 cm on-set has already been subtracted due to the differences in zero datums (see Freire *et al.*, 2011, for details). Hence, storm-surge levels for the 5, 10, 25 and 50-year return periods are presented in the third column of Table 1.

Table 1. Storm surge projections at Huelva and Faro locations for various return periods.

t (year)	S_{Huelva} (cm)	S_{Faro} (cm)	SWL_{Faro} (m ZH)
5	68	58	4.10
10	81	67	4.19
25	98	80	4.32
50	113	90	4.42

In order to determine SWL_t in Eq. (2), storm-surge heights at Faro (S_{Faro}) are added to the mean high water spring (MHWS) tidal level determined at Faro, of +3.52 m(ZH)[†]. These results are shown in the last column of Table 1.

The choice of the MHWS level is subject to discussion. Indeed, in the present analysis it is assumed independency of tidal and wave action, but storm surge is assumed to be dependent of the wave field. As mentioned above, if that was not the case, one would have to analyse total water level data as a whole (including run-up, which data is inexistent for the present site). Hence, it is used a probabilistic analysis (fitting p.d.f. to annual maxima) in order to determine the storm-surge and wave run-up, whose levels are coupled with a "likely to occur high tide water level". Since a wave storm can last more than a day (encompassing two high tides) and spring water occurs every 14-day, it was decided to use the MHWS tide level. The mean high water (MHW) tide level could also have been used, but a conservative stance was assumed for this vulnerability assessment.

Run-up heights for each return period, R_t, are computed using 10 different run-up formulations. Being a stochastic variable, the 2% run-up height is used in the present study. That corresponds to the

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[†] Relative to the Chart Datum, named as ZH, presently at 2.15 m below mean sea level (Freire *et al.*, 2011).

level that is, for each sea-state, exceeded only by 2% of the waves [‡]. Table 2 summarizes the 10 formulae, noticing that some authors proposed more than one formula. In this table, ξ_0 represents that Iribarren number, $\xi_0 = m \big/ \sqrt{H_s / L_0}$, where m is the beach slope, H_s is the significant offshore wave height, and L_0 is the deepwater wave length associated with the wave peak period, T_p. Most of the formulae include a dependency on the beach slope, m, which has not always been clearly defined in each formula. This is a varying parameter for most beaches, changing in time and along the beach profile. As this work aims at determining extreme run-up levels under high waves at high-tide, m is defined as the mean beach-face (or foreshore) slope. This takes the value 0.13 for Faro beach (Teixeira, 2009, p.48).

Table 2. Run-up formulae used in the present computations.

Authors	*R*
Hunt (1959), Battjes (1971)	$R = m\left(H_s L_0\right)^{0.5}$
Holman e Sallenger (1985)	$R = H_s\left(0.83\xi_0 + 0.2\right)$
Holman (1986)	$R = 0.55\, H_s\, \xi_0$
Nielsen e Hanslow (1991)	$R = L_{Ru}\left(-\ln(0.02)\right)^{0.5}$ $L_{Ru} = \begin{cases} 0.6\, m\, \left(H_s L_0\right)^{0.5} & \text{se } m \geq 0.10 \\ 0.05\, \left(H_s L_0\right)^{0.5} & \text{se } m < 0.10 \end{cases}$
Raubenheimer e Guza (1996)	$R = \frac{1}{\pi} H_s\, \xi_0^2$
Masselink e Hughes (2003)	$R = 0.36\, m\, \left(g H_s\right)^{0.5} T_p$
Stockdon *et al.* (2006)	$R_A = 1.1\left\{0.35 m\left(H_s L_0\right)^{0.5} + 0.5\left[H_s L_0\left(0.563 m^2 + 0.004\right)\right]^{0.5}\right\}$ $R_B = 0.043\sqrt{H_s\, L_0}$
Teixeira (2009)	$R_A = 0.8 + 0.62 H_s$ $R_B = 1.08\, H_s\, \xi_0$

Table 3. Hydrodynamic storm conditions for the return periods 5, 10, 25 and 50 years.

Return period (yr)	Hs,max (m)	Tp (s)	Duration (day)	Surge (m)
5	6.0	11.0	5.40	0.58
10	6.2	11.5	6.14	0.67
25	6.5	12.0	7.25	0.80
50	7.0	12.5	9.10	0.90

According to Freire *et al.* (2011), the wave height and wave peak period for the return periods of 5 to 50 years at the offshore of the Ancão spit are as indicated in the first 3 columns of Table 3. These numbers were compiled from different sources, but lack of thorough validation as long and local wave height data sets are not available. Note that Ferreira *et al.* (2006) determine $H_{s,50}$=8.1 m, but from data from a buoy located on the occidental south-west coast of Portugal (off Sines).

The computed run-up heights, R_t, are presented in Figure 3. The lower three predictions correspond to those of the dissipative formulae, and are discarded. The other seven results range within ±1 m for

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[‡] The authors recognise that one could have used the "significant run-up" ($R_{1/3}$) or the mean run-up (R_m) instead of upper-limit $R_{2\%}$. Indeed it is often used $R_{2\%}$ for design purposes of coastal structures and, as such, available formulae were used herein. However, for the present characterisation of an overwashing vulnerability index, a less extreme run-up level could have been used. The choice certainly is related with the risk levels associated with the occurrence of overwash events.

each return period, providing consistency to the estimates. In order to obtain a single value of R_t for each return period, it was decided to further ignore the highest and lowest estimates from the seven accepted ones, and then to compute the average of the remaining five central estimates. Adding to the average run-up heights the mean water levels, SWL_t, given in Table 1, the total water levels, N_t, result as 8.5, 8.8, 9.1 and 9.7 m (ZH) for the 5, 10, 25 and 50 yr return periods, respectively.

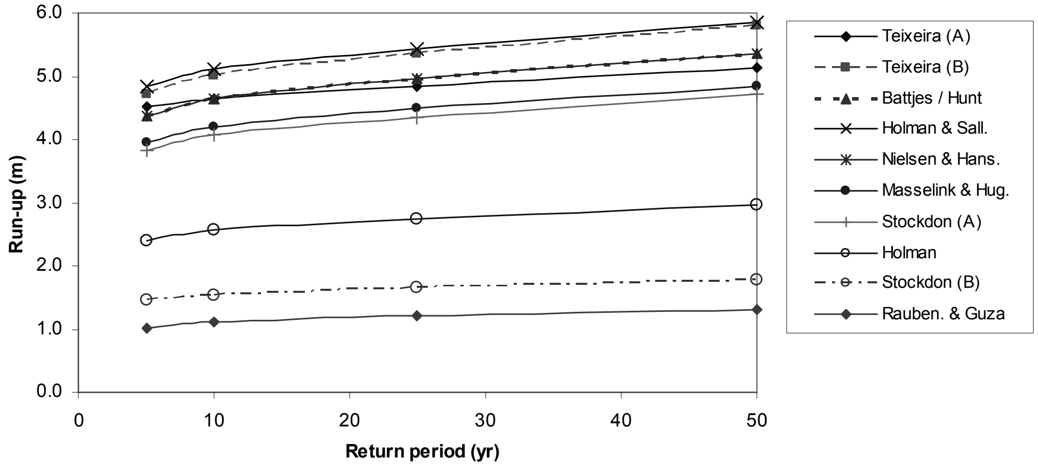

Figure 3. Run-up at Ancão spit as a function of the return period and predictive formula.

With both the mean water level and run-up height determined for each return-period, Eq. (2) allows to determine the corresponding maximum water levels, N_t, where t stands for the return period value. Those are compared with the dune crest height, h_c, as follows, forming the proposed overwash vulnerability index, I_g:

$$I_g = \begin{cases} 1 & \text{if } h_c > N_{50} \\ 2 & \text{if } N_{25} < h_c \le N_{50} \\ 3 & \text{if } N_{10} < h_c \le N_{25} \\ 4 & \text{if } h_c \le N_{10} \end{cases} \qquad (4)$$

The rationale for the above is that the vulnerability is extreme (I_g=4) if the dune crest height is lower than the 10-year return period total water level, and the vulnerability is low (I_g=1) if the dune crest height is higher than the 50-year return period total water level, meaning that it would (on average) be overwashed once in 50-years. Although the above limits and index are subjective and subject to discussion, it was defined according to the historical episodes in the study site, and agree with the results of other similar indexes.

3.2. Storm-erosion vulnerability index

As stated above, a storm-erosion vulnerability index is proposed, based on the (predicted) morphological response of the beach and dune system under a wave attack corresponding to a given return-period. This response is evaluated by means of a simple dune-resilience descriptor, such as the remaining dune volume or dune width.

Aiming at estimating beach and dune erosion and consequent retreat of the dune face during extreme maritime storm events, the process-based morphodynamic numerical model XBeach (Roelvink *et al.*, 2009), version 18, is applied and tested for storm conditions (wave and surge) corresponding to the return periods of 5, 10, 25 and 50 years.

The reference morphological and sedimentological conditions are here considered as part of the initial numerical conditions for the XBeach model. The reference morphological conditions correspond to a cross-shore profile located at cross-section 90, at the east of the central inhabited part of Faro beach. Its elevation was obtained by joining the depth, from -9.4 m (ZH) to 1.3 m (ZH), obtained from a hydrographic survey, to the dune geometry data, obtained through a LIDAR topographic survey. The reference sedimentological conditions, obtained through the sediment size analysis of a beach face surface sample, correspond to median grain size D_{50}=0.58 mm, and 90th-percentile grain size D_{90}=0.87 mm.

The first steep of the methodology was the identification of all the storms for which $H_{s,max}$ exceeded 4.5 m, using a 10-year (1998-2007) set of field data (from Faro-offshore wave buoy) with failure periods replaced by hindcast data (Capitão *et al.*, 2009). This yielded nine major storms, of which seven of them had South-west incoming waves, hence nearly perpendicular to the Ancão-spit coastline and with greater impact than south-east waves. The significant wave height time series from those seven storms is shown in Figure 4a. The maximum significant wave height occurring at each storm was positively correlated with the storm duration (Figure 4b), allowing to establish a relation between these two variables, and to determine a storm duration associated to each return period (4th column in Table 3). In the above, storm duration was identified as the period ranging from the first record immediately before and immediately after H_s=3.0 m, within the wave time series.

One of the seven storm-wave time series (Figure 4a) was chosen and scaled (up or down) in order to have the storm-wave characteristics determined in Table 3. In this case, the storm that occurred from 29/Jan/1998 until 06/Feb/1998 was selected (filled squares markers in Figure 4a).

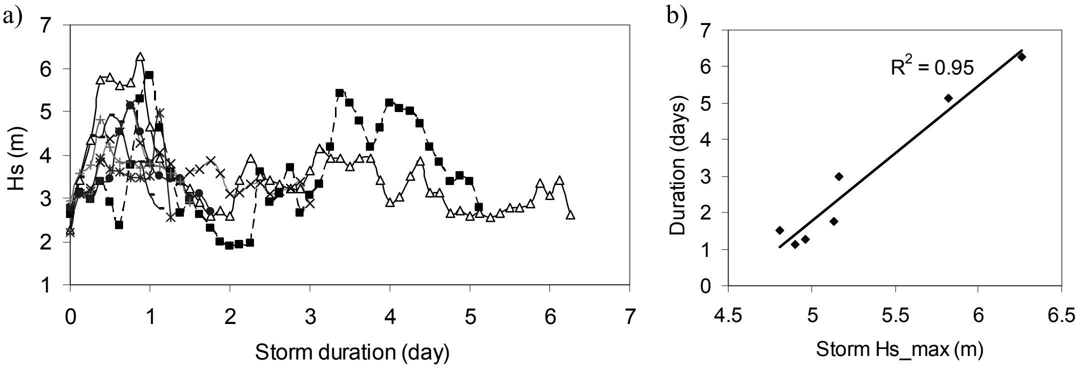

Figure 4. a) Major south-west storms offshore Ancão spit in the period 1998-2007; b) Storm duration versus $H_{s,max}$.

The water level input series applied in the XBeach model for each of the four return periods was determined from the tidal reconstitution of the water level that occurred for the storm selected above (from 29/Jan/1998 until 06/Feb/1998). To this time series was then added the storm surge contribution associated to each return period (5h column in Table 3).

Hence, all the time series of the hydrodynamic storm conditions, corresponding to the return periods 5, 10, 25 and 50 years, applied in the XBeach model are characterized by the parameters described in Table 3.

Figure 5 shows the modelled cross-shore profiles at the end of the applied storm-wave time series, associated to each return period. As expected, the model predicts beach foreshore and dune erosion, and accretion in the lower nearshore zone, offshore the breaker bar. Also, increasing return periods (and storm intensity) cause greater dune erosion.

The model results of interest for the present study are essentially the cross-shore beach/dune width (at several elevation levels) and the beach-dune volume (above several elevation levels). These are related with the beach profile evolution as seen in Figure 5. Indeed, for example, one observes that the beach/dune system has an initial width of about 200 m at height 2.5 m(ZH), which is considerably reduced as the beach erodes as a result of the different storm-wave impacts. The same occurs for the beach-dune volume that remains above a given height.

A storm-erosion vulnerability index, I_{SE}, is thus proposed based on the remaining non-dimensional beach/dune volume after the (modelled) impact of the 10-yr return-period storm-wave:

$$I_{SE} = \begin{cases} 1 & \text{if} \quad \frac{V_{10}}{V_i} > 60\% \\ 2 & \text{if} \quad 40\% < \frac{V_{10}}{V_i} \le 60\% \\ 3 & \text{if} \quad 20\% < \frac{V_{10}}{V_i} \le 40\% \\ 4 & \text{if} \quad \frac{V_{10}}{V_i} \le 20\% \end{cases} \tag{5}$$

where V_i is the initial beach/dune volume above 2 m (ZH), and V_{10} is remaining the beach/dune volume above 2 m (ZH) at the end of the 10-yr return period sea-storm. It is remarked that the present mean water level is set at 2.15 m (ZH). Thus, the proposed volume definition is basically the beach/dune volume above the mean water level.

Essentially, the above defines that the storm-erosion vulnerability is extreme (I_{SE}=4) if the remaining beach/dune volume after the occurrence of a 10-year return period storm is smaller than 20% of the initial (in this case, the pre-storm profile) beach/dune volume. By other words, the storm-erosion vulnerability is extreme if the beach/dune system losses more than 80% of its initial volume (in this case, determined at height 2 m (ZH). As the opposite extreme case, the storm-erosion vulnerability is low (I_{SE}=1) if the beach/dune remaining volume after a 10-year return period storm is greater than 60% of its initial volume.

The limits given in Eq. (5), like the elevation levels above which the remaining dune is of relevance, are subject to discussion and validation. Further, these limits are somewhat subjective (as are the classes “low”, “moderate”, “high” and “extreme”) and depend on the assets and values (social, economical, and environmental) to protect. In this paper, we propose this equation and apply it to a single beach profile at the Ancão-spit coast.

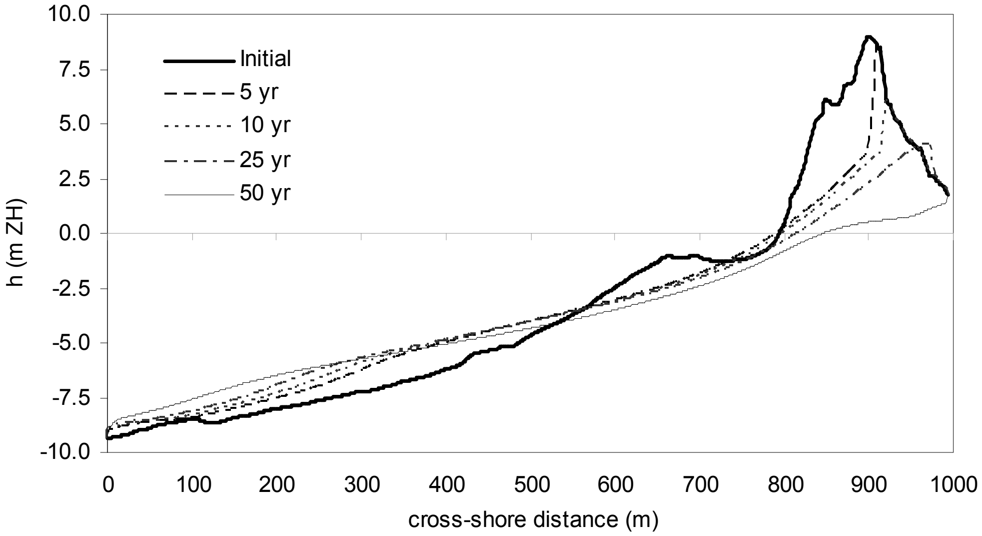

Figure 5. Final beach profile at the end of a storm with a given return period.

4. RESULTS AND DISCUSSION

4.1. Overwash vulnerability index

A comparison of the total water levels (determined in section 3.1) and the dune crest height along the shore (sections 100 m apart) at Ancão spit is given in Figure 6a. Applying the overwash vulnerability index definition (Eq. 4), it is plotted in Figure 6b the alongshore variability of that index for the same coastal sector.

Both figures evidence that the Northern-western sector (to the left) is more robust, with the dune crest heights above the 50-yr water level, indicating thus low vulnerability (I_g=1). On the opposite, the central beach (sections ~65 to 80), just in front of the shore-front residences of Faro beach, have the lowest dune crest heights, and are therefore an extremely vulnerable sector (I_g=4). In this region the dunes have been intensely modified by the human action, and are inhibited of developing and moving naturally. Further east (sections 80 to 90), the high-to-extreme vulnerability is in region of the lagoon-side inhabited town, thus allowing the ocean-front dune to evolve more naturally, although not reaching the height of the western sector.

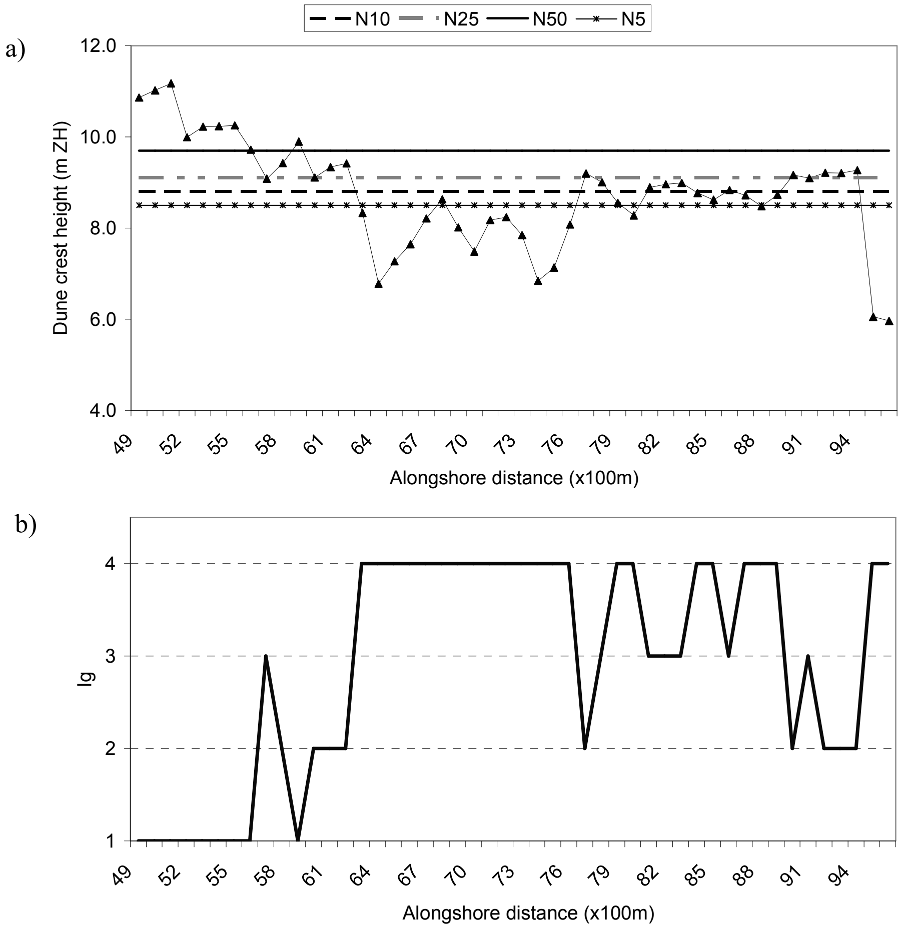

Figure 6. a) Dune crest height at Ancão spit and total water levels for each return period; b) Overwash vulnerability index along the Ancão spit.

4.2. Storm-erosion vulnerability index

Figure 7a shows the remaining beach/dune volume above the 2 m (ZH) and 4 m (ZH) heights, after the wave action of a given return-period storm, as compared to the initial one. This figure clearly illustrates that the beach/dune volume (e.g., defined above the 2 m height, that is, approximately the mean water level) reduced by nearly 50% at the impact of a 5-yr return period storm. For the 25-yr return period storm, the volume reduces to about 25%, and at the end no beach/dune remains above the 2 m (ZH) level. If one considers the 4 m(ZH) height, no volume remains above after the 25-yr return period storm. A similar behaviour is given by the parameter "beach/dune width", corresponding to the base-width of the beach/dune that rests above a given height, shown in Figure 7b.

From Figure 7a-b, one concludes that both the volume above or width at 4 m(ZH) are not suitable indicators of beach/dune resilience, as they decay fast towards zero, even at the impact of a storm with return-period less than 50 years. Moreover, the remaining beach/dune volume appears to be a better indicator of the resilience (as an opposite of vulnerability) than the beach/dune width, as the latter is a one-dimensional variable whereas the former includes that linear dimension and the vertical one (since the volume here considered is estimated assuming that the cross-shore profile area above 2 m(ZH) is constant per alongshore meter). Nevertheless, for most natural systems it is expected to exist a "natural" relation between beach/dune width at and volume above a certain height. However, it is also expected that this relation must be highly dependent on other characteristics of the dune, like the geological, the morphological and the biological characteristics, which are known to be correlated to the dune consolidation.

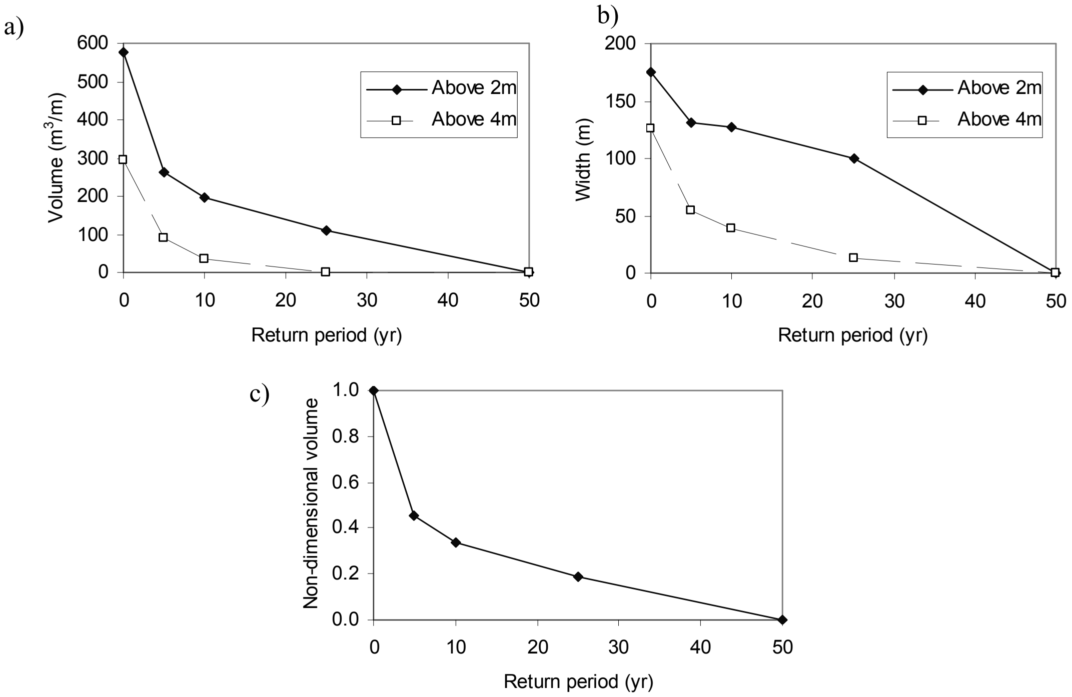

Figure 7. a) Remaining beach/dune volume after each return period storm-wave impact; b) same as a) but for the beach/dune width; c) same as a) but for the non-dimensional volume above 2 m(ZH).

Figure 7c shows the evolution of the beach/dune volume above 2 m(ZH) for the different return-periods, divided by the initial beach/dune volume.

Considering the proposed vulnerability indicator expressed by Eq. (5), Figure 7c further indicates that the beach/dune volume after the occurrence of a 10-year return period storm, V_{10}, is 33% of the initial beach/dune volume above 2 m (ZH), V_i. Therefore, based on the limits established in Eq. (5), it is concluded that I_{SE}=3, that is, the beach/dune system is highly vulnerable to storm-erosion.

This classification agrees with the one obtained at this section (cross-section 90) for the overwash vulnerability index, I_g=2 (see Figure 6b). At the neighbouring sections, 89 and 91, I_g=4 and I_g=3, respectively. Hence, averaging the overwash vulnerability index in a 300 m alongshore sector, this index results as "high". Although the overwash vulnerability and the storm-erosion vulnerability do not necessarily need to have the same value, as the dune height is a variable that directly and indirectly affects those indexes, respectively, it can be expected in some cases to exist equality between the values of these two indexes in the same area.

With respect to Eq. (5), it was selected to use the beach/dune volume at the end of the 10-year return period sea-storm, V_{10}. Determining storm wave conditions corresponding to a 10-year return period is generally accessible and does not require long time series of data (5 to 10 years are accepted). If one used a larger return-period condition for the storm-erosion vulnerability indicator, then one ideally needed to have longer data in order to determine the larger return-period storm-wave condition. That assessment would inevitably include greater errors in the estimates, and thus is desirable to define the storm-erosion vulnerability on the basis of a variable less prone to errors in the estimates.

According to this idea, the beach/dune volume at the end of the 5-year return period sea-storm, V_5, could have been used instead of V_{10}. Indeed such variable (V_5/V_i) was tested, with different limits for the levels of vulnerability with respect to those given in Eq. (5). As an alternative, one could thus consider:

$$I_{SE} = \begin{cases} 1 & \text{if} \quad \frac{V_5}{V_i} > 80\% \\ 2 & \text{if} \quad 60\% < \frac{V_5}{V_i} \leq 80\% \\ 3 & \text{if} \quad 40\% < \frac{V_5}{V_i} \leq 60\% \\ 4 & \text{if} \quad \frac{V_5}{V_i} \leq 40\% \end{cases} \qquad (6)$$

where the limits of V_5/V_i for each class have all been increased by 20% in relation to those when considering V_{10}/V_i .

As before, these numbers are subjective, but it appears reasonable to have low vulnerability of a system when its beach/dune volume after the impact of a 5-yr return period storm remains above 80% of the pre-impact beach/dune volume. Nevertheless, this will be subject to further investigation.

5. CONCLUSIONS

This work provides new indexes to determine a coastal system vulnerability to extreme wave action and high waters due to coastal storms. The methodology is applied at the Ria Formosa (Algarve, Portugal) coast, in particular, in an area of the Ancão spit. It is identified that wave action and high waters are the dominant hazards, potentially inducing dune overwashing and short-term storm-erosion. Hence, here we combine here long-term overwashing vulnerability (from Freire *et al.*, 2011) with storm-erosion vulnerability (inspired by the work of Ferreira *et al.*, 2006), using a predictive short-term beach numerical model.

It is proposed simple, heuristic, dune overwash vulnerability index, based on the work of Sallenger (2000), comparing the dune crest height with the water level predictions corresponding to a certain return-period. This index is traduced by means of Eq. (4), and the application of it enables to determine the overwashing vulnerability index at Ancão spit, and confirm that the region in front of the main ocean-front residential area of Faro beach is the most vulnerable.

Secondly, in order to evaluate the effect of the high-waves hazard, i.e., the hazard posed by the wave action under storm events that cause main and rapid dune erosion, it is proposed a storm-erosion vulnerability index, based on the (predicted) morphological response of the beach and dune system under a wave attack corresponding to a given return-period. This response is evaluated by means of a simple dune-resilience descriptor as the non-dimensional remaining beach/dune volume above a certain height (in this case, approximately at the mean water level), after the 10-year return period wave action. Using the XBeach model to predict the beach profile evolution after the impact of a certain return period hydrodynamic condition, it is concluded that the Ancão beach sector east of the main ocean-front residential area presents high vulnerability to storm erosion, a figure identical to the overwashing vulnerability index for that location.

Finally, it is exposed that the proposed vulnerability indexes are defined subjectively (as all other similar indexes), but agree with the vulnerability classifications for this site proposed by other authors (e.g., Ferreira *et al.*, 2006). Nevertheless it is concluded that further research is necessary to further assess and validate the proposed vulnerability indexes.

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