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Resumo

Galgamentos oceânicos são processos naturais sobretudo relacionados às tempestades. Sua prinicpal causa é a elevação do espraio acima do nível dunar. Como resultado são gerados fluxos de sedimento e água através da crista da duna e isto pode acarretar efeitos ao ambiente costeiro, comunidades e estruturas de engenharia. Atualmente regiões costeiras são amplamente ocupadas e, por isso, dentro do contexto de manejo costeiro, faz-se necessário a identificação de áreas susceptíveis ao galgamento. O presente estudo propõe-se a identificar áreas vulneráveis ao longo da Península do Ancão, Portugal, através do desenvolvimento de um mapa de vulnerabilidade. Para tal, foram realizados levantamentos topográficos da base (D_{LOW}) e crista (D_{HIGH}) dunar e os dados foram representados sobre um ortofotomapa em SIG. Foram estabelecidas três tempestades com 5, 10 e 25 anos de período de retorno e estimadas as características das ondas e níveis do mar (maré e sobreelevação meteorológica) associados. Estes dados possibilitaram o cálculo da elevação máxima do espraio (R_{HIGH}) através de uma parametrização direcionada às praias intermédias-reflectivas. A representação de R_{HIGH} sobre D_{LOW} e D_{HIGH} com uso de SIG resultou no mapa de vulnerabilidade. A base dunar da península é completamente vulnerável ao regime de colisão, isto é, as dunas estão em risco de erosão e recuo para qualquer dos períodos de retorno testados. O processo de galgamento está previsto principalmente na região próxima da barra de maré e na porção central onde a ocupação humana é intensa, neste caso podendo ocorrer com período de retorno de 5 anos. O método utilizado considera as principais forças causadoras dos galgamentos e é capaz de mostrar áreas em risco. Logo, é potencialmente importante para o manejo costeiro pois permite ações mitigadoras das conseqüências negativas em zonas costeiras ocupadas.

Palavras-chave: Galgamento Oceânico, Sobreelevação Meteorológica, Espraio, Ilhas Barreiras, Portugal, SIG.

Abstract

Overwash is a natural process mainly related to storm events. The major cause is the run-up elevation over the dune crest. Consequently, there is a flow of water and sediment over the dune and the process can affect coastal environment, communities, and engineering structures. Nowadays, coastal regions are extensively occupied; therefore, in the coastal management perspective there is the need to identify areas which are vulnerable to overwash. This study proposes the detection of these areas in the Ancão Peninsula, Portugal, by outlining a vulnerability map. Dune base (D_{LOW}) and crest (D_{HIGH}) were surveyed and plotted in orthophotographs using GIS-based software. Three different storm scenarios (5, 10 and 25 - year return period storms) and the associated waves and sea level (tide and storm surge) were established. According to these data, extreme wave run-up (R_{HIGH}) was calculated by a parameterisation set for intermediate-reflective beaches. The maps for collision and overwash regimes were designed by plotting R_{HIGH} values over the D_{LOW} and D_{HIGH}, using GIS. Dune base along the Ancão Peninsula is fully vulnerable to the collision regime, i.e. dunes are under erosion and retreat hazard for all the storm scenarios tested. The overwash process was identified mainly along the tidal inlet hazard area and within the human-occupied portion of the beach, where overwash was predicted with a 5-year return period. The method that was applied considers the main overwash driving forces and is able to depict hazardous areas. Therefore, it is potentially important for coastal management by enabling mitigatory decisions toward the negative consequences within occupied coasts.

Keywords: Overwash, Storm Surge, Run-up, Barrier Island, Portugal, GIS.

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1. Introduction

Coastal occupation is growing rapidly and contributes to increase the storm impacts risks at coastal regions. Occupied and natural coastal areas are subject to storm processes that cause beach and dune erosion, and overwash. Overwash results from the combination of storm surge and wave set-up (*i.e.* wave run-up) overtopping beach crest or coastal defences.

An overwash occurrence may be followed by inundation, onshore sediment transport, and wave attack. These processes are responsible for loss or damage of property as a result of flooding and sediment intrusion; damage of roads and other infrastructure; intrusion of sediment in navigation channels; requirement to remove washover deposits from public and private property; loss of mainland protection afforded by protective barriers or dunes if they are lowered by overwash; changes in natural backshore environment, shoreline recession, barrier island migration and increased susceptibility to barrier breaching (Kraus et al., 2002; Donnelly, 2006; Matias 2006; Vila-Concejo et al., 2006).

There is a need for classifying coastal lands and evaluating storm hazard vulnerability. These components are fundamental to forecasting storm impacts concerning the densely occupied coastal areas and the hazards caused by overwash. The potential exposure of a particular segment of coast depends on a number of variables including storm and coast characteristics. To assess overwash vulnerability the most important parameters to be evaluated are the high water levels, caused by high waves superimposed on the storm surge, beach morphology, and dune crest height. The assessment can be represented on a map of vulnerability, a valid tool for coastal zone management and decision making.

Donnelly et al. (2006) mention overwash occurrences along the coasts of Australia, Canada, Denmark, Ireland, Portugal, Spain, U.K., U.S.A., the Baltic and the Black Seas and the Great Lakes in Canada and in U.S.A.. In Portugal this natural process is well described within the Ria Formosa system by Andrade (1990), Andrade et al. (1998), Matias (2006), Matias et al. (2008) and Garcia (2008). By applying different methods these studies assert the Ancão Peninsula as a coast prone to overwash events. However, a map of overwash vulnerability set by oceanographic parameters and beach crest elevation survey has never been developed.

This dissertation is based on the establishment of overwash vulnerable areas along the Ancão Peninsula, which is located in Algarve, in the south of Portugal. In order to achieve the main research goal of this research, a set of intermediate objectives was established: the analysis of potential overwash according to hydrodynamic conditions; the investigation of overwash vulnerability according to barrier morphology and human intervention; the design of vulnerability maps depicting areas that are vulnerable to overwash and collision regimes; and the discussion about areas prone to overwash and the necessity of a coastal zone management and decision making plans.

2. Study Area

2.1. General Characteristics

The Ria Formosa is a barrier island system that constitutes the main physiographic unit of central and eastern Algarve coast (Figure 1) in southern Portugal (Andrade et al., 1998). The current configuration of the barrier system comprises seven barriers (two peninsulas and five islands) that stretch over 55 km. The connection between the backbarrier area and the ocean is through six tidal inlets. The system shows a cuspate shape with a western and an eastern flank, NW-SE and NE-SW oriented, respectively.

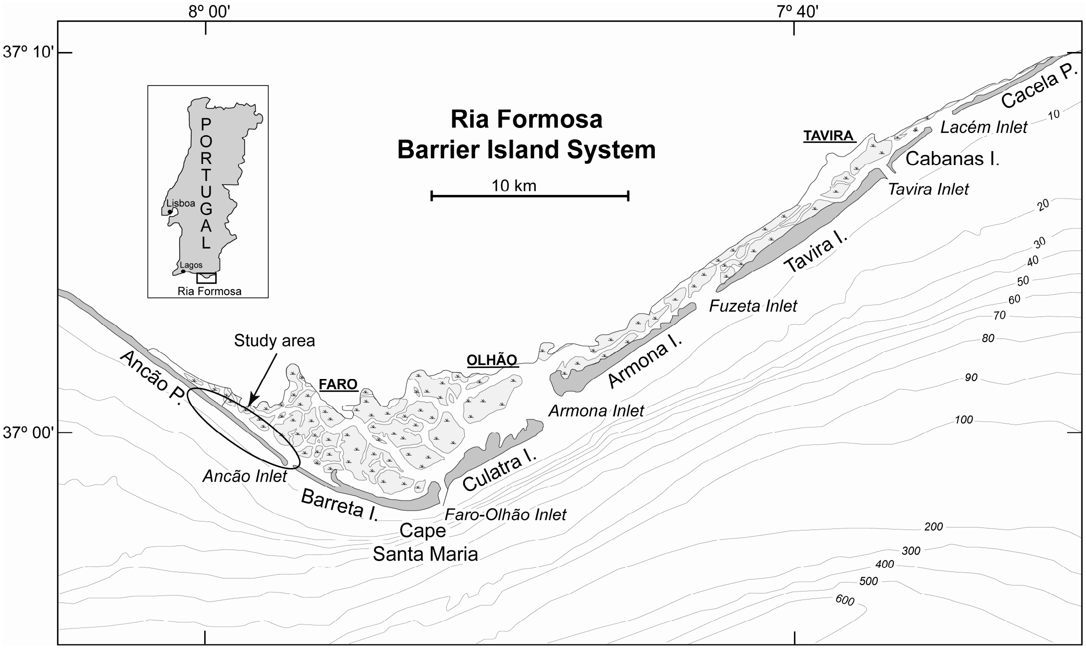

Figure 1 - Location of the Ria Formosa barrier system, comprising tidal inlets (italic), islands (I.), peninsulas (P.) and mainland cities. The area within the circle represents the study area (adapted from Matias et al., *in press*).

The Ancão Peninsula is located in the western flank of the Ria Formosa system. It constitutes the western attachment of the barrier system to the mainland. The mainland is composed by a soft cliffed coast. The length of Ancão Peninsula is variable (from 8.5 to 12.8 km between 1947 and 2001; Matias, 2006) because of changes in the Ancão Inlet position, which migrates eastward at rates of 40 to 100 m/year (Vila-Concejo et al., 2006). The peninsula is narrow (Figure 2) ranging from 50 to 250 m wide and the dunes can be single crested and high (5.5 m MSL; Matias, 2006). The ridge can be divided into three segments, west, central and east (Ferreira et al., 2006).

Figure 2 –The narrow and single crested dune ridge located between the backbarrier lagoon and the ocean at the western part of the Ancão Peninsula.

The eastern part is a low-density population area, consisting mostly of a fishermen settlement located mainly in the backbarrier margin. It is a dynamic area and the ocean front evidences accretion by the existence of a wide and vegetated backshore. Dunes are lower and incipient and consequently periodically overwashed (Ferreira et al., 2006). The Ancão Centre sector, which includes Praia de Faro, hosts an urban development that had the dune ridge completely destroyed by the construction of recreational and residential infrastructure (Matias et al., 2008). Some parts of the ocean front have been artificially stabilised with revetments in order to avoid shoreline retreat (Ferreira et al., 2006); this fact confirms the tendency in the sediment dynamics to be conditioned by anthropogenic activities (Matias, 2006). These structures inhibit shoreline retreat but are often overwashed during non-storm conditions, as previously observed in equinoctial spring tides (Matias et al., 2008) or in stormy conditions (Ferreira et al., 2006) (Figure 3). The western area is characterised by a stable and continuous foredune with blowouts and bluffs. There is a permanent scarp defining an ongoing shoreline retreat process (Ferreira et al., 2006).

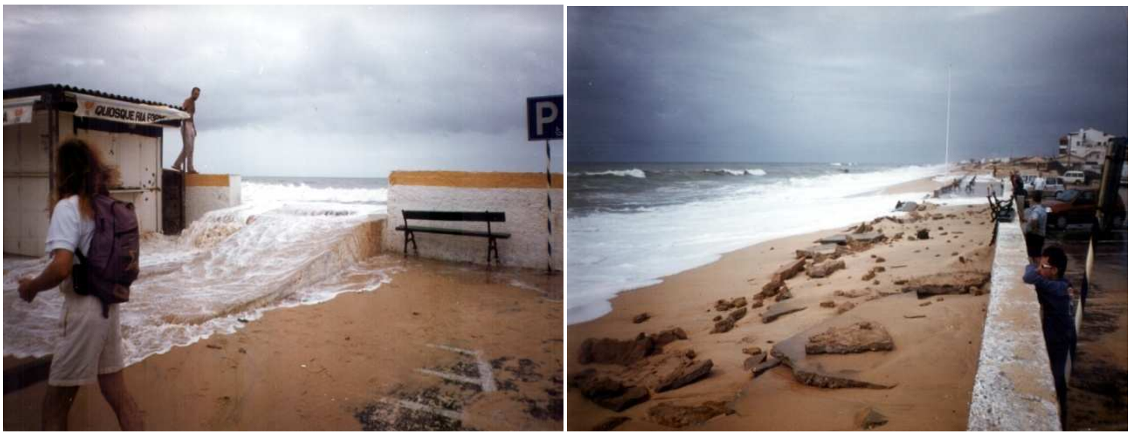

Figure 3 – Storm impacts in the Ancão Peninsula. (a) Overwash occurring within one of the gaps for beach access. (b) Storm damages in Praia de Faro.

2.2. Forcing Mechanisms

2.2.1. Climatic Characteristics

Climatic data were collected by a meteorological station located at Faro Airport and compiled by INMG (1991). They included wind, air temperature, and rainfall data in Faro from 1970 to 1980. Dominant winds in Faro are from the westerly quadrant (SW, W and NW) during 51% of the registered time. Throughout autumn and winter, the dominant winds are from the northerly quadrant (NW, N and NE) corresponding to 43% of the time. Westerly quadrant winds are prevalent during 62% of the spring time and 61% of the summer. The percentage of Levante events (E-SE) can represent 25% during the autumnal season.

The average annual value of the air temperature is 17.0°C. The values of the average monthly temperature vary regularly over the year, with a maximum in August (23.2°C) and a minimum in January (12.0°C).

Ria Formosa can be considered a semi-arid area (Faria et al., 1981). Annual rainfall ranges from 450 mm to 590 mm. The maximum number of consecutive days with no rain in Faro is about 188 days (Machado, 1980).

2.2.2. Oceanographic Characteristics

The study area is mesotidal with a mean tidal range of 2.8 m during spring tides and 1.3 m during neap tides with a maximum tidal range of 3.5 m (Vila-Concejo et al., 2006). The return period of a sea level 2.23 m above MSL (including storm surge) is 10 years (Gama et al., 1994).

The offshore wave climate is dominated by W-SW waves (71% of occurrences; Costa et al., 2001). Southeast waves (locally called Levante) that consist of short period waves generated by regional winds are also frequent (about 23%; Costa et al., 2001). Wave energy is moderate with a significant offshore wave height of 1.0 m (annual average) and an average peak period of 8.2 s (Costa et al., 2001). According to Costa (2001) calm sea with significant wave height lower than 1 m is registered during 68% of the year.

Storm is defined as an event with significant offshore wave height higher than 3 m (Pessanha and Pires, 1981; Melo, 1989; Costa, 1994). From 1986 to 1993, storm conditions corresponded to 1% of the offshore wave climate (Costa, 1994). Southwest storm waves have a significant average height higher than Levante storms (Costa, 1994). Southwest storms (64% of occurrence; Costa et al., 2001) can be harmful to the coast and can last for longer than 2 days; usual mean values for wave period and significant wave height are 8-11 s and 4 m, respectively (Andrade et al., 1998). Southeasterly storms (32% of occurrence; Costa et al., 2001) are short lived, waves demonstrate short period (6-8 s) and the maximum wave height is generally less than 5 m. A 5 m SE storm has an estimated return period of 50 years, while a 5.7 m SW storm is expected every 5 years (Pires, 1998).

The cuspate shape of the Ria Formosa system produces two areas under different breaking wave conditions (Matias, 2006). Since the Ancão Peninsula is located within the western flank of the system, it is directly exposed to the W-SW waves, which are dominant and more energetic. At the same time, this coastal patch is protected from Levante waves.

Net alongshore currents and littoral drift in this area are typically from west to east. For the western flank, various authors have presented estimations of net alongshore transport rates. Values obtained by the aforementioned authors range from 6,000m^3/year (Andrade, 1990) to 300,000m^3/year (Bettencourt, 1994).

3. Literature Review

Overwash is an important sedimentation-erosional process on barrier islands and spits (Leatherman, 1979b). It was primarily defined as the continuation of the swash uprush or wave run-up over the crest of the most landward (storm) berm (Shepard, 1973). Donnelly et al. (2006) define overwash as a natural event, which causes a flow of water and sediment over the beach crest that does not directly return to the water body (sea, ocean, bay or lake). According to Leatherman (1979a), the overwash surges result in the transport of considerable quantities of seawater and sediment to the backbarrier zone. The sediment is deposited on the barrier flats, marsh, or bay, depending on the width of the island and the storm magnitude.

The distinction between overwash and overtop over the barrier crest is set by Orford and Carter (1982). Overtopping and overwashing are complementary processes that are part of a continuum of wave/swash-related actions, whereby water and entrained sediment move landward over the barrier crest. Overtopping may be considered a process in which swash excursions just carry over the crest, causing vertical accretion at the swash-limit in the presence of rapid percolation through the dune crest. Overwashing is an extension of overtopping since it requires an increased volume of swash capable of generating a competent, unidirectional flow predominantly unaffected by percolation. Overwashing causes horizontal accretion on the backbarrier in the form of washover fans. Both processes can occur at the same place on the barrier crest under conditions of increasing or decreasing wave height, rising or falling tidal stage, and waxing or waning meteorological surge (Orford and Carter, 1982).

Matias (2006) sets two concepts: overwash flow and overwash event. The former is the simple passage of water over a determined beach crest. The latter is defined by a set of overwash flows that occur consecutively throughout a particular combination of oceanographic and morphologic conditions.

An overwash event is stated as a storm related phenomenon (*e.g.* Leatherman 1979a) that commonly occurs on sandy barrier beaches (*e.g.* Morton and Sallenger, 2003). Under non-storm conditions, overwash events can have the frequency of spring high tides (Matias, 2006). Overwash occurrence is dependent on different types of conditions. Factors controlling frequency, intensity and penetration of overwash include: marine conditions, such as wave height, wave period and tidal phase during storm peak (Fisher et al., 1974); surge height (Morton and Sallenger, 2003); relative orientation of a coast to the storm (Fletcher et al., 1995); nearshore bathymetry (Ritchie and Penland, 1988); barrier width (Morton and Sallenger, 2003), dune elevation (Sallenger, 2000); presence or absence of dune vegetation (Cleary and Hosier, 1979); and engineering structures (Hayden and Dolan, 1977). The overwash penetration distance decreases with barrier width, and increases with proximity to open water on the landward side. Wind stress can augment overwash processes by accelerating currents and generating water velocities that otherwise would not be obtained by wave run-up alone (Morton and Sallenger, 2003). The largest enhancement of flow velocity occurs when the wind direction and the angle of wave approach are both directed onshore (Morton and Sallenger, 2003).

Sallenger (2000) developed a storm impact scale which categorises the interaction between storm processes and barrier island geomorphology. The scale considers four different regimes which demonstrate great variation in magnitudes of change. The scale is based on four parameters: R_{LOW}, R_{HIGH}, D_{LOW} and D_{HIGH} (Figure 4a). R_{HIGH} and R_{LOW} correspond, respectively, to the high and low elevations of the landward limit of swash relative to a fixed vertical datum. R_{LOW} represents the continuously subaqueous elevation of a beach. Both parameters include elevation due to astronomical tides, storm surge and vertical height of wave run-up. D_{HIGH} is the elevation of the highest part of the "first line of defence" along a barrier beach, *i.e.* the elevation of the foredune ridge. Where the foredune ridge is present, D_{LOW} is the elevation of the base of the dune, otherwise $D_{HIGH} = D_{LOW}$.

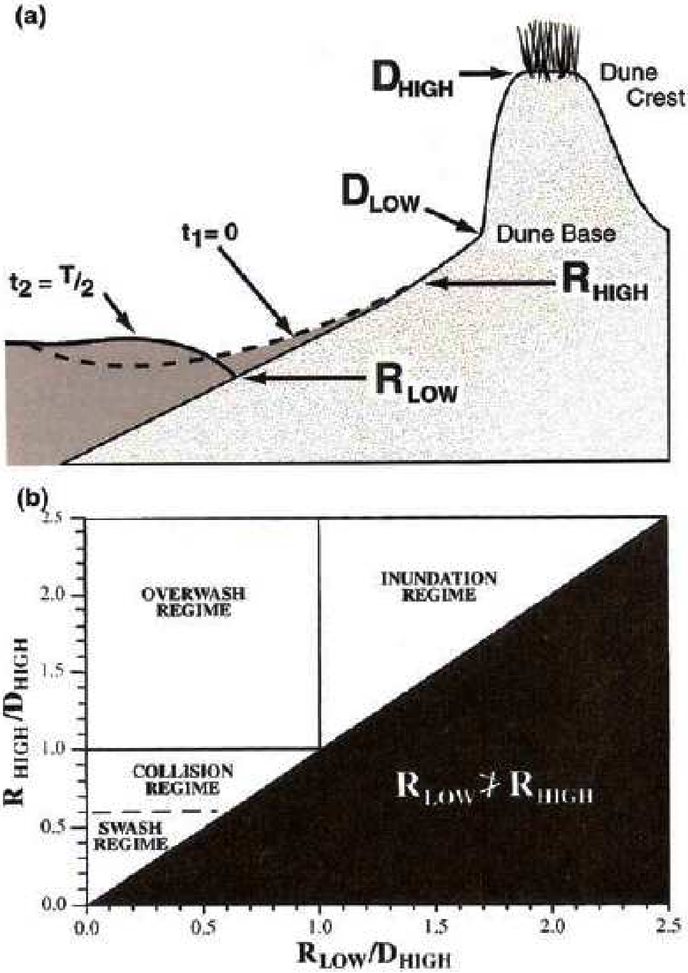

Figure 4 - (a) Sketch describing variables used in scaling the impact of storms on barrier islands. (b) Delineation of four different regimes that categorise storm impacts on barrier islands. From Sallenger (2000).

The storm impact scale has four regimes: swash regime, collision regime, overwash regime and inundation regime (Figure 4b). The swash regime is the condition, during a storm, where swash is confined to the foreshore, therefore, R_{HIGH} / D_{HIGH} is smaller than D_{LOW}/D_{HIGH}. According to Sallenger (2000) under swash regime, the beach foreshore erodes and sand is transported and deposited offshore. Sand only returns to the beach under calm weather conditions.

On beaches where there is a foredune ridge, as R_{HIGH} increases, run-up will eventually collide with the base of dune, inducing erosion. The collision regime occurs when R_{HIGH} / D_{HIGH} exceeds D_{LOW} / D_{HIGH}. The eroded sand is transported offshore (or alongshore) and, unlikely the swash regime does not typically return to re-establish the dune (Sallenger, 2000).

As R_{HIGH} continues to increase, overwashing or overtopping of a dune crest occurs when $R_{HIGH} > D_{HIGH}$. Therefore, the critical threshold

$$R_{HIGH}/D_{HIGH} = 1$$

(1)

defines the difference between the collision regime ($R_{HIGH} / D_{HIGH} < 1$) and the overwash regime ($R_{HIGH} / D_{HIGH} > 1$). In the overwash regime, as run-up overtops the dune, water can flow landward decelerating with distance. This gradient in flow leads to the erosion of the dune and deposition further landward.

When the storm induced sea level rise is sufficient to completely submerge a barrier island, the flows over the barrier are no longer a mere overwash. Rather, the previously sub aerial part of the barrier island is impacted directly by surf zone processes. The threshold for the inundation regime is

$$\mathrm{R_{LOW}}/D_{HIGH} = 1$$

(2)

Ephemeral inlets may form during the inundation process, which is an important landward barrier migration mode (Leatherman, 1979a).

There are developed studies that analyse and improve the determination of coastal vulnerability to overwash (Cleary and Hosier, 1979; Wetzel et al., 2003; Benavente et al., 2006; Stockdon et al., 2007).

Cleary and Hosier (1979) presented what probably is the first quantitative method for overwash prediction. The authors surveyed North Carolina southeastern coastline using cross-shore beach transects. They standardised and summed up the total island width, the total herbaceous and arborescent vegetation width, corresponding to dune recovery and erosion rate. The sum showed high correlations with the frequency of the overwash history at each transect. According to the results, overwash vulnerability levels (severe, moderate or low) were assigned along the coastline. The method is site specific and has probably been tested on a small range of storm occurrence, but it illustrates successful initial efforts to predict overwash events (Donnelly et al., 2006).

Wetzell et al. (2003), based on Sallenger's storm impact scale, used hindcast techniques to test, along the Outer Banks, North Carolina, U.S.A., the hypothesis that spatial variations in dune elevation could be used to predict overwash occurrences. The maximum elevation of wave run-up on the beach (R_{HIGH}) was estimated using Holman (1986) equation

$$R_{HIGH=}\,H_0\,(0.85 * \,\xi + 0.2) + \eta_{\mathrm{mean}}$$

(3)

where H_0 is the significant wave height and η_{mean} is the astronomical tide and storm surge. R_{LOW} was given by (Sallenger, 2000)

$$R_{LOW} = \,R_{HIGH} - \,H_0\,(0.85 * \,\xi + 0.06)$$

(4)

Both R_{HIGH} and R_{LOW} were coupled to pre and post-storm elevations of barrier island dune morphology (D_{HIGH} and D_{LOW}) and compared to the predicted storm hazards set by Sallenger (2000). Wetzell (2003) concluded that most of the beaches did not overwash. Nevertheless, some local occurrences were observed where R_{HIGH} exceeded $D_{HIGH,}$ indicating overwash prone areas.

Benavente et al. (2006) developed a potential coastal flood hazard map for Valdelagrana Spit, Cádiz Bay Natural Park, Spain. The authors modelled water surface elevation due to storm surge taking into consideration barometric set-up, wind set-up and wave set-up. Wave set-up included both set-up and run-up and it was determined by the equation given by Komar (1998) and modified by Holman (1986)

$$R = 0.36\,g^{0.5}H_0^{0.5}T\tan\beta$$

(5)

where H_0 and T represent deep water wave significant height and period and $\tan\beta$ is the mean beach slope. As a result, a hazard map was obtained superimposing a digital terrain model and sea level rise results. Moreover, the hazard map was capable of predicting the areas where future inundation events are likely to occur.

Stockdon et al. (2007) tested the predictive capability of Sallenger's storm impact scale to estimate coastal response along 50 km of the North Carolina coast to the landfalls of Hurricanes Bonnie (198) and Floyd (1999). Using a digital elevation model, the beach dune crest (D_{HIGH}) was digitalised and D_{LOW} (dune base) was calculated as the location of the maximum slope change within a region around the digitised line. Tidal levels, storm surges, wave run-up and wave set-up were gathered in order to obtain R_{HIGH} and R_{LOW}. The run-up maximum is dependent on deep-water wave height (H_0), wave period (T_0) and foreshore beach slope (β_f). The elevation of the 2% exceedance level for run-up, R_2, was estimated by the empirical parameterisation

$$R_2 = 1.1\left(0.35\,\beta_f\,(H_S L)^{\frac{1}{2}} + \frac{\left[H_S L\left(0.563\,\beta_f^2 + 0.004\right)\right]^{\frac{1}{2}}}{2}\right)$$

(6)

which includes wave-induced set-up and swash, where L_0 is the deep-water wavelength, defined as ${gT_0^2}/{2\pi}$.

The accuracy assessment of Sallenger's storm impact scale framework shows that it may be used to reasonably predict coastal response to severe storms and to explain part of the spatial variability observed in the magnitudes of shoreline and beach volume change. Errors in prediction may be associated to incorrect measures of storm-induced, extreme water levels, R_{HIGH}. According to Stockdon (2007) those errors in

R_{HIGH} may arise from modelled waves and storm surge, which are required to use the storm impact scale in a predictive manner.

Stockdon et al. (2007) define areas prone to overwash where there is dune erosion during the early storm stage, and subsequent dune collapse. Mean beach slope change (flattening or steepening) throughout a storm occurrence has a correspondent effect on R_2, decreasing or increasing the modelled elevation, respectively, thereby changing the area vulnerability to dune erosion or overwash. In this study, storm surge and wave run-up accounted, approximately, 48% (average for both Bonnie and Floyd storms) of the R_{HIGH}, indicating that wave-driven processes are equally important as surges to the total water level. Finally, a comparison among the four storm responses (swash, collision, overwash and inundation) evidenced that not only the beach volume change was larger within the overwash regime, but also that the change appeared to be more permanent. These shorelines changes were more evident where the beach slope was steeper, *i.e.*, a coastal patch corresponding to a higher run-up.

For the Ria Formosa barrier island system, Andrade (1990), Andrade et al. (1998) and Garcia (2008) proposed overwash vulnerability maps employing different analysis techniques. Matias et al. (2008) developed a classification of washover dynamics, including classification of overwash occurrence and evolution.

Overwash vulnerability for the Ria Formosa barrier system was analysed by Andrade (1990) by creating maps for all barrier islands based on foredune height, horizontal distance between the dune crest and the level -2 m in respect to mean sea level (MSL), the island width in respect to the -4 m MSL, and the type of foredune. The author stated that overwash was not relevant for the transference of oceanic sand to the lagoon, however it was important for: (1) the vertical accretion of newly formed island portions, (2) the generation of backshore sandy surfaces for embryonic dune development, (3) the periodic and intermittent fresh sand supply for aeolian mobilisation, and (4) the generation of deflation corridors with beach sand supply under onshore winds.

Andrade et al. (1998) used a multi-attribute rating technique (SMART) to analyse overwash vulnerability within the Ria Formosa System. The vulnerability to overwash was described as the product of the interaction between erosivity and susceptibility. Erosivity was defined as an attribute of ocean waves related to their ability to surge and overtop a pre-established surface (*e.g.*, the back-beach or a foredune) and is mostly dependent on wave conditions. Susceptibility represented the morphological properties that offer resistance or inhibit the waves to overwash over the back-barrier area or the foredune, and it is dependent on the amount and the rate of morphological evolution along any coast. The authors concluded that the vulnerability to overwash the Ria Formosa barrier system was governed by the recent morphodynamics of the coastal barriers, with special relevance to the processes and patterns of barrier accretion, foredune growth and anthropogenic action.

Matias et al. (2008) have systematically classified washover dynamics and overwash occurrence and evolution with reference to coastal changes along the Ria Formosa barrier islands. This system exhibited a decrease in overwash occurrence and washover dimensions. The classification indicated that the dominant formation mechanism of washovers within the Ria Formosa were inlet dynamics (24%) and structural erosion (19%), while human intervention mechanisms accounted for 12%.

Garcia (2008) developed a methodology for the overwash vulnerability evaluation on sandy and sparsely populated coasts, based on the coastal present conditions and the overwash history. Through washover morphology and distribution, detected by the analysis and comparison of aerial photographs, three vulnerability indices were established: Overwashed Shoreline Ratio (OSR), Maximum Overwash Intrusion Recurrence (MOIR) and Complete Barrier Overwash (CBO). The methodology was applied to the Ria Formosa barrier system and it showed a significant spatial and temporal variation. Overwash vulnerability varied from extreme to low, *e.g.* Barreta was considered under extreme vulnerability, whereas Tavira is unlikely to undergo overwash processes. The Ancão Peninsula presented medium overwash vulnerability, according to this classification. The central urbanised area of the Ancão Peninsula (Praia de Faro) is one of the most densely populated areas within the barrier system and has been previously identified as an area prone to overwash (Andrade et al., 1998; Ferreira et al., 2006; Matias et al., 2008). Garcia's method (2008), which is preferably applied to areas where washovers may naturally develop, could not be applied to the occupied and overwash hazardous areas of the Ancão Peninsula.

4. Methods

4.1. Topographic Data Acquisition

Before the topographic survey was carried out, exploratory field observations were made to examine the study area with the support of orthorectified aerial photographs (orthophotographs) taken in 2005. According to the visual perception and recent researches on the study area, the criteria for base and dune crest identification were established. The extension of the study area was also determined: it stretches from the Ancão Inlet to 5 km eastward, including the non-inhabited dune ridge.

Fieldwork was carried out on November 10th and 24th, 2008. A Real-Time Kinematic Differential GPS (RTK-DGPS), recording at 1 Hz, was used in order to register dune relief (dune base and crest). When a topographic surveillance is carried out there is an intrinsic error associated to the GPS caused by variation in the antenna position in relation to the ground. For a given 10° terrain slope and considering a 2 m antenna height above the ground, the pole vertical deviation causes a planimetric point position error of 0.35 m and an altimetric error of 0.03 m. (Baptista, 2008).

Dune crest (D_{HIGH}) was set as the highest portion of the frontal dune, *i.e.* where fixed and well developed dune vegetation could be observed and the sand transported by aeolian process was noticed. Where dune crest was not present, *e.g.* along the urbanised area, crest was defined as the top of the frontal construction line (top of wall fences). Dune base (D_{LOW}) was considered the lowest part of the crest, generally the limit of the foreshore and the dune ridge. Along the urbanised area D_{LOW} was registered as the base of the frontal construction. Where the surveillance of the top or the base of the frontal construction line could not be acquired, a unique line close to the buildings was surveyed.

The relief surveillance is under the operator's bias, because there is a difficulty in defining the correct limit of D_{LOW} and D_{HIGH} during fieldwork. The relief varies gradually leading to subjectivity in defining base and crest limits. The error caused by operator surveillance can be higher than the ones inherent to the equipment or the tilting of the GPS antenna.

Besides the alongshore topographic survey, cross-shore profiles were surveyed on October 30th, 2008. Sixteen profiles along the study area, localised every 300 m, were set in order to subsequently beach steepness calculation.

4.2. Data Processing

Long and cross-shore GPS data were plotted into ESRI ArcGIS 9.2 software. It allowed the identification of different characteristics which had been previously noticed during the topographic survey along the peninsula. According to the data and to the surveys carried out at the site, ten sectors were defined based on the foreshore morphology, the dune elevation and the anthropogenic occupation along the beach. For each defined coastal segment it was computed the value of the mean beach face slope, from the berm crest to approximately 1 m below MSL.

Ten years of oceanographic data were gathered, regarding storm surge and wave data - significant wave height, peak period, wave length and direction. Offshore wave data were recorded by the Instituto Hidrográfico de Portugal by using a directional wave-rider buoy offshore the Santa Maria Cape (Figure 1) at 36°54.3' N 7°53.9' W, 93 m depth (Costa, 1994). Records were obtained for 20 min at every 3 h, except during storm periods when data were recorded every half an hour. Storm events (significant wave height higher than 3 m) were identified for 10 years of data (June 1997 to June 2007). Because westerly storms are dominant and more energetic and the study area is relatively protected to E-SE waves, only W-SW waves ($180° < \theta < 270°$) were considered for the analysis. Stormy wave data were reduced to the highest daily record of significant wave height and its associated peak period and wave direction.

Meteorological and astronomical tides were compiled by the REDMAR database, a tide gauge network from the Spanish Port System (Puertos del Estado, 2009). For this study, data were gathered from a tide gauge located at the Huelva Port, Spain, at 37°7’48’’ N and 6°49’48’’ W. Storm wave data, previously treated, were linked to the equivalent highest daily storm surge registered by REDMAR.

According to the Instituto Hidrográfico de Portugal, Faro’s coast has mean spring high-tide corresponding to 1.4 m above MSL and 0.64 m as mean neap high-tide level. The average value is equivalent to a mean high water level (MHW) which rises 1 m above MSL. The latter was considered for the present analysis as the tidal phase over which each storm acts. This level is reached or exceeded in 50% of the high tides.

In order to predict the overwash hazard during a storm occurrence, three different scenarios were defined: 5, 10 and 25 - year return period storms. These scenarios correspond to storm magnitudes that are considerably important for coastal zone management and decision-making (*e.g.* definition of set-back lines, dune reinforcement) regarding beach assets, the design of human settlements and infrastructure, and the coastal environment itself.

Significant wave height (H_S) and associated wave direction (θ) corresponding to 5, 10 and 25 - year return period storm were ascertained by Pires (1998) using measured data. By plotting these H_S values and the registered data of the highest significant wave height (H_S) and the associated peak period (T_P) from June 1997 and June 2007 a linear estimative of T_P was standardised for the three storms scenarios. In order to determine standard values of storm surge (S) for the three given storms, a relation between the highest significant wave height (H_S) and associated storm surge (S) from June 1997 and June 2007 were plotted with the H_S determined by Pires. Hence, a linear estimative was set and the standard values of storm surge for storms with 5, 10 and 25 years of return period were ascertained.

The accomplished values for the standardised storms supported the calculation of "high" run-up elevation (R_2) represented as the value of a run-up that is exceeded 2% of the time (Sallenger, 2000). R_2 was obtained through the empirical parameterisation by Stockdon et al. (2006)

$$R_2 = 1.1\left(0.35\,\beta_f\,(H_S L)^{\frac{1}{2}} + \frac{\left[H_S L\left(0.563\,\beta_f^2 + 0.004\right)\right]^{\frac{1}{2}}}{2}\right)$$

(7)

where β_f is the foreshore slope, H_S is the significant wave height and L is the wavelength, defined as $gT^2/2\pi$.

Equation (7) is parameterised according to the wave-induced set-up (the $0.35\,\beta_f\,(H_S L)^{\frac{1}{2}}$ term), and the swash, both incident ($0.563\,\beta_f^2$ term) and infragravity (the 0.004 term), and, as a suggestion, it should be applied to the intermediate-reflective range of beach conditions (Stockdon et al., 2006).

High run-up elevation (R_2) was computed for each shoreline segment and for the established storm cases, considering the bulk of data regarding the beach slope and the storm attributes.

Finally, the highest elevation of run-up was calculated as

$$R_{HIGH} = R_2 + \eta_{mean}$$

(8)

where R_2 is added to mean sea level (η_{mean}), the sum of the astronomical tide (1 m above MSL) and the storm surge correspondent to a significant wave height (Hs) with a given return period (5, 10 or 25 - years).

4.3. Vulnerability Maps

A vulnerability map is a tool for establishing coastal hazards caused by a given event acting at a coastal area. The identification of collision and overwash prone areas is essential for the conception of planning and management programs concerned with economy, society, development and nature conservation.

In order to obtain such maps for the Ancão Peninsula, a base imagery composed by orthorectified images, from 2005, were imported into ESRI ArcGIS 9.2 software and referenced according to the Portuguese Melriça coordinate system (Datum 73). A shapefile containing the D_{HIGH} and D_{LOW} topographic information was created. Since the dune crest and base were gathered as punctual values, the *Editor* tool allowed the creation of a new feature represented as a unique line (polyline layer) connecting elevation attributes. However, these attributes could not be associated to the polyline. In order to comprise the relief data within the polyline layer, the layer was split using the *ET Geo Wizards* tool, following the option *Split Polyline with Layer*. Finally, the polyline layer was split into vertexes with height attributes.

The maps for overwash (D_{HIGH} values) and collision (D_{LOW} values) regimes were obtained by using the software tool *Select by Attribute* and run-up (R_{HIGH}) values obtained from equation (8). *Select by Attribute* dialog provided a selection of points within the D_{HIGH} and D_{LOW} shapefiles, where relief elevation was lower than the R_{HIGH} values. The selected segments which were lower than the run-up elevation were represented as areas under overwash and/or collision regimes.

The illustration of hazard-prone areas was completed using the *Buffer* tool from ArcToolBox. Buffers were plotted in order to differentiate the coast vulnerability to the three storm scenarios. They were designed with identical width but different colours to distinguish the storm's return periods (red, orange and yellow for storms with 5, 10 and 25 years of return period, respectively). The buffers were employed along the dune crest and dune base to define places under collision and/or overwash regime vulnerability.

5. Results

5.1. Morphologic and Oceanographic Characterisation

The Ancão Peninsula presents three areas with distinct morphologic characteristics: a dynamic and recent environment (near the Ancão Inlet, eastward) linked to a dune ridge with low elevation, a human modified area (centre), and, westward, a coastal stretch formed by a high-elevated dune ridge (Figure 5).


(a) (b)
(c) (d)

Figure 5 – The Ancão Peninsula sectors. (a) westwards of the Ancão Inlet. (b) Recent and low dunes near the Ancão Inlet (b) The extensively modified shorefront within the centre of the Ancão Peninsula. (c) The western area of the peninsula with a high-elevated dune ridge.

The ten individualised sectors are represented in Figure 6. Detailed description about beach morphology, dune elevation and human occupation is provided in Table 1.

Figure 6 – Representation of the study area and the stipulated ten sectors.

Table 1 –Description of the sectors within the study area and the calculated beach slope.

Sector	Characteristics	Beach Slope
1	Easternmost sector, corresponding to a non-inhabited area around the Ancão Inlet Accretionary sector as a result of downdrift sediment trap Dunes are low, in average 3.5 m above MSL, and incipient, as a result of eastward inlet migration	0.072
2	Dune ridge is localised slightly landward and it is in average 4.5 m above MSL Foredune is not occupied, however a few houses are set in the backbarrier side Accretionary sector evidenced by a vertically well developed berm and incipient dune ridge	0.064
3	Most dissipative beach morphology within the sectors Dune ridge in average reaches 5 m above MSL Foredune is not occupied, few houses are set in the backbarrier side Accretionary sector evidenced by a vertically well developed berm	0.061
4	Mean dune crest elevation is 6.5 above MSL and it is occupied in the backbarrier side Vertically and horizontally well developed berm	0.086
5	Dunes are lowered or destroyed due to dense anthropogenic occupation in both sides of the barrier Crest average elevation is 7 m above MSL Beach becomes more reflective	0.123
6	Dunes are absent because of dense occupation along the both sides of the barrier Mean crest elevation is 6 m above MSL	0.121
7	Densely occupied area corresponding to the main entrance to Praia de Faro Foreshore experienced beach nourishment and beach crest reaches 6.0 m above MSL Most reflective beach face within the study area	0.124
8	Dunes are strongly altered by rocky protection and lowered by human settlement Dunes reach in average 6.5 m above MSL	0.117
9	Dunes are preserved in the seaward side, although partially destroyed on backbarrier side Mean dune ridge elevation is 7.5 m above MSL	0.123
10	Westernmost sector corresponding to a non-inhabited area Shoreline under retreat process Dunes have blowouts and reach the highest elevation along the study area, approximately 8.5 m above MSL	0.124

Variation in height of dune crest and base is represented in Figure 7. Lowest dunes are concentrated in the eastern most segment of the beach, whereas the highest crests are localised westward. Beach steepness varies within this morphologic sketch, becoming more reflective westward (Table 1).

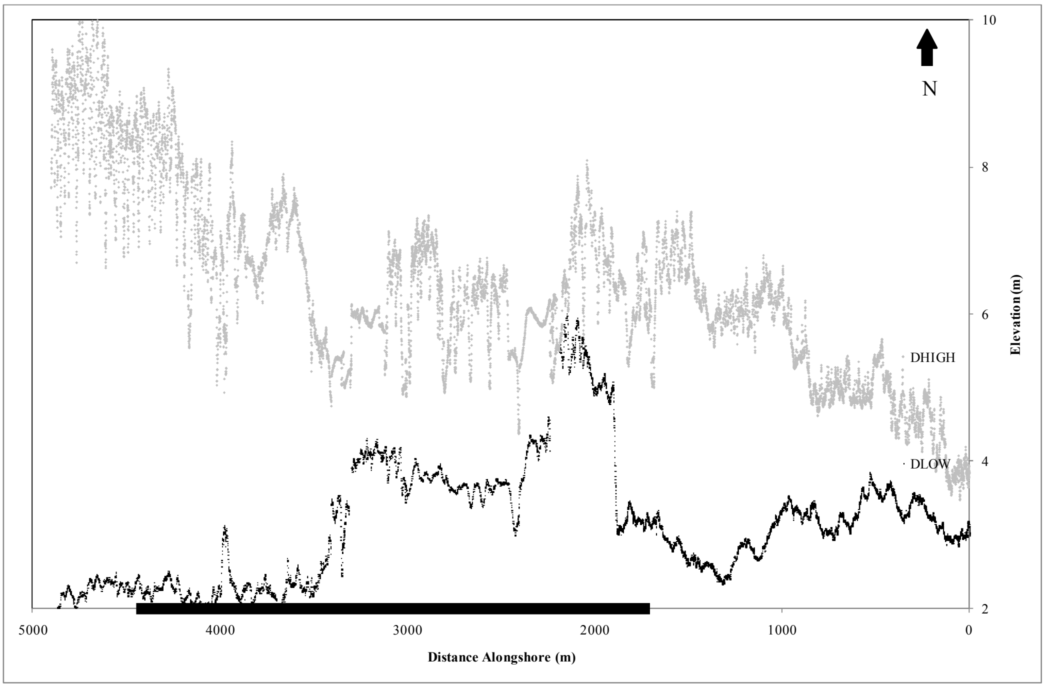

Figure 7 – The dune crest (top) and the base (bottom) elevations above MSL (m) versus the distance alongshore (m) along the Ancão Peninsula. The Ancão Inlet is on the right of the figure. The wide dark bar in the horizontal axis represents the urbanised portion of the Ancão Peninsula. General location is shown in Figure 1.

By plotting significant wave height (H_S) with associated peak period (T_S) and significant wave height (H_S) with associated storm surge (S) for stormy days from June 1997 to June 2007, a positive correlation was noticed. It also allowed the plot of the determined values of H_S for storms with 5, 10 and 25 years of return period by Pires (1998). Hence, a liner estimative was accomplished and T_S (Figure 8a) and S (Figure 8b) were standardised for the storms set. The final values which characterise the three storm scenarios are summarised in Table 2.

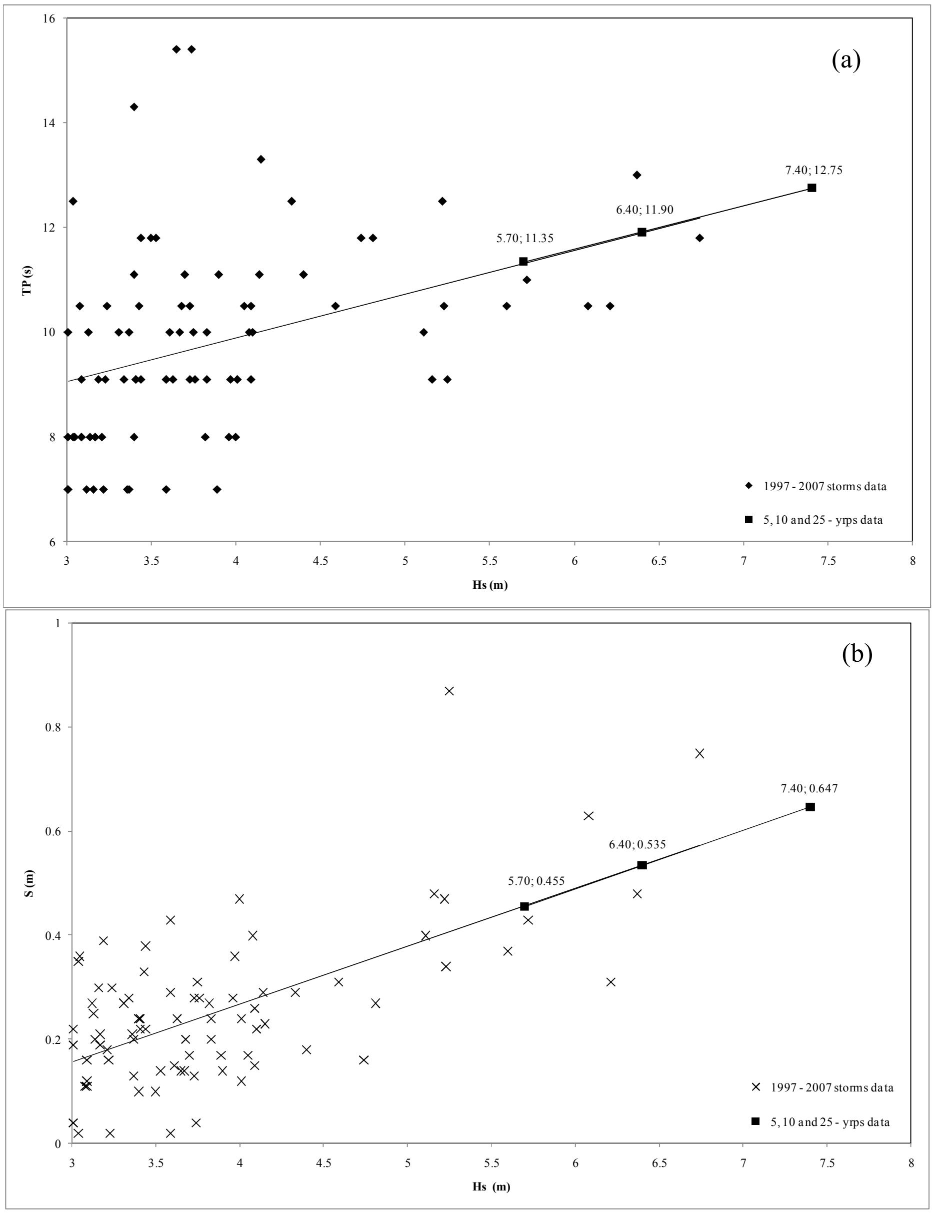

Figure 8 – Linear estimative of peak period (T_P) and storm surge (S) for the 5, 10 and 25 - year return period storm. (a) Daily highest wave significant height (H_S) versus peak period (T_P) from June 1997 to June 2007. (b) Daily highest wave significant height (H_S) versus daily highest storm surge (S) from June 1997 to June 2007.

Table 2 - Significant wave height (H_S), wave direction (θ) and associated peak period (Tp) and storm surge (S), for different return periods determined by (Pires, 1998).

Storm Characteristics	5 – years	10 - years	25 - years
H_S	5.7	6.4	7.4
θ	232	232	232
T_P	11.35	11.9	12.8
S	0.46	0.54	0.65

Beach slope (β_f), significant wave height (H_S), wave peak period (T_S), mean high water, and storm surge (S) are the basis for calculating extreme run-up (R_2, Equation 7) and the highest elevation of run-up (R_{HIGH}, Equation 8). The computed values are presented in Table 3.

Table 3 – Extreme run-up (R_2) and highest elevation of run-up (R_{HIGH}) for storm scenarios regarding the sectors within the study area.

Sectors	**Scenario (yrps*)**	**R_2 (m)**	**R_{HIGH} (m)**	**Sectors**	**Scenario (yrps)**	**R_2 (m)**	**R_{HIGH} (m)**
1	5	2.48	3.93	6	5	3.63	5.08
	10	2.75	4.29		10	4.03	5.56
	25	3.18	4.83		25	4.66	6.31
2	5	2.32	3.77	7	5	3.71	5.16
	10	2.58	4.11		10	4.12	5.65
	25	2.98	4.63		25	4.76	6.41
3	5	2.26	3.71	8	5	3.53	4.98
	10	2.51	4.04		10	3.92	5.45
	25	2.90	4.55		25	4.53	6.18
4	5	2.80	4.26	9	5	3.69	5.14
	10	3.11	4.65		10	4.10	5.63
	25	3.60	5.25		25	4.74	6.38
5	5	3.68	5.14	10	5	3.70	5.16
	10	4.09	5.62		10	4.11	5.65
	25	4.73	6.38		25	4.76	6.40

*yrps: year return period storm

According to the results sectors 1 to 3, evidenced similar and lower R_{HIGH} elevations. Sector 4 is a transition sector between the western ones (smaller values) and the higher values obtained between sector 5 and 10.

5.2. Overwash Regime

The overwash regime is analysed by comparing run-up elevation (R_{HIGH}) to the dune crest height (D_{HIGH}). Figure 9 plots the run-up elevation for each standardised storm and the dune crest along the study area.

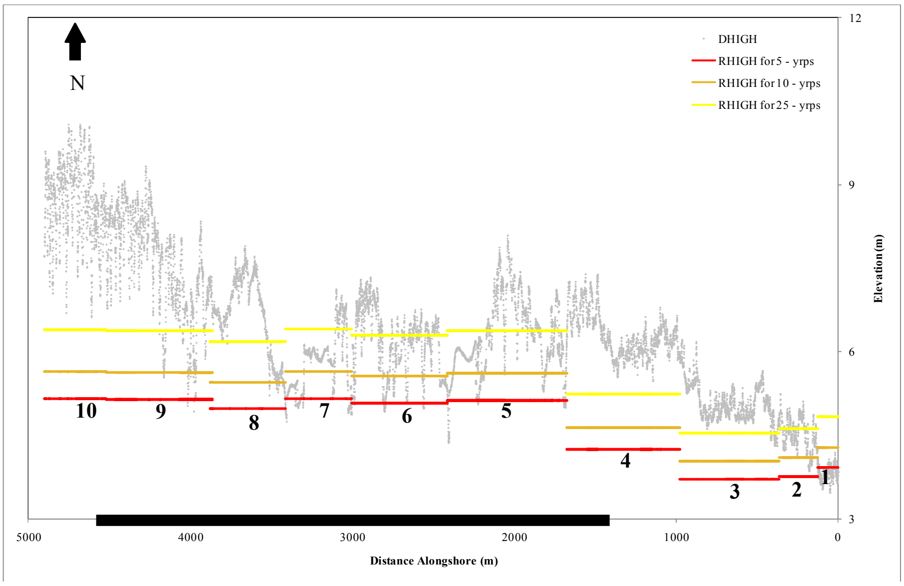

Figure 9 – Alongshore profile of dune crest height above MSL (m) and the modelled run-up (R_{HIGH}) variation along the ten sectors established in the Ancão Peninsula for the different storms scenarios. The wide dark bar in the horizontal axis represents the urbanised portion of the Ancão Peninsula. General location is shown in Figure 1.

The overwash vulnerability map is represented in Figure 10. The areas that are vulnerable to the event are depicted where the calculated run-up reaches higher elevation values than the dune crest.

The easternmost part designed as sector 1 showed low R_{HIGH} values (Figure 9). However, this segment is vulnerable to overwash regime for storms with 5, 10 and 25 – year return period (Figures 9 and 10).

Differently from sector 2, sector 3 does not appear to be a vulnerable area. However both sectors show similar R_{HIGH} elevation (Figure 9). Sector 2 shows a short

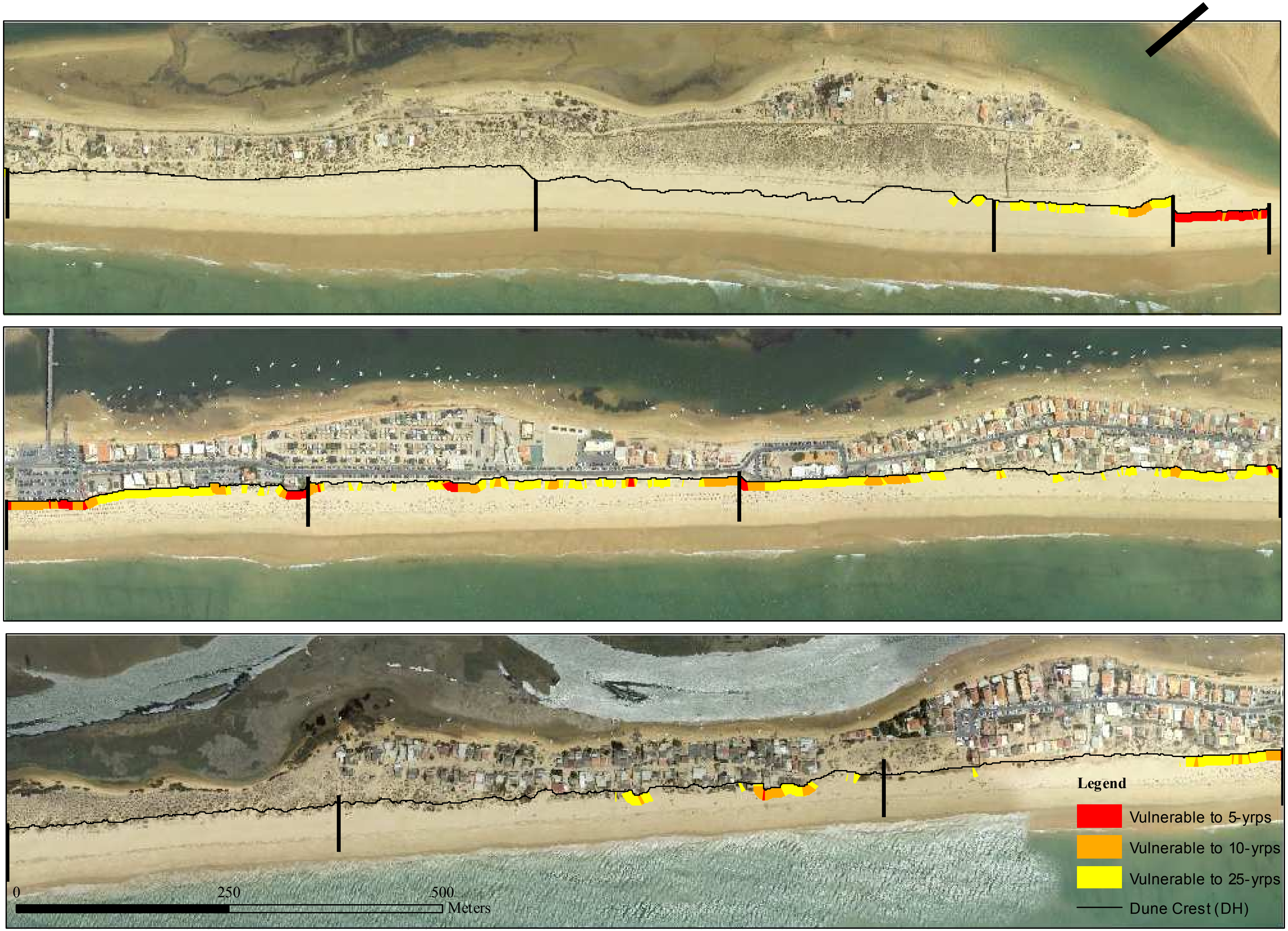

Figure 10 – Representation of overwash regime vulnerability along the study area for 5, 10 and 25 – year return period storm.

patch vulnerable to the 10 – year return period storm and a consistent area which would be overwashed under a storm with a return period of 25 years (Figure 10). Sector 3 appeared to be overwashed strictly during higher run-up levels and specifically in the east (Figure 10). Apart from this restricted area, this sector would not undergo overwash, which is also expressed within the contiguous sector 4. Despite the intermediate R_{HIGH} elevation in sector 4 this zone is not under overwash vulnerability for none of the storm scenarios.

Sectors 5, 6, 7 and 8 are the central densely occupied region of the Ancão Peninsula. Values for R_{HIGH} from sectors 5 to 7 are among the highest ones within the study area (Table 3). In this case higher R_{HIGH} led to hazard-prone areas within these sectors for all defined storm scenarios (Figure 10). A 5 - year return period storm was particularly depicted in lowered areas (*e.g.* dune gaps). Sector 8 is illustrated on the map as under low vulnerability to overwash caused by 10 and 25 – year return period storms. The low vulnerability of sector 8, when compared to the others urbanised sectors, might be explained by the high elevation of the dune and the lowest calculated run-up height.

High predicted run-up values (R_{HIGH}) were obtained for sectors 9 and 10, although the area is not equally vulnerable. The former showed a few areas which could be overwashed during 5, 10 and 25 – year return period storms (Figure 10). Sector 10 showed high R_{HIGH} level, but it is not prone to overwash processes in any of the storm conditions determined for this study (Figures 9 and 10).

5.3. Collision Regime

Vulnerability to collision regime is analysed comparing the values of the highest elevation of run-up (R_{HIGH}) obtained in Equation 8 to the dune base height (Figure 11).

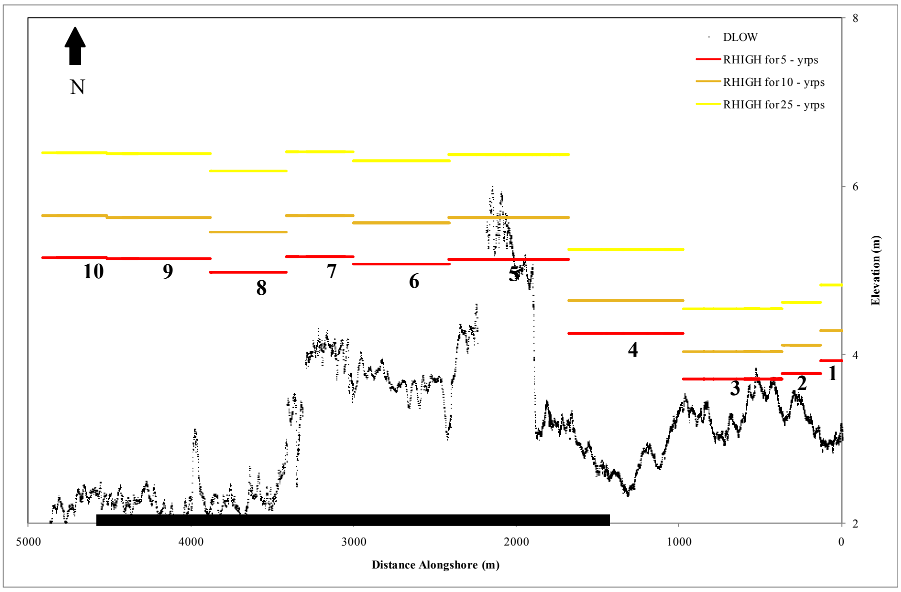

Figure 11 – Alongshore profile of dune base height above MSL (m) and the modelled run-up (R_{HIGH}) variation along the ten sectors established in the Ancão Peninsula for the different storms scenarios. The wide dark bar in the horizontal axis represents the urbanised portion of the Ancão Peninsula. General location is shown in Figure 1.

The surveyed dune base along the study area is entirely under collision regime for storms with 25 years of return period. The representation of collision regime caused by 5 and 10 - year return period storm is mostly continuous, except by a patch in sector 5 (Figure 12).

Figure 12 – Representation of collision regime vulnerability along the study area for 5, 10 and 25 – year return period storm.

6. Discussion

6.1. Overwash Regime

The eastern part of the study area (sectors 1 and 2) corresponds to a dynamic zone in the Ancão Peninsula driven by inlet processes. Tidal inlets are one of the most dynamic parts of a barrier island system, therefore, their vicinity is in extreme risk of erosion and overwash (Vila-Concejo et al., 2006). For sector 1, a low-lying margin under inlet updrift accumulation, the transient state of dune development within the migratory status of the Ancão Inlet leads to high overwash vulnerability. The Ria Formosa's most frequent washover formation mechanism is inlet dynamic, especially caused by updrift accumulation, which produces 57% of the washovers (Matias et al., 2008). Along inlet-related coasts the irregular dune development promotes overwash in lower areas. Hence, these areas have low threshold and overwash occurs even during typical winter conditions. Sector 2 has a less vulnerable profile to overwash regime because the beach face becomes wider and the foredune is displaced landward, higher and more vegetated in relation to sector 1. In addition to natural processes controlling this sector, influence of human features can also be observed. There, an elevated coastal path extends across the dune ridge and gives passage to beach users. This coastal asset is responsible for foredune trampling, which destroys the dune vegetation, promotes aeolian erosion and, consequently, generates overwash-prone artificial morphologies (Matias et al., 2008).

Westward, the barrier island develops a larger beach face and the foredune can reach 5 to 8 m in height. Apart from the vulnerable east portion of sector 3, which is still under the influence of foredune trampling and lowering since it is located immediately after the dune path, sectors 3 and 4 would not be affected by overwash events. The current accretionary condition, also existent in sector 2, leads to a wider beach, where there is vertical and horizontally development of a berm and dune enlargement. The Ancão Inlet formed a well-developed ebb delta, which acts as a sediment trap, thereby causing the observed seaward shoreline displacement (Ferreira et al., 2006). The sediment trapping is a consequence of the tidal currents acting in and out through the inlet channel which interrupts the regular eastward trend of the littoral net transport.

Another observed characteristic is the intermediate morphodynamic condition along the sectors 2, 3 and 4. There is also a smooth and irregular contact between the upper beach and the foredune caused by the colonisation on the upper beach by pioneer dune vegetation. The less reflective is the shore the more energy dissipation is achieved and, consequently, wave set-up decreases (Benavente et al., 2006). Hence, “high” run-up elevation (R_2), calculated considering wave set-up levels, is reduced and leads to a lower R_{HIGH}. Finally, lower R_{HIGH} levels induce lower overwash potential and shorter landward penetration.

The central area of the Ancão Peninsula comprises sectors 5 to 9. This portion of the barrier island is characterised by a reflective beach face, high R_{HIGH} elevation and dense urban occupation. According to the results, from sector 5 to the eastern area of sector 9 the beach crest would be extensively overwashed during 10 and 25 – year return period storms. Vulnerability to low storm intensity is often perceived in punctual areas, *e.g.* beach accesses.

The steeper profile throughout the area has a corresponding effect on R_2, and consequently R_{HIGH}. Under surging wave conditions there is little dissipation of wave energy across the beach face, and the majority of wave energy is reflected in the slope

(Stockdon et al., 2006). This situation is intensified along the steepest slope because wave energy dissipation by frictional processes is prevented from occuring along the beach. Therefore, wave set-up and run-up increase, fact that can undermine the dunes and produce either escarpments or washover fans (Benavente et al., 2006). Additionally, this coastal stretch congregates the most densely occupied area along the Ria Formosa (Praia de Faro). Along the coastline, human intervention is predominantly identified as shorefront buildings, foredune trampling and lowered or destroyed dunes. When present, the foredune is more linear if compared with what would occur under natural aeolian transport/construction as a result of aiding bulldozing, dune fences and revetments (particularly for sector 8). Man-made shore changes at this site altered the sediment budget and the coastal processes. The presence of coastal infrastructures prevents new embryo dune development and foredune restoration (Davidson-Arnott and Fisher, 1992), which increases the vulnerability to overwash.

Along the westernmost section of the study area the beach face is narrow, steep and the modelled run-up (R_{HIGH}) elevation is high and particularly within the last sector there is minimum or absent human intervention. From the western area of sector 9 to sector 10 the dune ridge reaches up to 10 m height and it evidences several aeolian erosional discontinuities in the form of blowouts. Seaward a recently formed embrionary dune exists, being fixed by incipient vegetation. This morphology is a consequence of updrift beach nourishments (since 1998), which re-established a sedimentary source to the area. Despite the reflective beach slope, high run-up elevation and erosional features within the dune ridge, there is low probability of overwash. The absence of hazardous areas, even considering the blowouts, is associated with blowouts base elevation. These morphologies are formed in the high dune top, rather than in the dune ridge base so that they are generally not affected by high run-up levels.

The western segment of the study area is an example of the importance of a well-formed dune ridge as a storm-protection function of the beach. It could be tempting to compare this natural protection with engineering structures, for example a seawall. However, the fundamental difference is that dunes are dynamic whereas seawalls are static (Leatherman, 1979a). Dunes are prone to erosion or accretion and act as sand reservoir for beach nourishment in storm conditions.

6.2. Collision Regime

According to the present results the dune base along the Ancão Peninsula is dominated by collision regime. As a pre-overwash phase, collision regime is associated with rising water levels, which lead to a reduction in overall beach width and thus increase the potential to extensive damage to dune ridge in the form of dune scarping. If the identified coastal areas prone to collision do not store sufficient volume of sediment in the embryo dune zone and in the foredune, overwash will potentially occur (Davidson-Arnott and Fisher, 1992).

Along sector 1 dune base has low elevation reaching less than 3 m above MSL. It is a low-lying zone where the dune ridge is recent and low and its base can be easily affected by low intensity storms. From sectors 2 to 4 the dune base becomes slightly higher reaching in average 3.5 m above MSL. Its seaward position, as a result of the wide dune ridge and recent accumulation, makes it more vulnerable to collision regime. As stated by Claudino-Sales (2008) the distance of the dune from the shoreline is an important factor controlling its survival because of dissipation of waves' energy within the beach face.

Sector 5 is the unique segment where a consistent dune area is not scarped by storms with 5 and 10 – year return period. There the dune base shows the highest elevation within the whole study area, reaching 5 m above MSL. This elevation is noticeable where the dune is extensively occupied by seafront buildings. There are only hypothesis to sustain a reason for the high dune base elevation in the area, *e.g.* natural processes, shorefront restitution by placing sediments with bulldozers. However, nothing can be assured yet.

The dune toe within sectors 6 and 7 for several times coincides to the base of constructions. This line is low, reaching 4 m above MSL, and is largely under collision risk. The high vulnerability to collision regime under storms with short return period is a consequence of the low dune base, its high exposition because of seaward location, and reflective beach morphology.

From sectors 8 to 10 the dune base is the lowest registered within the surveyed area. The dune toe elevation is in average 2.2 m above MSL and it has a seaward advanced position. Besides the low-lying seaward dune base, the reflective beach slope and high values of R_{HIGH} make the area extensively prone to escarpment.

6.3. Method Evaluation

Any hazard assessment involves a degree of uncertainty and, in this study, there is some inaccuracy associated with methods for field measurements and for overwash and collision estimations. Uncertainties can be related to the topographic surveillance (equipment and identification of dune base and crest limits), under or over estimation caused by run-up parameterisation and the presence of the berm within the foreshore.

The fieldwork was based in assessing dune elevation by GPS topographic surveillance which can show related uncertainties. There is an inherent error in the GPS data relief registration caused by any variation in the antenna's position in relation to the ground. The expected errors in both altimetric and planimetric point position can be, respectively, in a centimetric and decimetric scale. Furthermore, the dune base and crest assessment was a very subjective process and there was some difficulty in localising the dune features. The GPS operator for times experienced problems in defining the limits because the dune relief varies gradually along the beach. Besides some areas along the study area are vastly modified, which causes uncertainties in "dune base" and "dune crest" concepts. In order to obtain more precise data and to evaluate how deterministic these errors are it is advisable to have different GPS operators assessing the same area.

The calculated highest run-up (R_{HIGH}) values were not enough effective to overwash zones along the Ancão Peninsula where realistically it occurs. There are areas along the urbanised zone of Praia de Faro, especially within sectors 5, 6 and 7 that are overwashed during storms with short return period (Ferreira, personal communication). It suggests an underestimation, which can be linked to the run-up parameterisation. R_{HIGH} calculation is an empirical parameterisation of set-up, swash and run-up set for natural beaches. As Ancão Peninsula is occupied and modified by human interference, mainly at the central area, the applied prediction for extreme run-up may not be the completely adapted to these conditions. Moreover, this predictive model from Stockdon et al. (2006) is dependent on the foreshore beach slope, *i.e.* alongshore-variable slopes imply similar alongshore variability in swash excursion and run-up elevation. Hence, the dependence on beach slope has effects on the practical use of the parameterisation of run-up along beaches where complex foreshore slope is identified. Stockdon et al. (2006) compares a relative slope difference to a relative run-up error when alongshoreaveraged slope is used instead of a more accurate measure of slope at each alongshore line. On intermediate and reflective beaches with complex foreshore topography the alongshore variability in beach steepness may result in a relative run-up error equal to 51% of the variability between the measured and mean slope. Hence, taking into account the man-made variation along the foreshore particularly in the central area of the Ancão Peninsula, where underestimation of overwash's occurrence was mainly detected, it is possible to state that there is an error in the estimation of run-up elevation. Additionally, the mean difference between estimated and measured run-up for the research performed by Stockdon et al. (2006) was about -18 cm, indicating that the parameterisation tends to slightly underestimate the elevation of run-up.

In relation to the collision regime the presence of the berm is an important controlling factor because the berm width can determine the occurrence or not of such process. When a berm is wide the friction factor tends to reduce the limit of the overtopping run-up (Horn and Ling, 2006). Hence, the run-up does reach the D_{LOW} height by overtopping the berm, but cannot achieve the dune toe and collision regime does not succeed. Conversely, when the berm is narrow the run-up overtops this morphology and can reach the D_{LOW} causing dune scarping. Variations in berm width can be seen along the study area, *e.g.* from sectors 2 to 4 the berm is wide, whereas at sectors 9 and 10 the berm is narrow. However, the collision regime cannot be explained by these differences because the applied beach face slope calculation assumes a linear profile, *i.e.* a developed berm is not accounted.

For the present study it was not feasible to match the same set of information regarding wave data (H_S, θ and T_P) and mean sea level. Wave data was collected from the buoy at Santa Maria Cape, south Portugal whereas storm surge was registered in

Huelva, Spain. The spatial difference in these registered data might represent some difference in the final values of R_{HIGH}.

An important aspect of the applied method is the seasonal and annual variation within the set of data. Frequency and intensity of storm surges, high mean sea level and SW energetic waves are strongly variable along the year as a response of the storm events distribution during the seasons. Also dependent on the seasonality is the beach morphology evolution; consequently the surveillance date is important. Beach morphology is a response of the energetic events taking place during the winter and the consequent beach recovery ability. Hence the beach slope, which is a controlling factor for both overwash and collision regimes, will cause different scenarios depending on the time of the year that crosshore profiles were obtained.

Besides the data set, the consideration of the average mean high water as the best representation of the tidal level has important consequences for the obtained results. Storms with identical characteristics that act over lower or higher tidal levels will respectively induce lower or higher overwash vulnerability. According to Hofstede (1997) in a tidal coastal environment, the water level normally remains for much longer periods around the MHW than around MSL. Moreover, all storms with more than 5 - year return period will have duration of more than 2 days and therefore will act over a high tide level. Thus, a MHW can have greater significance when calculating driving forces which cause morphological impacts in mesotidal environments.

6.4. Previous Studies

A number of studies have been accomplished regarding overwash risk assessment within Ria Formosa. This section compares methods and results regarding overwash prone areas along the Ancão Peninsula. Studies conducted by Ferreira et al. (2006), Vila-Concejo et al. (2006) and Matias et al. (2008) mention certain stretches of the Ancão Peninsula as hazardous areas to overwash. There are, however, three other studies which determine overwash vulnerability: Andrade (1990), Andrade et al. (1998) and Garcia (2008).

Studies carried out by Andrade (1990) and Andrade et al.(1998) identified areas prone to overwash applying different methods. The first designed empirical maps based on coastal morphology's extension and geometry, whereas the later employed a vulnerability index based on multi attribute rating technique. Conclusions from both studies are coincident to the present survey. Westward, no vulnerable areas are spotted as a result of the high and continuous dune ridge. Central and eastern parts of *Ancão* are highly vulnerable due to, respectively, lowering and destruction of dune ridge and because of tidal inlet processes.

Despite the identified exposure along the centre of the peninsula, Andrade (1990) affirms that the hazard was likely underestimated because of the high physiographic modification which implies lack of accuracy in the applied method. Another constraint in the technique, also observed in Andrade et al. (1998), is the essential qualitative attribute of the method and lack of absoluteness. Therefore, the obtained results cannot be compared to others coastal systems because the bulk of data is specifically to a certain type of coast. Furthermore, the mentioned studies do not validate the methods with natural dynamic conditions for overwash occurrence, such as waves, astronomical and meteorological tides and run-up.

Another overwash hazard assessment was carried out by Garcia (2008). The author developed vulnerability indices to sandy coasts based on historical washover trends monitored in 54 – year aerial photographs. The author also refers some degree of overwash vulnerability of the Ancão Peninsula, since washovers are infrequent but tend to occur. Although the method in Garcia (2008) can properly identify whether an area is vulnerable to overwash or not, there are limiting factors in its applicability. Since the study is based in historical washovers trends registered from aerial snapshots, the assessment must be interpreted carefully given variations along the coast and overwash processes within the period of time between the photographs. Another constraint is the fact that the method is based on photographic interpretation of sandy surfaces and it is not applicable to densely occupied areas as the Praia de Faro. Overwash when occurring along human occupied areas covers the installed infrastructure with sand. The interpretation of sandy surfaces becomes unfeasible because washovers are artificially removed to guarantee access to roads, parking areas and to avoid structural problems.

The aforementioned conducted studies are able to define hazard areas by mapping coastal areas. The design of maps as practical and visual tools to identify hazardous coasts in dynamic environments is valuable. However there are a few constraints regarding the applied methods. In order to protect coastal communities and resources, a detailed understanding of the physical setting and of the processes responsible for change is required. The overwash main driving forces, terrain elevation data and land use information are essential to provide reliability to risk assessment associated with coastal hazards and they must be considered within the methodology.

6.5. Management Applications

The overwash is a natural process frequently caused by a storm component. However the current over occupied coastal areas leads to a concerning: the necessity of establishing hazardous coastal areas and setting shoreline protection measures.

Storms are important factors defining short-term shoreline movement and erosion history along a coastline. The identification of vulnerable coasts guides coastal mapping which is a tool for coastal management and decision making. Return period is a significant concept in this perspective and setting storm impacts with a short return period can be more expressive since it determines events more likely to occur. By understanding the magnitude and return period of storms it is possible to provide more accurate and comprehensive information to help coastal managers in emergency planning and therefore reduce impacts of natural disasters. When overwash occurs during a storm, variable quantities of water and sand or gravel are carried on landward. The subsequent wave attack and landward sediment transport may cause loss and damage of properties, coastal structures and roads, and in extreme cases, inundation.

The Ancão Peninsula is the west limit of the Ria Formosa Natural Park, which was created by the law number nº 373/87 effective as of December, 9th 1987. Besides, the coastal protected area is also designated as a wetland of international importance (Ramsar, 2008). The overwash causes important natural sediment transport processes in the system, as seen in the eastern zone of the peninsula. As the ecosystem is a natural park and the overwash is a natural and fundamental event for the system dynamic equilibrium, any proposed management plan has to integrate an adaption for this process.

The increased human pressure in the system, especially along Praia de Faro, where recreational infrastructure is well developed has been causing dune destruction or intense dune trampling that lowered the dune ridge and promoted the development of fragile sites. During maritime events of high energy overwash occurs within these lowered gaps. So that, most of the overwashed areas acquire an anthropogenic causal component. Furthermore, there is an intense occupation by the seafront constructions which leads to destruction of the dune ridge. Accordingly, the overwash vulnerability becomes higher.

A management approach for the Ancão Peninsula has to consider its economic importance in both regional and national scenarios. Considering the broad range of interests and stakeholders (traders, fishermen, beach users, tourists) and its classification as a natural park area the conflicts are expected. These conflicts rely especially on economic interests and conservation aspects. Hence, for a vulnerable, impacted and dynamic system as the one where the Ancão Peninsula is located, mitigatory actions should be developed in order to minimise negative anthropogenic impacts.

In order to obtain a final management plan for the area both mapping vulnerable areas and protection actions must be taken. The regularly overwashed areas such as lowered and destroyed dune ridge, inlet hazard areas, erosional shorelines and coast under human intervention must be identified in order to obtain a hazard trend along the coast. Particularly for shorelines evolving in response to both natural processes and human activities the mapping of exposed areas is strongly recommended. Hence, overwash vulnerability trend may be seen as a local strategy for coastal communities' protection and relocation, alteration of future urban development, as well as inundation assessments. Because overwash assumes a social-economic aspect along occupied coasts, the development of management actions is urgent.

Ramos and Dias (2000) state procedures taking place along the area and they are seen along the urbanised portion of Ancão Peninsula, although it is still largely vulnerable to overwash events. These procedures are beach nourishment, dune ridge enlargement, and filling the overwashed areas. The proposed establishment of dune fences and elevated paths across the dunes have already taken place in the eastern part of the peninsula.

An ideal management plan for the Ancão Peninsula vulnerable areas is the relocation of the current sea front buildings followed by beach and dune ridge recovery. The buildings which are constructed on the top of dunes and vulnerable to oceanographic forces should be relocated along the back barrier side. Furthermore, the new established community would be reorganised in pile houses. This type of construction allows the system's dynamic to occur and the beach can naturally be maintained by typical winter events (storm and overwash) and fair weather recovery period. Following this phase, the beach face and dune ridge could be nourished with, for example, sediment accumulated in the flood tidal delta from the Ancão Inlet.

A management plan has to mitigate storm impacts, whilst recognising the need for overwash to continue in order to retain the dynamic stability of the barrier system (Davidson-Arnott and Fisher, 1992). In preserving their natural state as much as possible and yet providing recreational opportunities, the need for protecting fixed developments through costly engineering programs is prevented (Leatherman, 1979a).

7. Conclusion

Setting the correct ocean's forcing is crucial when analysing potential areas to overwash processes. Wave attributes (significant wave height and wave length), astronomical and meteorological tides and run-up are key factors driving overwash occurrence. By choosing the best method for calculating run-up vertical scaling and matching it to tides elevation, the overwash extension is well defined.

Storm impacts are not equally identified along a barrier island due to the combined effects of alongshore-variable morphology of the beach and dune relative to the intensity of the ocean's forcing. Changes in topographic elements such as beach slope and dune morphology requires different hydrodynamic conditions to be overwashed.

For the study case of the Ancão Peninsula, collision regime is shown as a constant hazard, whereas overwash hazard varies temporally and spatially alongshore. The shore is largely affected by a storm with 25 - year return period, whereas a storm with 5 - year return period promotes overwash only at particular sites. For eastward immature and low dune crests, there is a significant connection between the overwash vulnerability and tidal inlet presence. The central area is the most vulnerable to overwash not only because of the reflective beach slope but also due to the lowering and destruction of dunes by human intervention. Ancão Peninsula has physiographic characteristics prone to overwash, such as the narrow barrier, the reflective beach slope and the exposition to the energetic SW events. However, the presence of a high dune ridge provides westward low vulnerability to overwash. These results highlight the importance of crest elevation as a natural shoreline protection against storm overwash.

The use of equations and the representation of run-up levels using hazard maps provide more realistic identification of areas prone to overwash when compared to methods applied in previous studies for Ancão Peninsula. Moreover, maps are effective tools for coastal zone management and planning. It is fundamental to map overwash prone areas because it is an indicator of hazards to coastal development. Using the results of a vulnerability assessment, it is possible to set building standards, land use guidelines along the coast and provide information for evaluation and design coastal intervention (such as fencing, nourishment and inlet relocation or stabilisation).

Because some bias was identified in the present method, which implied underestimation of overwash prone area's length, future research is still needed. Thus further studies are recommended concerning the following:

- The most relevant research effort for methods accuracy enhancement is an improvement of run-up formulations. Human intervention is an important cause for coastal instability and it accelerates and increments alongshore changes. Therefore, a parameterisation specifically developed for human modified coasts could give more robustness to overwash evaluation in Ancão Peninsula;
- Also important is to develop a parameterisation which is able to account the berm morphology (width and elevation) within the beach slope, which is still not possible by applying the current methods for storm impact assessment;
- It would be favourable to quantify the friction loss caused by width and elevation of a berm, especially for collision assessment;
- In order to compare how storm impacts vary along the study area, fieldwork should be performed during different periods. Comparisons between surveys would allow the register of beach morphology evolution, seasonal profile responses and its consequences in overwash and collision regimes occurrence.

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