CHARACTERIZATION OF MARITIME STORMS AND ANALYSIS OF THEIR EFFECT ON THE BEACHES SOUTH OF THE MONDEGO RIVER

Santos, M. I. M. A.[1]

May, 2017

Abstract: In the study of coastal processes and coastal dynamics, the analysis of storms impact is one of the most discussed topics in terms of management and defense of the coastal sector. The Portuguese west coast is exposed to the energetic wave climate that characterizes the North Atlantic, thus requiring permanent care as regards an efficient planning and management. This dissertation studies the phenomenon of maritime storms and the associated erosion to this short-term event. The two main objectives are to characterize the storms regime in the coastal stretch, between the Mondego and the Lis rivers' inlets, based on a wave climate time series (1952-2010), and to evaluate the impact of storms duration on erosive events, by applying a short-term morphodynamic numerical model, *Litprof,* for the analysis of the storms effect on the morphology of the stretch and comparing the erosive effect on events with the same power and different duration. The statistical analysis of the chronological series showed a coastal storms regime with high inter-annual and intra-annual variability, in number, duration and power, characterized by a strong seasonality, with an average duration and power of 3 days and 2654 m^2.h, respectively. The dominant frequency classes are [1-2[days and [800-1600[m^2/h (36% of occurrences). The numerical model, applied to several scenarios, predicted the preponderance of the duration factor, in relation to storms with similar power, leading to the conclusion that longer duration storms always generate larger effects (and higher transport rates) in the cross-shore profile, compared to shorter duration storms.

Keywords: Maritime storms, Numerical modelling, Cross-shore sediment transport, Beach profile evolution, Short-term erosion.

1. INTRODUCTION

The importance of the coastal zone in Portugal has been widely recognized in natural, economic and cultural terms, including about ¾ of the population and producing 85% of the country's wealth. However, the large diversity of activities affecting the coast is often responsible for conflicts of interest, leading to contradictory intervention strategies. This has led, for decades, to the degradation of the coastal system, largely due to problems related to coastal erosion, often involving extensive coastal areas (Santos, *et al*., 2014). The dynamics that characterizes these zones, coupled with the permanence of factors capable of modifying and affecting morphology and the sediment transport that occurs there, hinders the process of protection, prevision and coastal management.

The Portuguese coast, exposed directly to the Atlantic, particularly the west coast, is permanently under severe storms formed in the North Atlantic. Indeed, the risks associated with erosion and flooding of vulnerable areas are a constant concern, making it imperative to predict the impact of these events and the response of the beach-dune systems. This dissertation studies the phenomenon of maritime storms and the associated erosion, focusing mainly

---

[1] Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal, mariainessantos9@gmail.com

on two main objectives: the characterization of the maritime storms regime in front of the sandy coastal stretch, covering about 30 km south of the Mondego river's inlet, and the application of a short-term morphodynamic numerical model, *Litprof*, to analyze the effects of these erosive events on the morphology of the stretch and compare this same effect in selected storms with the same power and different duration.

The characterization of the storms regime is based on the analysis of wave parameters' time series (hindcast), from the period 1952-2010, applied to the Portuguese west coast. The statistical analysis focuses on the evolution in the number of storms, duration and power over the 59 years of study, both from an intra-annual perspective, considering the seasonality, and from an inter-annual one. The storms regime is characterized according to the duration and power parameters of the storm events; also, this characterization includes the selection of six erosive events to be simulated through the numerical model, considering two events for each power range (low, medium and high), characterized by different durations. It is therefore intended to determine the weight of the storm duration factor in the behavior of the coastal stretch beaches, when exposed to two distinct events (one with shorter duration and the other one with longer duration).

2. CASE STUDY

The coastal stretch analyzed is located in the central-western zone of Portugal and is bounded at north and south, by the Mondego and Lis rivers' inlets, with two jetties each one (40º10'8"45 N and 8º52'42'W) and (39º52'50 "N and 8º58'18" N), respectively. The stretch is approximately rectilinear and has a 30/32 km extension and an average direction of 19.6º N (Oliviera & Brito, 2015). It is made up mostly of a continuous sandy-dune system, with interruption in the rocky headland of Pedrogão. Along the stretch, there are seven artificial cross-shore coastal structures (groynes), in addition to the ones that delimit the stretch already mentioned: a field of five goynes at the Gala-Cova beach; a goyne in Costa de Lavos; and a goyne in Leirosa. This stretch is characterized by being permanently exposed to a wave climate regime that leads to an intense transport of sediments.

Figure 2.1 - Location of the study littoral stretch, extended between Mondego and Lis river's inlets. Source: Google Maps, April 2017.

3. DATA AND METHODOLOGY

3.1. WAVE CLIMATE AND SEA LEVEL

The wave climate time series was obtained by Dodet, *et al*. (2010), who applied a wave propagation spectral model to the northeast of the Atlantic Ocean, with a spatial resolution of 0.5º and a 6 hours time step, resulting in a chronological series (1952-2010) of 3 wave parameters: significant height (Hs), peak period (Tp) and mean direction (Dir) at the geographic coordinates point 40°00 'N and 9°00' W, at -37 m ZH, in front of the study area. The model was validated by the authors with observations of the Bilbao-Vizcaya, Cabo Sillero, Leixões, Figueira da Foz, Sines and Ocean Weather Station "Juliett" buoys.

The sea level takes into account both the astronomical tide and the storm surge component. The astronomical tide was determined by using the forecast tables obtained by the Hydrographic Institute (IH) for the year 2017 in Figueira da Foz (low tide=0.50 m ZH, high tide=3.50 m ZH). The meteorological tide component was calculated based on the study of FORTUNATO, *et al*. (2011), in which a method to obtain maximum levels and associated time series for different return periods for the Aveiro region (10-year return period corresponds to 4.27 m ZH) was applied. Following this, the elevation value for storm surge was found, 0.77 m ZH, and assumed to be constant for all storms. This approach was used to evaluate the morphological evolution considering the wave climate as the major driving factor, so it was established that the sea level was the same for all cases, in order to simplify the comparison. In the storms modelling the peak of the storm, i.e. the highest wave height verified, is matched with one of the peaks of the sea level (high tide situation plus storm surge).

3.2. ANALYSIS AND CHARACTERIZATION OF THE MARITIME STORMS REGIME

3.2.1. Storm events identification

The identification of extreme conditions of wave climate, usually associated with storm events, is based on the method "Peak-Over-Threshold Method" or peak above the threshold method, which defines individual storm events as a function of a certain "height threshold" and a minimum storm duration (Ciavola, *et al*., 2014). For the west coast of Portugal, Costa, *et al*. (2001) identified Hs> 4.5m as the height threshold. On the other hand, the necessary duration for a maritime storm event to be considered as such is defined according to the following criterion: the storm event initiates in the presence of a sequence of records with Hs>4.5m every 6 hours and lasting longer than 24h; and the storm ends in the absence of records with Hs>4.5m for 2 days, after the last record Hs<4.5m. From the application of the stated criteria to the wave climate time series, 328 events of maritime storms were obtained.

3.2.2. Estimation of storm events power

According to Dolan & Davis (1992) and after the application of the POT method, the total energy contained in a storm event, also referred to as relative power, is expressed in m^2.h and can be determined by the equation:

$$\boldsymbol{E = \int_{t1}^{t2} H_s{}^2\, dt} \tag{3.1}$$

where H_s is the significant wave height and respects the $H_s > H_{tresh}$ condition. H_{tresh} is the storm's threshold height (4.5m for the case study), $t1\ and\ t2$ are the start and end times of the storm, respectively.

3.2.3. Selecting maritime storm events for numerical modelling

The selection of maritime storms events for simulating with the *Litprof* model is based on the sole criterion of considering events with equal relative power and different duration. The selection of six events of both shorter duration and longer duration, among the events for each power range (low, medium and high power) - 2 events per range - was made according to the nearest relative power value recorded between both events, to focus comparison on the variable duration.

3.3. NUMERICAL MODELLING OF MORPHODYNAMICS DURING MARITIME STORMS

3.3.1. Model description

The numerical model applied for modelling the morphodynamics due to the hydrodinamics conditions, associated to each selected storm, was the *Litprof* model (DHI, 2016), which integrates the *LITPACK* modelling system. It is a quasi-3D morphodynamic model, based on the physical costal processes predominant in quasi-uniform beaches. The model describes the morphological modifications occurred in a cross-shore beach profile when subjected to a wave climate and sea level (tide and surge) time series. It is a numerical model composed by several sub-models of costal processes: a hydrodynamic model, a quasi-3D sediment transport model and a morphological model. The wave transformation processes considered are shoaling, refraction, directional dispersion, and wave decay due to energy dissipation associated to bottom dissipation and wave breaking. The processes which contribute to the sediment transport induced by the waves are: the wave vertical asymmetry, the Lagrangian flux, the circulation current next to the boundary layer (or streaming), the surface mass displacement due to breaking (or surface roller) and the undertow (Oliveira & Contente, 2012). *Litprof* operates through successive calls to the *STP* (Sediment Transport Program) and, using the PRFTABL function, calculates the sediment transport rates for certain hydrodynamic conditions by resolving two sediment transport modes, bed load and suspension. At the end of each time step, the model updates the bottom through the application of the continuity equation to the sediments.

3.3.2. Topo-hydrography and sedimentology

The selection of the representative cross-shore beach profile (denominated P7 profile) was made in previous studies, Oliveira and Brito (2015) and Oliveira (2016), based on a morphological characterization of the study area. The representative sediment median diameter was also obtained and defined as d_{50}=0.30 mm along the cross-shore profile, by calculating the equilibrium profiles associated to different d_{50} and adjusting them to the representative profile. The closure depth obtained in Oliveira (2016), for the same study stretch, was -13.6 m ZH, with -14 m ZH being adopted for the initial of the active zone.

In this study case a simplified cross-shore profile is used, in order to simplify the processes and interpretation of the phenomenon, which was obtained from the cross-shore profiles from each sub-section of the study zone and the associated equilibrium profiles. The median diameter of the sediment used in the modelling is d_{50}=0.50 mm, different from the one defined in Oliveira (2016), because in this case the sediments mobilized in cross-shore transport are, mostly, from the emerged beach, where a larger diameter of the grain displaced is observed compared to the submerged profile zone, the main study area in Oliveira (2016).

3.3.3. Propagation of the wave climate

The propagation of the wave climate from -37 m ZH to -14 m ZH water level, to obtain the hydrodynamic conditions at the entrance of the active zone, was done by using the *Transfer Wave Climate* tool contained in the *LITDRIFT* numerical module and the *Littoral Processes FM* software.

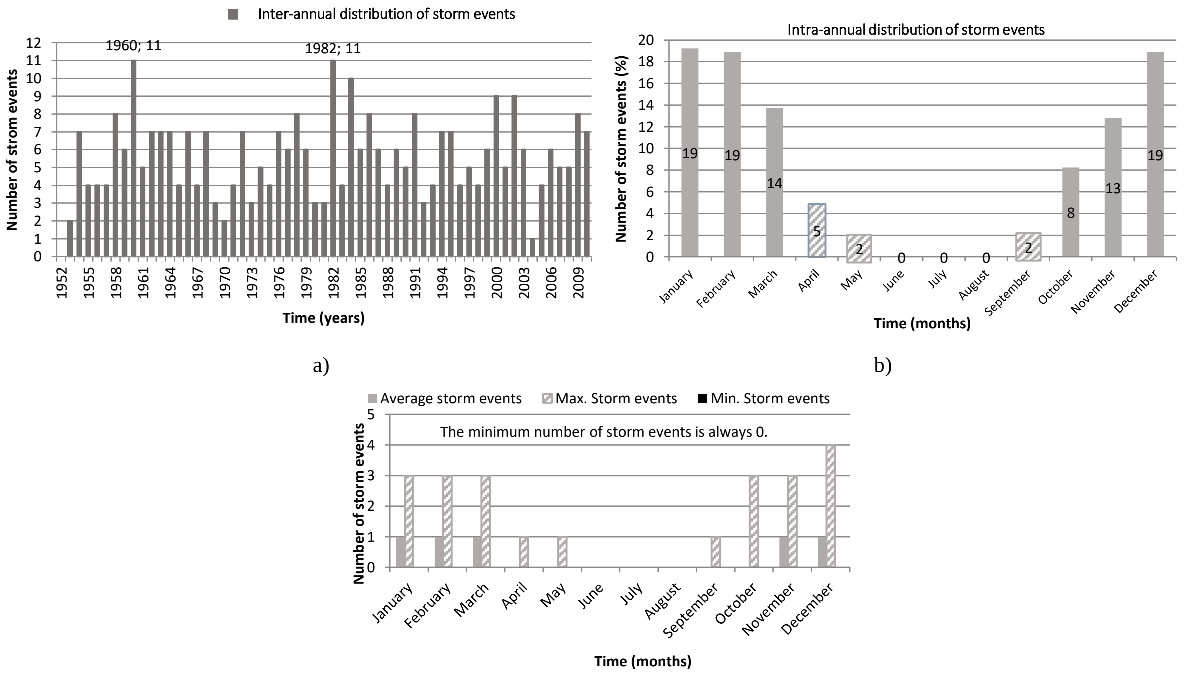
4. RESULTS AND DISCUSSION

4.1. ANALYSIS OF THE WAVE CLIMATE TIME SERIES AND CHARACTERIZATION OF MARITIME STORMS REGIME

4.1.1. Analysis of the wave climate time series

- *Number of storm events*

Inter-annual and intra-annual distribution



a) b)

c)

Figure 4.1 - a) Inter-annual and b) Intra-annual distribution of storm events, and c) Intra-annual distribution of the average, maximum and minimum number of storm events, from 1952 to 2010 in the coastal stretch of study, extended between Mondego and Lis River's inlets.

From the analysis of Figure 4.1 a) a high inter-annual irregularity registered during the study period is highlighted. It is observed that the maximum number of events observed during one year was 11 in the years of 1960 and 1982. The number of events per year was more frequent between 4 and 7, representing 68% of the total number of years under study (40/59 years), with 4 and 7 being the most recurrent. From Figure 4.1 b) and c), an intra-annual variability can be observed , clearly dependent on the seasonality associated with maritime seasons[2]. The months of January (19%), February (19%) and December (19%) showed a higher number of storm events, as expected. March and November are also months in which the storms occurrence is frequent, followed by October, April and, lastly, May and September. It should be noted that, during the 59 years of study, the occurrence of storm events was never observed in June, July or August. The minimum number of events is 0 and the maximum is 4 (occurred in December). The maritime summer months have, as expected, a lower maximum number of events, 1 event. Regarding the average number of events recorded, it is between 0 and 1, 0 in the summer months and October, and 1 in the remaining winter months.

---

[2] Maritime winter: October to March
Maritime summer: April to September

- *Duration and Power of storm events*

<u>*Inter-annual and intra-annual distribution*</u>

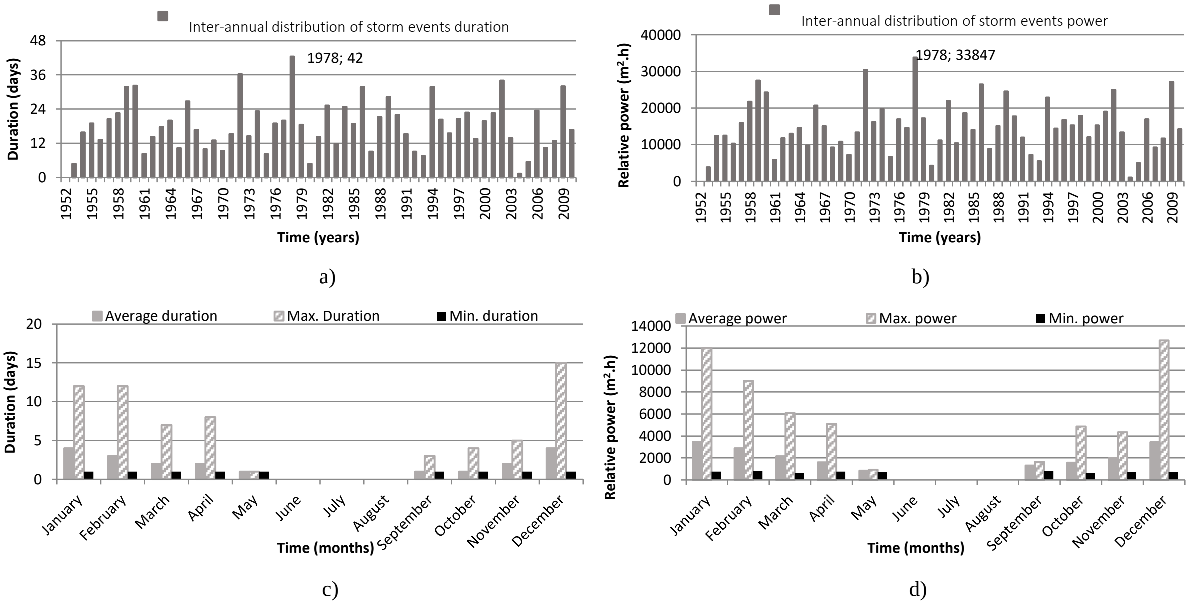


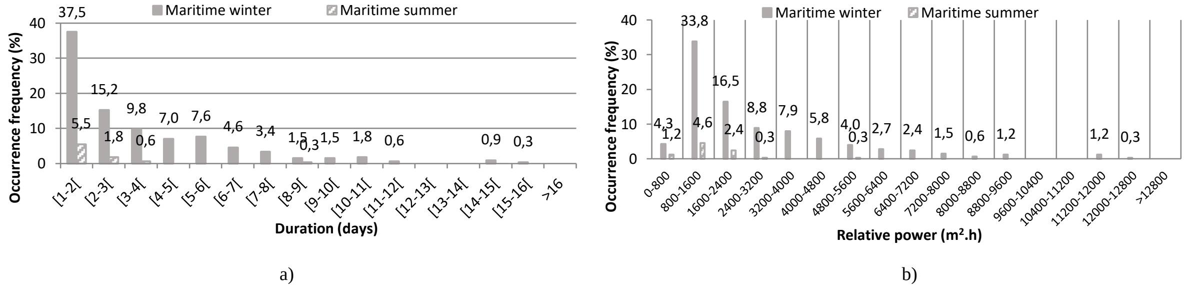
Figure 4.2 – **Inter-annual distribution of a) duration and b) power of storm events. Intra-annual distribution of c) duration and d) power average, maximum and minimum values of storm events, from 1952 to 2010, in the study coastal stretch, extended between Mondego and Lis River's inlets.**

The analysis of Figure 4.3 a) and b) revealed that the evolution of variables (duration and power), in the study period, was very similar, showing its peak in the year 1978. In terms of maximum values, the longest storm occurred in December and lasted for approximately 16 days with relative power of 12700 m^2.h, followed by events in January and February, both with 12 days of duration and high power. Regarding the duration and power mean values, they are within the [0 to 4] days and [0 to 3500] m^2.h intervals, respectively.

4.1.2. <u>*Characterization of maritime storms regime*</u>

- *Duration and Power of storm events*

The characterization of the maritime storms regime was based on the statistical parameters average, standard deviation, minimum and maximum, and 1st, 2nd and 3rd quartiles of storm events duration and relative power, the corresponding histograms and the duration-power histogram. According to the analysis of statistical parameters, the storms regime is characterized by an average duration and power of 3 days and 2654m^2.h; a standard deviation of 3 days and 2201 m^2.h; a minimum/maximum of 1/16 days and 646 m^2.h/ 12700 m^2.h, respectively; 50% of the storms have a duration between 1 and 5 days and power values between 1137 m^2.h and 3584 m^2.h; median duration and power values are 2 days and 1775 m^2.h, respectively. In duration and power histograms, 16 and 17 classes of frequency were defined, with an amplitude of 1 day and 800 m^2.h, respectively.



a) b)

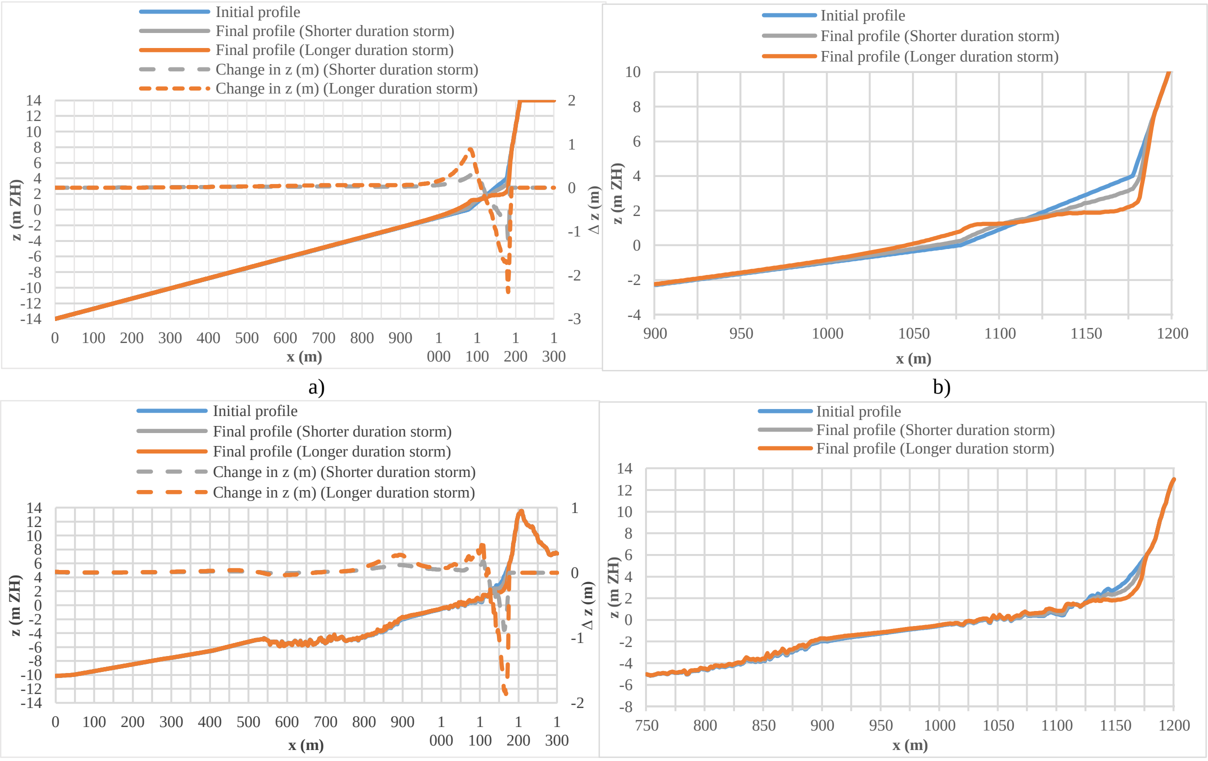
Figure 4.4 - **a) Duration and b) Power histograms of the maritime storms regime in the study coastal stretch, extended between Mondego and Lis River's inlets, from 1952 to 2010, considering seasonality.**

The analysis of Figure 4.5 revealed that storm events occurrences decrease progressively with the increasing duration of the events. The duration and power dominant frequency class is [1-2[with 43% occurrences and [800-1600[with 38% occurrences. The match of both classes includes 119 maritime storm events - 36% of the occurrences during the study period.

4.2. NUMERICAL MODELLING OF MORPHODYNAMICS DURING SEA STORMS

4.2.1. *Evolution of simplified profile and P7 profile*

- *Low power storms*



a)

b)

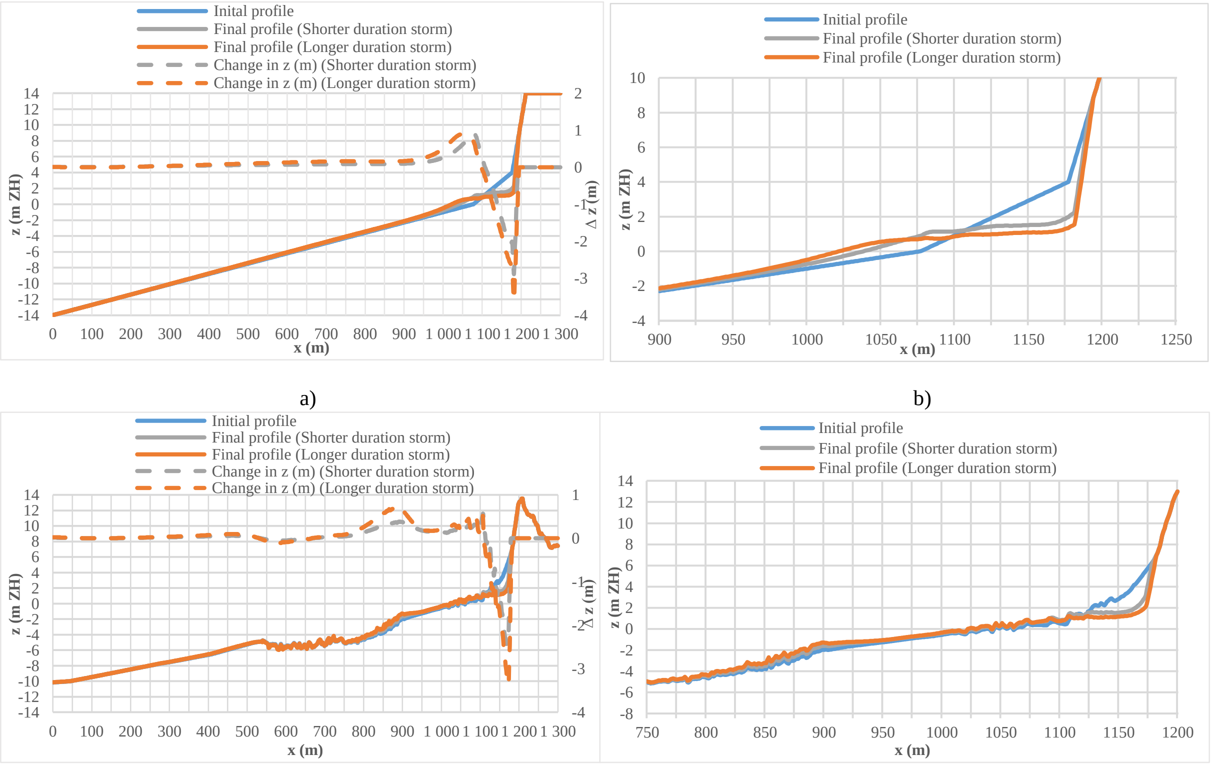
c)

d)

Figure 4.4 – Morphological evolution of a) simplified profile and c) P7 profile, for the shorter (42 h) and longer (108 h) duration storms, with low power, and corresponding change in z(m) (Δz <0 erosion, Δz> 0 accretion). b) and d) represents a detail of profile evolution for simplified and P7 profiles, respectively.

For both storms there is a variation zone of the initial profile, with greater amplitude for the shorter duration storm, caused by the mobilization and displacement of sediments that covers the entire beach face, the top of the submerged profile and the dune face, specifically its base. The extension of the zone is 200m and 300m for simplified and P7 profile, respectively. The erosion process begins with erosion of the dune face, causing the lowering of the beach profile. Simultaneously, transport and deposition of the eroded sediments in the adjacent zone (from the sea side) occurs, almost uniformly in P7 profile, in the beach face and top of the submerged profile, and longshore bar formation in the submerged profile. Accretion and erosion volumes are superior in the simplified profile for both shorter/longer duration storms, 82/39 m^3/m and 76/35 m^3/m, respectively. In P7 profile, these volume values are 66/31 m^3/m and 57/25 m^3/m, respectively. The sediment balance is positive. In simplified profile/P7 profile dune erosion volumes are about 22/35% and 25/39% of the total erosion volume, and the lowering and retreat of the dune base are 0.8/0.9m and 4/6m, and 1.7/1.8m and 6/10m, for the shorter and longer duration storms, respectively.

- *Medium power storms*



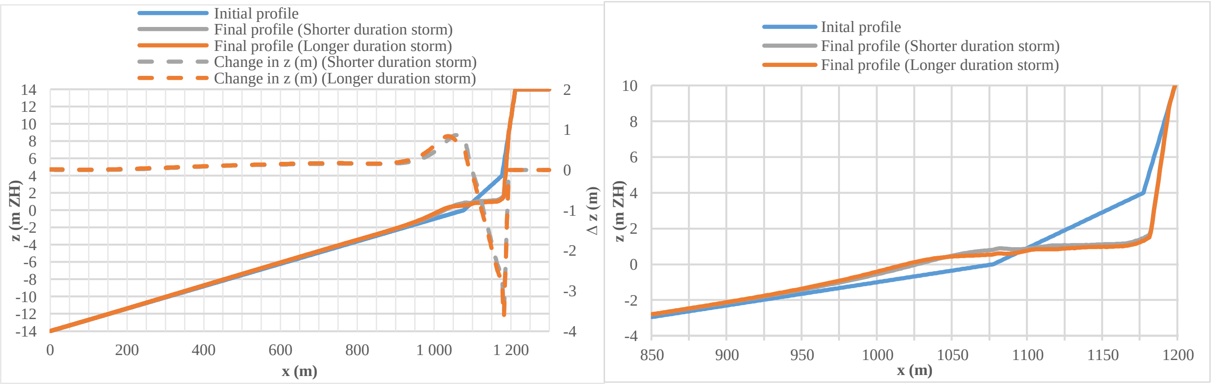
a) b)

c) d)

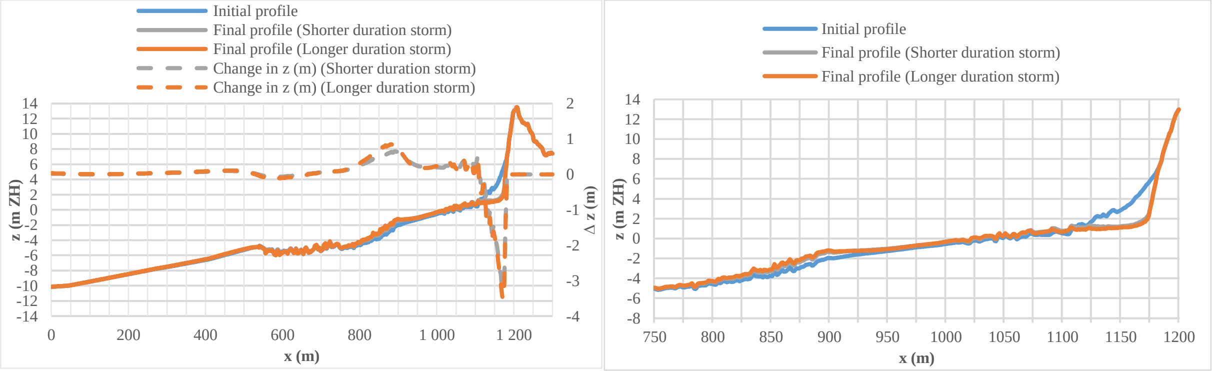
Figure 4.5 - Morphological evolution of a) simplified profile and c) P7 profile, for the shorter (150 h) and longer (258 h) duration storms, with medium power, and corresponding change in z(m) (Δz <0 erosion, Δz> 0 accretion). b) and d) represents a detail of profile evolution for simplified and P7 profiles, respectively.

The extension of the zone under significant variation in relation to the initial profile (beach face, top of submerged profile and dune face) is 300m and 450m for simplified and P7 profile, respectively. The erosion and accretion processes are similar to the ones described for the lower power storms. Accretion and erosion volumes are superior in the simplified profile for both shorter/longer duration storms, 168/117 m^3/m and 147/103 m^3/m, respectively. In P7 profile, these volume values are 146/95 m^3/m and 120/79 m^3/m, respectively. The sediment balance is positive. Dune erosion volumes in simplified profile/P7 profile are about 26/42% and 26/43% of the total erosion volume, and the lowering and retreat of the dune base are 2/2.2m and 7/13m, and 2.7/2.6m and 9/15m, for the shorter and longer duration storms, respectively,

- *High power storms*



a) b)



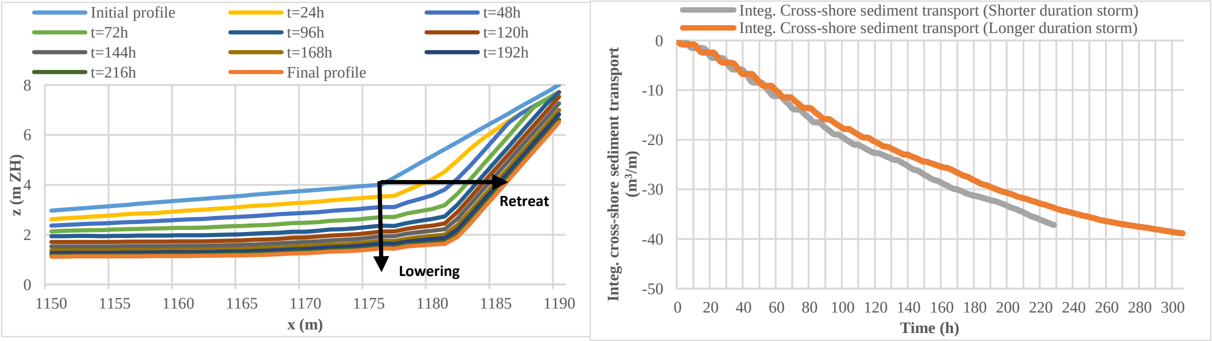
c) d)

Figure 4.6 - Morphological evolution of a) simplified profile and c) P7 profile, for the shorter (228 h) and longer (306 h) duration storms, with high power, and corresponding change in z(m) (Δz <0 erosion, Δz> 0 accretion). c) and d) represents a detail of profile evolution for simplified and P7 profiles, respectively.

The extension of the zone under significant variation in relation to the initial profile (beach face, top of submerged profile and dune face) is 350m and 450m for simplified and P7 profile, respectively. Accretion and erosion volumes are superior in the simplified profile for both shorter/longer duration storms, 180/168 m^3/m and 156/142 m^3/m, respectively. In P7 profile, these volume values are 160/140 m^3/m and 130/112 m^3/m, respectively. The sediment balance is positive. Dune erosion volumes in simplified profile/P7 profile are about 27/42% and 26/43% of the total erosion volume, and the lowering and retreat of the base of the dune are of and 2.6/2.5m and 9/15m, and 2.7/2.7m and 9/15m, for the shorter and longer duration storms, respectively,

4.2.2. *Evolution of the simplified profile and the transport rate at the base of the dune*

This analysis consists of studying the profile and transport rate evolution during storms in order to see how it proceeds, i.e., if it is carried out with greater intensity in the first few hours of the storm or if it is distributed evenly throughout its duration. As an example, the analysis for the profile point coincident with the dune base is shown below, in which there was a significant transport during a high power storm, leading to its retreat and lowering, in the simplified profile.



a) b)

Figure 4.7 – Evolution of a) simplified profile, identifying base dune' retreat and lowering, and b) sediment transport rate in the same profile zone (dune base), during a high power storm with duration t=228h.

The analysis of Figure 4.7 showed that, in the cross-shore profile, the transport rate evolved similarly in both storms (with shorter and longer duration). However it is always superior in the shorter duration storm. This is due to the fact that both storms have similar power and, therefore, storms with shorter duration imply bigger height waves and greater energetic capacity to carry the sediments, turning into a higher transport rate. A progressively decreasing profile variation/transport rate during the storm was also verified, being very reduced in the last hours, and leading to a situation of almost stabilization of the profile.

The differences in the results obtained for both profiles are, essentially, justified by their geometry differences. The simplified profile, although it is rather close to the real profile P7, has only three different slopes, one for each "zone" of the profile, making the requested phenomenon response easier without any other geometrical constraints, and improving the formation of accretion and erosion zones, as is the case. The P7 profile is a real profile and presents in its geometry singularities and greater irregularity zones, leading to a more uniform sediments deposition along the profile.

CONCLUSIONS AND FUTURE RESEARCH

This dissertation made possible the study of the erosive effect of maritime storms possible, occurred during the study period, in the sandy stretch south of the Mondego River’s inlet. The study was based on the analysis of a wave climate time series and on the characterization of the maritime storms regime, allowing to expand the knowledge of the existing coastal dynamics. This study predicted the erosive effect on the morphology of the beaches, exposed to maritime storms with the same power and different duration, using numerical modelling (*Litprof)*, by comparing its effects.

The statistical analysis of the wave climate time series showed a maritime storms regime with high inter-annual and intra-annual variability in number, duration and power, characterized by a strong seasonality. The months of January, February and December showed a greater number of events, and no events were observed in June, July and August. The maximum number of events registered in maritime winter and summer was 4 and 1, respectively. Regarding the duration and power parameters, a minimum/maximum of 1/16 days and 646/12700 m^2.h, respectively, were observed, with the maximum values occurring in December. The average duration and power verified on the storms regime was 3 days and 2654 m^2.h, with dominant frequency classes [1-2[days and [800-1600[m^2/h (36% of occurrences), respectively.

The numerical modelling of the maritime storms morphodynamics, with shorter and higher duration for low, medium and high power range, performed for the simplified profile and confirmed by the P7 profile, allowed to conclude that the duration of storms is dominant in the process of beach profile modelling, regardless of the power range. In all cases, the longer storm duration always leads to higher transport rates and larger beach profile changes, compared to events of shorter duration. In addition, it was verified that the sediment transport rate increases with storm power and, therefore, higher power storms also generate larger profile changes. The evolution of the profile and the sediment transport rate in the transversal profile showed that the transport rate always evolves similarly for both smaller and longer duration storms, but it is slightly higher in the smaller duration storm. Also, there is a progressive decrease in the profile/transport rate variation during the storm that leads to a situation of almost stabilization of the profile in the last hours of the storm.

In the future, it may be interesting to complement this study by determining the erosive effect on a beach profile under the action of several successive extreme events with reduced duration and power, whose total sum of duration and power should be similar/equivalent to one of a long duration and high power, so as to make the comparative study of the same effect on the two situations. Another suggestion for future research is the use of other morphodynamic models, e.g. XBeach model, which includes infragravity waves and swash processes, in order to compare the quality of the results obtained.

REFERENCES

Ciavola, P. *et al.*, 2014. *Prediction Of Storm Impacts On Beach And Dune Systems. Hydrometeorological Hazards: Interfacing Science And Policy,* Pp. 227-252.

Costa, M., Silva, R. & Vitorino, J., 2001. *Contribuição Para O Estudo Do Clima De Agitação Marítima Na Costa Portuguesa. 2as Jornadas Portuguesas De Engenharia Costeira E Portuária - Associação Internacional De Navegação,* Pp. 20.

DHI, 2016. *Profile Development. LITPROF User Guide.* Danish Hydraulic Institute.

Dodet, G., Bertin, X. & E Taborda, R., 2010. *Wave Climate Variability In The North-East Atlantic Ocean Over The Last Six Decad*es. *Ocean Modelling,* Volume Vol. 31, Pp. 120-131.

Dolan & Davis, 1992. *An Intensity Scale For Atlantic Coast Northeast Storms. Journal Of Coastal Research,* Pp. 840–853.

Fortunato, A. B., Rodrigues, M., Dias, J. M. & Oliveira, A., 2011. *Modelação Da Inundação Costeira Na Ria De Aveiro - 11º Congresso Da Água.*

Oliveira, F. S. B. F. & Contente, J., 2012. *Efeitos De Escala Em Modelação Númerica Da Erosão De Um Perfil De Praia,* Lisboa: 7º Simpósio Sobre A Margem Ibérica Atlântica.

Oliveira, J. N. C., 2016. *Modelação Do Impacte Do Prolongamento Do Molhe Norte Da Embocadura Do Rio Mondego Nas Praias Adjacentes A Sul.*

Oliviera, F. S. B. F. & Brito, F. A., 2015. *Evolução Da Morfologia Costeira A Sul Da Embocadura Do Rio Mondego, De 1975 A 2011. VIII Congresso Sobre Planeamento E Gestão Das Zonas Costeiras Dos Países De Expressão Portuguesa.*

Santos, F., Lopes, A.M., Moniz, G., Ramos, L. e Taborda, R. (2014). *Gestão da Zona Costeira – O Desafio da Mudança*. Relatório do Grupo de Trabalho do Litoral, Pp. 255.