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FORECASTING THE IMPACT OF STORM EPISODES ON BEACHES: PRESENT LIMITATIONS

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Title

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Authorship

HYDRAULICS AND ENVIRONMENT DEPARTMENT
Filipa S. de Brito F. de Oliveira
Research Officer, Estuaries and Coastal Zones Division

Collaboration

HYDRAULICS AND ENVIRONMENT DEPARTMENT

Martha Guerreiro
Research grant-holder

Rita Cavalinhos
M.Sc. Student

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Abstract

The application of credible morphodynamic forecast models to provide evidence-based information for coastal managers making decisions for re-profiling the beach and thus increase coastal resilience by restoring the sediment balance and providing space for coastal processes is a relevant issue since the future risk of coastal storm impacts is likely to increase. The study exposes the practical limitations and inevitable uncertainties found in the application of two state-of-the-art process-based morphodynamic numerical models to an Atlantic urban sandy beach under extreme wave energy and surge conditions. The erosion of the foreshore and backshore of this particular beach was characterised as function of the intensity and duration of the hydrodynamic forcing parameters. The models performance was evaluated and compared. A major conclusion achieved was that in order to obtain reliable simulations of the morphodynamics during high energy coastal events it is necessary to further develop and apply non-intrusive monitoring techniques, which enable accurate monitoring in such adverse environments, to capture the physics in those conditions and load correctly the numerical models. There is an urgent need to overcome the present limitation in order to achieve a higher level of reliability in beach erosion impact forecasts.

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1 | Introduction

Natural factors (like the sea level rise, the long-term variation of mean hydrodynamic conditions and the increase of frequency and intensity of maritime storms due to climate changes) and human-induced factors (like the reduction of the littoral drift due to sediment trapping by jetties, port sand trapping and dredging, river damming and sand mining, advanced occupation/urbanization of maritime fronts) are recognised for being responsible for long term erosion in coastal regions (European Commission, 2004). However, on the short-term, due to extreme hydrodynamic conditions, such as storms or hurricanes, the occasional rapid erosion as results of extreme events might lead to irreversible erosion when the mean conditions are such that there is net longshore transport pattern (Steezel, 1993).

Several studies point out the tendencies (of aggravation) of erosion along the Portuguese coast (Salman *et al.*, 2004; Dias, 2007; Gomes, 2007). Despite the uncertainty (and controversy), one of the causes pointed out by some authors (Andrade *et al.*, 2006; Meehl *et al.*, 2007) is the likely future increase of frequency and intensity of storm events. The sea level rise as a cause of erosion is unanimous among the scientific community.

In urbanised coastal areas as the present case study, the beach coastal protection function is even more important than its recreational function because despite being used by thousands of people during the bathing season it has a crucial defence role against wave action over public and private infrastructures. For this reason, understanding how the beach responds to storms is critical to safe and responsible coastal planning and management (Stockdon *et al.*, 2007). In order to accurately predict the coastal response to large storms, quantification and characterization of the impact of these is required. For the importance of the theme, the focus of this study is on the short-term erosion phenomenon that occurs when the water level and waves are high, due to low atmospheric pressure and strong winds, respectively. Specifically, on the evaluation the beach foreshore and backshore sand eroded volumes, responsible for the immediate retreat and lowering of the shoreline. Such knowledge is essential for coastal erosion management and planning, since it provides information for re-profiling the beach and thus increase coastal resilience by restoring the sediment balance and providing space for coastal processes.

Despite the existence of several numerical morphodynamic models of high level of resolution to predict beach evolution at a short-term time scale there is much to be done to make them credible for coastal management and planning. These models have been mostly developed, tested and improved by coastal scientists and engineers in research projects (many of these models are of complex application, with a large amount of empirical input parameters of difficult measuring in the field and,

therefore, predominantly calibrated and verified against laboratory experiments) and less times applied in consultancy projects (many times with large uncertainty associated due to the difficult calibration and verification of the models with field data. The ultimate objective of this paper is to demonstrate and alert to the dependency of the beach erosion impact forecasts on the morphologic, hydrodynamic and sedimentologic field data quality and quantity.

In the present study, these issues were addressed through the use of an Atlantic urban sandy beach. The study site is Carcavelos beach, with about 1400 m of alongshore extension and 100 m of width (in its central part), located near Lisbon, in the west central coast of Portugal (Figure 1). Its narrow backshore is limited by a vertical seawall of concrete and several infrastructures. It faces the North Atlantic Ocean, therefore, is exposed to an average wave regime highly energetic, despite the strong seasonality which characterises the west coast of the country (Oliveira *et al.*, 2002). Despite having headlands in both extremes, it is not a pocket beach because the active depth, that is, the submerged limit of the active beach, is further offshore than the headlands. The wave regime to which it is exposed and the proximity to a densely populated urban area make the beach a sea-land interface of high coastal risk. The maritime storm episode here analysed was the first of that maritime winter season and occurred in spring astronomic tide conditions.
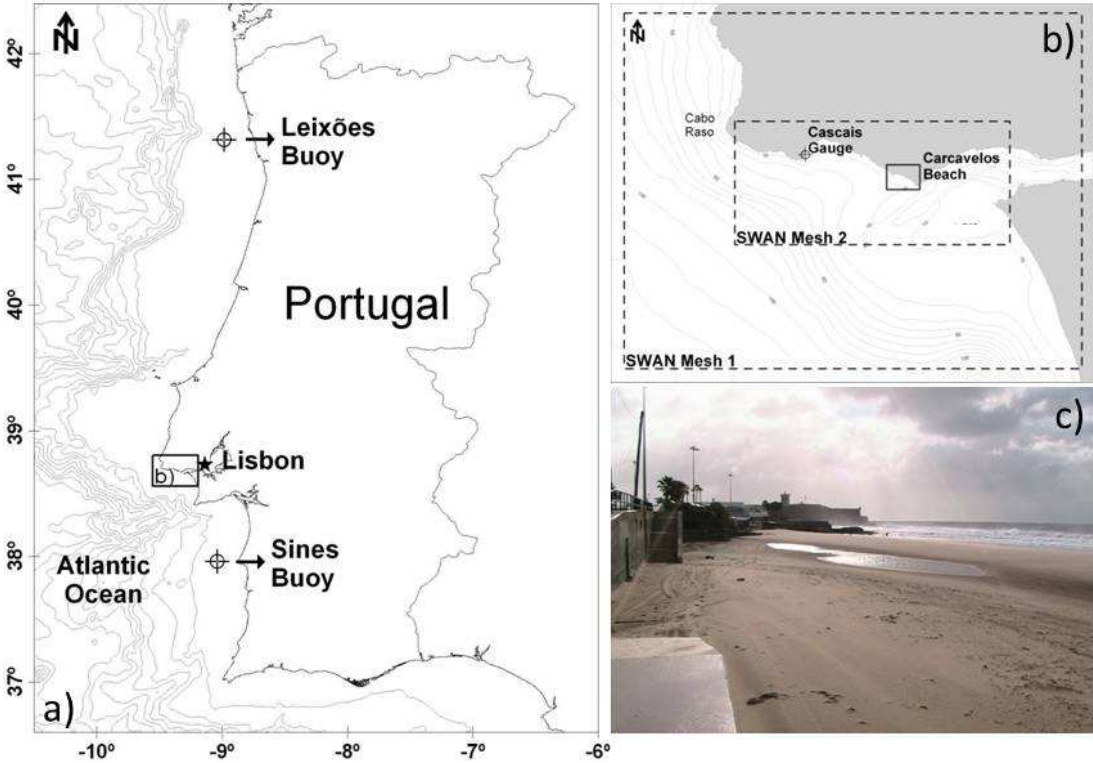
Figure 1 - Location of the study area: a) location of the Leixões and Sines buoys; b) SWAN meshes and Cascais gauge; c) beach view towards SE (oblique photograph).

In the present section the context, the problem and the objective of the study were pointed out. The study area was also briefly described. The following section describes the material and methods applied, which includes a description of the various types of data acquired, as well as the respective processing, and the numerical models application. The results and discussion are presented in section three, which is followed by a section of conclusions and recommendations.

2 | Material and methods

The methodology involved the following four main phases (each described in more detail in the subsections ahead):

i)   The characterisation of the twenty-four-hour hydrodynamic storm event (wave parameters and sea level) from the offshore until the beach, by integrating buoy data and numerical modelling of wave propagation.

ii)   The evaluation of the morphologic impact of the event through the comparison of the immediately pre-storm and immediately post-storm cross-shore beach profiles surveyed in locations which provided a good coverage of the total alongshore extension of the beach foreshore and backshore. It includes the evaluation of the beach foreshore erosion volume.

iii) The characterisation of the pre-storm foreshore surface sediment grain size distribution, based on the laboratory analysis of surface sediment samples collected in each surveyed profile.

iv)   The application of two process-based profile models, the Litprof (DHI, 2008) and the Unibest-TC (WL|Delft Hydraulics 1999), to simulate the morphodynamics of the complete active part of the profile, which includes the submerged part. The post-storm profiles and the erosion volumes measured were compared with the ones simulated numerically with each model. Further than analysing the agreement between predictions and observations the results of the two models were also compared. Comments on the large amount of the models input parameters are issued in order to make the models application conditions clear for non-experts in coastal morphodynamics science and engineering.

2.1   Hydrodynamics

The offshore wave climate in front of the study area was calculated based on wave data from the two nearest offshore buoys. The buoys were deployed at about 280 km north (Leixões) and 80 km south (Sines) from the study area along the same parallel (Figure 1a). A weighted average, in which the weights were the relative distance along the parallel from each buoy to the offshore position of the study area, was applied to each parameter of the wave data time series. The proximity of Sines determines the largest influence on the wave climate in the offshore of the study area. The calculated wave parameters were the significant wave height, Hs (m), the zero crossing period, Tz (s), and the mean direction, Dir (°) (Figure 2). The study period was the time between the 11:00 (hh:mm) of the 27/October/2011 and the 11:00 (hh:mm) of the 28/October/2011.

The sea level data series was obtained from a nearby gauge, located in Cascais (Figure 1b). It includes the two components, tide and surge. The average (during the study period) of the surge,

estimated based on the difference between the measured sea level and the predicted astronomic tidal level, was 0.36 m (Figure 2). The sea level is referenced to the National Hydrographic Datum, named Zero Hidrográfico (ZH), which level is 2.21 m below the present mean sea level (MSL) in the study zone.

The nearshore wave climate at -10 m ZH, the depth of the first seaward point of each of the five cross-shore profiles considered along the study area, was calculated using the SWAN model (Booij *et al.*, 1999). The model was applied using a system of two mesh fitting (Figure 1b). For the coarser mesh, a uniform square grid spacing of 250 m was applied over a total area of 910 km^2. For the refined mesh, a uniform square grid spacing of 50 m was applied over a total area of 180 km^2.
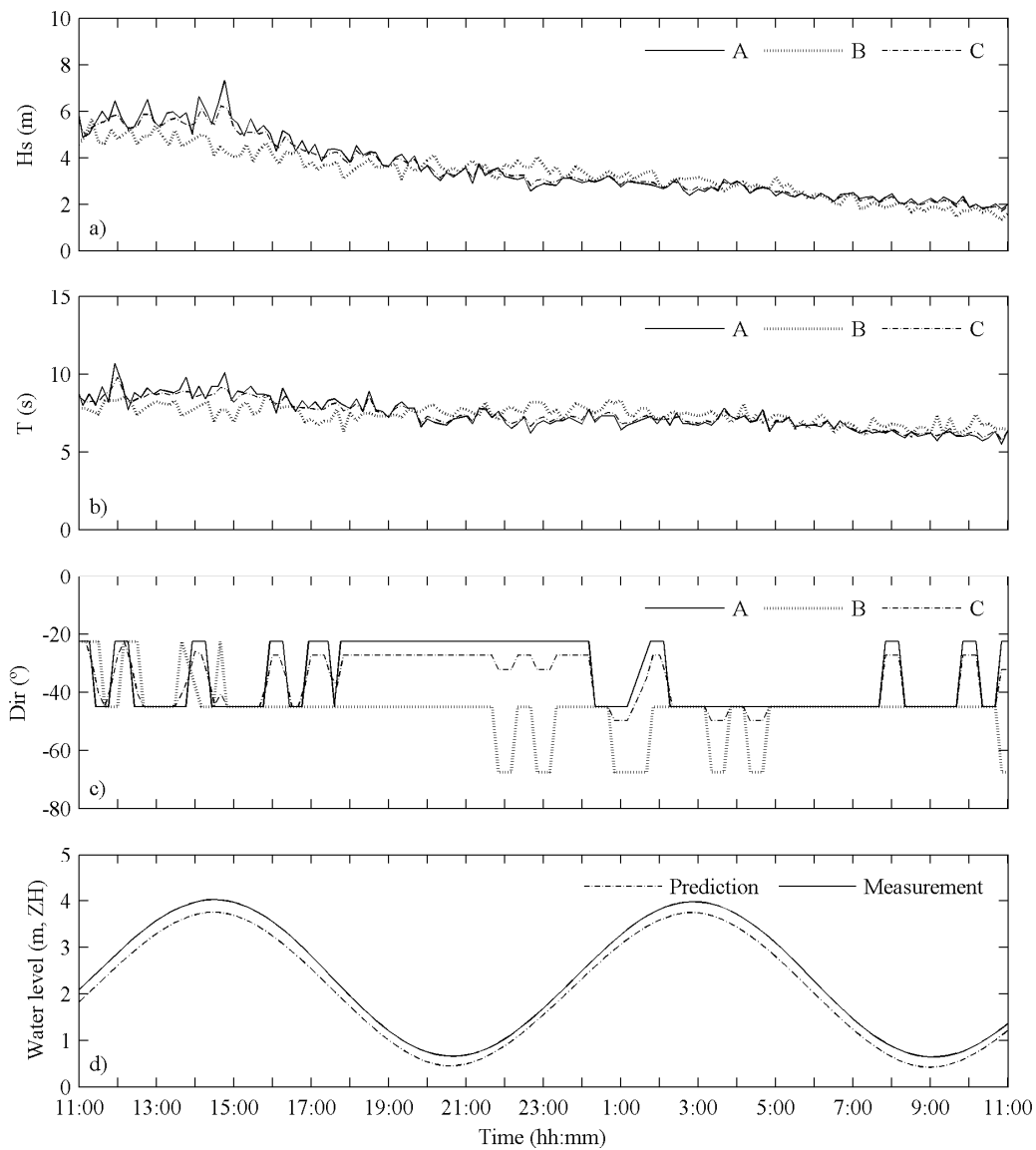

Figure 2 - Offshore wave parameters Hs, Tz and Dir in Sines (A), Leixões (B) and in front of the study area (C), and water level at Cascais gauge during the study period.

2.2 Pre-storm and post-storm morphology

Five cross-shore profiles where surveyed at low spring tide on the 27/Oct and 28/Oct, between 9:00 and 11:00 (hh:mm). The profiles were named from A to E from SE to NW, respectively (Figure 3). The beach shoreline main alignment (orientation relative to the geographic North) was approximately N120°. The survey was performed through a RTK-DGPS (with vertical precision of ±20 mm + 1.0 ppm). The horizontal coordinate system was the ETRS89 - European Terrestrial Reference System 1989. The vertical coordinate system was converted to the ZH. Due to the sea conditions, the cross-shore extension, on the horizontal plan, of the beach foreshore and backshore surveyed on the 28/Oct (post-storm) was slightly longer than on the 27/Oct (pre-storm). The lengths varied between 107-146 m and 150-179 m on the 27/Oct and 28/Oct, respectively. The profiles were interpolated along a uniform grid in the horizontal plan of spacing $\Delta x=1.00$ m.
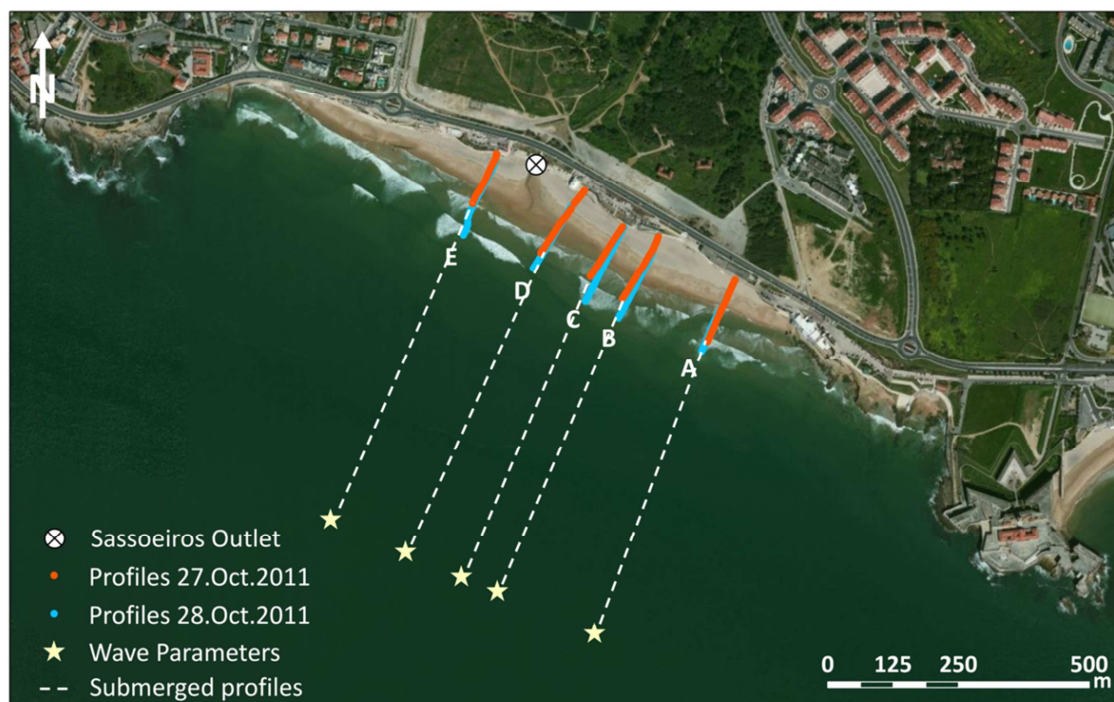
Figure 3 - Location of the cross-shore profiles A, B, C, D and E surveyed on the 27th and 28th of October/2011, location of the first seaward points of the five cross-shore profiles (at depth -10 m ZH) and location of the Sassoeiros outlet.

2.3 Beach sediments

Surface sediment samples were collected from the foreshore in each of the five pre-storm profiles and analysed in the laboratory. For each sample a sediment grain size analysis was performed. The grain size distribution parameters median diameter, D50, 90th percentile, D90, 84th percentile, D84, and 16th percentile, D16, were calculated. Together with the geometrical spreading, $\sigma=(D84/D16)^{(1/2)}$,

these parameters were used to characterise the grain size distribution of the beach and as input sedimentologic conditions in the numerical models (Table 1).

Table 1 – Sediment grain size parameters used in numerical models for profiles A, B, C, D and E.

Profile	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	D_{90} (mm)	σ (-)
A	0.26	0.34	0.45	0.49	1.315
B	0.23	0.32	0.48	0.55	1.444
C	0.27	0.35	0.47	0.54	1.319
D	0.28	0.34	0.45	0.49	1.267
E	0.23	0.28	0.34	0.35	1.215

2.4 Morphodynamic numerical modelling

During short-term beach erosion events the cross-shore component of the coastal processes is predominant over the longshore component, which explains the simplification behind the development of profile type numerical models to simulate the morphological evolution of the beach-dune systems during this type of events (Roelvink and Broker, 1993). These process-based models, focused on the profile response, assume that the sediment is redistributed across the active beach profile with no net gain or loss of sediment, and assume that longshore gradients are negligible. The sediment is extracted from the subaerial part of the beach, causing erosion, transported seaward, mostly by the intense undertow current, and deposited in deeper water, often as a longshore bar. Among these models are the Litprof and the Unibest-TC, applied in this study to investigate the morphodynamics along the cross-shore profiles active zone, which includes the cross-shore extension from the highest runup level until the deepest position where significant sediment transport occurs causing changes in the sea bottom. Both models are two dimensional in the vertical plan (2D-vertical) morphodynamic models, based on the physical costal processes predominant in quasi-uniforme beaches, that is, beaches where the incident wave direction can be variable but the isolines of bathymetry are approximately parallel to the shoreline. Both models describe the morphological modifications occurred in a cross-shore beach profile, with its own sedimentologic characteristics, when submitted to a wave, tidal and surge time series.

The Litprof model is composed by three sub-models of costal processes: an hydrodynamic model, a quasi-3D sediment transport model and a morphological model (for bottom update). 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 that progress towards the shore considered in the model are: the wave vertical asymmetry, the lagrangian flux (due to the wave horizontal asymmetry), the circulation current next to the boundary layer (streaming), the surface mass

displacement due to wave breaking (surface roller) and the undertow. Since infragravity waves (resultant from nonlinear harmonic interactions from short wave groups) are not taken into account, the model does not consider swash motions (which up to a large degree result from wave group forcing of infragravity waves) (Tucker 1954), that is, the extension of the active zone ends in the last wet cell due to the combined action of the setup (a lower frequency rise in the water level due to wave breaking) and the short (or gravity) waves. The model, that also considers the contribution of the bottom slope (gravity force) to the sediment transport, resolves the two sediment transport modes, bed load and suspension. At the end of each time steep, the model updates the bottom through the application of the continuity equation to the sediments.

The Unibest-TC is composed of five sub-models: a wave propagation model, a mean current model, a wave orbital velocity model, a bed load and suspended load transport model and a bottom update model. The wave transformation processes considered are shoaling, refraction and decay due to energy dissipation. The mean current profile model computes the vertical distribution of the wave-averaged mean current in both longshore and cross-shore directions accounting for wind shear stress, wave breaking, bottom dissipation in the wave boundary layer and the slope of the free surface. The wave orbital velocity model computes the time series of the near-bed wave orbital velocity accounting for the wave asymmetry, wave group related amplitude modulation and bound long waves, therefore, representative for irregular wave groups. Like in the Litprof model, the Unibest-TC resolves the two sediment transport modes, bed load and suspension. The suspended sediment flux is computed as the product of the wave-averaged current and concentration profiles, which are obtained from the mean current profile model and a time-averaged advection-diffusion equation respectively. The bed load transport is computed as function of the instantaneous bed shear stresses, which are determined by the near bed velocity signals. These last are composed of the generated time series for the near-bed wave orbital velocity plus the time-average current velocity near the bed. After the computation of the transport rates along the profile, the bed level changes are computed from the depth integrated mass balance equation.

Depending on the model, the statistical parameters of the wave height and period used in the boundary conditions time series at the first seaward profile grid point were either the root-mean-square wave height, Hrms, or the significant wave height, Hs, and the zero crossing period, Tz, or the peak period, Tp. The relationships applied were Hs=1.416Hrms and Tp=1.29Tz (Goda, 1985). The two models also use different parameters to characterise the grain size distribution along the profile: the Litprof uses the D50, and the geometrical spreading, σ, whereas the Unibest-TC uses the D50 and the D90.

Both models require a large number of input parameters associated to conditions of wave, flow, transport, morphodynamics, boundary and numerical stability. Some of these empirical parameters

are quite difficult to measure in storm conditions. Such restriction can be overcome by using the default values recommended by the models developers. These default values were defined as being the ones which best represent the widest range of possible physical conditions previously tested. Among these parameters, some are common to both models. For these, the same values were considered. Prior tests of sensitivity were done with both models and the results revealed that the most effective calibration parameters were: wave dissipation related parameters and roughness height for waves and currents morphological parameters. It is likely that some of the values assumed for the parameters which were not possible to measured locally brought uncertainty into the predictions. However, this issue meets the objective of this study and it is what a non-expert in beach morphodynamics wants to know: how uncertain the predictions can be if the default values are used for the large amount of parameters which cannot be measured due to the sea-state and weather conditions.

3 | Results and discussion

3.1 Hydrodynamics

The results of wave propagation from the offshore until the five positions at depth -10 m ZH, corresponding to the first seaward grid points of the five cross-shore beach profiles, revealed the time and spatial (alongshore) variation of the wave climate in front of the beach, at the entrance of the surf zone, during the study period (Figure 4).

a) Regarding the time variation of the wave climate, it was found that:

- The wave height decreased from nearly 2 to 0.5 m. Values above 1.5 m were observed until 14:30 (hh:mm), that is, approximately during the first 3.5 hours, and values above 1.0 m were observed until 02:00 (hh:mm), that is, approximately during the first 15 hours of the event.

- The wave period decreased from 9 to 6 s, being the highest rate in the first 9 hours (from 11:00 until 20:00 (hh:mm) on the 27/Oct).

- There was a significant change in the incident wave direction from the first to the second day. The incident waves, which showed a nearly normal incident direction to the shoreline during the first day (the direction normal to the main shoreline alignment is N210°), became slightly oblique, that is, rotated towards NW on the second day (after 00:00 (hh:mm) on the 28/Oct).

b) Regarding the spatial variation of the wave climate, it was found that:

- The wave period was practically constant in space.

- The wave height revealed a slight increase of incident energy alongshore, from NW to SE (from profiles E to A, respectively). This was mostly due to the effect of protection against offshore incoming waves offered by Cabo Raso (Figure 1b), the nearest large scale headland north of Carcavelos, which induces a change of direction in the main alignment of the shoreline in the region, and thus, generates the phenomenon of wave diffraction (transference of wave energy along the wave crest) when the direction of the offshore incoming waves (in Figure 2) is intercepted, as it is the case.

- For the incident waves direction, the spatial variation is more evident for the highest waves, during the first day. The highest waves tended to be more oblique relatively to the cross-shore direction from the NW to the SE profiles.

It can be concluded that the spatial variation of the wave parameters is relevant because the alongshore extension of the beach is only about 1400 m. The analysis of the evolution of the wave climate and sea level allows to conclude that the worst hydrodynamic condition occurred on the 27/Oct at 14:00 (hh:mm), when the waves reached the greatest height and the sea level was higher than 4 m ZH.
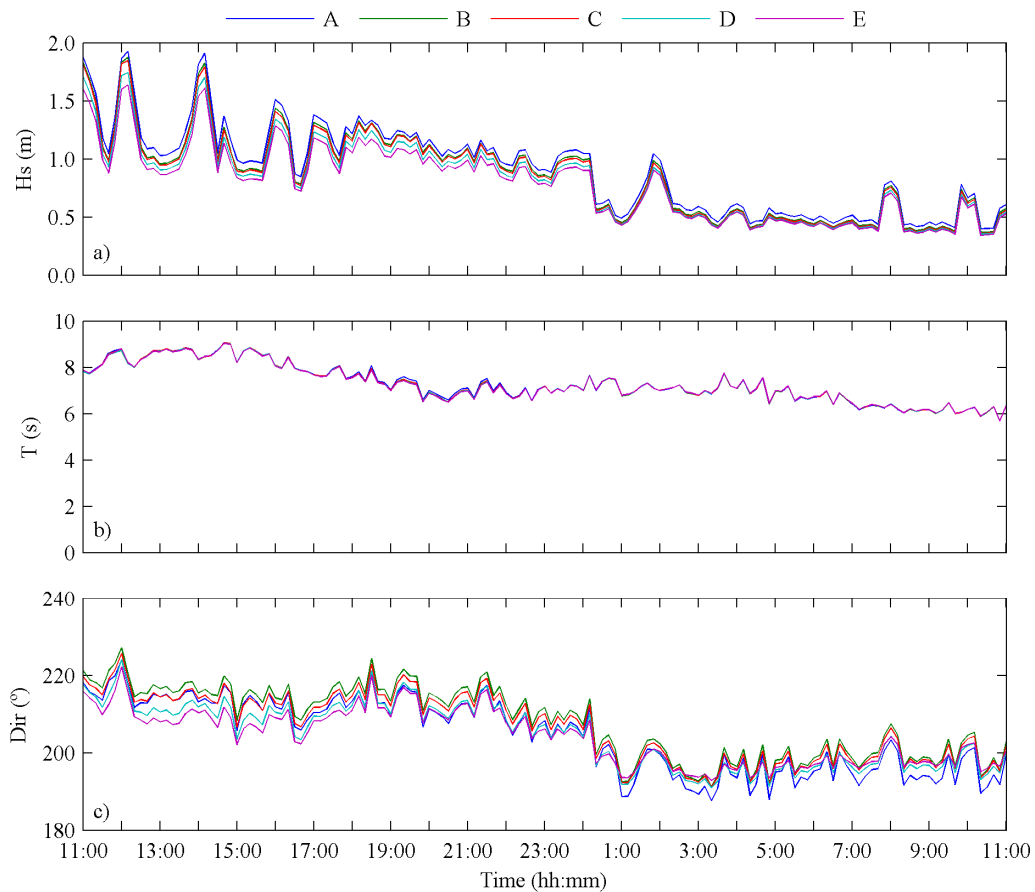
Figure 4 - Hydrodynamic parameters Hs, Tz and Dir at the entrance of profiles A, B, C, D and E (at depth -10 m ZH) during the study period.

3.2   Geomorphological conditions

The analysis of the profiles measured on the 27/Oct showed that the upper part of the beach face, above MSL, is slightly steeper in profiles A and B than in profiles C, D and E (Figure 5). The morphology of profiles C and D is also distinct from the other profiles regarding the extension of a trough existent on the top of the beach berm which is shorter for these two profiles. It is likely that this shorter extension is due to a temporary stream discharge, named Sassoeiros, which crosses the centre of the beach (Figure 3). This stream is diverted during the summer (bathing season), but during episodes of storm, with intense rainfall, the discharge increases and the stream flows directly to the beach. During these occasions the stream presents a varying meander pattern in this sector of the beach, causing local erosion, by pushing the surface sediments seaward and lowering the beach foreshore, in the absence of interaction with waves. Such features were observed in the pre-storm profiles (Figure 5).
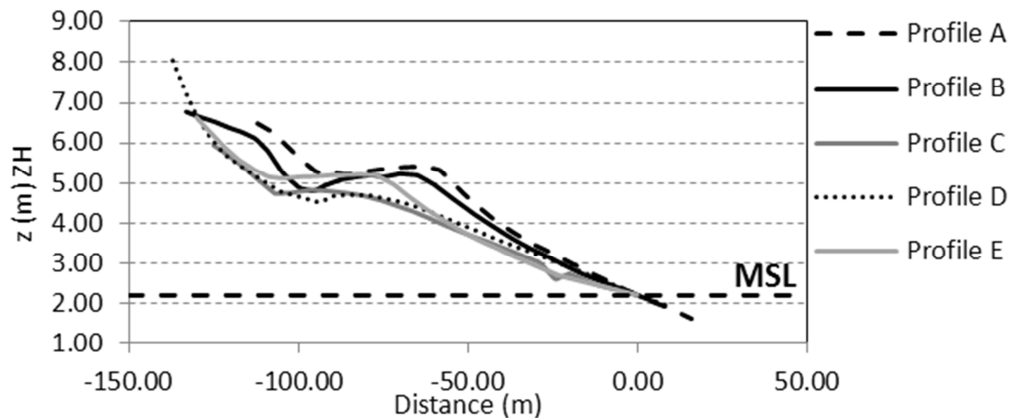
Figure 5 - Cross-shore beach profiles A, B, C, D and E measured on the 27/October/2011.

Regarding the evolution of the stream trajectory during the study period, it was noticed that on the 27/Oct the watercourse was aligned with the cross-shore direction near profile D, whereas on the day after the watercourse revealed a meander pattern along the top of the beach berm and its mouth was displaced towards the cross-shore profile C. At the peak of the storm, the waves reached the top of the berm in the central sector, that is, the interaction between the stream and the waves occurred along the total beach foreshore and backshore.

The results from the grain size distribution analysis (in Table 1) revealed that the beach sediment was mainly median grain size sand and that the well sorted (low variance) sediment was uniform alongshore. Thus, it can be concluded that the higher steepness of the beach face of profiles A and B was not correlated with coarser sediment in those profiles. Such fact leads to another conclusion: that the alongshore variation of the profiles morphology was mostly due to the impact of the Sassoeiros stream and to the alongshore variation of the incident wave action.

Due to the sea-state conditions, either immediately pre-storm or immediately post-storm, it was impossible to perform hydrographic surveys in the surf zone. Thus, since it was the first storm of the maritime winter season, the submerged part of the five immediately pre-storm cross-shore profiles, required for the numerical modelling, was assumed linear, based on last hydrographic survey available (performed during the maritime summer).

3.3   Morphological evolution

The five cross-shore beach profiles measured on the 27/Oct and on the 28/Oct (pre- and post-storm, respectively) are plotted in the left column of Figure 6 together with the numerical predictions of the cross-shore post-storm profiles estimated with the Litprof and the Unibest-TC models. The variable

change in z (m) along the profile (calculated as the profile final vertical coordinate minus the profile initial vertical coordinate, for each grid point), which allows a better interpretation of the morphological evolution, for the measured and predicted beach response, is plotted in the right column of Figure 6. Negative values of change in z correspond to erosion and positive values correspond to accretion.

The volume mobilised in each beach foreshore and backshore profile during the study period can be seen in Figure 7. These last results were calculated for the measured profiles (occurred evolution) and the numerical profiles (predictions). Two indicators were used for a better analysis, the volume of the total emerged (foreshore and backshore) profile and the volume of the emerged profile below 5 m ZH.

In the following subsections, the interpretation and discussion of the results of the morphological evolution is organized as follow: firstly for the real evolution occurred, secondly for the numerical predictions.

3.3.1   Measured results

The measured morphological evolution shows the following main characteristics (Figures 6 and 7):

a)   There was a distinct response from the five monitored profiles regarding the total foreshore and backshore sediment balance.

b)   In the two southeastern profiles, A and B, occurred intense erosion.

c)   In profile C the total foreshore and backshore sediment balance was accretion. When observing the evolution in detail (in Figure 6), it can be seen that this phenomenon of accretion was mostly localized in the upper part of the beach profile, above 4 m ZH. It is likely that this is consequence of the interaction between the rainwater stream and the waves.

d)   In the five profiles, most of the erosion occurred above the MSL, more precisely, in the beach face between the levels 3 and 4 m ZH.

e)   In the two northwestern profiles, D and E, the global cross-shore sediment balance of the emerged profile was nearly null. However, like in profiles A and B, occurred erosion below 5 m ZH, despite much less than in these last two (about 20%).

f)   The average sediment balance in the five profiles was -2.16 $m^3.m^{-1}$ and -2.23 $m^3.m^{-1}$, for the complete and the below 5 m ZH emerged parts, respectively.

The decrease of incident energy, from SE to NW, obtained from the hydrodynamic results analysis (pointed out in section 3.1) explains partially the alongshore erosion gradient observed in the beach. However, it is likely that the differences in the evolution of the profiles observed, besides being due to the interaction between the rainwater stream and the waves are also due to the highest steepness of the pre-storm beach face of profiles A and B.
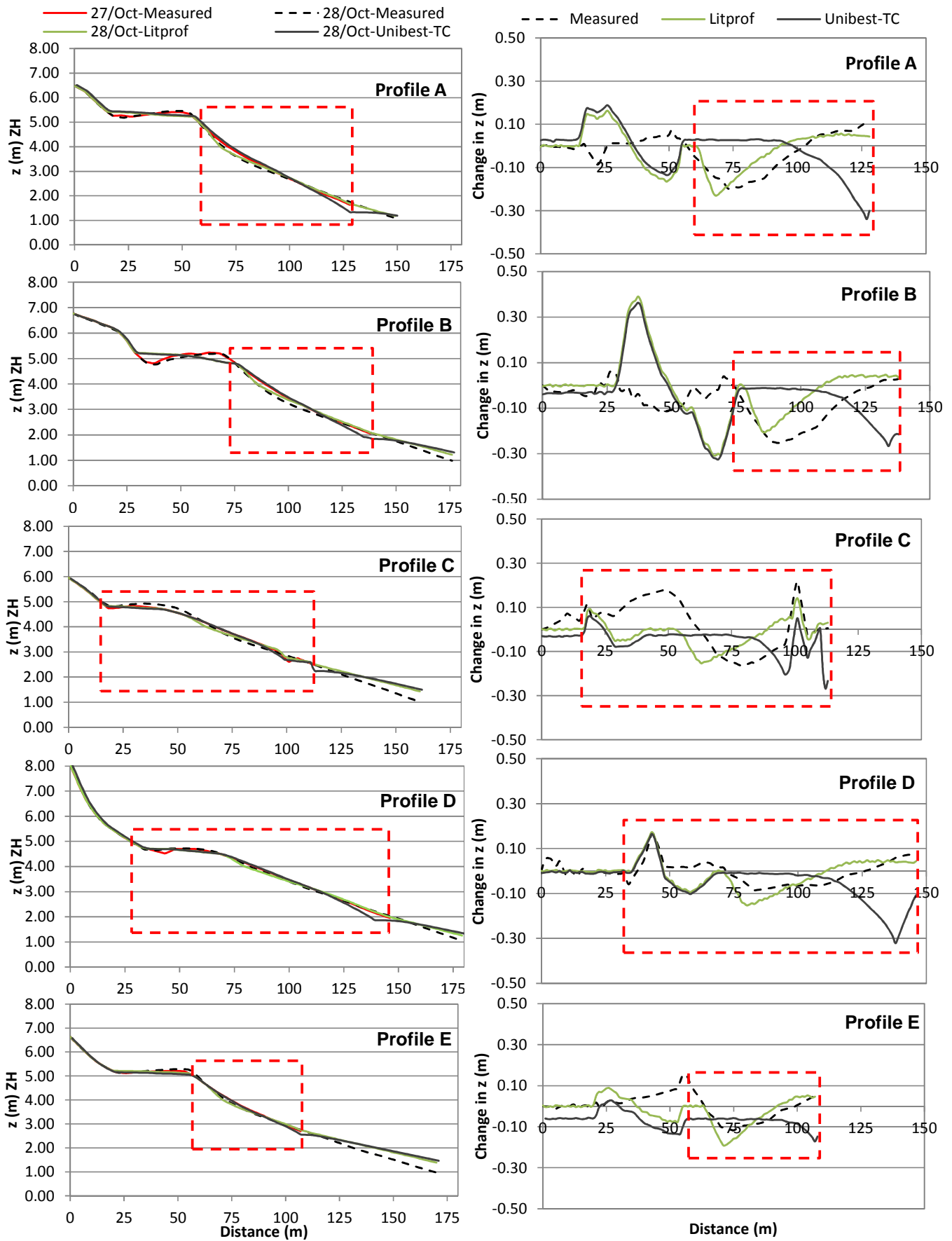
Figure 6 - Morphological evolution of profiles A, B, C, D and E: profiles measured on the 27/Oct and profiles measured and predicted on the 28/Oct (left column); and corresponding change in z (m) (<0 ⇒ erosion and >0 ⇒ accretion) (right column).
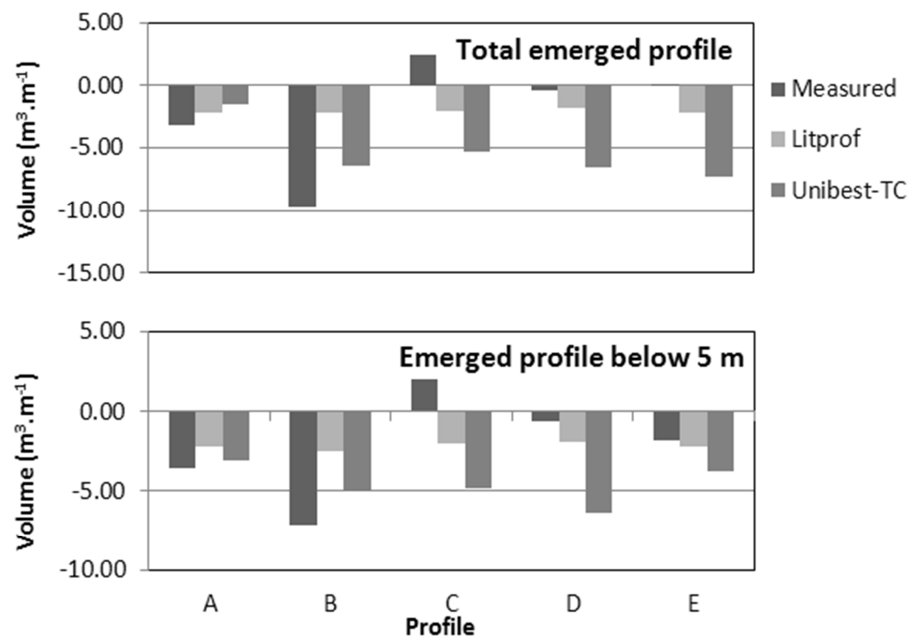
Figure 7 - Change in volume in profiles A to E (<0 $\Rightarrow$ erosion and >0 $\Rightarrow$ accretion), for the total and below 5 m ZH part of the emerged profiles.

3.3.2   Numerical predictions

The application of the two numerical models allowed simulating the morphological evolution of each of the five cross-shore profiles during the study period (Figures 6 and 7). However, it must be highlighted that it was expected to obtain a disagreement between measurements and predictions for the profiles C and D, since these were the ones which morphological evolution was affected by the interaction of Sassoeiros stream with the waves, process which cannot be considered in neither of the numerical models. Bearing in mind the objective of this study, the analysis and discussion of these results is focused in two main aspects: the precision or quality of the predictions and the comparison of the models performance.

The predicted evolution shows the following main characteristics regarding the foreshore and backshore sediment balance (Figure 7):

a) The best similarity with measured results was obtained for profile A, the one exposed to the highest energy.

b) For the reasons mentioned above, the erosion in profiles C and D was in large disagreement with the numerical results, as expected. It was overestimated numerically.

c) Both models underestimated the erosion for the most vulnerable part of the beach, the SE extreme, profiles A and B, and overestimated the erosion for the NW extreme, profile E.

d) The Litprof model presents more uniform results alongshore than the Unibest-TC model and these results (erosion volume) are lower in the case of the first model.

e) The average sediment balance in the five profiles was -2.12 and -2.19 $m^3.m^{-1}$ for the Litprof model and -5.41 and -4.63 $m^3.m^{-1}$ for the Unibest-TC model, for the complete and the below 5 m ZH emerged parts, respectively.

The comparison of the final profiles (measured and predicted) and of the change in z (m) along the profile below 5 m ZH (measured and predicted), both in Figure 6, allowed concluding:

a) The Litprof profiles present the erosion in the correct location of the beach face, between the level 2 and 5 m ZH, with the highest intensity between the level 3 and 4 m ZH, as observed.

b) The Unibest-TC profiles present the erosion process at the lower part of the beach face, slightly below the location where the erosion was observed.

c) Both models tended to smooth out the trough existent on the top of the berm of the profiles A, B and E, creating a platform in its place, phenomenon which was not observed.

4 | Conclusions and recommendations

This paper addresses practical limitations and inevitable uncertainties found when aiming to predict how a narrow urban beach responds to a maritime storm using numerical forecast models. Such information as always been important for coastal planners and managers taking decisions for re-profiling the beach and thus increase coastal resilience. However, since the future risk of coastal storm impacts is likely to increase, the subject gained extreme importance.

An urban beach was used to investigate the accuracy of the predictions of two reliable short-term process-based morphodynamic numerical models when the maximum field data possible to acquire under sea-storm state conditions was provided to the simulations. Immediately pre- and post-storm surveyed cross-shore profiles were used to characterise the beach foreshore and backshore. The bathymetry of the surf zone could not be inspected due to the lack of safety conditions (for humans and instrumentation). However, since it was the first storm of the maritime winter season, the geometry of the submerged part of the cross-shore profiles was assumed linear, based on the last hydrographic survey available (performed in the maritime summer season). The hydrodynamic forcing conditions at the entrance of the surf zone were calculated based on a methodology which uses data from the two nearest offshore buoys and from a local gauge.

The results revealed that the beach sediment, mainly median well sorted sand, was uniform alongshore but there was an alongshore gradient of energy, that is, an alongshore variability of the beach exposure to wave action. A rainwater stream, which discharge is larger during events of this type due to the frequently associated rainfall, also proved to influence locally the morphology of the beach. The interaction of the stream with the waves caused less erosion in the foreshore and backshore of the beach than the one observed in the foreshore and backshore of the beach sectors submitted only to wave action. The post-storm profiles and cross-shore erosion volumes measured were compared with the ones simulated numerically with both models. The models were not expected to reproduce the localized effect of the interaction between the stream and the waves. However, for the rest of the beach, both models underestimated the erosion for the most vulnerable part, the SE extreme, and overestimated the erosion for the NW extreme. In the overall, the Litprof model reproduced more approximately the erosion volume than the Unibest-TC model. The Litprof model was able to reproduce accurately the location of the erosion of the beach face whereas the Unibest-TC reproduced its location slightly below the observed place.

Despite the advanced numerical models applied, the forecast of the sea-land interface morphodynamics under high energy conditions remains a very complex issue. The numerical models are mainly verified in laboratory cases, where the experiments undergo in optimised conditions, that is,

the measurements are maximised in order to control the forcing hydro-sedimentological conditions and to register the maximum possible parameters which characterise the beach profile response. However, when these models need to be applied in prototype beaches, there are limitations regarding the acquisition of data for their validation and for characterising the conditions to be tested. The main problem is the bathymetry of the surf zone, which, despite being determinant for the ongoing hydro-sedimentological processes, cannot be inspected efficiently with the present state-of-the-art techniques. In sites like the case study here presented, when the sea-state conditions allow to perform the post-storm hydrographic survey, the beach is already undergoing recovery.

The main lesson from this study is that for using this type of forecast models with confidence in site applications, and thus, providing evidence-based information for planning and management, a new field monitoring approach, based on reliable non-intrusive techniques (more efficient than Lidar and video monitoring) to capture relevant parameters, like the bathymetry, the vertical profile kinematics and the vertical sediment concentration, in such adverse environment, needs to be developed. The data used in this study, which was the maximum possible data collected using human resources and measuring instrumentation in field campaigns, was insufficient. Monitoring the surf zone in such sea-state conditions is absolutely necessary to perform the models validation.

Acknowledgments

References

Andrade, C., H.O. Pires, P. Silva, R. Taborda and M.C. Freitas, 2006. *Coastal Zones*. In: F.D. Santos and P. Miranda (eds.), Climate changes in Portugal. Scenarios, Impacts and Adaptation Measures - Project SIAM II, Gradiva, Lisboa.

Booij, N., R.C. Ris and L.H. Holthuijsen, 1999. A third-generation wave model for coastal regions, Part I, Model description and validation. *Journal of Geophysical Research*, C4, 104, 7649-7666.

DHI 2008. *Profile development. LITPROF user guide*. Danish Hydraulic Institute, Denmark, 74 pp.

Dias, J.M.A. 2007. Evolution of the portuguese coastal zone. *Revista Encontros Científicos. Artigos Científicos: Área Turismo*, No. 1, 8-28.

European Commission 2004. *Living with coastal erosion in Europe: sediment and space for sustainability. A guide to coastal erosion management practices in Europe*. Office for Official Publications of the European Communities, Luxembourg, 162 pp.

Goda, Y. 1985. *Random seas and design of maritime structures*. University of Tokyo Press, Tokyo, Japan.

Gomes, F.V. 2007. The Portuguese coastal zone management. *Journal of Integrated Coastal Zone Management*, Vol. 7, No. 2, 83-95.

Meehl, G. A., T.F. Stocker, W. Collins, P. Friedlingstein, A. Gaye, J. Gregory, A. Kitoh, K. Knutti and Co-authors, 2007. *Global climate projections*. In: Solomon, S., Manning, D.Q.M., Chen, Z., Marquis, M., Averyt, B.K., Tignor, M. and Miller, L.H. (eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 747-846.

Oliveira, F.S.B.F., P.M.S. Freire and S.H.C.D. Larangeiro, 2002. Characterisation of the dynamics of Figueira da Foz beach, Portugal. *Journal of Coastal Research*, No.36, 552-563.

Roelvink, J.A. and I. Broker, 1993. Cross-shore Profile Models. *Coastal Engineering*, Vol. 21, 163-191.

Salman, A., S. Lombardo and P. Doody, 2004. *Living with coastal erosion in Europe: Sediment and Space for Sustainability, PART I - Major findings and Policy Recommendations of the EUROSION project*. RIKZ, EUCC – The Coastal Union, IGN France International, UAB, BRGM, IFEN and EADS Systems & Defence Electronics, 57p. In: http://www.eurosion.org/reports-online/part1.pdf.

Steezel, H.J. 1993. *Cross-shore transport during storm surges*. PhD Thesis, Delft University of Technology. 242 pp.

Stockdon, H.F., A.H. Sallanger, R.A. Holman and P.A. Howd, 2007. A simple model for the spatially-variable coastal response to hurricanes. *Marine Geology*, 238, 1-20.

Tucker, M.J. 1954. Surfbeats: sea waves of 1 to 5 minutes' period. *Proceedings Royal Society London*, Ser. A 202, 565-573.

WL|Delft Hydraulics 1999. UNIBEST-TC. *A generic tool to investigate the morphodynamic behaviour of cross-shore profiles. Manual.* WL | Delft Hydraulics, The Netherlands, 42 pp.