RELIABILITY OF BEACHES AS DEFENCE AGAINST STORM IMPACTS UNDER A CLIMATE CHANGE SCENARIO

Agustín Sánchez-Arcilla[1], Marta Gómez[1], Vicente Gracia[1], Xavi Gironella[1] and Manuel García-León[1]

An analysis of the probability of failure of beaches along the Catalan coast (Northwestern Mediterranean) is presented. The failure condition is defined when waves are able to overtop the beach and reach the backshore. The analysis is performed by means of a verification equation where most of the related variables are assumed to be stochastic. The probability of failure of beaches is calculated by means of MonteCarlo simulations for present conditions and different climate change scenarios. At present 14% of the Catalan beaches fail the proposed protection function against storms. Under a high-end climate change projection (A1FI) 21% of beaches will fail.

Keywords: Beach flooding, MonteCarlo simulations, Climate change, Overtopping

INTRODUCTION

Beaches can be understood as natural defences against storms. This protection function is achieved through a minimum beach width and elevation. Waves are able to reach the backshore whenever any of these geometric properties is not "enough" of a limiter and, thus, coastal flooding results. In urbanized coasts, flooding has important economic consequences due to water velocity and depth affecting private properties, public infrastructure and massive sand deposits that have to be removed. In such areas extreme events have been responsible of important economic and human looses. Sánchez-Arcilla et al. (2012) reported damages of 11 M€ only for the storm of December 2008 that affected about 400 km of coastline in the north-western Mediterranean. The Spanish government has contracted works for a total amount of 43 M€ to repair the damages caused by Hercules storms (January 2014) along the Atlantic coast.

In most countries, the coast has been intensively occupied and supports fundamental economic infrastructures that need to be defended. This development has been done under the assumption that the coast is stable and there is no uncontrolled impact by marine factors. However, the life time of coastal infrastructure is usually very large and the original beach conditions under which construction took place can change in such a way that "unexpected" flooding or erosion are likely to occur. This is more evident if the sea level rise is taken in consideration, resulting in a pressing need to evaluate the beach defence capacity against storms.

In this paper a probabilistic analysis to evaluate the defence capacity against flooding for a characteristic set of NW Spanish Mediterranean sandy beaches is presented for present and future conditions. This will be the basis to assess reliability for sand deposits as natural coastal defence elements suitable for uncertain future climates.

STUDY AREA

The Catalan coast, located in the Spanish north-western Mediterranean (see Fig. 1), has an approximate length of about 700 km. A wide variety of environments can be identified ranging from cliffs with pocket beaches (mainly located at the north) to low lying sedimentary coast at the south. Sandy beaches represent 36% of the coast most of them being urban (about 150 km). Urban sandy beaches are typically limited in their backside by a seafront promenade and infrastructures like streets, roads, railways and houses. In the last years, the maintenance and development of promenades has been one of the major investments undertaken by the Spanish government (more than 50M€ only in the Catalan coast).

Natural (cliffs) and artificial (harbours or groins) barriers control sediment dynamics along developed coasts like those in the Mediterranean. This results for the Catalan coast in 21 littoral cells (see Fig. 1), with up to 331 well defined (from an administrative and management perspective). The sediment size ranges from 0.2 to 2 mm and its spatial distribution is the result of various beach nourishments (typically with sediment grain size greater than 0.4 mm), the presence of obstacles (naturals or artificial) and the characteristics of the drainage basin (small and short intermittent river flows usually create coarse beaches whereas long permanent rivers with larger basins provide fine

[1] Enginyeria Hidràulica Marítima i Ambiental, Universitat Politècnica de Catalunya, Jordi Girona 1-3 Mòdul D, Barcelona, 08034, Spain

sediment). The sediment size of the sediment determines the existing beach slope. In general terms the mean beach has an average width of about 37 m and a sediment size of about 0.7 mm being the foreshore slope greater than 1.10 (CIIRC, 2010). The northern sector is where the narrower beaches can be found whereas the central part (in the area of influence of the city of Barcelona) has comparatively wider ones. Finally, in the southern part, beaches are characterized by fine sediment and gentle slopes.

Figure 1. Examples of beach failures along the Catalan coast (NW Spanish Mediterranean sea).

The Catalan coast is located in a fetch limited environment. The mean offshore significant wave height for the area is 0.7m with an associated wave period of 7 s. The directional distribution of waves at the Northern and Southern part of the coast show a predominance of NW and N components whereas at the central part the East and South directions are dominant. Cateura et al. (2004) identify two main meteorological situations which trigger wave storminess, an intense high-pressure centre on the British islands which induce strong NE and E winds and a Mediterranean cyclo-genesis in front of Catalan coast generating E winds. The maximum recorded Hs is about 6 m (with Hmax up to 10 m) and peak periods of about 14 s. Figure 2 shows the wave directional diagrams at different locations along the coast obtained from the existing wave buoys for the period 1984 to 2007. As it can be seen Northeastern and Eastern components feature the highest waves whereas the southern component, although present, has typically lower values.

The analysed coastal stretch is situated in a micro-tidal environment. The astronomical tidal range is less than 0.4m although during storms the associated surge can reach values up to 1 m. There is no direct correlation between wave storms and surges (Mendoza, 2008) that is, storms can be found in wave records with and without an associated increase of the mean water level.

METHODS

A common approach to evaluate the protection capacity of a beach, that is the ability to dissipate the incoming wave energy, is through the evaluation of a flooding potential function. Coastal flooding is a complex process where wave characteristics, mean water level and beach morphology (even the barrier effect of infrastructures) interact. The detailed interaction and feedback mechanisms within a given storm determine the existence of sea flooding and its intensity. Surge has been defined as the major hydrodynamic factor controlling coastal flooding (Jorissen et al., 2000, Woth et al, 2006) although for the Mediterranean case wave intensity has been revealed of the same order of importance (Mendoza, 2008). However, a wave storm can take place with a number of water level conditions and with very different pre-existing beach widths, resulting in substantially different answers.

During a storm all involved variables evolve very rapidly (small size, semi enclosed sea) being very difficult to characterize accurately. As an example, the initial configuration of the emerged part of the beach can lead to different flooding results: an initially strong swash transport can facilitate higher wave run-up and as a consequence a more intense flooding that may become unbounded during the storm development. A wide range empirical formulas can be found in the literature (e.g. Hunt, 1959;

Mase, 1989 Stockdon et al., 2006) which mainly express the wave run-up as a function of the Iribarren number, usually based on offshore wave parameters. This introduces a number of fundamental uncertainties, notably the effect of near-shore morphology (Gonzalez Marco et al, 2008) and in particular the time evolving beach profile slopes. In most studies, risk assessment is typically evaluated assuming as known all involved variables and their relationship (see e.g. Bossom and Jiménez, 2011).

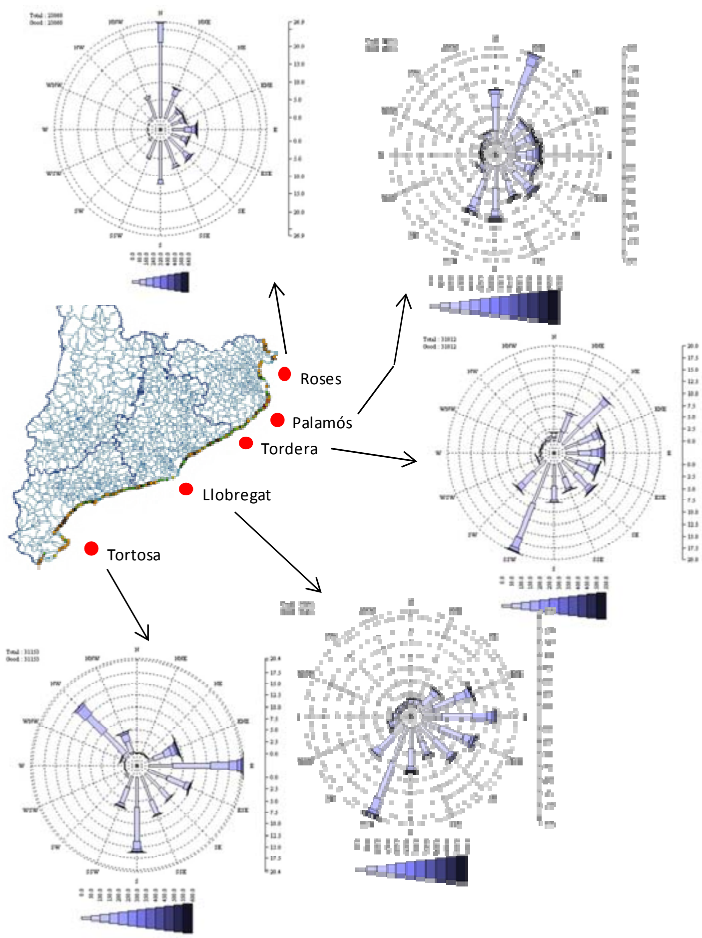

Figure 2. Wave directional diagrams along the Catalan coast for the period 1980-2007.

In this study we propose a probabilistic based analysis to evaluate the capacity of defence for sandy beaches. The "vertical" capacity of beaches as natural coastal protection against flooding can be mathematically expressed in terms of wave run-up and mean water level using the Eq. 1.

$$Z = Ru - \left(R - MWL - \Delta h\right) \quad (1)$$

Where *Ru* represents the wave run-up, *R* the dry beach level, *MWL* is the astronomical component and *Δh* is the meteorological (storm surge) part of the mean water level oscillation. Figure 3 shows a schematization of these variables. Using eq. 1 the beach "vertical" failure takes place for $Z > 0$. Because the wave run-up and mean water level variables are stochastic the reliability assessment must be based on probabilities. The probability of failure of the beach (P_f) is calculated by means of Montecarlo simulations using Eq.2

$$P_f = \frac{\sum i}{n} \quad (2)$$

where $\sum i$ represents the number of cases that satisfies Z>0 and n is the total number of analysed cases. The determination of P_f is only possible if n is large and representative enough to ensure there is convergence towards the "true" solution. In our case the number of tests used has been always 10000 or above (see Fig. 4 as an example of convergence).

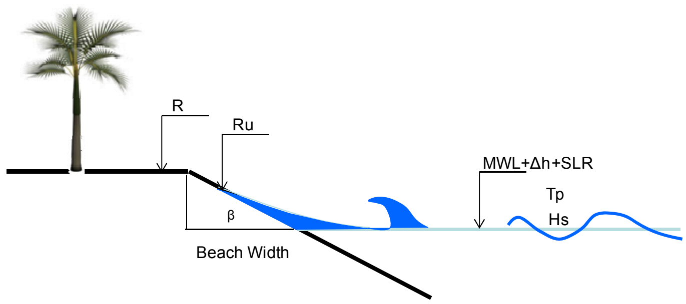

Figure 3. Typical beach profile and related variables used to evaluate flooding probabilty

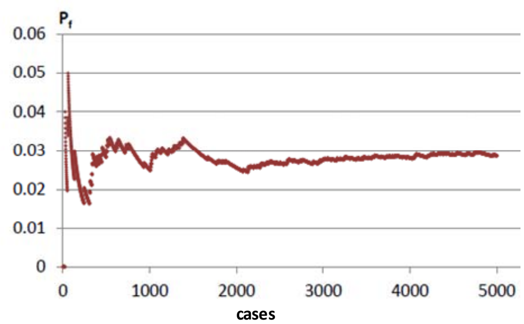

Figure 4. Probability of failure of Lloret de Mar beach (Northern Catalan coast) as a function of the number of tests.

The run-up has been evaluated using Stockdon et al. (2006) equations. Wave conditions in the formula were defined with probability functions for the extreme and mean conditions obtained for different locations along the coast (see Fig. 2) following the results of CIIRC (2010) in order to reproduce the spatial wave climate variability. The extreme probability distribution functions used are scalar and do not reflect the directional variability, providing the same wave intensity for all sectors. However, as it can be seen from Fig. 2 there is indeed a directional dependence. This aspect has been included in the analysis by taking into consideration the observed wave directional patterns in such a way that P_f is redefined as:

$$P_{f,Dir} = P_f \cdot P_{Dir} \qquad (3)$$

where P_{Dir} represents the probability of occurrence for a specific wave direction. Wave directions able to produce flooding are beach specific, that is, reflect the beach orientation and plan shape and as a consequence its wave exposure.

The proposed Eq. 3 allows describing more realistically coastal flooding because it incorporates the directional "level" of exposure to waves. Wave steepness (S) is assumed to have a normal distribution function ($N(S_{mean},\sigma)$) and it has been evaluated for each location (See Fig. 2). Table 1 summarizes the main hydrodynamic variables used for the analysis.

MWL is characterized by the tidal harmonic components defined for the area (Puertos, 2009) and Δh is described by means of a Weibull type probability function obtained from an existing tidal gauge (Puertos, 2009) located at the Barcelona Harbour (close to Llobregat area in Fig.2).

A total of 331 sandy beaches have been defined according to their administrative names following CIIRC (2010). In each case the mean beach slope $tan(\beta_{mean})$, has been calculated as the ratio between the level of the backshore (typically a seafront promenade) and the beach width using different points. A normal distribution function is assumed to be representative of the beach slope ($N(\tan\beta_{mean},\sigma)$). In each beach the P*f* and P*f,Dir* is obtained using the proposed formulations. This analysis is repeated for the different climate change scenarios defined by IPCC (2007) which predicts an increase of the mean water level between 0.18 m and 0.59 m (see Table 2) by the year 2100. Figure 5 shows as a summary flow chart and the characteristic variables used in the analysis.

Table 1. Weibull (A,B,C) parameters and wave steepness along the Catalan coast (see Fig.2 for location)

Location	Wave climate			Wave steepness	
	A	B	C	S_{mean}	σ
Tortosa	2.196082	0.648725	0.932048	0.0237179	0.009898
Llobregat	2.170677	0.640203	1.075288	0.0242262	0.007503
Tordera	2.116469	0.83713	1.145478	0.0241326	0.007678
Palamós	2.153234	0.800313	1.001975	0.0249239	0.008484
Roses	2.080956	1.269278	1.231023	0.0202844	0.004448

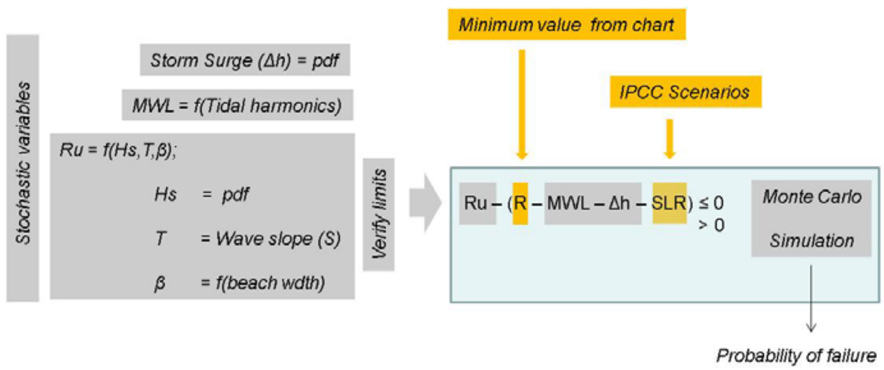

Figure 5. Flow chart for determining the probability of failure. R and SLR are taken as deterministic whereas the rest of variables are considered as stochastic.

Table 2. Sea level rise (m) according to different IPCC (2007) scenarios

	SLR (m)
B1	0.18-0.38
A1T	0.20-0.40
B2	0.20-0.43
A1B	0.21-0.48
A2	0.23-0.51
A1FI	0.26-0.59

RESULTS

Present conditions

Prior to add the SLR as an input variable, a validation analysis based on present hydrodynamic forcing has been considered. This step will provide useful insight on the performance of the proposed methodology, determining the actual coastal state and cross-checking the outputs with the available coastal observations.

As it has been stressed in the previous section, the wave direction as a clustering variable has a key role in the analysis. The use of Eq. 2 driven directly with a scalar Weibull distribution function leads to an overestimation of the probability of failure for extreme events (Figure 6), particularly for low-lying sandy coasts as the Ebro delta (south part of the Catalan coast), or the Llobregat and Tordera deltas (central part). The Northern stretch of the coast presents more frequent wave storms (Bolaños et al. 2009) and it exhibits a higher probability of beach failure at the short-term range. However, when the associated directions (and their respective weights based on occurrence frequencies) are considered, the results present a coastal risk landscape more in accordance with actually observed patterns (CIIRC, 2010).

The Ebro Delta at the South and the Northern part of the coast have lower probabilities of failure within a typical year whereas the sediment starved beaches located in the central part of the coast remain highly vulnerable. Special attention must also be given to the central part (Maresme coast, NE and in the upstream direction from Barcelona) where the lack of beach width exacerbates coastal flooding risks.

If the failure of the beach is considered for a range of $P_{f,Dir}$ between 0.01 and 0.03 it can be seen that the Northern sector of the coast has about 11% of beaches in this range (2.4 km) whereas the central part shows about 8% of beaches (2.4 km) in this class. This sector is characterized by a higher hinterland and is also showing the area of influence of Barcelona, where coastal interventions preclude the inundation of existing infrastructures. Finally, the southern part presents 11% of beaches (5,6 km) with $P_{f,Dir}$ between 0.01 and 0.03 reflecting the low-lying nature of the coast.

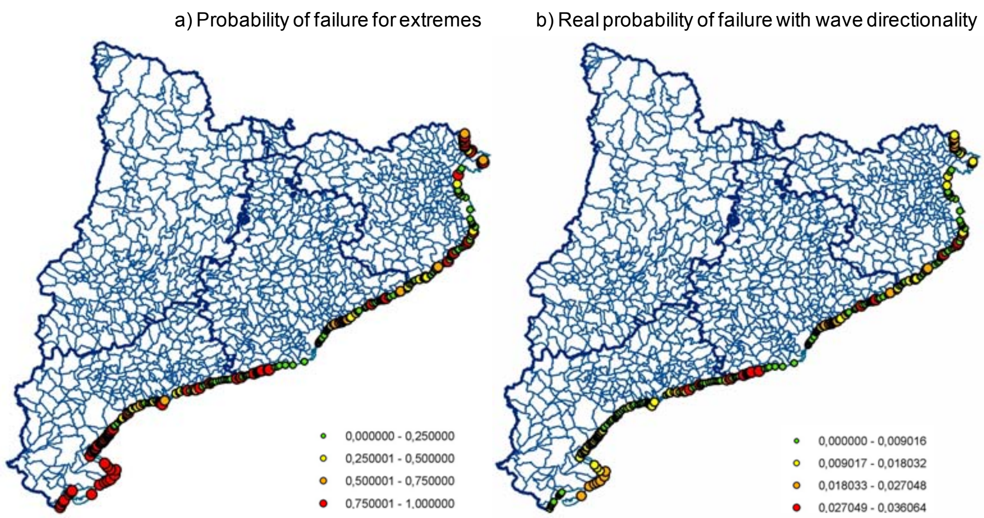

Figure 6. Probability of beach failure along the Catalan coast for present conditions considering only wave extremes (a) and considering the present wave direction distribution (b).

The results become more consistent for gentle beach slopes and open sandy beaches (defined as functional beaches), with some limitations of the methodology for pocket beaches and where there are coastal defences such as sea promenades and/or infrastructures prone to suffer and modify wave impacts and overtopping. Thus, if only functional beaches are considered, the obtained values indicate “failing” beaches in about 4% of cases for the Northern and central part of the Catalan coast and about 6% of the beaches for the Southern coast.

Climate change scenarios

Figure 7 shows the probability of failure along the Catalan coast for the B1 and A1FI sea level rise scenarios (AR4 of IPCC). An important increase in the probability of failure of beaches can be observed with respect to present conditions as expected. If the B1 scenario is considered it can be seen how beaches located in the southern part of the coast are the most vulnerable, reaching probabilities of failure of about 0.03; this corresponds to 3% of the time within a typical year, when the beaches can be overtopped by waves (failure). Tables 3 and 4 summarize the values of $P_{f,Dir}$ in the range 0.01 to 0.03 for the B1 and A1FI scenarios respectively.

Table 3. Percentages of beaches and associated length with a $P_{f,Dir}$ in the range 0.01 to 0.03 for the B1 scenario.

	All beaches		Functional beaches	
	% Beaches	% Km	% Beaches	% Km
Northern	13.38	3.06	5.35	2.49
Central	9.36	3.28	4.68	2.19
Southern	16.39	7.27	8.7	6.5

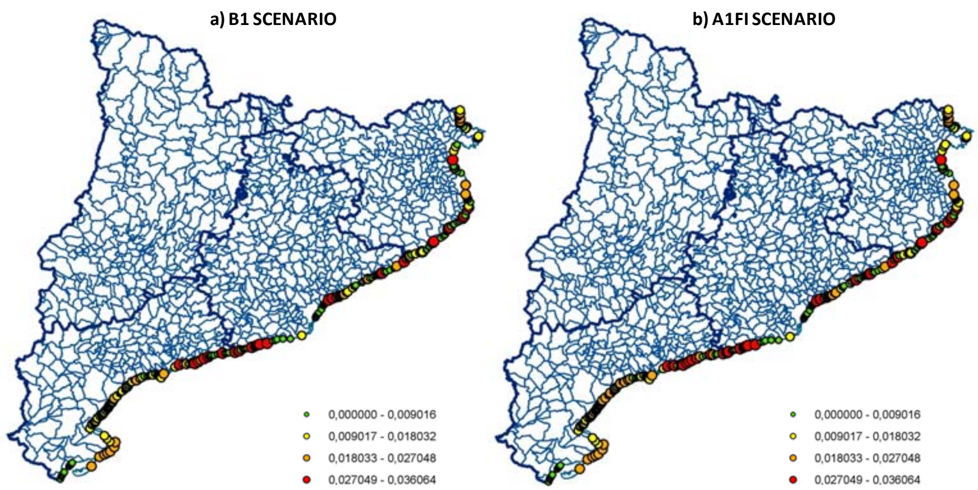

Figure 7. Probability of failure with wave directionality for two climate change scenarios a) B1 and b) A1FI

Table 4. Percentages of beaches and associated length with a $P_{f,Dir}$ in the range 0.01 to 0.03 for the A1FI scenario

	All beaches		Functional beaches	
	% Beaches	% Km	% Beaches	% Km
Northern	15.72	3.46	6.69	2.84
Central	10.37	3.72	5.02	2.23
Southern	17.73	7.67	9.36	6.87

Figure 8 shows the number of beaches with a P_f greater than 0.75 and $P_{f,Dir}$ between 0.01 and 0.03. The results only consider those cases where the formula is deemed directly suitable (what has been called functional beaches). As expected, the number of beaches failing in their ability to defend the backside increases with an acceleration of sea level rise. However, the consideration of wave directionality is less sensitive to this trend, especially for scenarios B2, A1T and A1B. That is, under a mean sea level increase of 0.4m beaches failing in their defence capacity do not augment significantly.

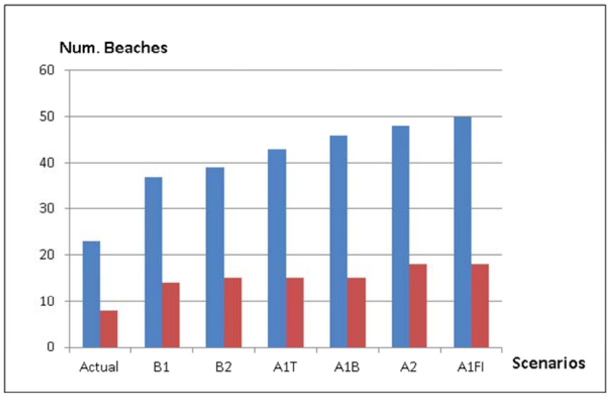

Figure 8. Number of functional beaches with a high probability of failure for different climate change scenarios (Blue bar represents beaches with P_f>0.75; Brown bars are beaches with $P_{f,Dir}$>0.01)

SUMMARY

The proposed methodology permits a quantitative beach defence (functionality) assessment. The beach width function is very sensitive to the plan shape and alongshore geometry and variability, leading (when not considered) to some unrealistic results. At present about 14% of Catalan coast beaches fail the defined protection function against storms (9% of the total length) under present climate conditions. Under an "optimistic" climate change projection (B1) 19% of beaches will fail and under a high-end climate change projection (A1FI) a minimum 21% of beaches will fail. This is without considering the projected changes in wave storm patterns or the accelerated sea level rise of AR5 scenarios, all of which will likely contribute to even higher probabilities of failure.

ACKNOWLEDGMENTS

This work has been supported by the European Union projects RISES-AM (contract FP7-ENV-603396) and iCoast (Grant Agreement ECHO/SUB/2013/661009). The last author acknowledges the PhD scholarship from the Government of Catalonia (DGR FI-AGAUR-14). The data analyses have been supported by the Spanish Research projects COVARIANCE (CTM 2010-19709-MAR) and PLANWAVE (CTM 2013 – 45141 –R).

REFERENCES

Bolaños. R., Jorda. G., Cateura, J., et al. 2009.The XIOM: 20 years of a regional coastal observatory in the Spanish Catalan coast. *Journal of Marine Systems*, 77, 237-260

Bossom, E and Jiménez, J. 2011. Probabilistic coastal vulnerability assessment to storms at regional scale – application to Catalan beaches (NW Mediterranean). *Nat. Hazards Earth Syst. Sci*., 11, 475–484

Cateura, J., A. Sánchez-Arcilla, and R. Bolaños. 2004. Wind climate at the Ebro delta and its relation with the sea state – clima de viento en el delta del ebro. Relación con el estado del mar. El clima, entre el mar y la montaña : *IV Congreso de la Asociación Española de Climatología.*

CIIRC, Centre Internacional d'Investigació dels Recursos Costaner. 2010. Estat de la zona costanera a Catalunya, Vol I, II, III I IV. Barcelona. Generalitat de Catalunya.

Gonzalez Marco, D., Bolaños, R., Alsina, J.M., Sanchez-Arcilla, A., 2008, Implications of nearshore processes on the significant wave height probability distribution. *Journal of Hydraulic Research* Vol 46, pp 303-314

Hunt, I.A. 1959. Design of Seawalls and Breakwaters. *Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers*, Vol. 85, No. WW3, pp. 123-152.

IPCC, 2007. Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jorissen, R., Litjens, J.& Mendez-Lorenzo, A. 2000. *Flooding risk in coastal areas. Risks, safety levels and probabilistic techniques in five countries along the North Sea coast*.The Hague, Ministry of Transport, Public Works and Water Management.

Mase, H. 1989 Random wave runup height on gentle slope. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 115(5), 649–661.

Mendoza, E.T. 2008. *Coastal Vulnerability to storms in the Catalan Coast*. MsC Thesis. Universidad Politécnica de Barcelona. 138pp

Sánchez-Arcilla, A., Gràcia, V., Solé, J.M, García, M. and Sairouni. 2012. in: *Comprehensive Flood Risk Management Research for Policy and Practice*. Forecasting Beach Morphodynamics. The Shoreline Border as a Control for Flooding Risks. Edited by Timo Schweckendiek, CRC Press 2012, DOI: 10.1201/b13715-122.

Stockdon, H. F., Holman, R. A., Howd,P. A. & Sallenger, A. H. 2006 Empirical parameterization of setup, swash, and runup. *Coastal Engineering* 53(7), 573–588.

Woth, K., Weisse, R. & von Storch,H. 2006 Climate change and north sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models. *Ocean Dynamics* 56 (1), 3–15.