6TH INTERNATIONAL CONFERENCE
ON FLOOD MANAGEMENT
September 2014 - São Paulo - Brazil

APPLICATION OF THE EUROPEAN FLOODING DIRECTIVE TO COASTAL AREAS IN SPAIN: METHODOLOGY AND TOOLS TO GENERATE FLOOD HAZARD AND RISK MAPS

A. Tomas[1], M.D. Ortiz[2], R. Medina[1], F.J. Méndez[1], F.F. Jaime[1], O.F. Castellanos[1], F. Fernandez[1] and J.L. Lara[1]

1. *Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, C/Isabel Torres nº15. Santander, 39011, Spain; (+34) 942201616; E-mail: medinar@unican.es*
2. *Dirección General para la Sostenibilidad de la Costa y el Mar. Environment Spanish Ministry, MAGRAMA. Plaza San Juan de la Cruz s/n. Madrid 28071, Spain; E-mail: Dortiz@magrama.es*

ABSTRACT: The purpose of the European Flooding Directive (2007/60/CE) is to establish an European framework for the assessment and management of flood risks. The aim is to reduce the adverse flooding consequences such as human health, environmental and cultural heritage, and economic activity. In Spain, coastal zone flood hazard and risk maps are managed by the Environment Spanish Ministry (MAGRAMA, *Dirección General para la Sostenibilidad de la Costa y el Mar*). These maps are designed using the methodology and tools developed by the Environmental Hydraulics Institute (IH Cantabria) from *Universidad de Cantabria*. This methodology allows performing accurate and quick flood hazard maps along the Spanish coast, due to the combination of high-resolution marine climate data bases, advanced numerical models, innovative data mining techniques, and statistical models.

Key Words: Flooding Directive, Flood Hazard, Spanish Coast, Storm Surge, Waves

1. INTRODUCTION

The Directive 2007/60 of the European Council published on the 6th of November 2007, on the assessment and management of flood risks (hereinafter Flood Directive), whose transposition to the Spanish Law is the RD 903/2010 published in the National Bulletin (BOE) No. 171 of the 15th of July 2010, has the objective to generate new tools to assess the risk and reduce potential consequences of floods.

The Environment Spanish Ministry (MAGRAMA, *Dirección General del Agua y Dirección General para la Sostenibilidad de la Costa y el Mar*) is managing the implementation of the aforementioned Flood Directive, following three different stages: a) a preliminary flood risk Assessment (already developed), by determining potential areas of flood risk; b) elaboration of hazard and risk maps for the potential flood risk areas (stage 1) (will be finished by the end of 2013); and c) establishment of management plans for the identified areas (to be finished by the end of 2015).

It is important to point out that the second stage of the implementation included the participation of different external consultants for the generation of the hazard and risk maps. IH Cantabria established the main guidelines, and gave technical support for adequate and homogeneous methodologies and tools. Some important geo-spatial data were taken from the C3E project (Climate Change on Spanish Coasts, www.c3e.ihcantabria.es), recently developed by IH Cantabria.

The determination of coastal flooding areas for the whole Spanish coast requires an integral analysis of the processes involved, which include wave dynamics at the surf zone and sea level fluctuations along an 8000 km coastline.

The aim of this study is to present the tools and methodologies developed for the study of coastal flooding and the design of hazard and risking maps that are required by RD 903/2010, using historical hindcast for marine dynamics (waves, storm surge and astronomical tide), high resolution hydrodynamic models and data-mining techniques.

This work is based on the following activities: a) development of a methodology to estimate coastal flooding extent for a country scale; b) development of an automated software tool to calculate the coastal hazard; and c) development of a methodology to estimate coastal flooding risks. This paper is mainly focus in a) and b).

2. CONCEPTUAL FRAMEWORK

Coastal flooding due to the simultaneous action of wave, surge, and tide dynamics is a complex phenomenon. Some issues should be taken into account for a fair estimation of the flooding characteristics, related with of the following physical processes the interaction between them (see Figure 1): a) flooding at any beach or any coastal stretch should be referred to a mean sea level (MSL), composed by astronomical tide and storm surge (AT+SS) for any given bathymetry; b) because of the propagation of waves over the coastal profile, breaking occurs, resulting in a down and upward movement of the water body along the beach profile (Run-Down and Run-Up, RD and RU); c) the simultaneous interaction between wave dynamics (RU and RD), sea level fluctuations, and bathymetry characteristics should be taken into account. All these aspects occur randomly on time and space and are related to a probabilistic behaviour of each forcing involved. Therefore, each maximum flood event has a probability of being exceeded at each coastal location, and to occur again as a function of the return period (in years).

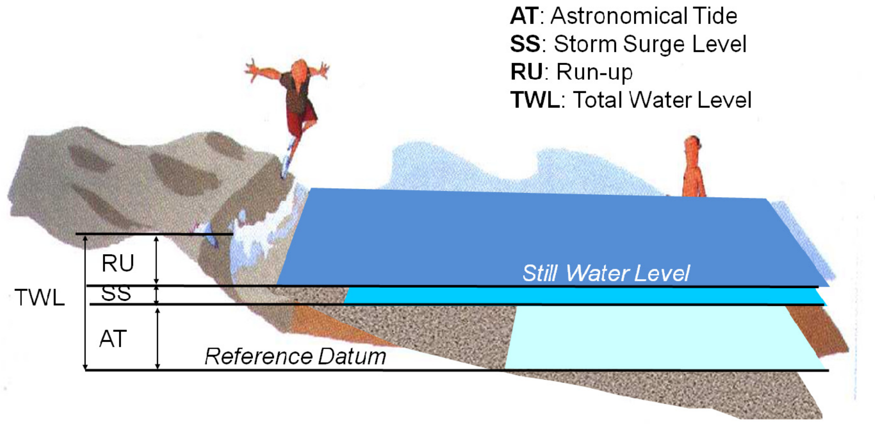


Figure 1: Total Water Level factors

3. STEPS OF THE METHODOLOGY

As highlighted, the complexity of the different aspects that makes up the estimation of floods along the Spanish coasts make necessary to establish a pragmatic methodology to cope with the important aspects of the problem. In this paper, an affordable, and efficient methodology is presented (see Figure 2), based on the combination of data bases, numerical models, data mining tools and statistical models.

Since the main coastal flooding issues in Spain are associated to wave-induced events, a 2DV approach all along Spanish coastline is proposed. Offshore oriented coastal profiles are extracted every 200 m.

Since the main hypothesis of this 2DV approach is that a static inundation due to waves, tide and surge levels occur, only those ocean-open zones are included in the analysis, discarding inner bays, estuaries or artificial basins. To evaluate the wave propagation, interaction and dissipation processes along the profiles, the IH-2VOF model (www.ih2vof.ihcantabria.com) is used. This model solves accurately hydrodynamics in surf zone due to waves and sea level (Torres-Freyermuth et al., 2007). This model yield RU and RD time series over any coastal profile, and a typical RU2% value could be obtained, as the RU related to the 2% maximum waves of the sea state, which is a widely design value to define the Total Water Level (i.e., Holman, 1986).

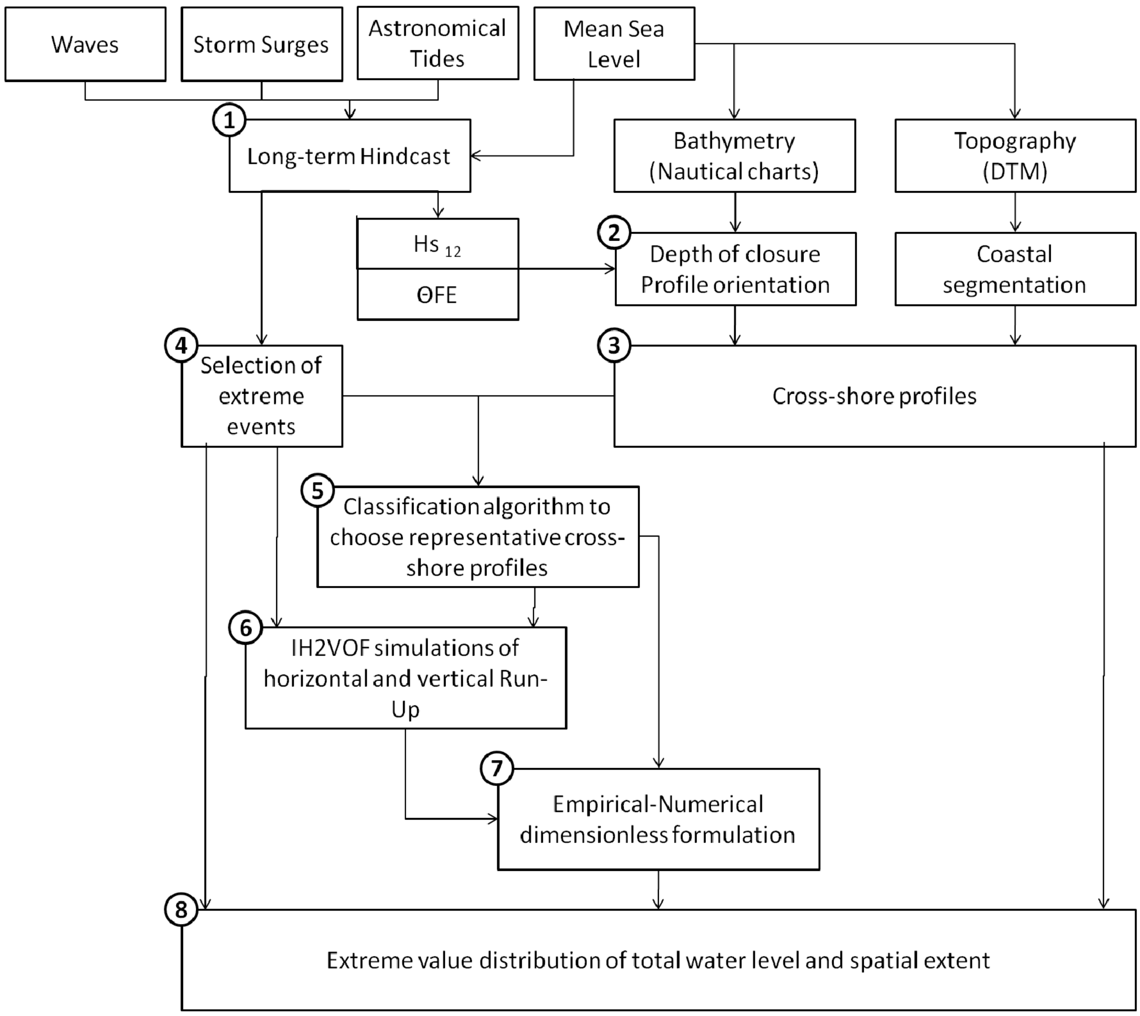


Figure 2: Sketch of the methodology

3.1 High resolution marine dynamics data bases

Reliable long-term databases for wave and sea level are taken from the C3E project (www.c3e.ihcantabria.es). These homogeneous data cover the whole Spanish coast with a maximum alongshore spatial of 200 m. This uniform and continuous data cover hourly information from 1948 to 2008 (more than 60 years). An exhaustive validation and calibration process with instrumental data were performed using all available the instrumental data bases (buoys, tide gauges and satellites), verifying the excellent quality of these databases (see figure 3).

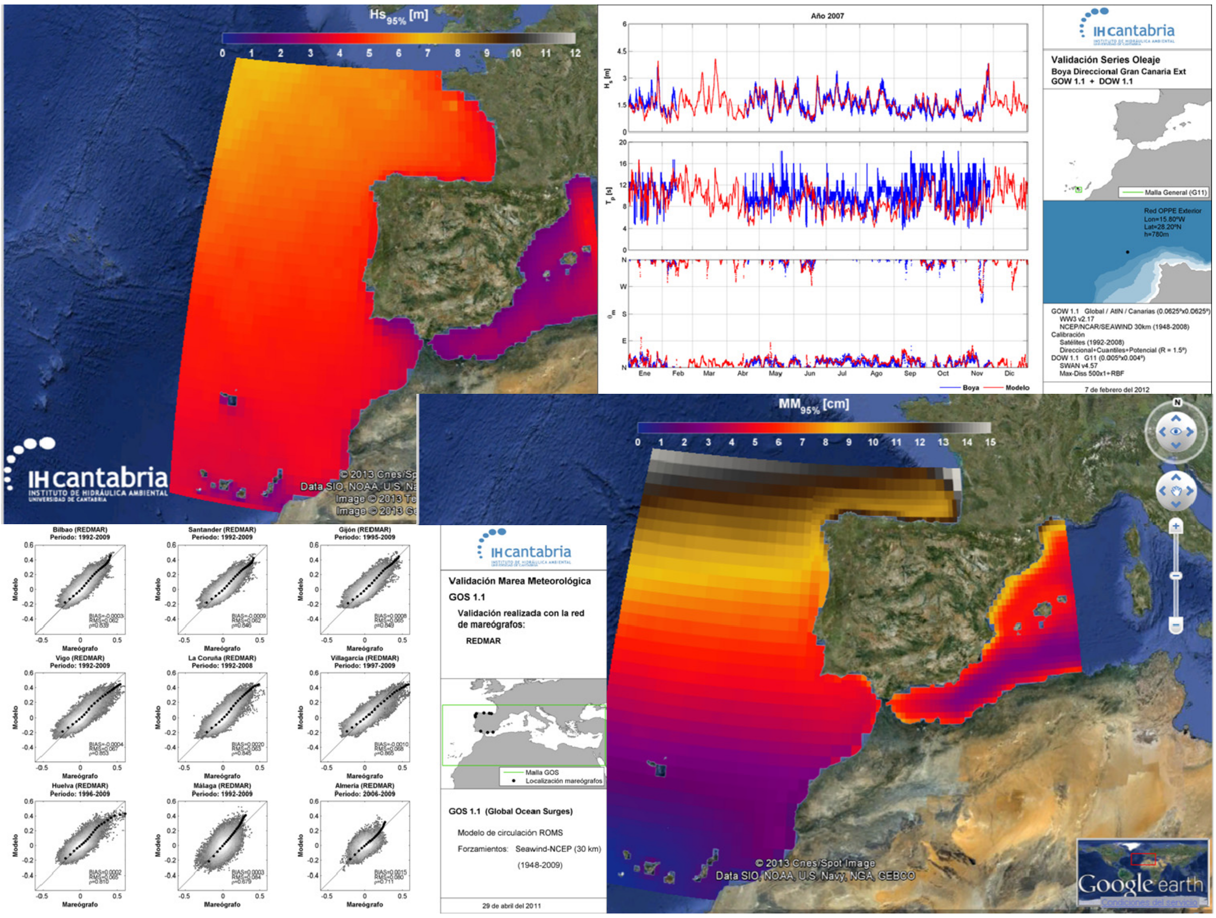


Figure 3: C3E database examples. Spanish significant wave height percentile of 95% (upper-left panel). Sea state time series validation with a *Puertos del Estado* buoy (upper-right panel). Storm surge level validation with some *Puertos del Estado* tide gauges (lower-left panel). Spanish storm surge level percentile of 95% (lower-right panel).

The astronomical tide was obtained from the Spanish tide-gauge network (*Puertos del Estado*, Ministry of Public Works), including 68 tidal constituents to obtain tide series for each location. Storm surge data were numerically hindcasted (GOS, Global Ocean Surge, Cid et al., 2013) by the implementation of the 2-D barotropic Regional Ocean Modelling System (ROMS) model with a 1/8 degree spatial resolution.

Nearshore wave time series (DOW, Downscaled Ocean Waves) were generated using the SWAN model, at 200 m spatial resolution, to propagate the deep water Global Ocean Wave (GOW, (Reguero et al., 2012) reanalysis towards the coast with a hybrid downscaling methodology (Camus et al., 2013).

3.2 Closure depth and profile orientation

Some wave parameters at shallow water are defined, in order to determine the protocol for the bathymetric profile selection. The main parameter which determines the profile selection is the mean energy flux direction (θ_{FE}) related to the storms, taken at the profile toe. Since this direction represents the general orientation of the flooding along the coast. Terrain profiles should be selected following this first criterion. The initial position of each profile corresponds to the depth closure for beaches (h*). The calculation of both θ_{FE} and h* are dependent on the significant wave height exceeded 12 hours per year (Hs_{12}), as you can see in the example of figure 4.

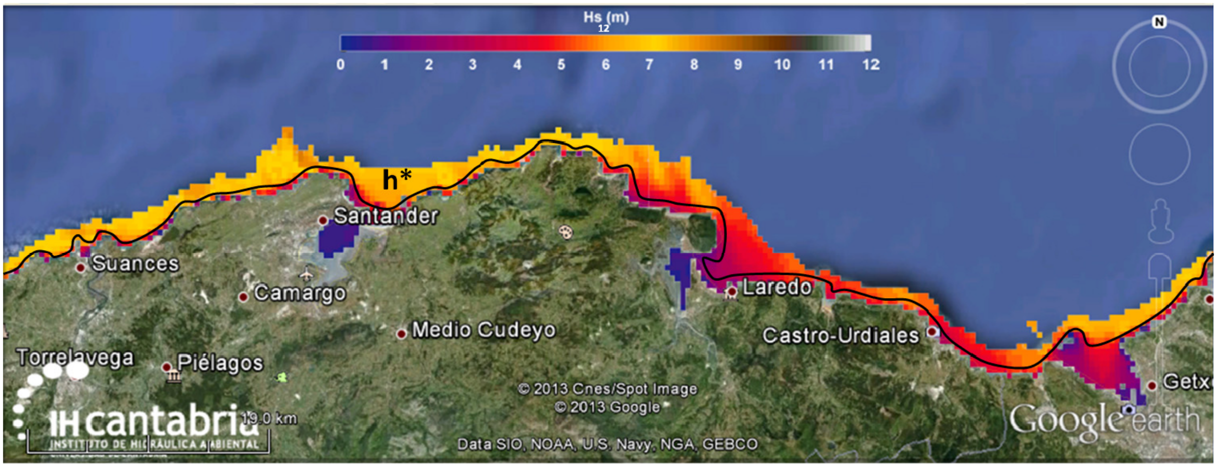


Figure 4: Closure depth along the Cantabrian coast.

3.3 Segmentation in transects to obtain cross-shore profiles

Following the previous considerations, the Spanish shoreline is segmented every 200 m. This spatial resolution corresponds with the resolution of the wave database at shallow water (DOW database), and represent adequately the alongshore evolution of waves and sea levels.

Once the plain segmentation of coastline is determined a cross-shore profile analysis is carried out. The overall profile consist in the integration of two different parts: a) the bathymetric profile (submerged), generated with theoretical Dean's Profile (1991) from the depth of closure (h*) to the coastline; and b) the topographic profile (emerged) taken from a Digital Terrain Model (DTM), from the coastline to an inner zone of the terrain (see Figure 5).

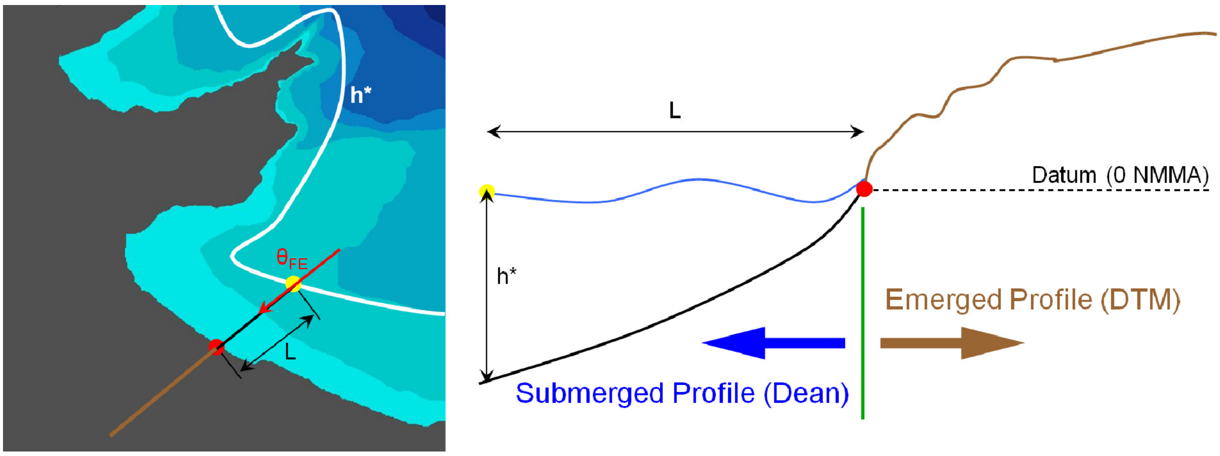


Figure 5: Sketch to determine a submerged and emerged profile.

Following this procedure, about 30000 profiles around Spain (emerged and submerged) are defined. Figure 6 shows an example of the cross-shore profile locations at Formentera Island, Balearic Islands.

Figure 6: Cross-shore profiles on Formentera Coast (Balearic Islands).

3.4 Selection of extreme events

As mentioned before, 60-year hourly wave and sea level database are used. Sea level (storm surge and astronomical tide) and wave (significant wave height and peak period) data are extracted at the location corresponding with the beginning of each profile, resulting in more than 500000 sea states.

We have considered events choosing at least 3 storms per year (61 year x 3 storms/year = 183 storms). This selection is based on the construction of a total water level proxy (TWL=RU+SS+AT), where the RU is calculated following Stockdon et al. (2006) formulation.

3.5 Classification of representative cross-shore profiles

The number of profiles obtained (30000) with the number of storms obtained (183), yield a huge amount of information which would require a high numerical CPU effort to evaluate the flooding with the IH-2VOF model. Therefore, an optimization of CPU resources should be made, through a data-mining statistical technique. A clustering and selection algorithms (Camus et al. 2011) is then applied, in order to select a handle number of sea states and terrain profiles to be simulated with the model (~1000 runs). Clustering is applied to dimensionless variables which relate the geometrical characteristics of the profile and waves and sea level values. Figure 7 shows an example for a constant Iribarren number (Ir, see equation 1) that yields a same dimensionless run up.

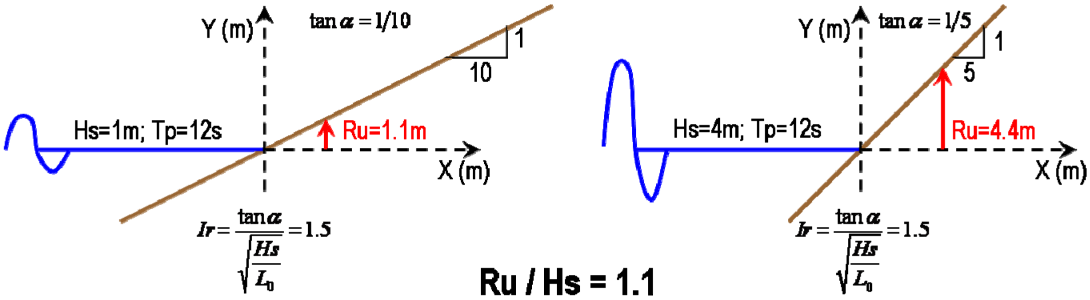


Figure 7: Example of two beaches with different mean slopes (1/10 at the left panel and 1/5 at the right panel) and different wave incident conditions (Hs=1m at the left panel and Hs=4m at the right panel) but with the same Iribarren number (Ir=1.5) and the same dimensionless Run Up (Ru/Hs=1.1).

In general, dimensionless run up is proportional to the Iribarren number (Stockdon et al, 2006; EuroTop, 2007), in which for a mean beach slope of y/x, you can state:

$$\frac{Ru}{Hs} \sim Ir = \frac{\tan\alpha}{\sqrt{\frac{Hs}{L_0}}} = \frac{\tan\alpha \cdot \sqrt{Hs \cdot L_0}}{Hs} = \frac{{}^{y}\!/_{x} \cdot \sqrt{Hs \cdot L_0}}{Hs} = \frac{{}^{y}\!/_{Hs}}{{}^{x}\!/_{\sqrt{Hs \cdot L_0}}} \qquad [1]$$

where *Hs [*m] is the significant wave height, and L_0 *[m]* is the deep water wave length defined with the wave peak period. Note that *Ir* is the mean slope for planar beaches in the dimensionless profiles.

After these assumptions, a k-mean based clustering technique is applied to define a number (~100) of representative profiles of all the profiles and storms along Spanish coast. Figure 8 present the final classification obtained, which consider different shapes for the selected profiles depending on: slopes, dunes, reefs, sandbars, etc.

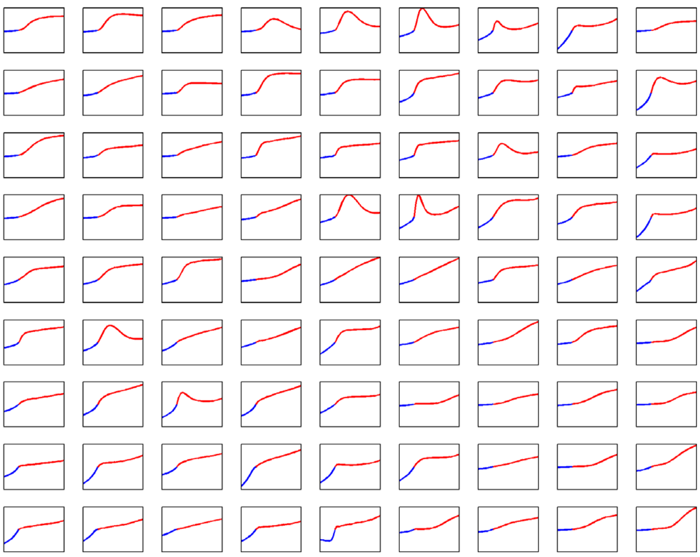


Figure 8: 121 k-mean classification of dimensionless profiles, only the 81 more representatives are shown. Emerged profile in red and submerged profile in blue.

It is important to notice that clusters presented in figure 8 only represent the centroids for the most representative dimensionless profiles. Since these centroids are geometrical simplification of the real profiles, geometrical variations should be expected. Therefore 10 real profiles have been numerically run with the IH2VOF model (for each cluster).

3.6 Numerical simulation

The state-of-the-art IH-2VOF model (www.ih2vof.ihcantabria.com) is used to calculate the run-up over real profiles. IH-2VOF solves the full Navier-Stokes' equations, and accurate solve the surf and swash zones hydrodynamics (Torres-Freyermuth et al., 2007; Lara et al, 2011; Ruju et al., 2013). An exhaustive validation was performed for this model, using laboratory tests, focused on non-linear processes of wave transformation over the surf zone.

The use of this model have the following advantages: a) it does not require simplifying assumptions to determine the wave theory to use; b) no pre-selection of the breaking type or the breaking location along the beach should be needed; and c) swash dynamics are characterized by a total transformation of the incident wave dynamics and by the transformation of physical processes with different spatial scale (small-scale turbulence with shorter periods than the incident wave to average flows and large scale infragravity waves, with far superior periods to that of incident wave). Moreover, all above-mentioned processes are highly influenced by other local factors like the shape of the beach profiles, which affects to breaking and run-up (see figure 9).

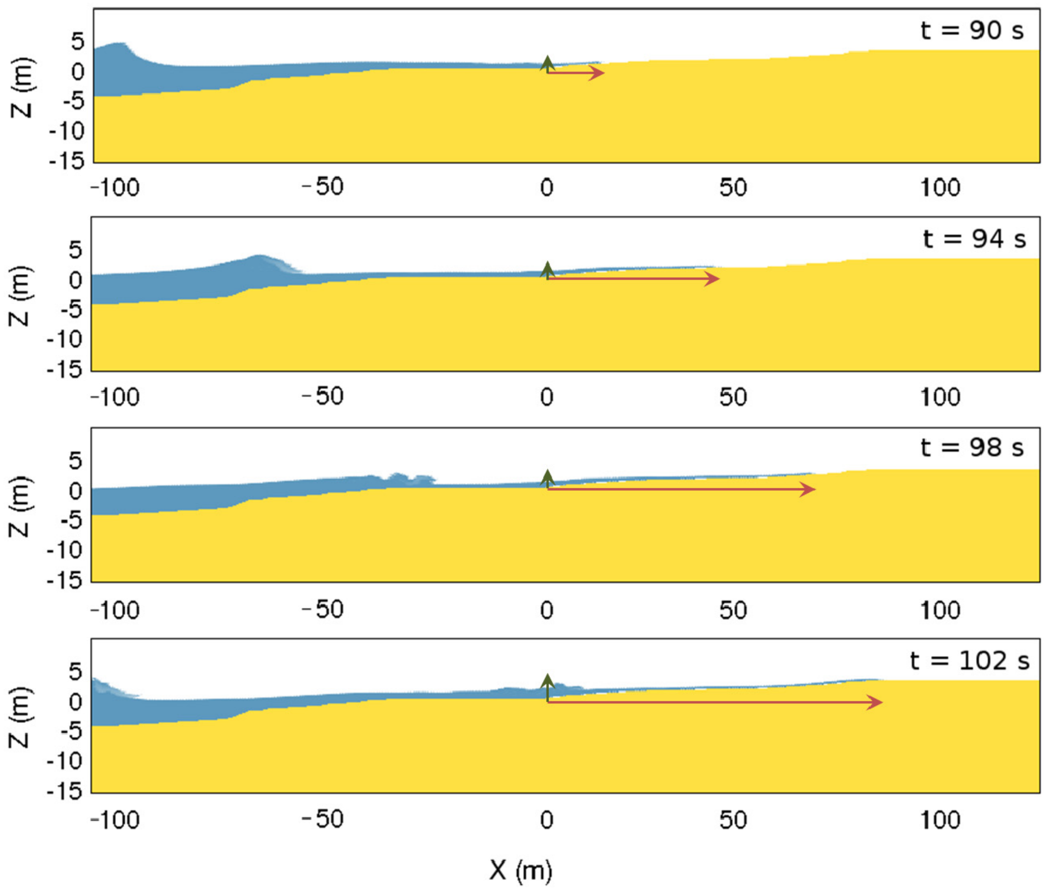


Figure 9: Beach numerical simulation with the IH2VOF model. Snapshots of four free surface instants. Red arrow is the horizontal run up and green arrow is the vertical run up

3.7 Empirical-numerical formulation for vertical and horizontal run-up

Once the sea states and the profiles selected are simulated with the IH-2VOF model, both vertical (VRU2%) and horizontal Run Up (HRU2%) were obtained. With this information for each cluster an analytical fitting procedure is realized, in order to easily predict the behaviour of these two variables for each cluster, following the next procedure: a) a storm sea state (Hs, Tp, AT and SS) is defined; b) real profile is calculated its corresponding non-dimensional values; c) the corresponding cluster is searched; and d) the fitted formulations of the corresponding cluster are used to calculate the values of HRU2% and VRU2%.

Thus, the collection of fitted empirical-numerical formulation for HRU2% and VRU2%, in each cluster, can be used to extrapolate or predict similar cases for other non-simulated sea states with the numerical model, without having to run the model again. In figure 10 some examples of HRU2% formulations are shown.

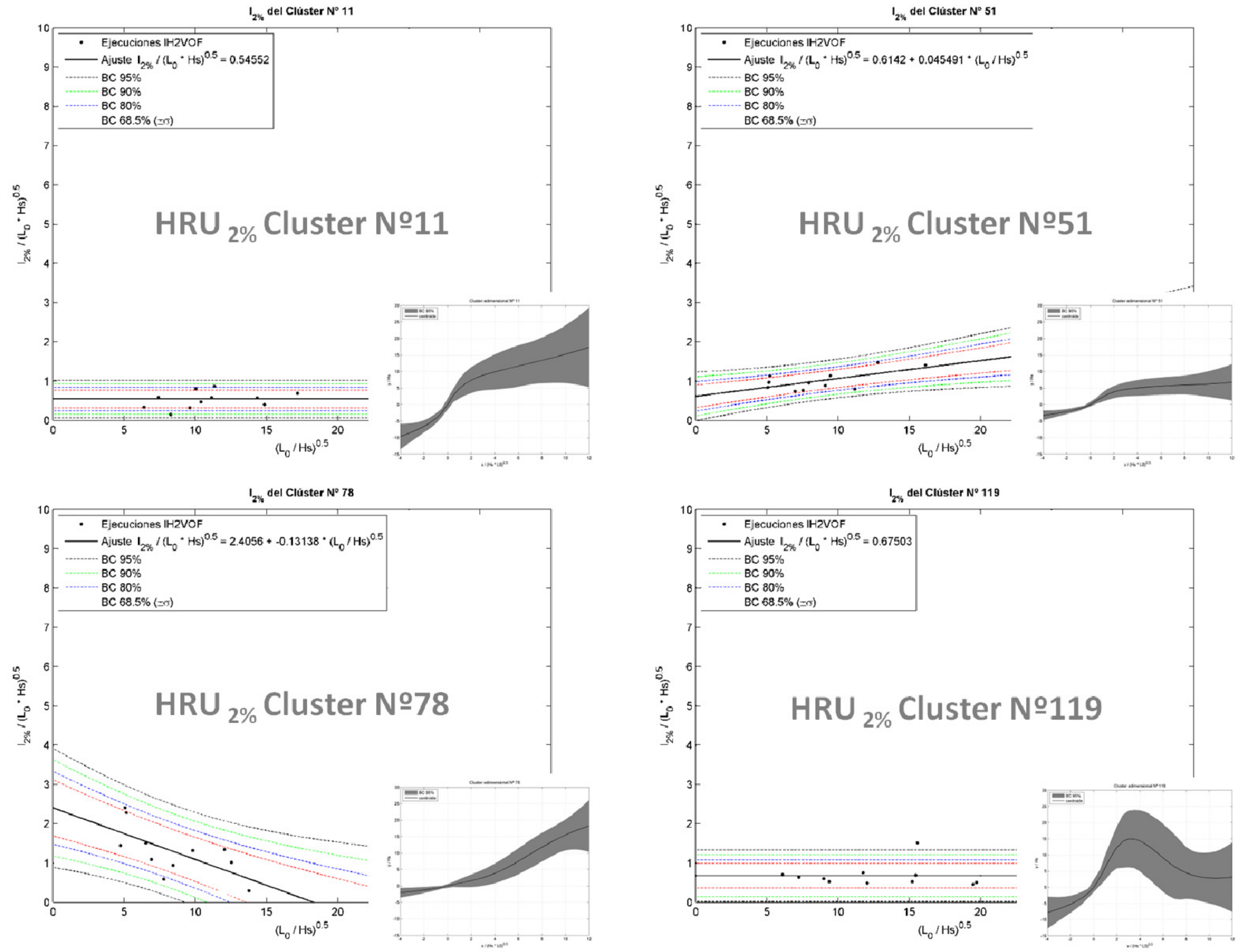


Figure 10: Empirical-numerical formulation of horizontal run up of 2% (HRu2%) for clusters Nº 11, 51, 78 and 119.

3.8 Extreme value distribution of total water level and spatial extent

To obtain extreme flood events associated to a particular return period, it is necessary to characterize the long-term extreme value events for each profile. Once all flooding factors (vertical and horizontal) have been calculated in step 7, it is fitted an extreme value distribution (total water level and spatial extent) with the POT technique (Peaks Over Threshold), assuming that the occurrence rate of events is distributed according to a Poisson process and that exceedances follow a Generalized Pareto Distribution (GPD). GPD-Poisson is identical to GEV model (Generalized Extreme Value), stating the result of the fitting in terms of annual maximum and return period.

Before the fitting of the extreme value distribution, the variables should have the same spatial and vertical reference system, in order to the final results could be aggregated geographically. For example, the fitting of the extreme total water level distribution is obtained as a result of the superposition of vertical Run-Up 2%, sea level (AT and SS) and the Datum (see figure 1). On a similar way, the horizontal spatial extent is done with respect to the cross section between the topography and the Datum (see the right panel of the figure 4). At the left panel of figure 4 it is shown an example of a SE extreme value distribution, with its 90% of confidence level. The spatial extent is plotted versus return period in years (Tr).

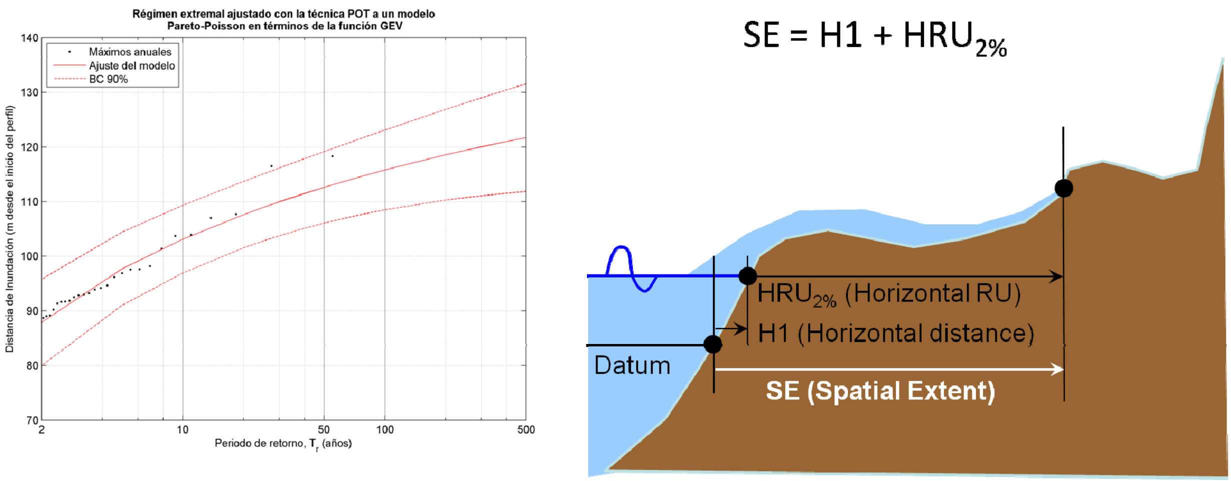


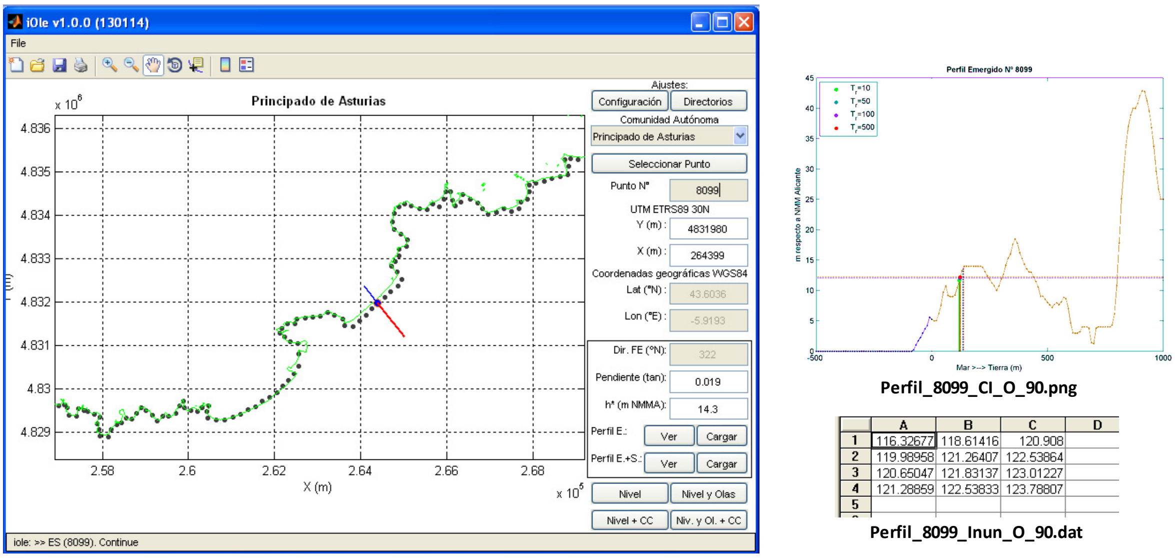
Figure 11: Extreme value distribution of the Spatial Extent (left panel) and Spatial Extent definition (right panel).

Once the fittings for each profile are done, total water levels and spatial extent flooding values are calculated for different return period (Tr=10, 50, 100 and 500 years).

4. SOFTWARE IOLE

A software which incorporates the calculation and application of the previous methodology has been developed. Hence, the calculation of flood extent at every location along the Spanish coast is automatized. The software incorporates all C3E dynamics and profiles along the Spanish coastline, but is versatile enough to incorporate other geometries. Also, the results generated (data files and figures) facilitate their inter-communication and compatibility with other programs. The manual, the software and some references can be downloaded from www.iole.ihcantabria.com

Figure 12 shows an example of the main application's Graphical User Interface (GUI) and some results that are obtained from a particular profile (in Spanish). In the center-left panel of the GUI, panels for image editing and panels for visual information are located. Right side panel of the GUI, working panels are located (settings, location, parameters and results) that show the information of a selected point and guide us through the work routine for calculating the flood extent on each profile.



	A	B	C	D
1	116.32677	118.61416	120.908	
2	119.98958	121.26407	122.53864	
3	120.65047	121.83137	123.01227	
4	121.28859	122.53833	123.78807	
5				

Figure 12: iOLE’s main interface (left). Examples of files results for wave & sea level flooding in the profile Nº 8099 (90% confidence interval): graphical output (upper-right panel) and numerical output (lower-right panel).

Four buttons that identify the four modes of use of the software are shown in the results panel: Sea Level; Sea Level + Climate Change; Sea Level & Waves; and Sea Level & Waves + Climate Change. Note that this methodology allows to incorporate the climate change effects on the dynamics, both sea level and wave; which enables to estimate the influence of such changes with hazard maps and flood risk.

5. CONCLUSIONS

A new efficient and accurate methodology to elaborate hazard flooding maps has been generated along the Spanish coasts. The existence and quality of C3E databases have been essential to define the methodology both quickly and homogeneously.

The complex coastal flood processes have been simulated with the numerical model IH-2VOF, which is one of the most advanced one in its class. Based on the results of IH-2VOF, an empirical-numerical formulation to calculate the VRU2% and HRU2% has been made. They are valid for the entire range of dynamics and geometries of the Spanish coasts. The large amount of information used is efficiently managed using data-mining statistical techniques to classify and select these high-dimensional variables.

The tools have been already used by external consultants for the coastal flooding risk assessment throughout the Spanish coast with a very high spatial resolution (transects every 200 m).

6. AKNOWLEDGEMENT

The authors thank to the Environment Spanish Ministry (MAGRAMA, *Dirección General para la Sostenibilidad de la Costa y el Mar*) for funding iOLE project (Technical Assistance to the Development of Hazard and Risk Maps due to Coastal Flooding). This work was also partly funded by the Project ‘iMar21’ (CTM2010-15009) from the Spanish government. The authors wish to thank Gabriel Díaz-Hernández whose detailed comments greatly improved the quality of this manuscript.

7. REFERENCES

Camus P., Mendez F.J., Medina R., Cofiño A.S., 2011: “Analysis of clustering and selection algorithms for the study of multivariate wave climate”. *Coastal Engineering* 58:6, 453-462.

Camus P., Mendez F.J., Medina R., Tomas A., Izaguirre C., 2013: “High resolution downscaled ocean waves (DOW) reanalysis in coastal areas”. *Coastal Engineering*, 72, 56-68.

Cid, A., Castanedo, S., Abascal, A. J., Menéndez, M., Medina, R. 2014. "A high resolution hindcast of the meteorological sea level component for Southern Europe: the GOS dataset". *Climate Dynamics*. doi:10.1007/s00382-013-2041-0

Dean, R.G., 1991: “Equilibrium Beach profiles: Characteristics and applications”. *Journal of Coastal Research*, 7, 53-84.

EurOtop (2007). Wave Overtopping of Sea Defences and Related Structures - Assessment Manual. (Disponible en http://www.overtopping-manual.com/manual.html)

Holman, R.A.,1986: “Extreme Value Statistics for Wave Runup on a Natural Beach”. *Coastal Engineering*, 9:6, 527-544.

Lara J.L.; Ruju, A.; Loasada I.J. (2011) Reynolds averaged Navier–Stokes modelling of long waves induced by a transient wave group on a Beach. *Proceedings of the Royal Society A-Mathematical, Physical and Engineering Sciences*. 467: 1215-1242

Nielsen, P.; Hanslow, D.J., 1991. “Wave runup distributions on natural beaches”. *Journal of Coastal Research,* 7:4, 1139–1152.

Reguero, B.G.; Menéndez, M.; Méndez, F.J.; Minguez, R.; Losada, I.J. (2012) A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards. Coastal Engineering, 65, 38-55. doi:10.1016/j.coastaleng.2012.03.003

Ruju, A.; Lara J.L.; Losada, I.J. (2012) Radiation stress and low-frequency energy balance within the surf zone: A numerical approach. *Coastal Engineering*. Vol. 68, pp. 44-55

Stockdon, H.F.; Holman, R.A.; Howd, P.A.; Sallenger, A.H., 2006: “Empirical parameterization of setup, swash, and runup”, *Coastal Enginineering*, 53, 573-588.

Torres-Freyermuth, A.; Losada, I.J.; Lara, J.L., 2007. “Modeling of surf zone processes on a natural beach using Reynolds-Averaged Navier-Stokes equations”, *Journal of Geophysical Research. Oceans. AGU. (American Geophysical Union),* 112, C09014. doi: 10.1029/2006JC004050