Regional geomorphic vulnerability analysis to storms for Catalan beaches

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Abstract

A framework to estimate coastal vulnerability to storm impacts at a regional scale is presented. It assesses the physical coastal vulnerability to storm impacts by separately estimating two components: flooding and erosion. It covers the following steps: (i) characterization of the forcing, (ii) evaluation of the induced beach response – inundation and erosion – (hazards quantification), (iii) coastal zone characterization, (iv) definition of a coastal vulnerability index to storms – a composite of two partial vulnerability estimations, the flood vulnerability and the erosion vulnerability indices-, and (v) assessment of the coastal vulnerability. Instead of assessing the vulnerability associated with a given storm, the forcing is defined in terms of representative storms which are obtained by classifying storms in the area using a 5-class system similar to that used for hurricanes (weak, moderate, significant, severe and extreme). Later, a vulnerability assessment for the entire coast to each storm category is produced. The method has been derived for and applied to the Catalan coast (NW Mediterranean) but can be easily adapted to other coasts. It permits managers to identify

coastal stretches sensitive to a given storm class for a given induced hazard (flooding, erosion or combination of both) to decide where to take actions.

NOTATION

B	beach/dune crest height
D	dimensionless fall velocity ($H\, w_f / T$)
$d50$	sediment mean grain diameter
E	storm energy content
EIP	erosion intermediate parameter
EVI	erosion vulnerability index
FIP	flood intermediate parameter
FVI	flood vulnerability index
Hs	significant wave height
$Hsmax$	significant wave height at the peak of the storm
JA	dimensionless beach profile parameter
$Ru_{2\%}$	2% exceedence value of runup height (above still water level)
t	time
$\tan \beta$	beach slope
T_p	wave peak period
T_pmax	wave peak period at the peak of the storm
w_f	sediment fall velocity
z	beach elevation above still water level
ΔV	eroded volume from the inner part of the beach due to the impact of a storm

ΔX	beach retreat due to the impact of a storm
ξ	storm surge
σ_{Ru}	standard deviation of run-up estimations of a storm class
τ	storm duration

1. INTRODUCTION

The impact of storms in coastal areas induces a series of impulsive morphodynamic responses or hazards, especially important in sedimentary environments such as beach and dune erosion, overwash and/or inundation of low-lying areas. When this happens in developed / urbanized areas, they are usually accompanied by damages to infrastructures and/or affectation of coastal uses and resources. This means to move from coastal hazards to harms and, bearing in mind their potential consequences, one of the usual (and important) needs of coastal managers should be to know the potential of a coastal stretch to be harmed by such processes. Thus, in the recently signed Protocol[1] on ICZM in the Mediterranean by the EU and the Mediterranean countries there is a specific chapter on Natural Hazards (chapter 22) where the Parties are advised to undertake vulnerability and hazard assessments of coastal zones and take prevention, mitigation and adaptation measures to address the effects of natural disasters.

In this context, we adopt the recommendation of the FLOOD*site* project to define (coastal) vulnerability as the potential of a (coastal) system to be harmed[2]. Its assessment should let coastal managers to anticipate potential damages along the coast to a given agent and this has originated numerous approaches from different standpoints, objectives, processes and scales (see McFadden et al[3]). Here we address the topic considering a single source of coastal hazards, the assessment of coastal vulnerability to the impact of storms. Moreover, as a first step only the physical (geomorphic) vulnerability is examined. Even restricting the analysis to a single process –storms-, to a single component of the coastal system – geomorphic- and to a single country - the Spanish coast - different approaches can be found[4,5,6].

The main objective of this paper is to present a methodology to estimate the coastal vulnerability to storm impacts at a regional scale to be applied in the Spanish Mediterranean coast. Due to the typical geomorphology of the Mediterranean Spanish coast and taking into account the spatial distribution of main coastal uses and, that most of storm-induced damages in natural coasts occur in beaches, the methodology is mainly designed to be applied to beaches. In any case, it can be integrated in a broader coastal vulnerability assessment framework where other processes and environments could be easily included.

The developed methodology is schematised in Fig. 1 and it consists of a five-steps procedure: (i) characterization of the forcing in the study area; (ii) evaluation of the induced beach response – inundation and erosion – (hazards quantification), (iii) coastal zone characterization – a GIS database comprising data on all the beaches along the Catalan coast has been created-, (iv) definition of a coastal vulnerability index to storms – a composite of two partial vulnerability estimations, the flood vulnerability and the erosion vulnerability indices-, and (v) assessment of the coastal vulnerability. This paper presents the overall developed methodology and it highlights some results obtained after applying it to the Catalan coast (Fig. 2).

Although this work has been done for the Catalan coast, the proposed methodology is general enough to be applied / adapted to other coastal areas. Moreover, due to the representative characteristics of the study area in terms of waves and coastal morphology, it is also expected that the framework can be directly applied to most of NW Mediterranean coasts.

2. Area of study

The Catalan coast is located in the NE Spanish Mediterranean (Fig. 2). It is about 700 km long and it comprises a large variety of coastal types such as cliffs, large bays, pocket beaches and long straight beaches and deltas. It supports a large variety of coastal uses and resources resulting in a coastal zone comprising high natural value areas to highly developed ones.

Data used to characterize storms were obtained from records of a network of existing wave buoys and tidal gauges along the Catalan coast (Fig. 2). For the purposes of this analysis, data registered by a Datawell waverider directional buoy located in Cap Tortosa (Ebro delta) in the southern part of the Catalan coast (Fig 2) at a depth of 50 m and at approximately 8 km off the coastline were used. This buoy was selected because it has the longest directional wave record in the Catalan coast and it has been operating since June 1990 until present.

Mean water level variations during each storm were obtained from tidal records registered by a tide gauge located in the Barcelona Harbor (Fig. 2). The data consisted of a time series of hourly tide levels registered since 1992.

In addition to this data, a 40-year hindcast time series of wave and sea level along the Catalan coast, obtained within the Hipocas project[7] has also been used to characterise the spatial variations in storm characteristics along the coast and to assess their long-term variation.

To characterize the range of existing beaches along the Catalan coast two main representative types have been selected, i.e. reflective and dissipative beach profiles. The reflective profile is composed by coarse sand ($d_{50} \geq 0.6$ mm) with a relatively high berm and a steep slope ($tan\ \beta \geq 0.1$), being representative of areas such as Costa Brava (Northern coast) and Maresme (central coast along Barcelona). The dissipative profile is composed by fine sand (d_{50} ~ 0.20-0.25 mm), with a low berm and very mild slopes ($tan\ \beta$ ~ 0.01 - 0.02). These beaches are frequent in the Costa Daurada (Southern coast at Tarragona) and the Ebro delta.

3. Storm characterization

The first step in the developed methodology is to define the forcing or source of considered hazards, i.e. the storm. Taking into account that this is a first approach to regional analysis, we have decided to group storms into classes comprising events of similar characteristics instead of analysing individual storms. Thus, if a wave forecasting system predicts a storm with given wave height and period, instead of assessing the vulnerability associated with those specific conditions, we identify which is the corresponding storm category for which the assessment should be already available.

To this end and to maintain an analogy with existing extreme events classifications[8,9,10] a 5-class scale was adopted: I - weak, II - moderate, III - significant, IV - severe, V - extreme. This was done through three steps: (i) storm definition, (ii) selection of the storm characterization parameter and (3) selection of classification method.

A wave storm can be simply defined as an event where the wave height exceeds a given threshold during a certain time period. Due to the objective of the analysis, this threshold was selected in such a way that events exceeding its value will induce a significant coastal response (erosion and inundation). According to previous analysis on beach profile response to storms in the area[11], a storm is here defined as an event where the wave height (*Hs*) exceeds a threshold value of 2 m during a minimum duration of 6 hours. This minimum duration was imposed to assure that the storm had time enough to induce processes of interest.

As the objective of the classification was to characterize induced impacts on the coast, the selected classification variable to represent this property was the storm "energy content", *E*, which was also used by Dolan and Davis[10] and which was defined as

$$E = \int_{t1}^{t2} Hs^2 \, dt \tag{1}$$

where *t1* and *t2* delimited the duration of the storm, τ.

Once storms were characterized through their *energy content*, they were classified by means of cluster analysis and supervised classification. In this work, the average linkage method was used. The final result was a 5 category classification defined taking into account the obtained dendrogram partition, the cluster consistency and the *energy content* variation within each group.

Resulting class-averaged values of *Hs, Tp* and duration, τ, for each storm type are presented in Fig. 3 and Table 1. As it can be seen, when storm classes are defined with mean values of *Hs* and τ they present a strong linear relationship, with a monotonous increase in the magnitude of both variables as storm energy (and category) increases. With respect to wave periods, they are very similar for lower storm classes (I to III) reaching values of *Tp* up to 8 s whereas the most energetic classes –IV and V- present longer periods (up to 11 s). In terms of energy content, the averaged content increases three times from class-I to class-II and, from this level, the energy content approximately doubles in each pass from one category to the upper one.

Due to the coastal configuration the E-NE direction has associated a very long fetch and it also corresponds to the direction of strongest onshore blowing winds in the area. As a result of this, E-NE wave storms are the most energetic ones and they are also the most frequent (60 %) comprising all the recorded IV and V storms. S storms have only a 15 % of occurrence and although they are of lower intensity they are responsible of significant shoreline rotations in bayed beaches[12]. Full details on the classification process and resulting storm classes can be seen in Mendoza and Jiménez[13].

4. Coastal hazards

The impact of storms in the coastal zone induces a series of morphodynamic processes, especially relevant in sedimentary environments such as beaches and dunes. For the purposes of this work, two main processes have been considered as the most relevant ones in terms of the induced response, which represent two of most common coastal hazards: flooding and erosion. Because potential damages associated with both hazards are different, we have decided to analyze the vulnerability associated with a single event – the storm- by separately calculating each induced potential response. Thus, we shall associate to each storm class the magnitude of induced individual hazards (flooding and erosion) along the Catalan coast.

4.1. Flood potential

The ***flood potential of a storm*** can be described as the potential temporary inundation of coastal areas due to wave action during the storm. Vulnerability assessment to flooding is a relatively straight forward task since it basically consists in evaluating which is the extension of the coastal zone to be inundated by a given water level (the event)[14]. Its accuracy will depend on the quality of the description of the coastal topography, the inclusion of the coastal response to the event and the evaluation of the water level during the event. To be properly calculated it requires good quality topographic data, an inundation model and a good description of the water level during the event.

Due to the selected large spatial scale we approach to the evaluation of the flood potential in a simpler manner. We define the flood potential as the maximum elevation of the mean water level associated with each storm class, being calculated as the sum of the contributions of the wave run up, Ru, and the storm surge, ξ.

The induced wave run-up during storms, $Ru_{2\%}$, was calculated by using the expression proposed by Stockdon et al[15] who derived it by using only field data (no scale effects included) obtained in reflective and dissipative beaches. Individual run-up estimations are done at the peak of the storm, i.e. maximum induced $Ru_{2\%}$. The final run-up associated with each class is obtained by averaging the $Ru_{2\%}$ values calculated for all storms recorded within the class. Estimated class-averaged run-up values for each storm class and beach type are shown in Fig. 4. As it was expected, as higher the intensity of the storm is, the larger the run-up will be, with practically doubling the magnitude of the run-up from type-I storms to type-V ones for reflective beaches. For the selected representative beach slopes for the study area, the estimated run-up for reflective beaches is about two times larger than the one associated with dissipative ones. Obtained values for both profile types represent the envelope of expected values for any beach along the Catalan coast.

Storm surges in the area were characterized by analysing hourly tidal data recorded at the Barcelona Harbour from August 1992. It has to be considered that these water levels have been recorded in a sheltered area and they should not properly include effects visible in open coasts such as the contribution of wind set-up. As a consequence of this, obtained values must be considered as the minimum expected water level increase. Fig 4 and Table 1 show the calculated class-averaged storm surges where no well defined trend is detected. According to this variable, storms can be grouped into three groups: types I, II and III with $\xi \leq 0.20$ m, type IV with surges between 0.20 m and 0.40 m and, type V with $\xi > 0.40$.

If both contributions to the flood potential of storms in the area of study are compared, it can be clearly seen that along the Catalan coast, the main contributor to inundation during the impact of storms is the wave-induced run-up.

4.2. Erosion potential

The ***erosion potential*** can be described as the potential beach erosion induced by the impact of a storm when no constraints exist. This is characterized by two bulk parameters (see Fig. 5): the maximum retreat of a given control line in the beach (e.g. the shoreline), ΔX, and the eroded volume from the inner beach ΔV.

The erosion potential of each storm class was estimated following the procedure developed by Mendoza and Jiménez[11,16]. First, a selected number of storms belonging to each class are used to calculate the induced erosion in a beach profile by using the Sbeach model[17,18]. Calculations are done for a theoretically infinite beach width to estimate the maximum erosion induced by the storm without any restriction such as that introduced by the presence of seawalls and/or waterfronts. Secondly, these calculated erosion values are parameterized in terms of a beach profile change parameter. The final goal is to obtain an erosion predictor that fed with simple variables defining the storm (instead to use the full time series of wave characteristics during the storm as it was done with the model) will estimate its potential erosion. This parameter is afterwards used to calculate the erosion induced by all the storms included in each category. As in the case of flooding, this analysis was separately done for reflective and dissipative beaches because the magnitude of the induced erosion in both profiles to a given storm will differ.

The final used beach change predictor was the one proposed by Jiménez et al[19] which is based on the dimensionless fall velocity D (= $H / w_f T$). It includes the D-parameter as a function of the excess of the actual D-values (for a given storm) above the equilibrium condition modulated by the beach slope. It is given by:

$$JA = \left| D_e - D \right|^{0.5} \tan\beta \tag{2}$$

To properly reproduce the erosion simulated by the model, the JA-parameter had to be modified by including the storm duration, τ, i.e. $JA \cdot \tau$, which is consistent with the already observed importance of storm duration on the induced morphodynamic response[20]. Fig. 6 shows the relationship between eroded volumes calculated with the Sbeach model and the corresponding $JA \cdot \tau$ values for reflective and dissipative beaches. It has to be mentioned that the use of predictors without including the beach slope results in very poor prediction capability[16].

Fig. 7 shows the calculated class-averaged potential eroded volumes for each storm class and beach type. Again, and as it was expected, the higher the storm intensity is, the larger the eroded volume will be. Mean eroded volume values range from 11 m^3/m/storm to 103 m^3/m/storm for classes I and V respectively in reflective beaches and, from 7 m^3/m/storm to 28 m^3/m/storm for dissipative ones. These results indicate that the storm potential erosion in dissipative beaches would be about one third of the corresponding to reflective ones, provided they are similarly exposed to wave action during the storm. It has to be considered that in this first estimation significant overwash and breaching processes have not been included in the calculations which imply that class IV and V storms induced erosion should be under-predicted in dissipative beaches.

The large difference in erosion magnitude from class-IV storm to class-V one was probably due to the fact, that there was only one storm classified as extreme. This storm consisted of a double peak wave event with the highest waves recorded during the entire period and, with a very long duration (7 days comprising the two peaks). This resulted in an extremely high energy content event inducing significant damages to ports and beaches along the Spanish Mediterranean coast.

5. Coastal vulnerability

Once coastal hazards have been estimated for each storm class, the next step was to build a framework to integrate this information with actual data of beach characteristics along the coast in such a way that we can assess its vulnerability. This implies to relate the hazard intensity with a variable characterising the capacity of the beach to cope with this process. In other words, this combination will measure the potential of the system to be harmed.

This was done within a GIS-environment where a database comprising data on all beaches along the Catalan coast was included. The database contains basic information such as location, orientation, beach type, sediment grain size, width, height and hinterland properties.

Due to the spatial scale of the analysis, it is necessary to take into account the variability of storm and beach properties along the entire regional coast. Geomorphologic variability is directly implemented in the database since specific data for each beach are already included. On the other hand, to take into account the spatial variability on storm properties and induced hazards, the Catalan coastal area was divided into 8 geographical zones where wave conditions during storms can be considered relatively homogeneous after propagation towards the coast. The definition of these areas was based on the use of a spatial database of hindcasted wave conditions during the period 1958-2001[7] and by analysing propagation patterns of storm conditions towards the coast simulated by using the WAM model. Thus, a single storm defined by a set of conditions at an offshore location could belong to different storm classes along the coast depending on the area to be considered.

As it was previously mentioned, vulnerability indicators have been built by combining variables characterizing hazards intensity – erosion and flooding potentials – and beach parameters characterizing its capacity to cope with those processes. Thus, the Erosion Vulnerability Index includes the beach width whereas the Flood Vulnerability Index includes a measure of the local values of the height of the beach/dune crest.

The Erosion Vulnerability Index, *EVI*, is defined in function of a erosion intermediate parameter, *EIP*, which is defined for each storm class as

$$EIP = \frac{\left(\Delta X + \alpha \sigma_{\Delta X}\right)}{W} \qquad (3)$$

where ΔX is the representative storm-induced shoreline retreat of the corresponding class for the given beach type, $\sigma_{\Delta X}$ is the standard deviation of the retreat calculated for all storms within the class, α is a factor to account the safety level of the analysis (here use a value of 1) and *W* is the beach mean width.

Similarly, the Flood Vulnerability Index, *FVI*, is defined in function of a flood intermediate parameter, *FIP*, which is defined for each storm class as

$$FIP = \frac{\left(Ru + \alpha\sigma_{Ru}\right) + \xi}{B} \qquad (4)$$

where *Ru* is the representative run-up of the corresponding class for the given beach type, σ_{Ru} is the standard deviation of the run-up calculated for all storms within the class, ξ is the representative storm surge of the storm class and *B* is the height of the beach/dune crest.

These parameters are evaluated for each beach included in the database taken into account their location along the coast (potential changes in the storm intensity), the beach type (reflective or dissipative, which condition the magnitude of the induced erosion and water level at the shoreline) and actual beach width and height (this parameter has to be regularly updated as coastal geomorphology changes through time).

Once *EIP* and *FIP* are known, the corresponding Erosion Vulnerability Index *EVI* and Flood Vulnerability Index *FVI* were calculated following the functional rule represented in Fig 8. This function assigns zero vulnerability to situations where the combination of the hazard intensity and the respective beach dimension determines the potential of the coast to be harmed to be very low, whereas it assigns a value of 1 to combinations indicating "full damage".

As a first approximation, we have defined the "safest situation" (zero vulnerability) for a storm class with respect to erosion to a beach configuration given by $W \geq 2\left(\Delta X + \alpha\sigma_{\Delta X}\right)$, i.e. the actual beach width is equal or larger than two times the representative retreat induced by the considered storm class. Similarly, for the case of flooding, the "safest situation" (zero vulnerability) for a storm class corresponds to a beach configuration given by $B \geq 2(Ru + \alpha\sigma_{Ru} + \xi)$, i.e. when the representative total water level associated with the considered storm class is equal or less than the half of the beach/dune crest.

On the other side, the maximum vulnerability (1) is assigned to situations where the actual beach width is equal or narrower than the representative retreat associated with the analyzed storm class for erosion (*EIP* ≥ 1) and, to situations where the actual beach height is equal or lower than the representative total water level for inundation (*FIP* ≥ 1).

Between these two extremes, the corresponding (erosion and inundation) vulnerability index linearly increases as a function of *EIP* and *FIP* values. Finally, a qualitative 5-class scale has been defined ranging from *very low* to *very high* vulnerabilities by taking intervals of 0.2 units in *EVI* and *FVI* (Fig 8).

As an example of application, Fig. 9 shows values of the erosion and flood vulnerability indexes assessed in two stretches of the Catalan coast comprising reflective (Barcelona city coast) and dissipative beaches (Ebro delta) to the impact of class-V storms.

Results obtained for the Ebro Delta are reflecting the existence of very wide (wider than 100 m), low- lying (dissipative) beaches with heights around 1.3 m except in the Riumar area where the existence of a dune row increases it up to 2.4 m. Although the representative total water level value for dissipative beaches is relatively low, the low height of these beaches determines the corresponding *FVI* value to be Very High, with the exception of the Riumar area, where the existence of a higher elevation decreases its value down to Medium vulnerability. The relatively low erosion values estimated for dissipative beaches together the large width of Delta beaches determine the *EVI* value to be Very Low. Again, it has to be considered that overwash induced erosion has not been fully considered in this first approximation. Fig. 10 shows the behavior of this area under the impact of a storm of this category, where beaches are fully inundated.

Results obtained for reflective beaches along the Barcelona city waterfront reflects that high water levels (as corresponds to steep beaches) associated with this V-class storm clearly exceed the beach height (averaged value of about 3 m), determining *FVI* values to be Very High. With respect to erosion, the combination of narrow widths (between 10 and 20 m) and the large retreat values associated with the impact of a class-V storm determines the *EVI* to be Very High. The lower obtained values for Nova Icaria and Sant Miquel beaches (Medium vulnerability) are due to the fact that they are significantly wider (30 and 40m respectively) and that they are partially sheltered (a local correction factor is included).

Fig. 11 shows the impact of a class-V storm on Barcelona beaches. The Nova Icaria beach (at the forefront on the right picture) shows flood marks up to the promenade in the back (beach fully inundated) but it was wide enough to be fully damaged by erosion. On the other hand, the narrower Bogatell beach (in the back of the photo) together the full inundation, it experienced the direct impact of the waves on its promenade due to the nearly fully shoreline retreat during the storm. The case of Sant Sebastia and Barceloneta beaches (left picture) is similar to the described before. Thus, the Sant Sebastia beach (in the forefront) shows marks of fully inundation but still, it maintains a subaerial beach after the impact of the storm, whereas La Barceloneta beach (at the back) is nearly fully eroded downward the groin and, the promenade is fully exposed to wave action.

6. Discussion and conclusions

In this paper a framework to estimate coastal vulnerability to storm impacts at a regional scale has been presented. It has been derived for the Catalan coast (NW Mediterranean) but can be easily adapted to other coasts. The framework estimates the physical vulnerability of the coast to storms by separately estimating two partial hazards: flooding and erosion.

Instead of estimating the vulnerability associated with a given set of wave conditions, the method assesses the vulnerability induced by representative storms of the area. To do this, storms are first classified using a 5-class system similar to that used for hurricanes (weak, moderate, significant, severe and extreme). This permits coastal managers to associate a given set of wave conditions to one storm class and, to the corresponding vulnerability map of the Catalan coast, where they can easily and rapidly identify the areas sensitive to such storm conditions.

The selected functional relationship to define the erosion and flood vulnerability indexes, *EVI* and *FVI*, is based on the ratio of two magnitudes representing the potential harm and a beach variable characterizing its ability to cope with it. In the case of flooding these variables are the total water level associated with the storm class and the actual beach height respectively. In the case of erosion they are the shoreline retreat associated with the storm class and the actual beach width. In both cases, the variable characterizing the harm is obtained from statistics of calculations of total water level (wave runups and surges) and induced retreats for all storms within a class and, as larger the number of storms are, the more robust the estimation will be.

In the example of application included here, vulnerability assessment for a class-V storm in some beaches along the Catalan coast, a qualitative agreement has been observed between calculations and the reality. At present, a first generation of vulnerability maps has been produced for the entire Catalan coast[21], which can be viewed through Google Earth by using a kml file provided upon request.

Because the vulnerability assessment largely depends on beach characteristics (height and width) and they are significantly affected by coastal dynamics, it is necessary to periodically update their values, especially when extreme events occur. This will permit managers to update their vulnerability assessments and the corresponding plans to manage it. In the case of the Catalan coast, because a large part of beaches are experiencing significant long-term erosion, it is expected that even under a steady wave climate (intensity of coastal hazards associated with storms), the vulnerability will tend to increase due to a lower capacity of the beaches to cope with the harm.

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Table 1. Averaged characteristics of storm classes recorded during the period 1990-2004.

Storm Class	**occurrence (%)**	**duration (h)**	***Hs* max (m)**	**T_p max (seg.)**	**E (m^2 h)**	**ξ (m)**
I	56	13	2.6	7.3	57	0.17
II	25	32	3.1	8.3	175	0.16
III	14	56	3.4	8.2	343	0.13
IV	4	76	4.3	9.9	634	0.27
V	1	161	6	11.1	1369	0.53

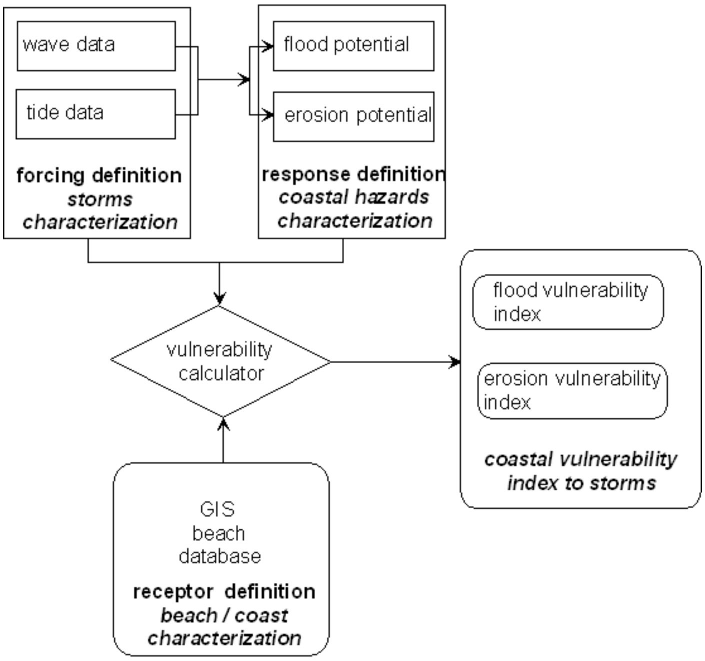

Fig. 1. Methodological approach to assess coastal vulnerability to storms.

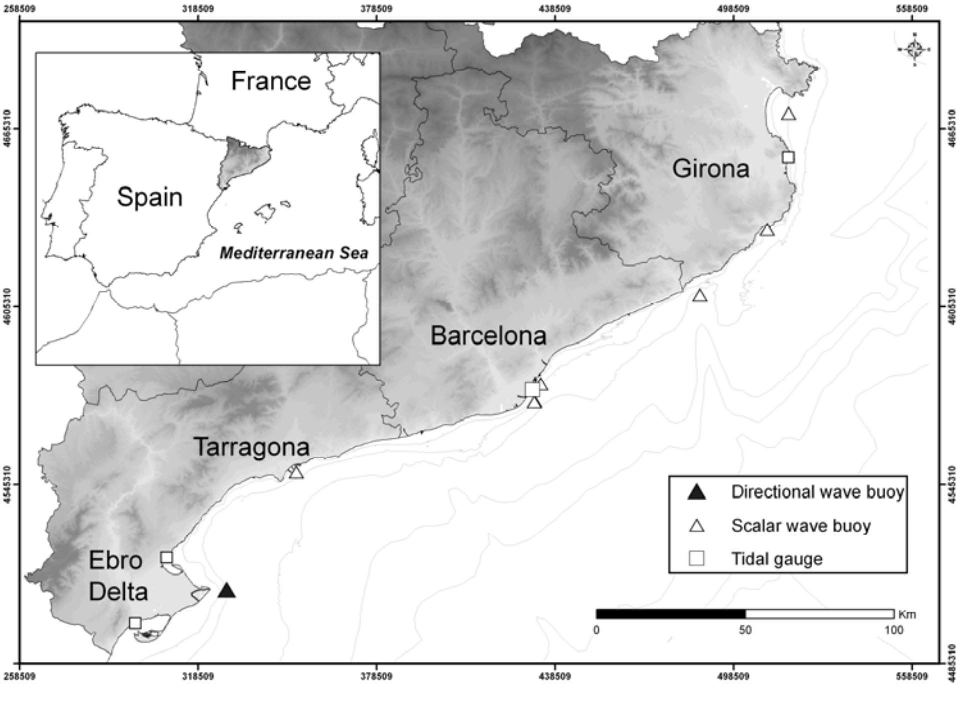

Fig 2. Area of study and location of wave buoys and tide gauges.

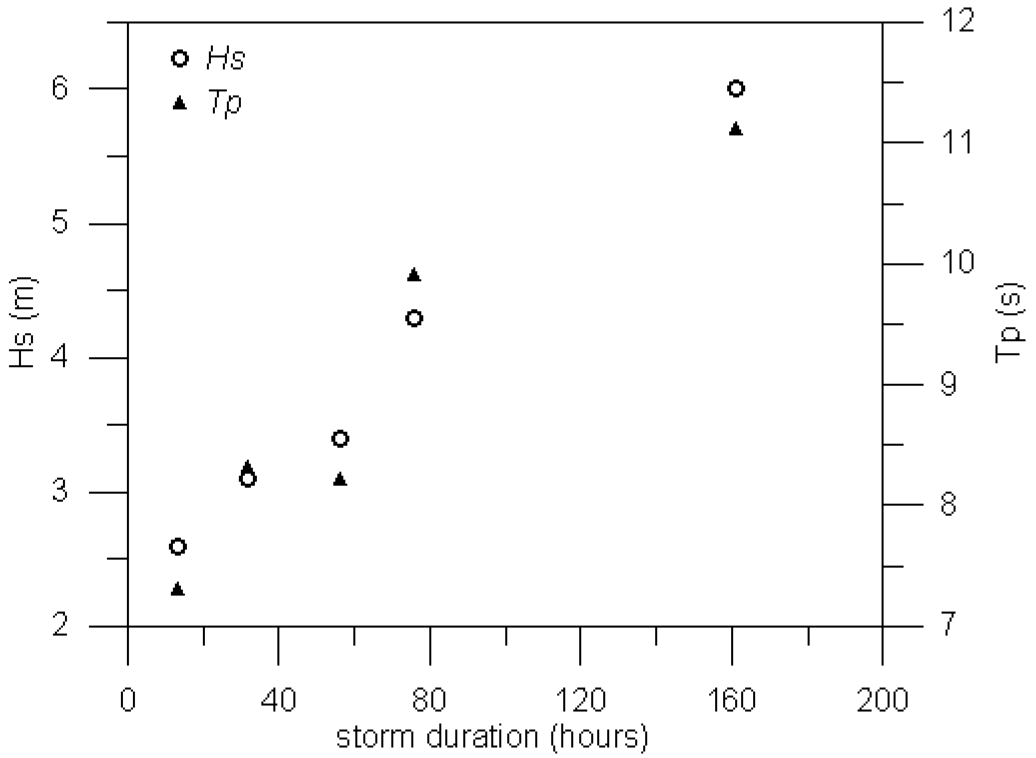

Fig. 3. Class-averaged values of *Hs* and *Tp* at the storm peak *vs* storm duration.

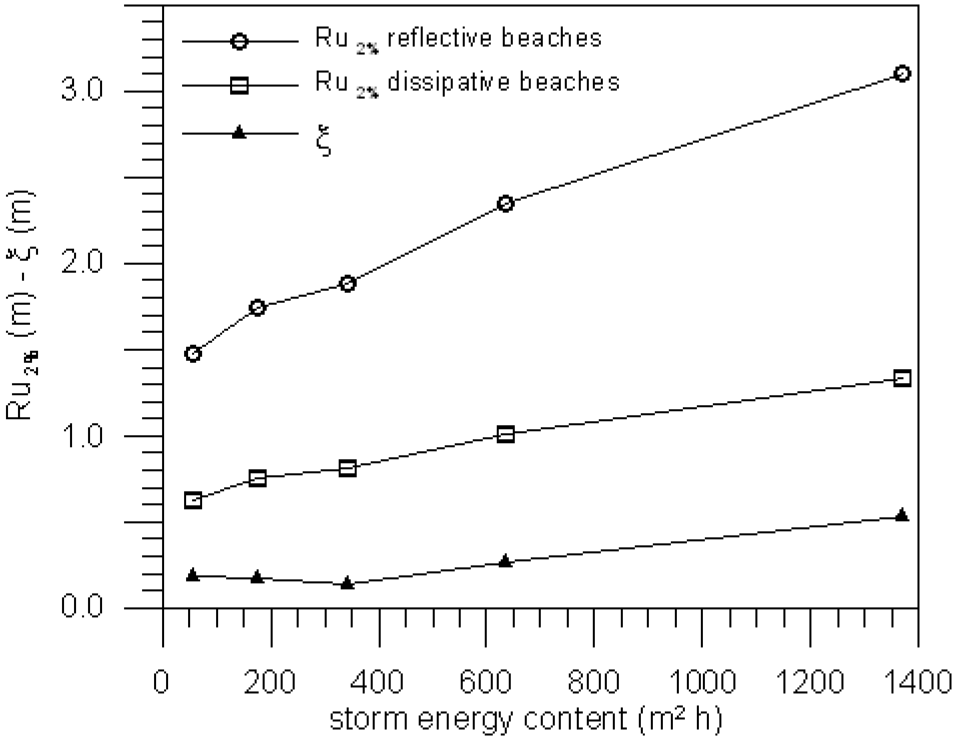

Fig. 4. Class-averaged values of wave run-up in reflective and dissipative beaches and storm surge.

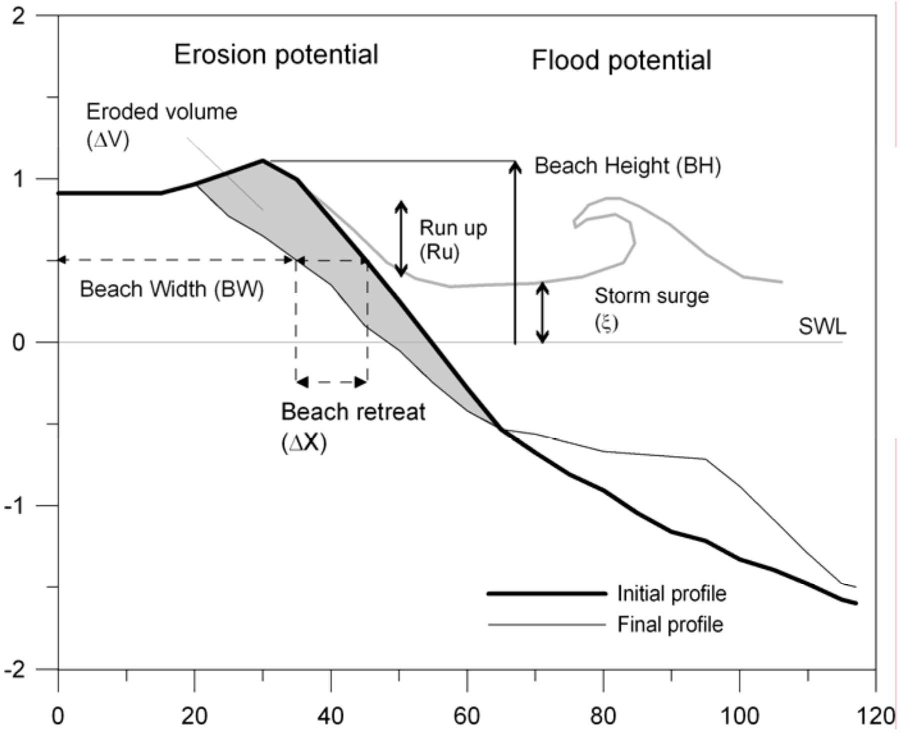

Fig. 5. Beach profile parameters and definition of erosion and flooding variables.

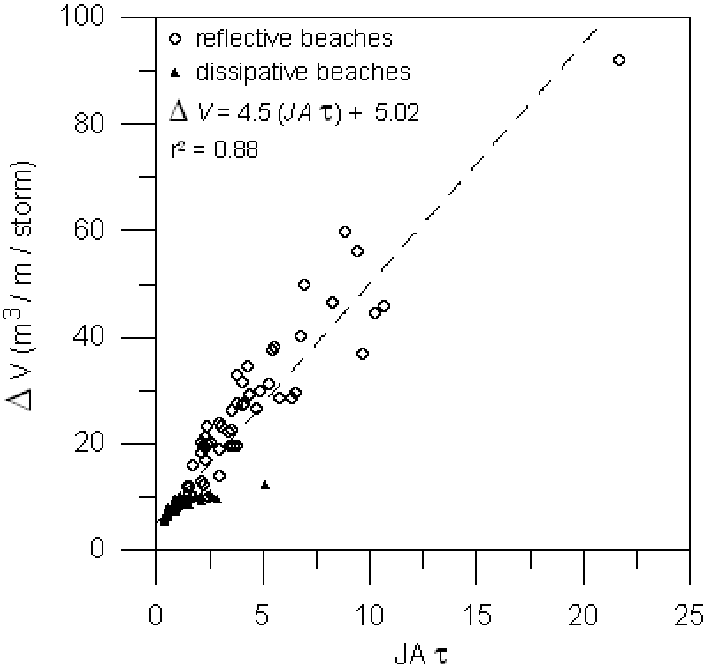

Fig. 6. Calculated maximum eroded volumes in reflective and dissipative beaches by using Sbeach *vs* corresponding *JA* τ values.

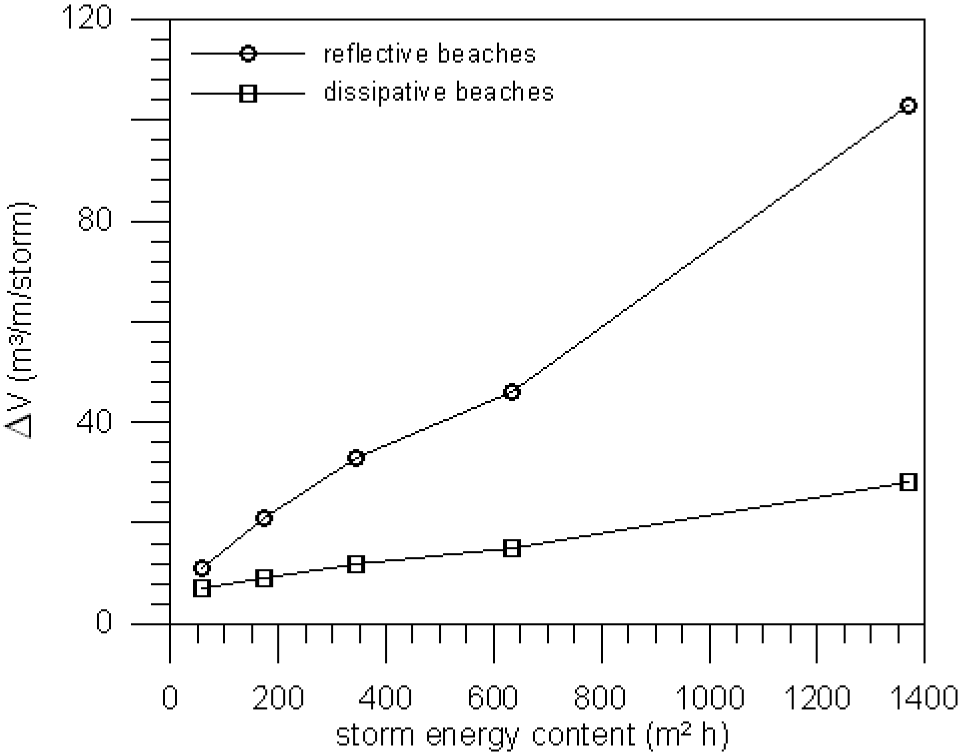

Fig. 7. Class-averaged values of eroded volumes in reflective and dissipative beaches.

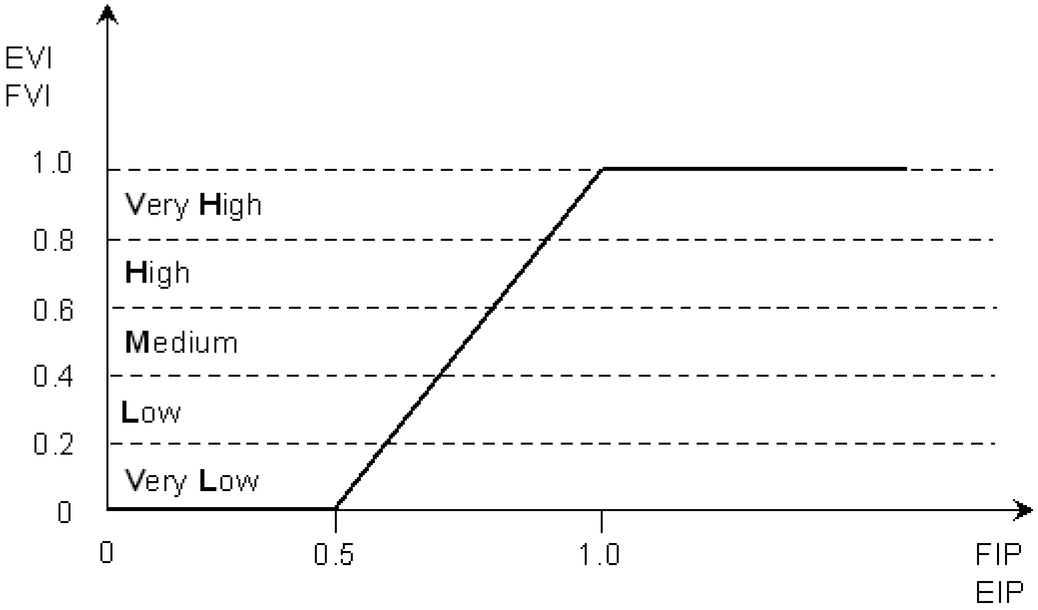

Fig. 8. Functional relationship adopted for the erosion and flood vulnerability indexes.

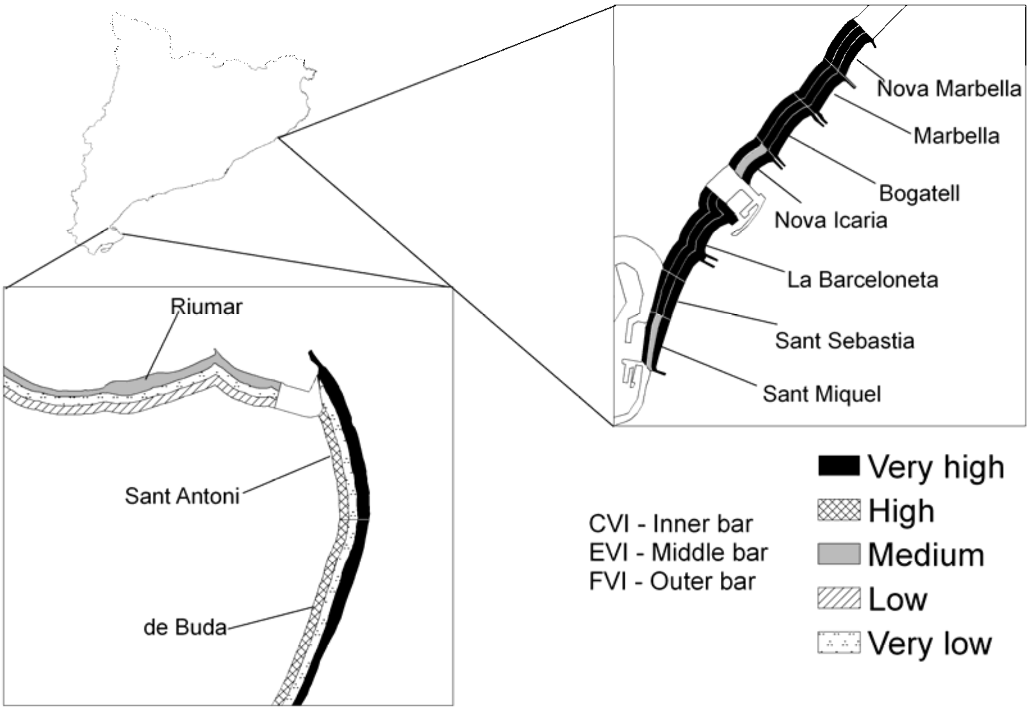

Fig 9. Coastal vulnerability assessment to a Class-V storm in the Ebro delta and Barcelona beaches.

Fig 10. Ebro delta beaches _Cap Tortosa- during the impact of a class-V storm.

Fig 11. Barcelona city beaches: Sant Sebastia and Barceloneta (left panel) and Nova Icaria and Bogatell (right panel) during the impact of a class-V storm (courtesy of the Coastal Monitoring Station in Barcelona. http://elb.cmima.csic.es).