Universitat Politécnica de Catalunya

Laboratori d’ Enginyeria Marítima

Coastal Vulnerability to Storms in the Catalan Coast

Memoria presentada por

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Chapter 2

Study Area and Available Data

2.1 Study Area

Catalonia is situated in the NE Spanish Mediterranean (Figure 2.1.1) with a large geographical territory and a coastal fringe of approximately 700 km long (IDESCAT, 2005). Although the coast is relatively short it is very varied in terms of geomorphology with cliffs, embayed beaches, long stretches of sandy beaches and deltas. Taking into account the coastal geomorphology, the Catalan coast can be divided into 7 areas (Figure 2.1.2).

Costa Brava (Girona)**.** This region presents a very indented and rocky coast where low and high cliffs are the dominant feature, especially in the northern part. The rocky coasts are not as steep as the cliff coasts and normally lower that 20 m. Due to this, the beaches are relatively short and limited by headlands in a form of bay- beaches usually composed of coarse sand.

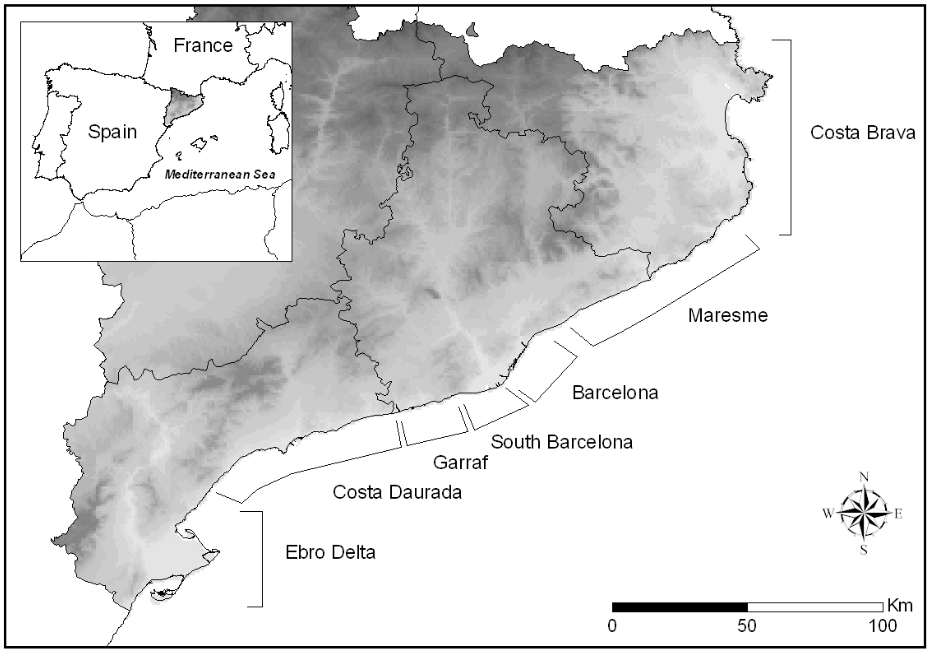

Figure 2.1.1: Main zones of the Catalan coast.

Maresme. It extends from north to south from the Tordera River to Mongat (northern part of Barcelona city). This beach was originally a long quasi-continuous and uninterrupted beach of coarse sand. Nowadays it is artificially segmented in seven cells due to the construction of six ports.

Barcelona. This area extends from the Besos River to the Llobregat River (Port of Barcelona) and it is a highly engineered coast with artificial embayed beaches formed by medium size sand.

South Barcelona. Located at the south of the Port of Barcelona, it includes the Llobregat Delta and the neighbouring beaches which extend from the Llobregat River to Port Ginesta, forming a continuous fringe of fine sandy beaches of approximately 19 km long.

Costa del Garraf. This area acts as a transition from the Baix Llobregat beaches to the Costa Daurada beaches. It presents low cliffs with pocket beaches (some artificial ones) and the majority of these beaches present fine sands.

Costa Daurada. Basically composed of long open beaches characterized by having an almost straight coastline, being usually associated to low-lying coasts. The dominant beach is a mild slope one with fine sediment.

Ebro Delta. Situated in the south part of Tarragona. The low lying coasts are important sedimentary deposits formed by contributing rivers that flow into the sea. It presents very mild slopes with very fine sediment deposits of the Ebro river and do not have any rocky formations.

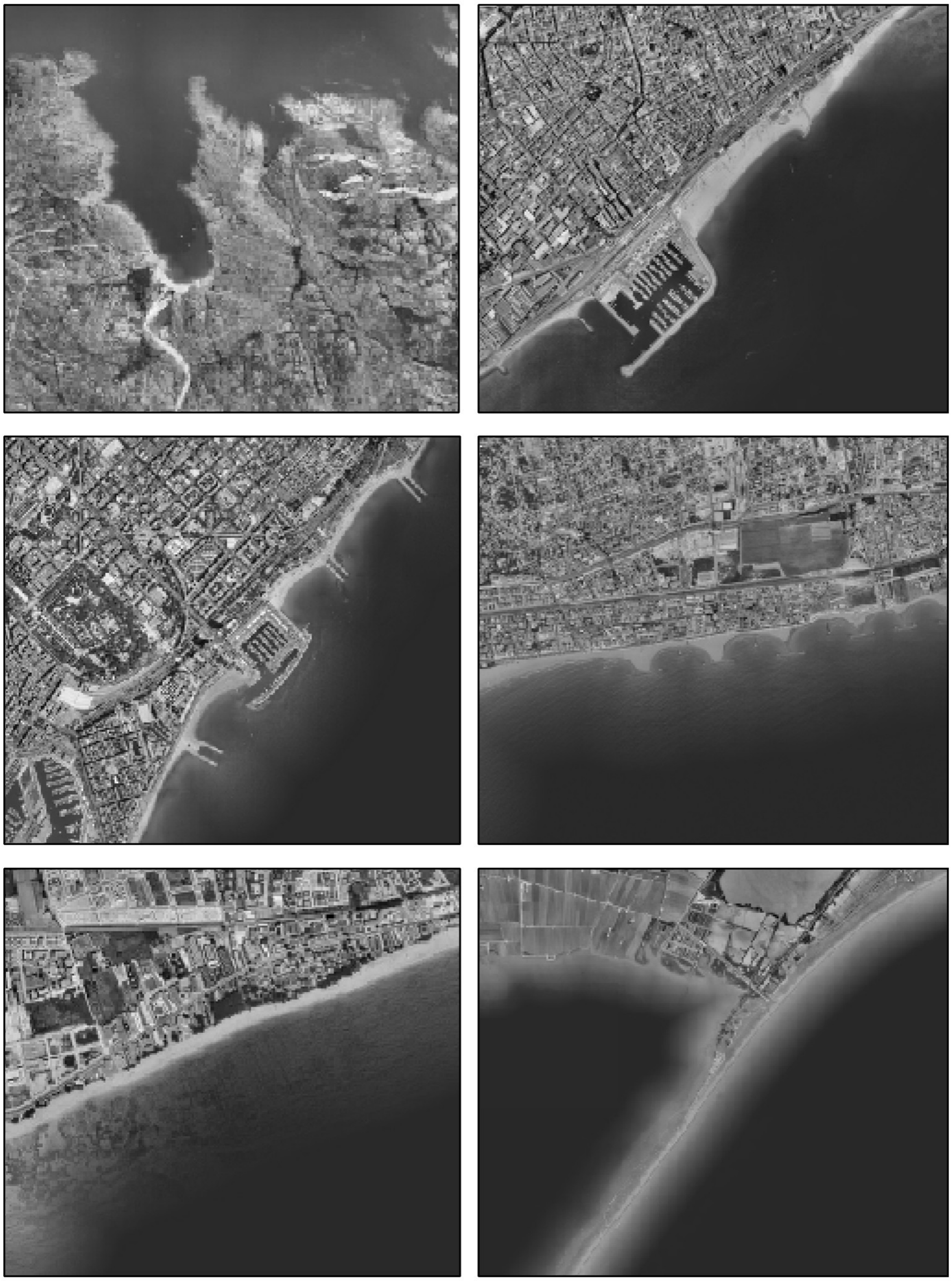

Figure 2.1.2: Main beach environments found in the Catalan coast. From left to right and from top to bottom: Costa Brava, Maresme, Barcelona, Costa del Garraf, Costa Dorada and Ebro Delta.

2.2 Data

This section describes the principal sources of information available along the Catalan coast and the time extent of each of the available series as well as the measured parameters. The main data used are: waves, water level and beach profiles.

Within the wave characteristics, the available information in the Catalan marine region can be grouped in two big categories: (i) instrumental information, (ii) information obtained through numerical simulation of meteorological conditions. This section also contains the zonation of the Catalan coast according to the wave characteristics.

The tide description was based exclusively on instrumental information, while the types of beach profiles were obtained through measurements.

2.2.1 Wave data

Instrumental Information

Within the instrumental category we find a series of wave buoys (scalar and directional) distributed along the littoral (see Figure 2.2.1) managed by the Generalitat de Catalunya and Puertos del Estado, which cover a time lapse of 22 years.

The Xarxa d’ Instrumentació Oceanográfica i Meteorológica (XIOM) belongs to the Generalitat de Catalunya and is constituted (among other equipment such as tide gauges and meteorological stations) by five wave buoys, referred from now on as Trabucador, Cap Tortosa, Llobregat, Blanes and Roses.

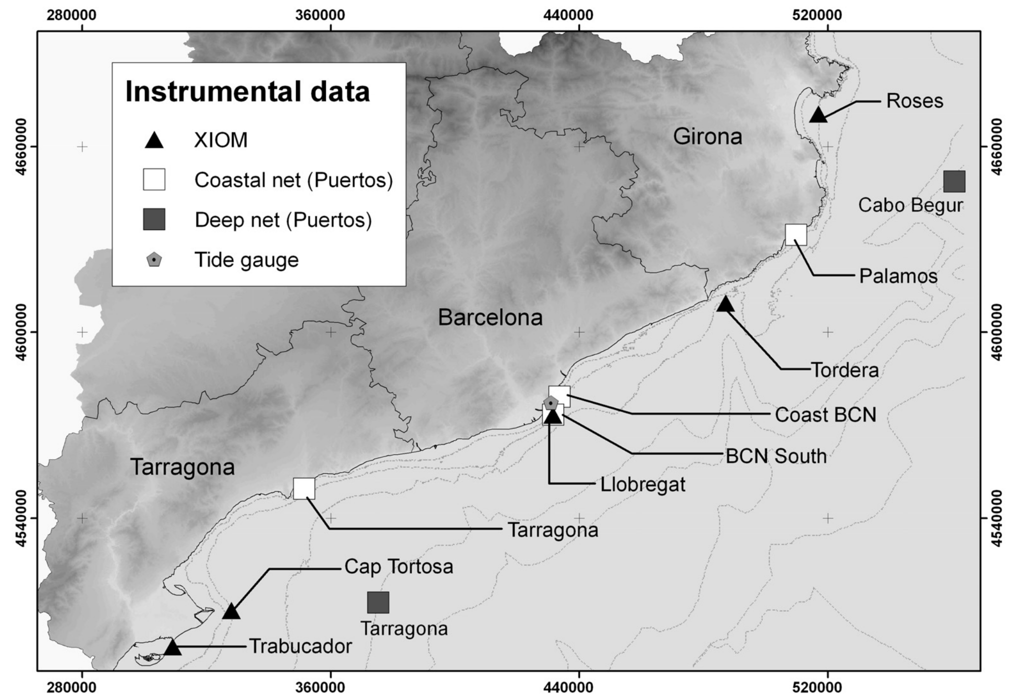

Figure 2.2.1: Localization of the existent wave buoys (1984-2004) and tide gauge (1992-3004) in the Catalan coast.

The measurement dates of the registered data are presented in Figure 2.2.2. The Trabucador buoy stopped being operational in mid 1998. For the purposes of this study the end of the series was established in December 2004.

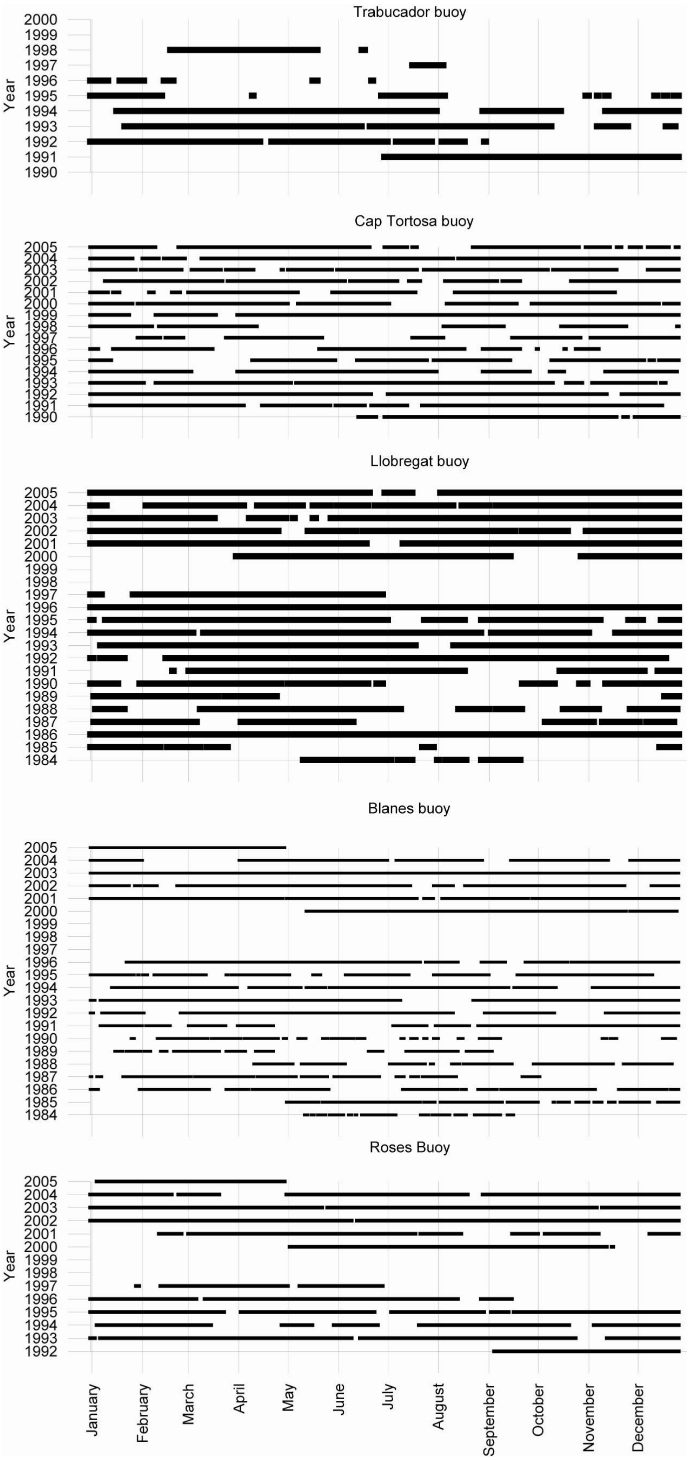

Figure 2.2.2: Valid measurement periods for the different wave buoys of the XIOM net.

Table 2.2.1: Main characteristics of the buoys from the XIOM net.

Name	*Type*	*Model*	*Sampling interval*	*Latitude*	*Longitude*	*Depth (m)*
Trabucador	Directional	Waverider	3h - 1h	40 36.12 N	00 44.47 E	8.5
Cap Tortosa	Directional	Waverider	3h - 1h	40 43.29 N	00 58.89 E	60
Llobregrat	Scalar*	Waverider	3h - 1h	41 16.69 N	02 08.48 E	45
Blanes	Scalar	Waverider	3h - 1h	41 38.81 N	02 48.93 E	74
Roses	Scalar	Waverider	3h - 1h	42 10.79 N	03 11.99 E	46

*Directional from February 2004

The Llobregat (until February 2004), Blanes and Roses are scalar buoys while the Trabucador, Cap Tortosa and Llobregat (from February 2004) are directional ones. Table 2.2.1 resumes the principal characteristics and localization.

In the case of the directional buoys, these produce two types of information: real time and spectral data. The real time data consists in measurements taken 1/1.28 s. From these data the receptor builds the time series of wave height and period that are used to make the statistical analysis. The time series consists of 20 minutes of data. The spectral data are fast Fourier transformations (FFT) of 8 series of 256 consecutive measurements. The 2058 points are obtained in 1600 s (26‘40”). The mean spectre of the 8 analyses is done within the buoy. The Scalar buoys only manage real time data.

The work scheme is essentially the same in all buoys and consists of a ground base receptor for each wave buoy where all the data process takes place and then is stored in a hard disc; this information is sent to a single server. Once the data has gone through a post processing filter it is stored in two types of archives, statistical and spectral.

Simulated data

This type of data is divided in two big groups: WANA and SIMAR 44 (also known as HIPOCAS), both generated and distributed by Puertos del Estado. The WANA consists in predictions using the wave model WAM (WAMDI, 1988). These predictions are done in a grid with a cell size of 0.125° x 0.125°.

In the case of the WANA data for the Mediterranean, the obtained information of the model in each point is the wave directional spectrum, from which the basic information such as the *Hs*, *Tp*, mean direction, etc. is obtained (Gunther *et al*., 1991; Gómez & Carretero, 1997). The available data in the Catalan coast covers a time period that starts in January 14th 1996 to April 26th 2006 in a temporal series of each data given every 3 hours for each of the nodes that can be seen in Figure 2.2.3.

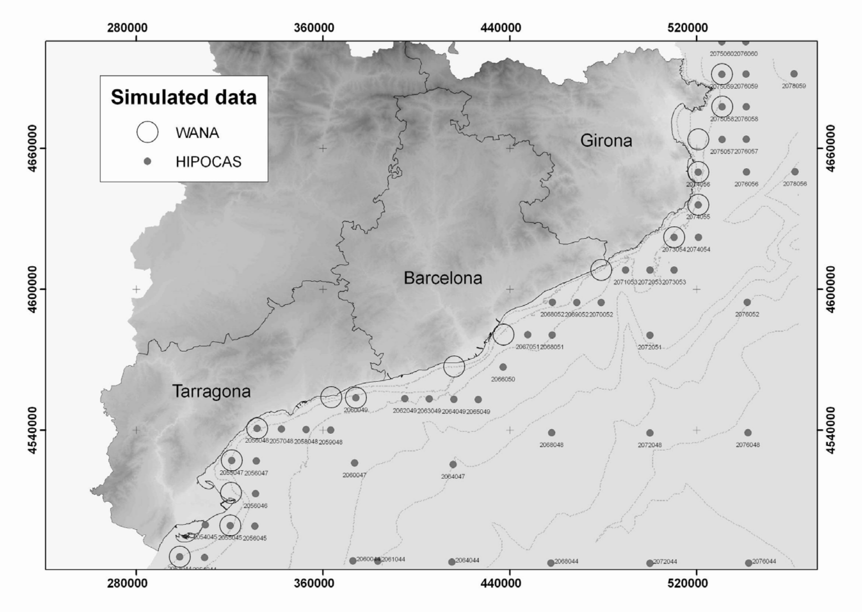

Figure 2.2.3: Available SIMAR - 44 (HIPOCAS) and WANA nodes in the Catalan coast.

The SIMAR 44 data have been generated using high resolution modelling of the atmosphere, sea level and waves. The Mediterranean simulation has been done within the European project HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe, Guedes Soares *et al*. (2002), (http://www.mar.ist.utl.pt/hipocas/).

The available data presents a temporal series of storm surge, significant spectral wave height (*Hm0*), mean period (*Tm*), peak period (*Tp*) and mean wave direction, providing a data of the state of the sea every three hours (Figure 2.2.3).

The main advantage of the WANA and HIPOCAS data is that includes directional information (H,T,θ) which is fundamental for the analysis of coastal processes and that are available along the entire coast, and theoretically speaking could be used to cover the absence of directional data in different points of the coast.

The principal disadvantage lies in the fact that the data is predicted by models and not actually measured, so the values of the different information are mere estimation of reality. Although these predictions are calibrated with a series of control points (in the case of HIPOCAS, the original and calibrated information are given) and might be considered that the obtained error is acceptable mainly having in mind the lack of other type of wave data in these areas, the truth is that the use of the data requires an ad hoc calibration considering the instrumental data.

Annex **A** presents a comparative analysis between the HIPOCAS data and the Cap Tortosa buoy in order to obtain data equivalence. As an example of this analysis, Figure 2.2.4 shows the comparison of the simultaneous significant wave height data of the HIPOCAS node 2056046 time series and the data recorded by the wave buoy in Cap Tortosa (Ebro Delta) covering from June 1990 (starting time for the buoy) to December 2001 (final time of the node 2056046). In general, it can be seen a tendency to underestimate the *Hs* data within the HIPOCAS series for the values under an *Hs* = 3 m. In fact if an equivalence relation is obtained between the two series, which in case of being linear would be given by an adjustment of least squares (represented in the figure next to the 1:1 line), the wave height of the HIPOCAS series would be approximately 66% of the value registered in the buoy. The statistics of the linear adjustment are Bias = -0.18, SI = 0.47 y RMSE = 0.38, with a relation of HIPOCAS= 0.66 H_{buoy}+0.087

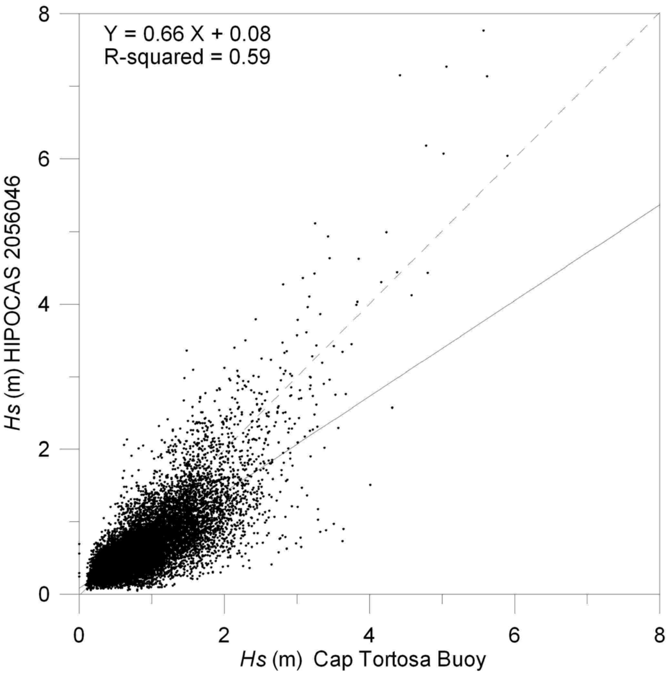

Figure 2.2.4: Simultaneous *Hs* data of the HIPOCAS series vs. the registered data of the Cap Tortosa buoy.

Figure 2.2.5 shows the temporal series of *Hs* from the HIPOCAS data and the Cap Tortosa buoy, where a magnitude difference between the values is observed nonetheless, the modelled data follows the wave pattern recorded by the buoy.

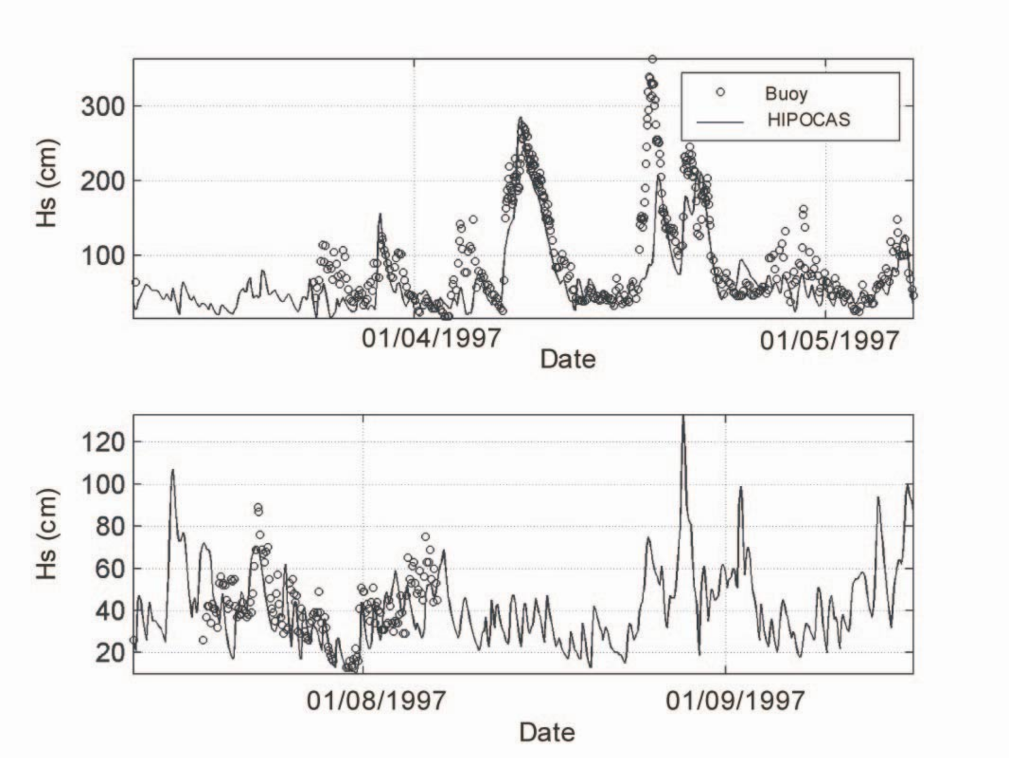

Figure 2.2.5: *Hs* comparison of temporal series from HIPOCAS records and Cap Tortosa buoy.

Even though the modelled data lacks precision, we can assume that the error is equal in all sites, therefore if it over predicts this will be equally for the entire coastline and the whole time series. In this sense the modelled data is useful to characterize the spatial en temporal variability of the waves on a long term basis.

Zonation of the Catalan Coast

The Catalan coast has an approximate length of 700 km. The fact of being a semi-closed sea along with the orographic characteristics of the area that control and condition the wind patterns, create significant variations of winds and waves along the littoral. For this reason whenever we want to characterize the wave climate along the whole coast, it is inadequate just to have wave information of single point of the coast, and therefore it is necessary to have available information of a series of areas along the coast where a certain existence of homogeneity in the variables that define waves can be accepted.

Only with this information the spatial variability of the waves can be adequately reproduced along the shoreline, in such a way that whenever we need to characterize the forcing factors that control the morphodynamic processes in a specific zone, the most representative wave data of that area is used.

With this preamble, the objective of this subsection is to make a first approach of the analysis of the spatial variability in the Catalan coast, in order to resolve the existence of areas of certain homogeneity taking on account the characteristics of the waves.

In order to make a spatial analysis, it is mandatory to have available data with sufficient spatial and temporal resolution. As seen in the previous subsection, there is a series of wave buoys that have recorded data during different periods (figures 2.2.1 and 2.2.2). Although it may seem that the number of buoys is enough to analyze the spatial variability, the reality is that the majorities of these buoys are scalar and lack the information of wave direction which is one of the main components when characterizing the waves and its morphodynamic effects. Likewise the different duration of the time series make it difficult to select time periods for simultaneous recorded intervals.

Consequently this analysis makes use of the HIPOCAS data base in order to characterize the temporal and spatial variability (see Figure 2.2.3). Despite the fact that the modelled data presents errors or uncertainties mentioned before, the interest of this study is to obtain the variability in relative terms along the coast and since it is constituted by the same data, it is considered acceptable.

Whenever we talk about the wave climate, we implicitly talk about a series of variables that describe the waves. Therefore different variables and their statistics have been considered for the Catalan coast zoning, which includes: significant wave height, mean period, peak period maximum, mean and standard deviation for the three last variables, energy and the rose chart of wave height. The spatial distribution of the main variables was analyzed considering only the data points closer to the shoreline from the grid used by the HIPOCAS.

Directional Distribution As said before wave direction is one of the principal variables when characterizing the forcing factors that act in the coast in terms of morphodynamic behaviour. Figure 2.2.6 presents different wave rose charts of wave heights obtained for the total time duration of the different grid points selected along the study area.

As can be seen, there is a significant variation in the directional distribution of the waves from the northern most part to the southern most part. The extreme northern part (Cap de Creus and Golfo de Roses) is clearly dominated by the presence of the N component, due to the influence of the locally generated waves by the action of the Tramuntana (northern) winds. Advancing to the south but still in the Costa Brava region, the northern component is still important although rolling towards the NNE and with a significant increase in the percentage of waves with the S (SSW) component, in other words the distribution becomes bidirectional.

Further south, having passed the Tordera delta, the northern component stops being dominant, and directions from NNE-NE to ESE become significant and present a somewhat homogeneous distribution. It is also important to mention the contribution (the most important) from waves of component SSW. This distribution is maintained along the Maresme coast down to the Llobregat delta where the waves roll to the Eastern direction. From the Llobregat delta moving southwards along the Costa Dorada, given the orientation of the coast the waves of the NE components practically disappear, and reappear further south in the Ebro delta region. In this area situated in the southern extremity of Catalonia also emerge waves of a NW component due to the action of the local Mistral which is created inland.

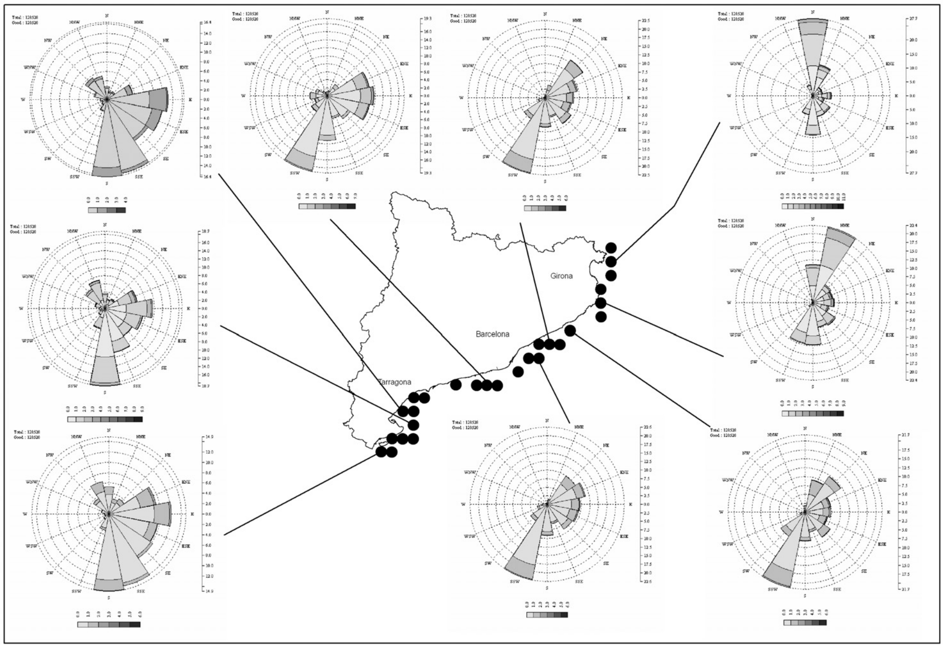

Figure 2.2.6: Wave rose with direction from the available HIPOCAS nodes along the Catalan coast.

In terms of *Hs,* from the Ebro delta to Barcelona the highest values come from the E and S directions whilst in the northern part come from the N and the NW.

Wave height and wave period. Figure 2.2.7 shows the registered maxima *Hs* distribution in each HIPOCAS node along the coast during the available data period. The distribution presents two zones where *Hs* accomplish the highest values; the northern most part and the Ebro delta. The northern part of the Costa Brava presented the maximum registered wave heights (*Hs*max = 11.05 m), moving south to the Maresme region the wave height decreases until reaching the South Barcelona location were the wave height increases again reaching about 8 m. Further south, the Garraf and the Costa Dorada locations presented the minimum values until reaching the Ebro delta with wave heights higher than 8 m and decreasing again to the southern most part of the Catalan coast. The mean values of *Hs* for the entire time series presented values between 0.47 and 0.77 m with a standard deviation between 0.3 and 0.5.

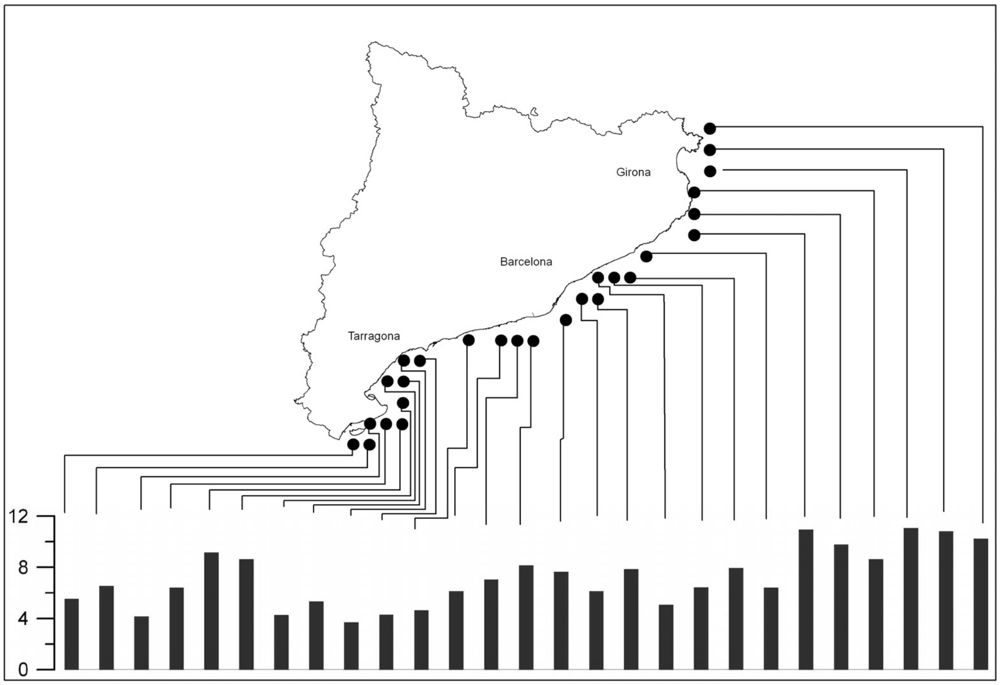

Figure 2.2.7: *Hs* max from the available HIPOCAS nodes along the Catalan coast (magnitude of the variable is given in meters of the vertical bar).

Differently from the *Hs*, the registered values of the maximum registered *Tp* present a much more homogeneous distribution with a reduced variability and range of variation, which is defined by a minimum value of 12.3 s and a maximum value of 16.3 s (see Figure 2.2.8).

The maximum values of the wave period are located in the southern most part of the Catalan coast, in the Ebro delta region, while the area with the lowest wave period is situated in the northern most part. However if the averaged values of *Tp* were analyzed instead of the max values, the northern part presents the longest periods (5.1 s) while at the southern parts of Barcelona the values decrease until reaching 4.5 s. As well as the first wave period analysis the standard deviation values present insignificant differences along the coast.

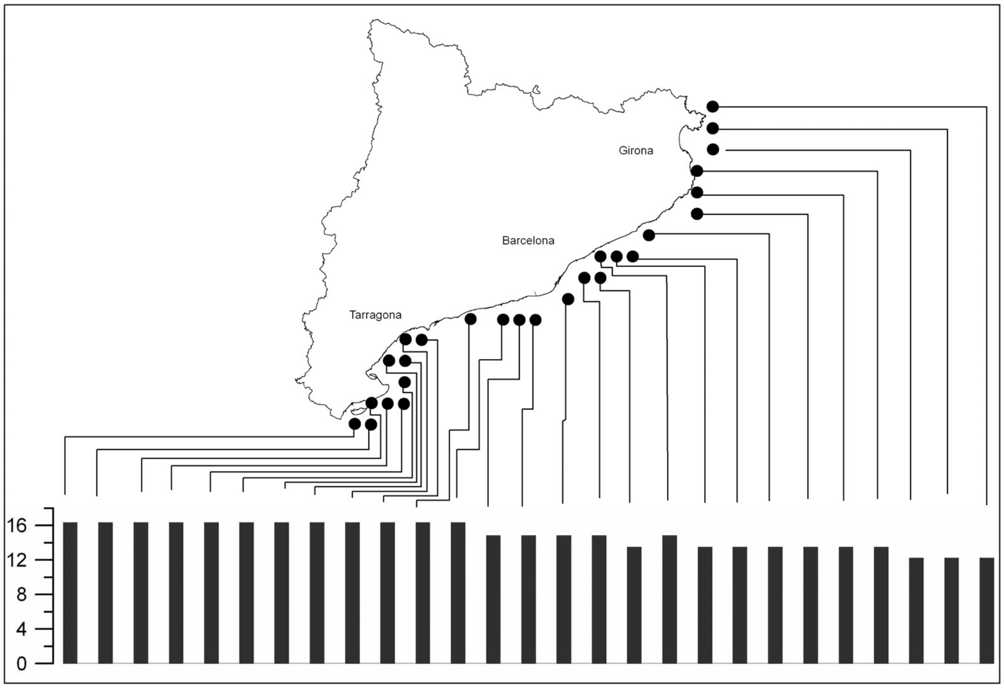

Figure 2.2.8: *Tp* max from the available HIPOCAS nodes along the Catalan coast (magnitude of the variable is given in seconds of the vertical bar).

Whenever evaluating the results presented in Figures 2.2.7 and 2.2.8 one must have in mind that the represented values are derived from a statistical time series (in this case the maximum value) and are not necessarily simultaneous. However it is important to consider such values since making a zonation of the coast in terms of the wave induced morphodynamic processes must bear in mind the variation of the wave characteristics along the coast under determined conditions, for there might be the case of two areas with same *Hs* value but produced by different conditions and could be considered as homogeneous in terms of wave effects.

As an example of simultaneous variability produced during the generation and propagation of an event in the coast, Figure 2.2.9 exemplifies the wave domain predicted by the WAM model along the Catalan coast for an E storm which was formed in October 2003. The figure presents the *Hs* conditions during the peak of the storm and clearly shows a gradient of wave height with decreasing values of *Hs* ranging from 5 m in the North to 2 m in the south.

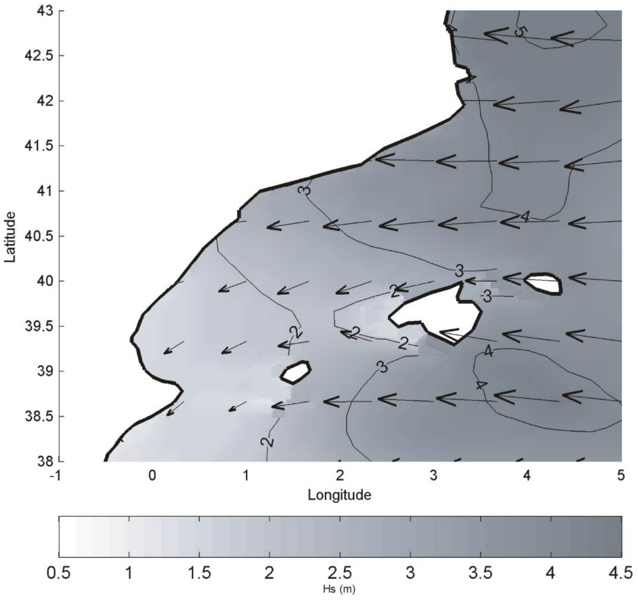

Figure 2.2.9: Wave height simulation using WAM of an E storm in the Catalan coast (October 2003).

Final zonation Considering the previous sections, the waves along the Catalan coast present a quantifiable spatial variability which becomes quite significant, depending on the analyzed parameter. In terms of this variability and taking on account the wave propagation along the coast it is possible to create areas or sectors where wave characteristics can be considered homogeneous. The most significant parameters used when creating the sectors were wave height and direction, given that the wave periods do not present significant variability in the region.

Having in mind the obtained distributions, the zonation of the Catalan coast as a function of the wave conditions is proposed in Figure 2.2.10. This distribution consists of eight zones: (I) Costa Brava N, (II) Costa Brava S, (III) Maresme, (IV) Barcelona- Llobregat, (V) Costa Dorada, (VI) Tarragona, (VII) Ebro Delta N, (VIII) Ebro delta S.

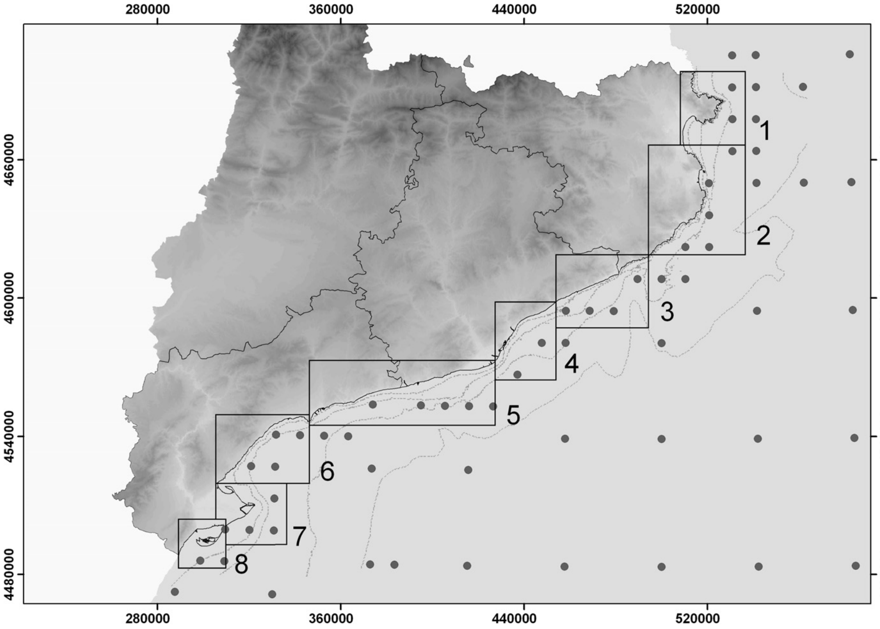

Figure 2.2.10: Zoning of the Catalan coast as a function of the wave pattern.

2.2.2 Tide data

The REDMAR is the tide gauge net from Puertos del Estado which contains historical and real time data of sea level covering from 1992 until present. The net is constituted by 14 acoustic sonar tide gauges, 7 WLTS 3791 Aanderaa pressure gauges and 12 Miros radar sensors.

This work has used the data from the WLTS 3791 Aanderaa pressure gauges which obtain the sea level from the measurement of the hydrostatic pressure and the water temperature in a fixed submerged position. This gauge is employed with a compensating unit for the atmospheric pressure so the sea level data is corrected for this effect.

The tide gauge is located in Latitude 41.350, Longitude 2.160, within the Barcelona harbour (see Figure 2.2.1) and extracts sea level, astronomical tide level and surge tide level data every 5 minutes. The data is subsequently filtered and averaged in order to obtain the tide data every hour. The study used hourly data covering a time lapse of 12 years starting in August 1992 until December 2004.

An example of this information is shown in Figure 2.2.11 and contains data of sea level, astronomical tide and the storm surge from 1992 to 2004. The astronomical tide and the sea level show a skip, of the data which was caused by the change of the datum in 1998, the storm surge was not affected by this change. More detailed information from this series is shown in Figure 2.2.12 where the sea level is presented in dots, the astronomical tide in a dashed line and the storm surge in solid line for November 2001, this month contained the highest residual tide during the 1992 - 2004 time series.

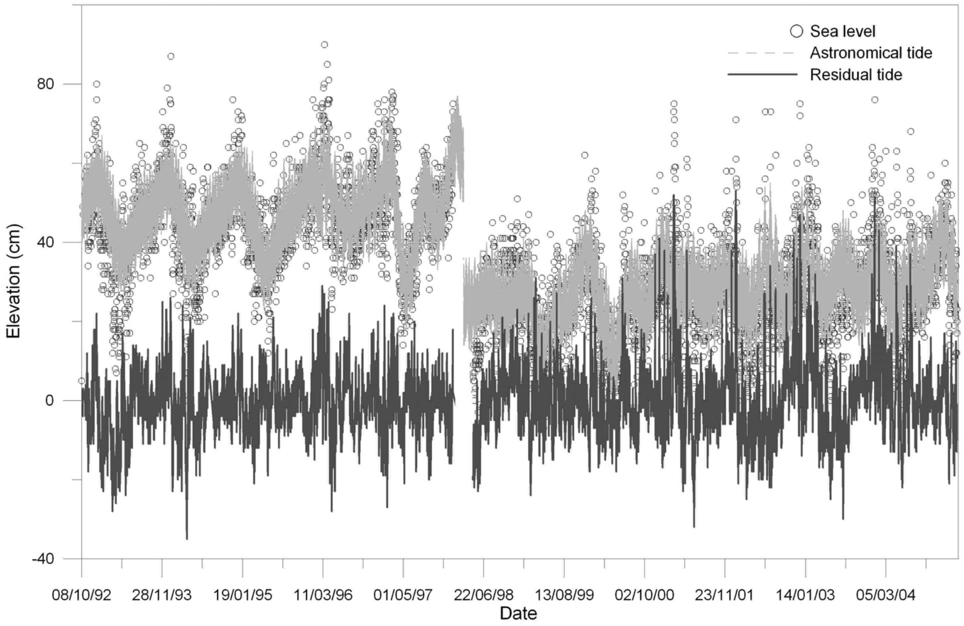

Figure 2.2.11: Sea level, astronomical tide and storm surge information from 1992 – 2004.

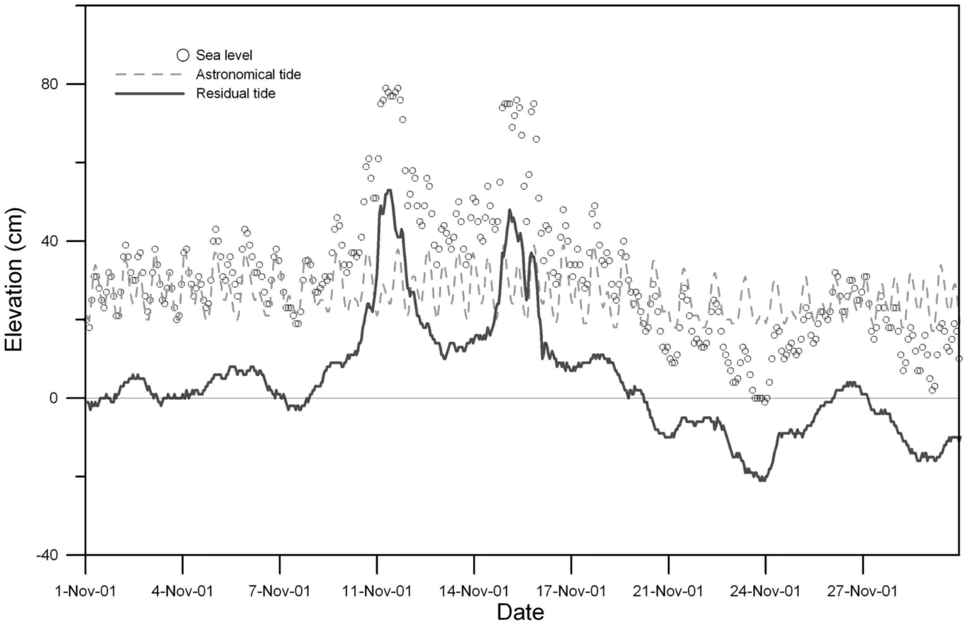

Figure 2.2.12: Sea level, astronomical tide and storm surge information from November 2001.

2.2.3 Beach profiles

One of the most conspicuous features in the coastal zone is represented by the beaches, which are basically deposits of sediment. Beaches are constantly changing due to wind, tides, storm activity, and the actions of humans. A typical sandy beach is composed of the following areas: the foreshore and the backshore, the foreshore is mainly the beach face, from the lowest part of the low tide to the highest part of the berm closest to the beach face. The backshore consists of the berms (Figure 2.2.13). A berm is created by wave action and represents the highest area on the beach that waves can carry and deposit sand.

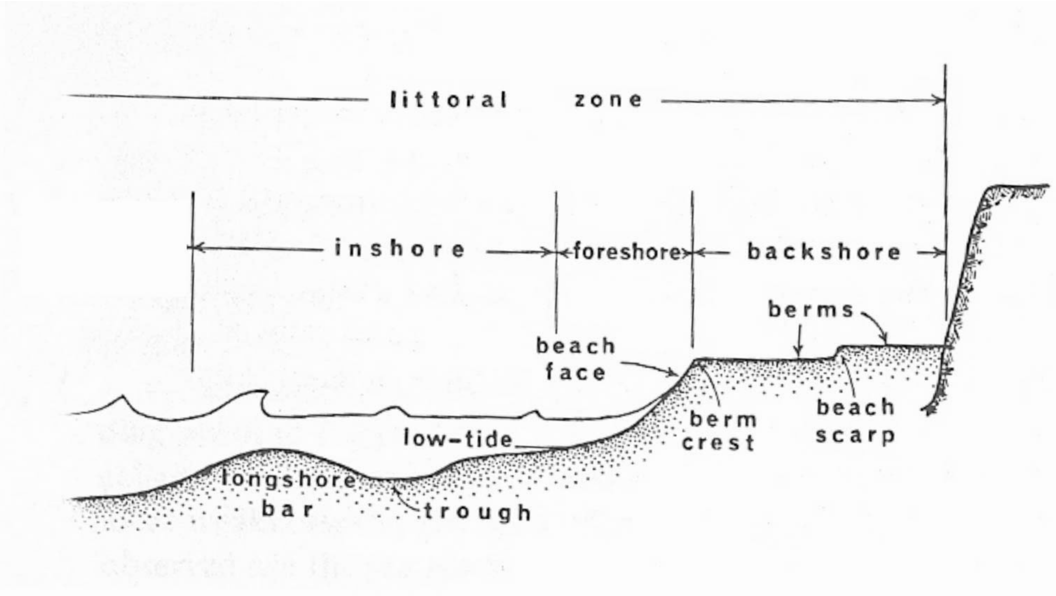

Figure 2.2.13: Terminology to describe the beach profile, taken from Komar (1997).

A principal aspect of the beach is its dynamic behaviour, due to the loose grain sediments that respond to the waves and currents. The beach profile can be viewed as an effective mechanism which causes waves to break and dissipate their energy. The beach serves as a buffer, protecting sea cliffs and adjacent infrastructure from the wave action. If there is a long term loss of sand from the beach, the beach will be unable to serve as a buffer and damages to property will become more probable.

The most common form to determine changes in the beach is through beach profile monitoring. The beaches in this work have been separated following the classification given by Wright & Short (1983), using two principal beach (measured) profiles to characterize the Catalan zone: reflective and dissipative (see Figure 2.2.14) which represent the range of existing profiles found along the coast.

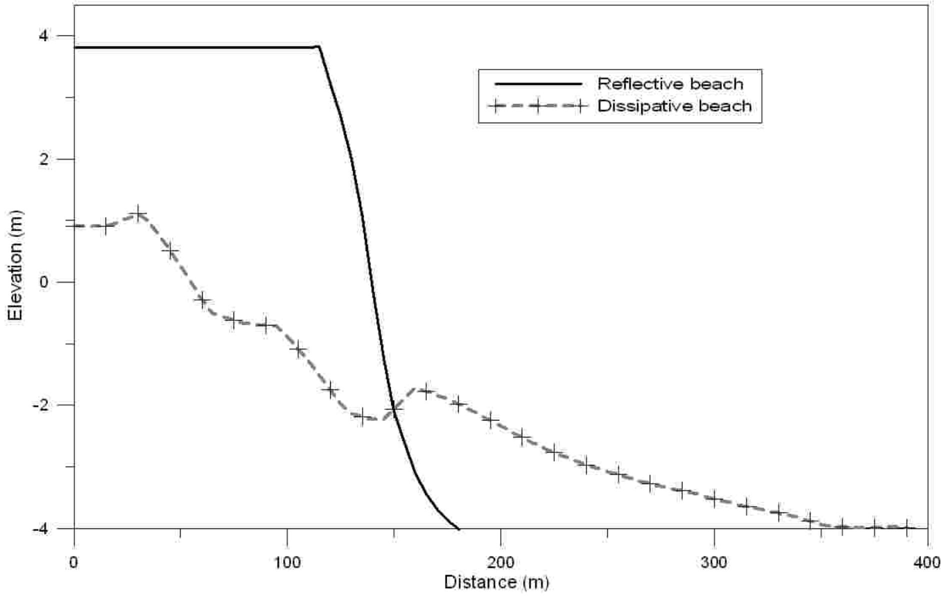

Figure 2.2.14: Reflective and dissipative beach profiles characterized in the study.

A typical reflective profile is usually composed by coarse sand (d50 ≥ 0.6 mm) with a relatively high berm and a steep slope ($\tan\beta \approx 0.1$) and it can be considered as representative of coastal areas such as the Costa Brava and Maresme and can be seen in Figure 2.2.15 (top case). The dissipative beach profile is composed by fine sand (d50 ≈ 0.25 mm), with low berms, very mild slope ($\tan\beta \approx 0.01$) and are easily overtopped during storms. These beaches are mainly present in the Costa Dorada and the Ebro delta regions (see Figure 2.2.15 lower case).

Figure 2.2.15: Example of a reflective (top) and a dissipative beach (bottom) found in the Catalan coast.