Coastal Flood Hazard Mapping at two scales. Application to the Ebro delta

Doctoral Thesis

Presented by

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Summary

A methodological framework for Flood Hazard Mapping and Damage Assessment to Coastal Storms was proposed in this thesis in two working scales: A long-term scale related to Relative Sea-Level Rise, and an episodic/extreme scale related to storm events. The incorporation of coastal response to storm events in this framework is a basic part of this proposal. This methodological framework was aplied to the Ebro Delta.

In terms of the long term scale, the Relative Sea Level Rise is the main process that can cause important changes in low-lying coastal areas, such as Ebro Delta. Three possible scenarios of sea level rise were reproduced to determine potentially flood areas considering the paper of the inner structures - like channels, docks and highways - in the floods prevention.

The extreme/episodic scenario is associated to processes that have very large return periods and do not exhibit a periodicity in the time. Flood areas associated to coastal storms with return periods of 10, 50, 100 and 500 years were identified. For this aim, the coastal morphodynamic response and the backbeach flood distribution were studied.

Additionally, an evaluation of the lost and damages associated to flood was carry out. For this study, the values of the ecological services of the ecosystem were used. An indicator of Coastal Vulnerability to the Erosion by Storms was also implement.

Resumen

Esta tesis propone un marco metodológico para la determinacion de Areas con Riesgo a Inundaciones y la Evaluación de Daños por Tormentas Costeras, en dos escalas de trabajo: una a largo plazo relacionada con la Elevacion Relativa Nivel del Mar y una episódica/extrema relacionada con eventos de tormenta. La incorporación de la respuesta morfodinamica de la costa a eventos de tormenta es una parte fundamental de esta propuesta. Este marco metodológico fue aplicado en el Delta del Ebro.

El principal proceso en el escenario a largo plazo que puede causar cambios importantes en zonas costeras con poca elevación (por ejemplo, el Delta del Ebro), es la Elevación del Nivel del Mar. Por lo anterior, se reproducen tres escenarios de elevación del nivel del mar para determinar áreas potencialmente inundables, teniendo en cuenta el papel de las estructuras interiores -como canales, diques y carreteras- en la prevención de inundaciones.

El escenario extremo o episódico, se asocia a procesos con periodos de retorno muy amplios y que no presentan una periodicidad en el tiempo. En este caso, se identificaron las áreas inundables asociadas a tormentas costeras con periodos de retorno de 10, 50, 100 y 500 años. Para la determinación de estas àreas, se identifico la respuesta morfodinámica de la costa y la distribución de la inundación en la parte posterior de la playa.

Así mismo se llevo a cabo una evaluación de los daños y perdidas asociadas a la inundación. Para lo cual se emplearon los valores de los servicios ecológicos del ecosistema. Y se implemento un indicador de Vulnerabilidad Costera a la Erosión por Tormentas.

Resum

Aquesta tesi proposa un marc metodològic per a la determinació d'Àrees amb Risc d'Inundació i l'Avaluació de Danys per Tempestes Costaneres, en dues escales de treball: una a llarg termini relacionat amb l'Elevació Relativa del Nivell del Mar i una altra episòdic/extrem relacionada amb esdeveniments de tempesta. La incorporació de la resposta morfodinàmica de la costa als esdeveniments de tempesta és una part fonamental d'aquesta proposta. Aquest marc metodològic va ser aplicat al Delta de l'Ebre

El principal procés en l'escenari a llarg termini que pot causar importants canvis en zones costaneres amb poca elevació (per exemple, el Delta de l'Ebre), és l'Elevació del Nivell del Mar. Degut a això, es reproduïxen tres escenaris d'elevació del nivell del mar per a determinar àrees potencialment inundables, tenint en compte el paper de les estructures interiors -com canals, dics i carreteres- en la prevenció d'inundacions.

L'escenari extrem o episòdic, s'associa a processos amb períodes de retorn molt amplis i que no presenten una periodicitat en el temps. En aquest cas, es van identificar les àrees inundables associades a tempestes costaneres amb períodes de retorn de 10, 50, 100 i 500 anys. Per a la determinació d'aquestes àrees, es va identificar la resposta morfodinámica de la costa i la distribució de la inundació a la part posterior de la platja.

Així mateix, es va dur a terme una avaluació dels danys i pèrdues associades a la inundació. Per a això es van emprar els valors dels serveis ecològics de l'ecosistema. I es va implementar un indicador de Vulnerabilitat Costanera a l'Erosió per Tempestes.

Contents

List of Tables.

List of Figures.

1. Introduction

“Kalau tak ingin terlimbur pasang, jangan berumah di tepi laut.”
If you don’t want to get flooded, don’t build a house next to the sea.

“Sekali bah, sekali pantai berubah”
Once there is a flood, the beach will change

Indonesian proverbs

1.1 Flooding in the Coastal Zone

The coast has a great environmental diversity and resources given its interface character. This makes it a particularly attractive area for human settlements as well as economics activities, most of them within a few kilometers from the coastline (Nicholls and Branson 1998).

Demographic trends in human population in coastal areas worldwide show that almost 70% of the global population lives and develops economic activities on the coast or not farther than 60 km from it. This percentage is increasing, this means that coastal occupation and use of the area could double in less than 30 years (Norse 1994), for example, the EU coastline extends 101,000 km along 20 of the 25 member countries. Over the past 50 years the population of coastal municipalities has doubled to reach 70 million in 2001 (EUROSION, 2004).

The coastal area is and will remain an important area for human development. Therefore it is subject to a variety of pressures that can create conflicts between them. The possibility to attain a sustainable development [of the coastal zone] depends on a deep and thorough knowledge of these areas and the dynamics that take place there.

The dynamical nature of the coastline makes it difficult to accurately determine the risk and vulnerability of a community or area. Extreme storm events can cause erosion or floods which may increase the risk of a community. These problems are associated with deficient planning process in developing areas which do not usually include measures to reduce natural hazards, and therefore they can cause human suffering and economic losses that could be avoided at least partially.

Flooding is the most frequent natural hazard across Europe mainly due to rivers, causing distress and damage wherever it happens (FLOODSite 2004). Because of the potential risk to human life, economic assets and the environment, Europe's commitment for sustainable development could be severely compromised if appropriate action is not taken. Along this line of thought the European Community developed in 2000 the Water Framework Directive 2000/60/EC (WFD) to establish a framework for Community action in the field of water policy. Through this directive the EU imposes the development of basin management plans to be carried out to achieve a satisfactory ecological and chemical status, which will contribute to mitigate the floods effects.

Based on the WFD recommendations and in order to cover the requirements about flood management and risk, the Floods Directive 2007/60/EC (FD) (officially the 'Directive of the European Parliament and of the Council on the assessment and management of flood risks') was proposed and developed. The objective of the FD is to reduce and manage the risks that floods pose to human well-being, environment, infrastructure and property. It will promote flood mapping in all areas with a significant flood risk, and it will create flood risk management plans through a broad participatory process. Given the diversity across the EU in terms of geography, hydrology and settlement structure, the proposed Directive provides considerable flexibility for Member States to determine the level of protection required, and the measures to be taken to achieve this level of protection.

The FD also defines and introduces two new terms in addition to the set established by the WFD: Flood and Flood Risk. The first term introduced, **Flood** means the temporary covering by water of land not normally covered by water. This shall include floods from rivers, mountain torrents, mediterranean ephemeral water courses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems. The second one is **Flood Risk** which means the combination of the probability of a flood event and the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event.

FD lays down the basis for the preliminary assessment of risk and the minimal analysis to be performed; from the maps of the hydrographic conditions of the basins, to forecasts of future floods. And it increases the need to generate flood risk maps, which establish the geographical areas (possible risk scenarios) that could be flooded according to the following causing scenarios:

• Floods with a high probability (likely return period, once in every 10 years)
• Floods with a medium probability (likely return period, once in every 100 years)
• Floods with a low probability (extreme events).

In all previous cases it is necessary to include information on projected water depths, flow velocities and areas of bank erosion or debris flow deposition. These same maps must also provide information of potential damage to the environment, the potential economic damage and the number of inhabitants potentially affected.

The FD provides the basis for flood risk management plans that member states should develop. These plans should be published and come into effect by December 2015, subjected to revision and updating every six years. The FD and the measures taken to implement it are closely linked to implementation of the WFD. The Commission proposes to fully align the organizational and institutional aspects and timing between the Directives, based on basin districts, the competent authorities and a committee established by the WFD.

The FD does not define which risk level is 'significant', nor does it require a precise calculation of flood risk. The FD only requires hazard maps and vulnerability maps and to indicate their possible combinations, without any further prescriptions about the method or the output. However, it may be valuable to make true flood risk maps that reflect the definition of flood risk as a function of hazard and vulnerability.

As a result of the directives, governments need to develop maps of flooding associated with extreme events of medium to high probability. Therefore is necessary a precise and detailed study of the factors causing floods on the coast, how they behave, their probabilities of occurrence, the coastal response to this stress (flood, forcing and associated effects), and the values damaged by floods.

The management of flood risk is a critical component for public safety and quality of life. Coastal floodings are a threat to communities located along European coastlines. The potential risk to human life, economic assets and the environment is large and is increasing due to natural factors such as erosion, waves, rising sea levels, climate change, etc. and anthropogenic factors such as coastal urban development mainly.

Flood hazard mapping is an important part of coastal zone management because it provides easily-read, rapidly-accessible charts and maps with information of risks associated with the coast. And is a very useful tool for the administrators and planners to identify areas of risk and prioritize their mitigation / response efforts.

The Directives approved by the European Commission lay the fundaments for its development by providing basic characteristics that must be satisfied, but do not specify a basic methodology to be used. For this reason it is necessary to develop methodologies or frameworks which will provide the tools for its accomplishment.

Thus for a sustainable develop in the coastal zone, it is important to search and to develop a methodology for flood hazard mapping in which factors associated with coastal response will be taken into account to assist in the production of risk and vulnerability maps of the coast in an easy way.

In this study different methods for incorporating the coastal response associated to impact of storms are analyzed and compared by applying them to one low-lying stretch of the Catalan coast where a high-precision Digital Elevation Model (DEM) exists and where the coastal morphodynamic response is well characterized. A Vulnerability Indicator is also proposed to assess the impact of flooding in the area.

1.2 Objectives

The main goal of this thesis is to develop a framework to asses the impact of floods in the coastal area due to storms, taking into account the response of coastal morphodynamics and to test a methodology to assess vulnerability to such events. This will be done at two work scales (long-term events & episodic events), due to their different importance and influence on the coastal floods.

To achieve the general objective four specific objectives are identified:

Characterization of the forcings that affect the coastal zone. Determination of the methodologies used to evaluate the forcings (storms, return periods, runup, overtopping)

Characterization of the coastal response. Evaluation of the coastal response and selection of the parameters or models to achieve characterization.

Determination of the flooding and its extension. Estimation of the flood extends with the use of numerical modeling.

Assessment of vulnerability to these events. Development of an Vulnerability Indicator to inundation in case of storms. Evaluation and mapping the coastal vulnerability to flooding for coastal storms.

1.3 Structure

This thesis is structured in seven chapters with the following contents:

Chapter Two Contains a background and review of work-related flooding in coastal areas and the different points of view from which they are treated, contained, remedied, or amended.

Chapter Three describes in detail the methodologies in which the framework is based

Chapter Four characterizes the physical, biological and economical aspects of the study case (Ebro Delta).

Chapter Five presents resulting proposed methodology and the application to the case study. The first part identifies the forcing agents and the second part describes the impact on the receptor

Chapter Six introduces the discussion about the strengths and weaknesses of the proposed methodology, and the problems identified in the study area.

Chapter Seven exposes the conclusions of this thesis and suggests possible research lines for further development of the subject.

References and Literature used in this work are listed in the Chapter Eight, and complementary materials are presented in the annexes.

2. Mapping Coastal Hazards. State of the Art

What is a scientist after all?
It is a curious person looking through a keyhole,
the keyhole of nature,
trying to know what's going on.

Jacques-Yves Cousteau

A flood hazard map shows the spatial distribution of the flood threat, the intensity of flood situation and their associated execeedance probability for either a single or several flood scenarios.

Flood Hazard Mapping (FHM) is a vital component for appropriate land use planning in coastal zones because it can prevent damage of life and property from flooding in the short and the long term. FHM also provides information that can include past flood records, flood anticipation, and potential evacuation routes.

FHM was traditionally carried out by gathering, collecting, and analyzing hydrological data, which involved a large number of field observations and calculations. This traditional approach uses historical data of flood events to delineate the extent and return times of floods. With the development of remote sensing and computer analysis techniques, the traditional sources can be supplemented, thus yielding to improvements in FHM, and this leading in turn to better planning.

In FHM large number of variables involved broaden the range of the final answer. It is therefore necessary to consider each of the input variables and understand their divergences. In this chapter we only address the techniques implemented in the final mapping of the flood, how they have been raised and implemented to improve the final calculation of inundation. The variables and their divergences for the used methodology are discussed in the methodological chapter.

Nowadays, in FHM several types of approaches are used. Most of the work has first been done in rivers to determine flash floods or storm floods. Then the previously developed models have been adapted to their application in coastal areas. After an extensive review, we can consider two major types of approaches. The first is completely based on theoretical and numerical flooding, and employs mathematical models. The other one that uses Geographic Information Systems (GIS) as the basic working tool. In this second case, the rise of the flood is not considered as an isolated phenomenon; it also takes into account the geographical, physical, and social environments adjacent to the flood. A 'new' approach that is recently being used consists in the combination of the two approaches with the inclusion of mathematical results into the data gathering within the GIS, as well feedback between the mathematical model and GIS is also included to obtain more detailed results

2.1 The Stillwater Method & GIS

The straightforward way to determine a flood is to establish a stillwater level, consider that not coastal response exist, and then trace these levels on the ground with the help of topographic data. Based on this premises the flood affected areas are determined. It is the most simplistic way and the most used at the beginning. Initially GIS used this approach and gradually implemented others improvements. In the case of the combination of GIS and mathematical models are presented the stillwater case (the model determines the water level, but not the coastal response) or when there is a feedback between model and GIS, to include the coastal response and behavior of coastal flooding. The use of GIS and models together, provides a strong and comprehensive tool for FHM.

GIS is a system that comprises hardware, software, geographic information and specific procedures to support the capture, analysis, modeling and deployed spatially referenced data for solving the complex problems of land management and planning (Clarke, 1997). GIS is therefore an increasingly important tool because it enable the handling of large amounts of data and therefore planning and continuous updating of the possible risk management plans. GIS could be used to extract information from digital elevation data for input to a hydraulic model, and then be used to map the potential or current spatial extent of floodwaters.

As an example of the use of GIS we have the work done by *Thumerer et al.,* (2000) in England where he develops a whole system of flood risk management. Other authors like Gambolati *et al.,* (2002), Zerg & Wealands (2002), Sanyal & Lu (2004), and Webster *et al.,* (2004), presented similar works with the unification of numerical models with GIS or only GIS.

Thumerer *et al.,* (2000) and Gambolati *et al.,* (2002), conducted their studies based on the basic idea of identifying a stillwater level and its spread to the adjacent coast, but they improved the original approach to obtain new results. Thumerer *et al.,* (2000) combined oceanographic and climatic research with data on sea defences, elevation values, and patterns of landuse. A risk assessment model was developed to estimate flood return periods according to different climate change scenarios for the years 2050 and 2100. Flood risks were modeled as a function of the height and condition of sea defences, land elevations, and subsidence rates. They allowed flood risks to be promptly calculated for each management unit for any point in the future by computing predicted extreme water levels, adjusting them for isostatic adjustment, comparing these values with the level of protection provided by coastal defences, and estimating flood probabilities (figure 2.1). Gambolati *et al.,* (2002) studied the coastline evolution of the Eastern Po Plain due to sea level change caused by climate variation and to natural and anthropic subsidence. The outcome from the various modeling simulations developed to predict the various processes affecting the coastal stability were georeferenced and visualized using GIS. Estimation of the potentially flooded lowlands and related water elevation at a given time was performed with GIS by intersecting the ground level with the expected mean sea level at the same time and with the selected return period.

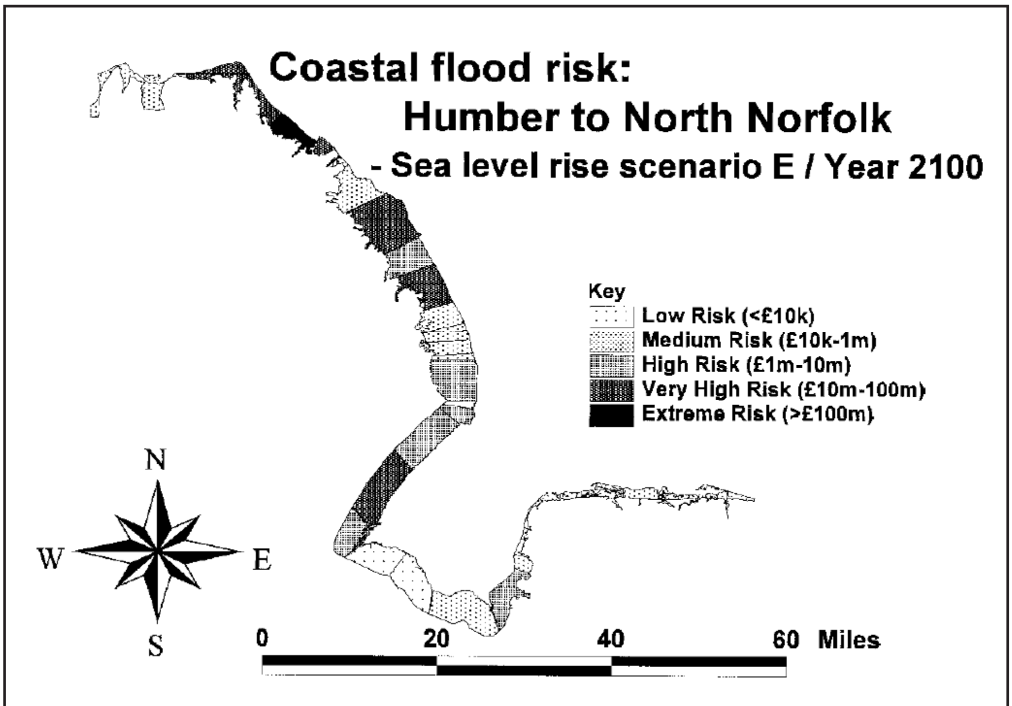


Figure 2.1 Scenario for Annual Flood Risk for Sea Level Rise by Thumerer (2000)

On behalf of a better management of floods, FHM developers try to improve the techniques and develop tools for the decision-making; one example is the work of Zerg & Wealands (2002) who develop a software tool to assist and help risk managers with risk management decision-making. Data from storm surge models, provide detailed estimates for coastal-zone planning and then this information is associated with a GIS and a management database. The output from such models is an array of time-series flood surfaces for each study domain for a range of scenarios. Others authors have attempted to express inundation risk as a function of ground elevation and proximity to the coast by assuming stillwater inundations.

2.2 The Mathematical Way

Within the numerical modeling approach, there are variations in how to analyze and simulate the flooding and its causes, depending on the mathematical basis and how to simplify the flood. One-dimensional (1D) flow is used for the simulation of channels or rivers. In the case of flood plains (both coastal and terrestrial) a two dimensional model (2D) is necessary. In few occasions the models use three dimensions (3D), because of the mathematical complications that would arise. The final results are then taken to a cartographic expression that is used in FHM.

Numeric or mathematical modeling is an abstract representation that uses mathematical language to describe the flooding. Eykhoff (1974) defined a mathematical model as a "representation of the essential aspects of a system (or a system to be constructed) having knowledge of the system as useful."

The use of mathematical models for FHM, was first employed for the development of flooding models for rivers and river basins (Bates & De Roo 2000; Galy & Sanders 2000; Werner 2001) and have subsequently been adapted to coastal flooding (Colby *et al.,* 2000; Battjes & Gerritsen 2002; Zerg & Wealands 2004; Bates *et al.*, 2005; Hunter *et al.,* 2005). The problem associated with these models is the resolution of the Boundary Conditions specified on the side of the coast, and the characterization of water levels.

The models developed specifically for the marine environment are normally associated with the modeling of hurricanes and storms. In these cases the problems are due to the inclusion or specification of the coastal response in the model. The follow one represent to illustrate how FHM and mathematical models have evolved (Flather 1994; Hubbert G.D. & McInnes K.L. 1999; Cheung *et al.,* 2003; Peng *et al.,* 2004; Cowell & Zeng 2003; Nielsen *et al.,* 2005; Bradbrook K. 2006).

Flather (1994) proposed a numerical model, for storm surge prediction for the bay of Bengala. A simple modification of the standard depth-averaged storm surge equations was introduced to represent either 1D flow, as in a channel, or 2D flow, as in the open sea. This modification allows 1D flow along a river channel to transform into 2D flow as the water surface elevation rises above the bank level and floods adjacent land areas.

The model developed by Hubbert & McInnes (1999) utilized a methodology for wetting and drying which depends not only on the sea surface height relative to the adjacent topography, but also on the distance traveled by the coastal interface based on the velocity of the current immediately seaward of the boundary. Instantaneous wetting and drying of grid cells, which can generate noise in the numerical solutions, is therefore minimized. This technique is found to be extremely robust in complex terrains, under severe atmospheric forcing conditions and a wide range of grid spacings.

Peng *et al.,* (2003) modeled hurricane-induced currents, storm surge and inundation using a modified scheme of Hubbert G.D. & McInnes K.L. (1999). To determine if a land grid point will be inundated, the height of the water at the grid cell adjacent to the coastline is compared to the topographic height next to it on land. If the water is higher than the adjacent land, then flooding is possible and a second criterion (distance) is examined. If the distance is larger than the grid size, then the grid cell turns into water. Otherwise, flooding will not occur at this time. One of the modifications made to the Hubbert & McInnes scheme is the choice of the inundation speed which is computed from the surface current derived from a 3D model. Xie *et al*. (2004) introduced a modified version of the scheme that incorporates mass conservation and the flexibility to choose inundation speed based on three-dimensional flow fields. This new scheme was incorporated into a three-dimensional storm surge model.

Cheung *et al.,* (2002) built a model package that simulates coastal flooding resulting from storm surge and waves generated by tropical cyclones. The package consists of four component models implemented at three levels of nested geographic regions. The storm surge and local tides define the water level in each nearshore region, where a Boussinesq model uses the wave spectra output from SWAN to simulate the surf-zone processes and runup along the coastline. The water level increases in the nearshore region are assumed to be uniform. The Boussinesq model provides a wave-by-wave description of a given sea state at the prescribed time and simulates the surf-zone processes and runup along the coastline of the nearshore region

Cowell & Zeng (2003) presented a GIS-based model that integrates a random simulation, and fuzzy set theory for predicting geomorphic hazards subject to uncertainty. Coastal hazards are modeled as the combined effects of sea-level induced recession and storm erosion, using grid modeling techniques. The principal aim of this technique is to reshape the DEM of the coast. With this information, it is then possible to calculate the continuous shoreline-change along the coast, together with associated the coastal hazard contours. This was one of the first attempts to include coastal response in the FHM.

Bradbrook K. (2006) developed a multiscale 2D dynamic flood model, known as JFLOW. The model is based on a 2D diffusion wave equation. The two underlying principles are: Mass conservation within each cell and calculation of the fluxes between the cells. The basic characteristics of the model are: the methodology is a raster-based approach, driven by an underlying DEM; each cell has a specific ground level and water depth; Water can move to surrounding cells where the water level is lower; Water will pond in low spots until the water level is high enough to spill; And the velocity of movement depends on the water surface slope and surface roughness.

2.3 The Feedback Experience

To achieve more accurate results, the researchers merged more precise techniques, and used mathematical models in conjunction with GIS. As an example there is the work of Webster *et al.,* (2004) which from a DEM derived from LIDAR data, and with data from storm-surge water levels, represented the possible scenarios of flooding under rising sea levels. The modeling of the flooding was conducted in a GIS. The flood modeling was done on the LIDAR ground surface DEM. The flood limit for each water level was captured as a vector boundary. These vectors were used to select only polygons that were contiguous with and open to flooding from the harbour. In Spain J. Benavente, *et al.,* (2006) presented an evaluation of storm flooding hazard in Valdelagrana spit and marshes (SW Spain) using GIS and numerical models. After calculating theoretical storm surge elevation, a DEM was made by adjusting topographic data to field work and detailed geomorphological analysis. The resulting height of water surface rise along the beach was added to the height of local zero level. Lines of flooding extent for each storm were obtained by superimposing the previously created DEM and the sea level rise results.

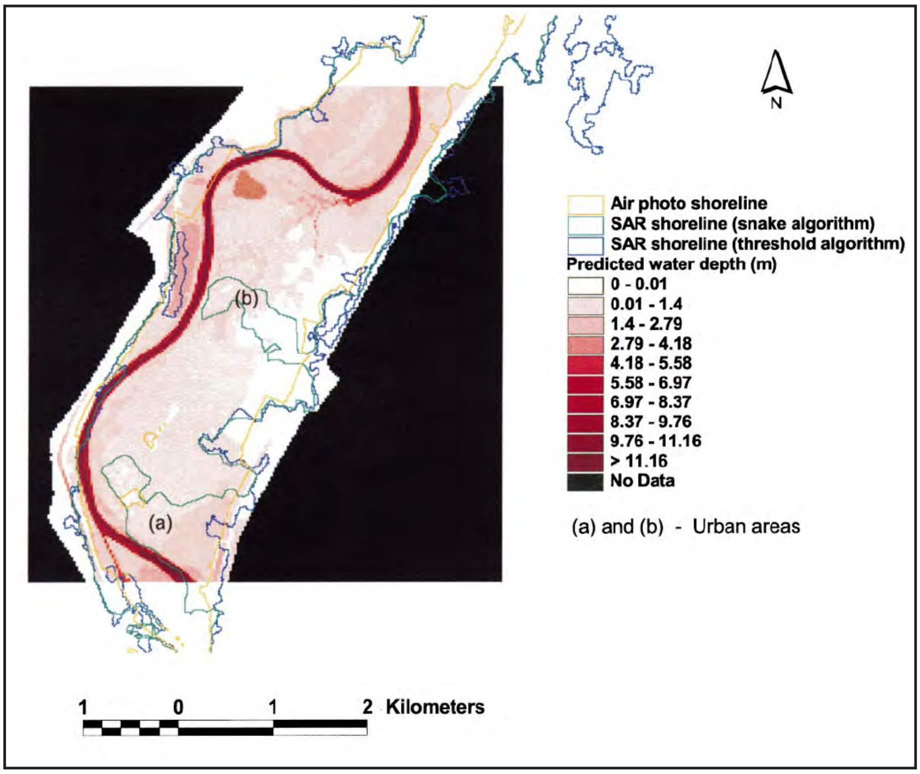


Figure 2.2 Comparison between water depths predicted and SAR,
by Bates and de Roo (2000)

Others examples of combining GIS and numerical models are the work of Colby *et al.,*(2000) where they implemented a hydraulic extension program called HECGeoRas3.0 (USACE, 2000) within ArcView 3.2 GIS software (ESRI, 1999). They used the water levels from the model, the DEM data considered a stillwater inundation level. The other example is the work of Bates & De Roo (2000) where they applied the LISFLOOD model (which had been used in rivers) to calculate flooding in the coastal area. Air photo and Synthetic Aperture Radar (SAR) data for flood inundation extent are available to enable rigorous validation of the developed model. It is important to emphasize the combination of the mathematical model with a DEM, and then its use in a GIS (figure 2.2). Working in a similar way, Hunter *et al.,* (2005) worked with storage cell codes to simulate flow on fluvial and coastal floodplains. These models consider the floodplain as a series of discrete storage cells, with the flow between cells calculated explicitly using some analytical flow formulae such as the Manning equation.

Based on previous works,in this study we propose a modeling coastal flooding methodology, which is driven with GIS. It uses a raster-type approach at the time of the flooding, and the changes caused by the waves on the beach (erosion, accretion). One should take into account that modeling of surge levels for low-lying coastal areas that are not, or insufficiently, protected by natural dunes or man-made dykes will only give realistic results if overland flooding is included. The possibility to combine the flooding data and information from the ground, landuse, and socioeconomic values provides a more detailed picture of the area of interest. It is then possible to generate flood and vulnerability maps.

3. Methodology

La méthode est nécessaire pour la recherche de la vérité.

Rene Descartes

3.1 General approach

With the aim of proposing a new approach to determine the flooding in the coastal area, the general methodology of Source-Pathway-Receptor (SPR) developed within the FLOOD*site* project was used as starting point and adapted to the specific characteristics of this work. Figure 3.1 shows the SPR approach applied to delineation of flood hazard areas in coastal sedimentary environments due to the impact of extreme events.

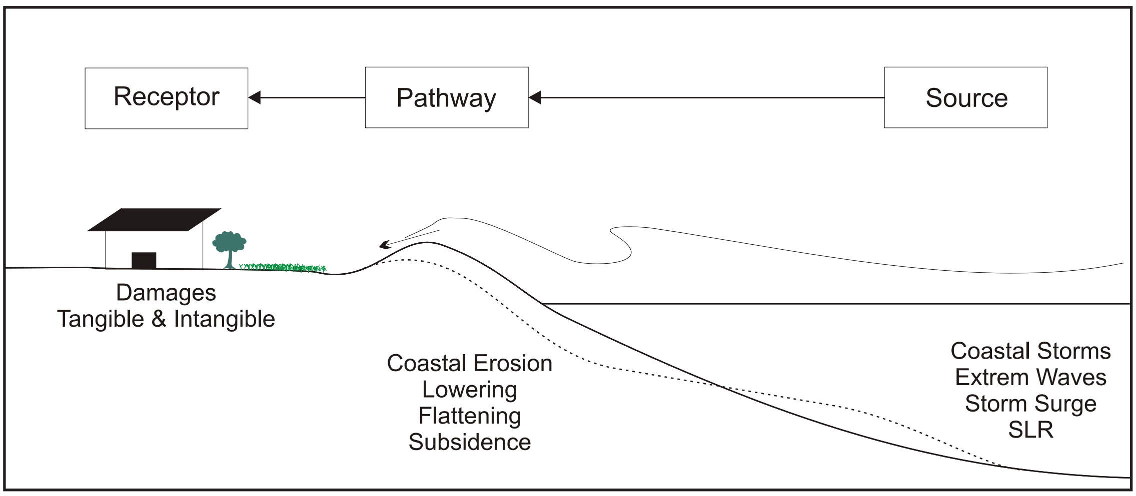


Figure 3.1. Source-Pathway-Receptor model for Coastal Flood Hazard Mapping
(From Jiménez *et al* 2008)

Sources refer to marine forcings inducing the flood event. In this work we have selected two flood risk sources, differentiated primarily by the scales of time and space that affect the coastal zone. The first one is associated to long-term processes which are given by RSLR and, the second one is associated to episodic/extreme events which are given by storm impacts. *Pathways* refer to processes leading to coastal flooding induced by agents such as: coastal erosion, lowering and flattening of the beach profile and finally the inundation. The characterization of the *Receptor* refers to the estimation of the flooding effects in the territory, the flood extent and valuation of vulnerability and damage.

In what follows the main techniques and methodologies used to constitute our working framework are described below. Figure 3.2 summarizes this in graphic form, also the stages and different approaches.

We propose a methodological approach for FHM and the determination of the vulnerability associated with flooding at two scales: long term events (SLR) and episodic/extreme events. In order to fit the SPR scheme, first the maximum flood level has to be determined (stillwater in the case of SLR, or runup and overtopping in case of extreme events), which will gives the Sources. Then the Pathways have to be defined and also the working methodology described. The final step identifies the flood zones and their association with vulnerability values (the Receptor).

In the first place we describe, the methodology associated with the Long-term processes (SLR), their importance and the working strategy in this study. In the second place, we address the proposed methodology for extreme or episodic events.

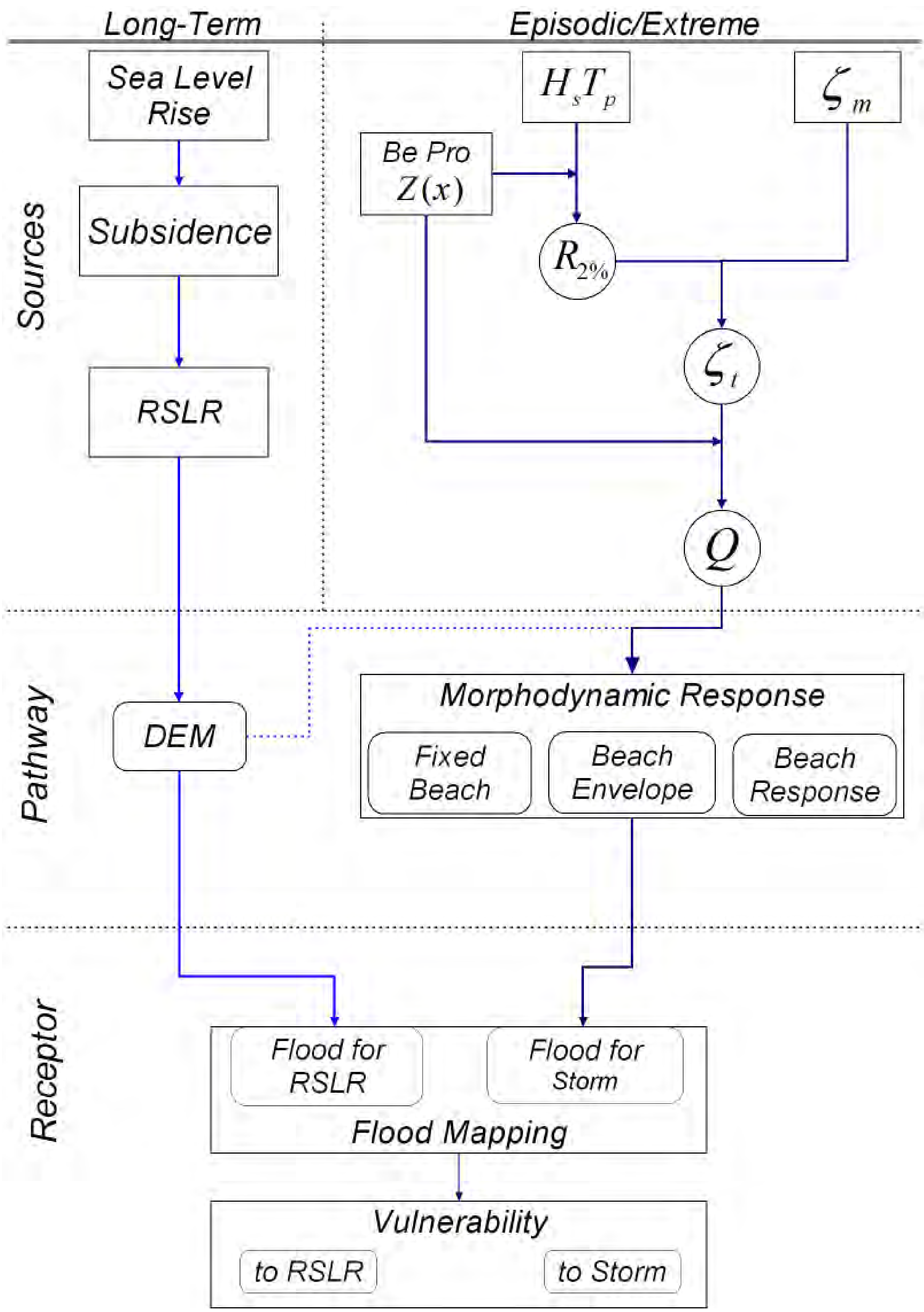


Figure 3.2.Methodological Approach to assess vulnerability and mapping to storms

3.2 Sea Level Rise (Long-Term Events)

Processes acting at the long-term scale will have important implications for a low-lying coastal environment, especially in a scenario of rising sea level because the only way to avoid direct inundation by the sea is the vertical accretion of the coast.

To give an idea of the potential vulnerability to RSLR, we reproduce three scenarios of SLR to determine the areas potentially prone to be inundated, taking into account the role of hinterland structures -such as levees, dikes and roads- in preventing flooding in impounded areas.

Source

SLR projections for the next 100 years are based on different computer simulations of the atmosphere and ocean for a range of emission scenarios. The projections of climates and sea-level rises changes are made using computer models of the Earth's climate. These Global Climate Models also known as 'Global Circulation Models' or 'Atmosphere–Ocean Global Circulation Models' (AOGCMs), simulate the effect on the atmosphere and oceans of different possible future scenarios of greenhouse gas emissions. A range of future scenarios are used because we do not know exactly how human-induced greenhouse gas emissions will vary over the coming century, and therefore we cannot define exactly how the emissions will translate into climate changes and sea-level rise. Mainly because of this uncertain projections of changes in temperature, sea-level rise, etc, are presented as ranges, rather than a single value. A more detailed summary of global projections of future climate change can again be found in the IPCC 'Summary for Policymakers' and in the full Working Group I report. IPCC 2007a, 2007c.

Although eustatic sea level is presently rising only a few millimetres per year, this condition has widespread influences on physical and ecological processes on coasts (IPCC 2007). The rate of SLR determines how quickly areas will be inundated according to their slope, the rate at which wetlands, such as salt marshes, must accrete vertically to maintain their surpratidal and intertidal extent, the rate of erosion and shoreline recession, and the rate of sand exchange between the beach and the nearshore.

Sea level is a function of the ocean surface, which is controlled by: the volume of ocean water, the volume of the ocean basins, and the distribution of the water, and the land surface, which is affected by crustal deformation and sediment compaction. The two primary factors dictating the present rate of SLR are thermal expansion due to heat uptake by ocean surface waters and water input caused by the transfer of water from the land to the oceans (IPCC 2007).

The IPCC (2007) estimates that sea level will rise from 0.18 to 0.59 m relative to the 1980-1999 position by the end of this century. This range is based on different Atmospheric-Ocean Global Circulation Models using various warming scenarios (Meehl, *et al.,* 2007). Based on this estimates and with the average of subsidence for the Delta Ebro (1.5 mm/y) (Somoza *et al.,* 1998) we propose three scenarios of sea level rise (Lower, Medium and Higher) for this work (table 3.1). Ibáñez *et al*., 1997 estimated subsidence rates and SLR for that area resulting in a RSLR between 3 and 7 mm per year, as our scenarios contemplate.

Table 3.1. Scenarios of RSLR to 100 years (to 2100)

	Lower (m)	Medium (m)	Higher (m)
SLR(IPCC)	0.18	0.38	0.59
Subsidence	0.15	0.15	0.15
Total RSLR	0.33	0.53	0.74

Pathway

In this scale the flooding of the coastal area is determined considering a still sea-level rise. This is allowing that the study area has an active fraction represented by the beach area (consisting mainly of sand). This fraction is considered to react in a proactive manner. This reaction is based on the concept of an equilibrium beach profile which is a statistical average profile that maintains its form apart from small fluctuations including seasonal effects (figure 3.2) this is also known as the Bruun´s rule (Bruun 1962). Also we have a passive fraction of the study area (represented in this case by crop fields and nearby areas) that are flooded, for being below sea level and have a direct connection to the sea.

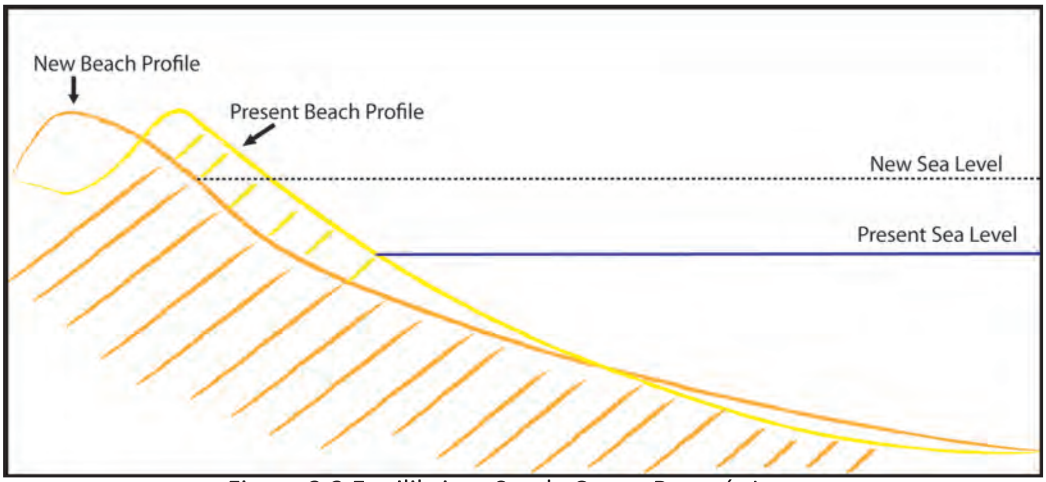


Figure 3.3 Equilibrium Sandy Coast. Bruun´s Law.

A Digital Elevation Model (DEM) (which is used as a benchmark for the rest of this work) is employed to determine the changes in the coastal and littoral zones due to rising sea levels

Elevation data used in this work are based on a DEM derived from LIDAR data obtained by the Institut Cartogràfic de Catalunya. The LIDAR is a laser altimeter that measures the range, from a platform with a position and altitude determined from GPS and an inertial measurement unit (IMU). Essentially, they utilize a scanning device which determines the distance from the sensor to the ground, of a series of points roughly perpendicular to the flight direction. A terrestrial DEM and intensity image were generated from the LIDAR data. The data used in this study were acquired in 2004 and has a spatial resolution of 1 m and a vertical accuracy of 15 cm. The sensor used was a laser Optech ALTM 3025 (Airborne Laser Terrain Mapper), operating at the infrared wavelength of 1064 nm; hence, it does not penetrate the water surface.

To simulate the delta inundation at a reasonable computational cost, the DEM was aggregated to 5 m resolution. This size was selected after testing the effects of the cell size in masking the effects of the presence of canals and small dikes separating rice pads.

The study area in figure 3.4 is a very low-lying region with a maximum elevation above MSL of about 4 m. Table 3.2 shows the percentage of the delta surface below given elevations. These data clearly show that the system is potentially highly vulnerable to floods since about 49 % is below an elevation of +0.5 m.

Table 3.2. Distribution of deltaic surface per elevations.

Elevation	Surface	
(m ab MSL)	(ha)	(%)
< 0.5	16,296	49.09
0.5-1.0	7,539	22.71
1.0-2.0	5,968	17.98
2.0-3.0	2,495	7.52
3.0-4.0	754	2.27
> 4.0	141	0.42

From DEM data and with the help of the methodology described in Martin (1993) and using IDRISI software (Geographic Analysis) from Clark Labs we generated the maps for the flood scenarios for RSLR. The methodology for determine the flooded area, use the DEM data in a raster image, Martin propose create first two Boolean images, one showing the actual situation, and other with predicted flooded scenario. Then through overlay subtraction of these two images, be left with the area flooded by the SLR scenario. Sometimes there are some areas in the results that are identified to be under sea level, but are physically separated from the ocean. These are areas that lie below the predicted sea level, yet because of the surrounding topography, the rising ocean water will not be able to reach them. In fact, only the areas connected to the original water source will be flooded. Therefore, it is necessary to determine the existence of connectivity between these areas and the sea, to exclude those areas that have no direct communication. To do that we consider an aggregation of the areas based on their identifier and a common boundary. Further filtering was applied to smooth the edges of the flooded areas. The filter used was a maximum filter, where the output value correspond to the maximum of the kernel set, in this case 7 x 7 pixels.

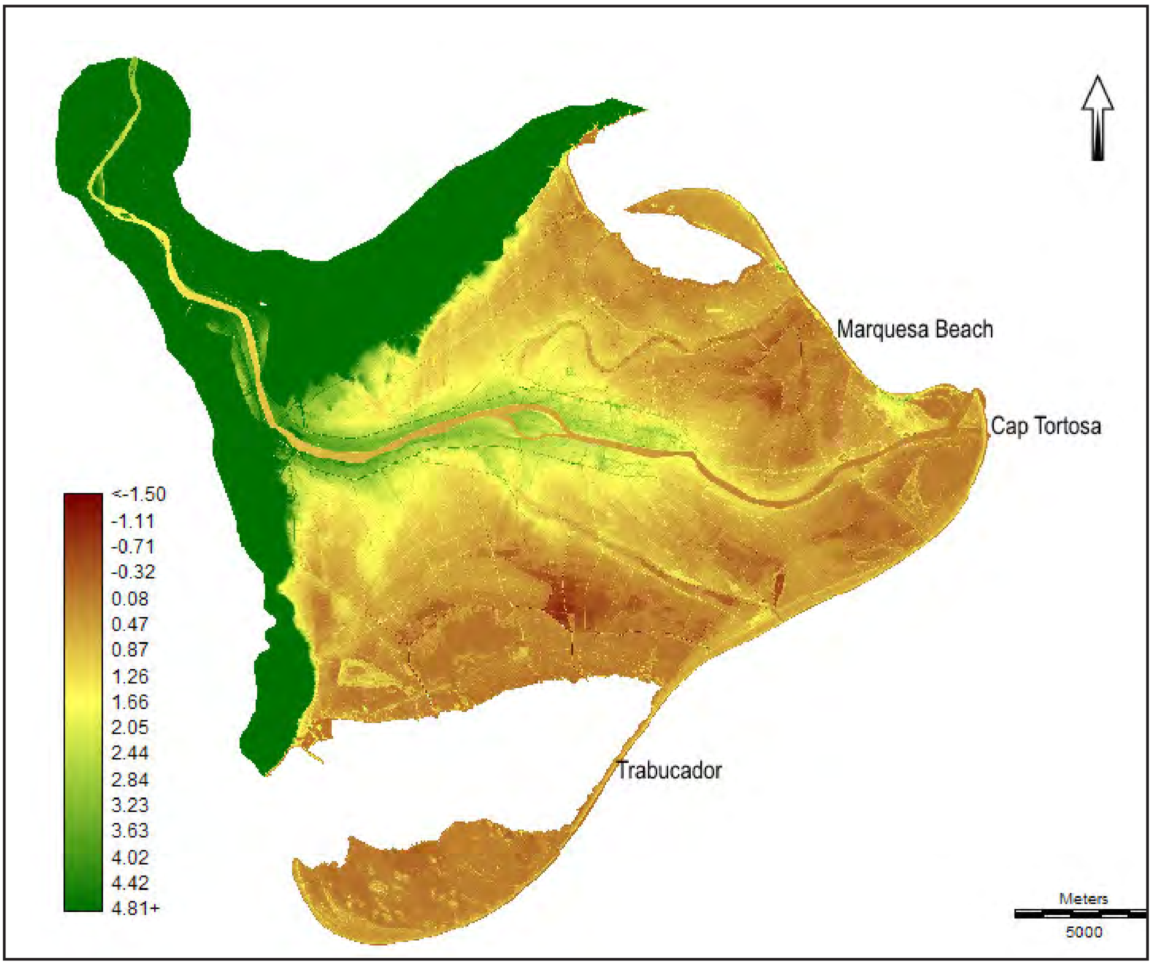


Figure 3.4 Digital elevation model for the study area.

Receptor

The maps of the previous step were used in combination with the data of the area (habitats, values, etc), to assess the vulnerability of the coastal zone to RSLR as well as the potential economic losses for ecological services.

To combine the data, we use a geographic tool, called regionalization, which is defined as the drawing of geographic boundaries in consideration of common elements,either economic, social, cultural, geographical, administrative and/or political. The regionalization of a territory is a framework for decisions that promote the country's development within the planning process. For this work, and considering the scale of it, a habitat map was used to regionalize the Delta (from the habitats map generated by the ICC, which includes the urban area) (figure 3.5).

Figure 3.5. Delta Ebro habitats

The Ebro Delta presents eight habitats distributed in 31,066 hectares where the most part correspond to cropland that encompasses rice-crops and another irrigated crops.

To find out which habitats will be affected in the different scenarios of flooding, we carried out an overlap between the maps of habitats with the information concerning the flooding. This is accomplished with the help of GIS. With these, we will know the degree of impact on the area and the percentages of affected habitats.

3.3 Episodic/Extreme

In the case of episodic or extreme events, the process is somewhat more complex, as it is necessary, to determine first what we consider extreme events and their return period. Then it is possible to determine the other components (runup, overtopping) and the response of the coast. After this we can determine the area impacted by the flooding, the level of impact or effect that allows the subsequent calculation of vulnerability, and finally map everything together. Next, we use the previous scheme (SPR) to describe the general methodology and each of the processes involved.

Source

The first step consists in the estimation of a total water level at the shoreline. The total water level at the shoreline corresponds to the sum of the sea-level, astronomical tides, storm surge and wave runup. This is done by using the response-method approach, which is based on measured or simulated water levels and waves as they occur in nature. The water level of interest (associated to a given probability or return period) is directly calculated from a probability distribution of total water levels.

In order to calculate the water levels and since our methodology is proposed for a coast without any protection but natural beaches, the runup model proposed by Stockdon *et al* (2006) has been selected. The runup ($R_{2\%}$) is calculated for each beach profile scenario (according to each beach profile definition method, see below), and wave climate of T_R (10, 50, 100 years and extreme). The differences in runup magnitude are controlled by the use of a different beach slope since wave conditions are the same in all the cases. Obtained runup values are then added to simultaneous water level data (ζ_m) to build up the total water level time series (ζ_t).

Total water level data are then fitted to an extreme distribution to estimate the water level associated to given probabilities or return periods.

Once the target total water level has been estimated, the next step is to calculate overtopping rates (*Q*) for those cases where the runup exceeds the beach/barrier crest. This will determine the volume of floodwater penetrating to the hinterland and, in consequence, determining the extension of the flood hazard area. The overtopping volume has been calculated following the method used by FEMA (2003) to estimate the inundation in low-lying coasts. The following describes in detail the formulas used in this part of the methodology.

The Data

The first step consists in the selection of the data available in the study area, and the construction of a wave time series for the statistical analysis of extremes values. In the area near our study zone there are no long records of waves or wind data, only 20 years long buoy measurement. For this reason we consider using the HIPOCAS database (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe) which is a 44 years hindcast of winds, waves and sea levels (Guedes-Soares *et al.,* 2002). In previous studies (Mendoza 2008) it was observed that in case of storms or large events HIPOCAS data tend to increase the values, especially in the case of the wave height. Because of this, in this work an adjustment of the maximum annual data from HIPOCAS was made.

HIPOCAS data ranges from 1957 to 2001, so we added information from the buoy located in Cap Tortosa (1990 to 2007) that is part of the XIOM net from the Generalitat de Catalunya. To merge both types of data a calibration of the HIPOCAS data using a least squares linear regression between the overlapping years (1990-2001) was performed, with HIPOCAS value as the independent variable, (that was done for the maximum annual storm conditions, wave height, and wave period)(Figure 3.6).

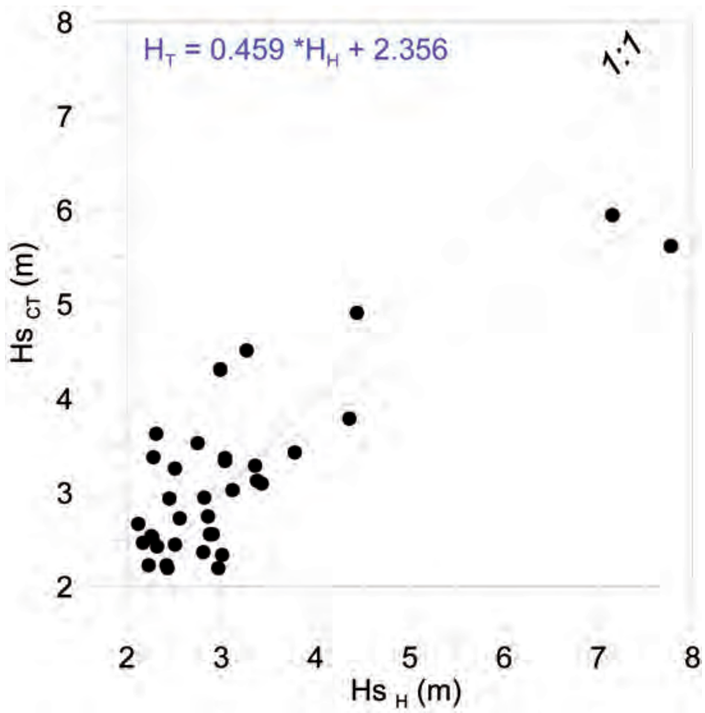


Figure 3.6 Calibration of Annual Storms. HIPOCAS and data from Cap Tortosa Buoy. Jiménez et al (2009)

Statistical Analysis

The combination of extreme wave and storm surge is normally associated with extreme events in the coast, severe coastal erosion or overtopping. The assignment of frequencies to flood levels in the coastal environment is difficult because flooding is the result of the interaction of a number of complex processes. These processes include, for example, astronomic tide, storm generated sea and swell, wind and pressure setup, wave setup, wave runup, overtopping, relative sea level change, beach erosion, tsunamis, and rainfall contribution. Many of these components may be significant in a particular study, and must be considered not only separately but also altogether since interdependencies may be statistically critical and the combined effects may include both linear and non linear interactions. The statistics of the several processes by joint probabilities could be problematic. (Divoky & McDougal 2006).

There are two general approaches for addressing this type of problem: an event based analysis and a response-based analysis.

Traditionally, coast flooding risk has been defined using an event based approach by which major storms are identified and extreme values analysis are applied to derive the probabilities of extreme storm wave events. Subsequently these have to be combined with similar extreme events of astronomic tide and storm surge levels using joint probabilities to derive the extremes of potential flood elevations. The traditional methodology for calculating extreme values is carried out through a probabilistic analysis which seeks joint probability or a combination of extreme events; this implies a simplification and a degree of subjectivity in the definition of the joint events. (Fassardi, 2006)

For this work we proposed the use of *response approach*, in which one does not just look at one or a small number of disturbances, but instead examines a very long flood record at the site, either observed or simulated, and from that determines the 1% response by direct frequency analysis of the final water levels. Since the total flood water level is not generally available from observations, this approach will usually require simulations of the flooding mechanisms. The star point could be, for example, the local storm history. (Divoky & McDougal 2006).

This methodology is based on the direct measurement of waves, wind, or the phenomenon to be studied, considering it as a final process, and minimizing the statistics associated with its components. Considering that the physics and statistics of the components of the event are implicit in the observer data. This is a data-intensive method requiring approximately 30 year of reliable and continuous records for all the processes contributing to the final flood hazard. Thirty years is a common rule of thumb for an extreme value analysis aimed at determinating the 100 year return period conditions. (Divoky & McDougal 2006).

In the absence of measured data, site-specific long-term shallow water hindcast satisfy the need for data and provide adequate input for the computation of corresponding long-term Total Water Levels (TWL) time histories from which extreme levels can be computed.

Callaghan *et al.,* (2008) describe a *Full Temporal Simulation* (adapted from the work of Hawkes *et al.,* 2002). These simulations estimate the extreme values of beach erosion from simulated wave climate. We have used a modified model based on this work to determine the values of wave climate and overtopping.

Wave hindcast at the location of interest is used as input to a wave runup model to derive the corresponding long-term history. The wave runup is added to measure or predict still water level to obtain the TWL time history. Finally, an extreme value analysis is performed to compute for instance the 1% annual extreme TWL (100 years return period)

A response based approach, offers the main advantage of an assumption concerning the joint probabilities of the astronomical tide, storm surge, swells and seas setup/runup that do not need to be addressed since the risk of coastal inundation can be determined from the analysis of the long-term TWL (the response) that result from the combination of these processes. In many ways, this is a more objective approach since any joint probability assumptions of events and simplifications do not have to be made.

The computed long-term TWL histories represent the response to the various processes that concurrently occur in nature. It allows for the computation of more realistic risk levels as opposed to a less realistic determination of risk based on the joint probabilities of the individual events that compose the response. Furthermore, a response based approach allows addressing the effect of duration on erosion and overtopping of protective structures during high TWL events (Fassardi, 2006)

For the two cases (event and response) a statistical analysis of extremes was conducted. In this analysis, we fit candidate probability distributions to an array of extreme significant. The candidate distribution functions are Fisher-Tippett Type I and Weibull with exponents ranging from 0.75 to 2.0. The analysis was performed with the help of software ACES developed by CEDAS based in Goda 1988.

Runup

The most relevant induced process in coastal flooding studies is the runup. After a wave breaks, a portion of the remaining energy will energize a bore that will run up the face of a beach or sloped shore structure. The wave runup refers to the maximum vertical height above the stillwater elevation (tide and surge) on which the water rises on the beach or structure (Sorensen, 1997). (figure 3.7)

Runup is a very complex phenomenon, that is known to depend on the local water level (including surf beat or infragravity wave effects), the incident wave conditions (height, period, steepness, direction), and the nature of the beach or structure being run up (e.g., slope, reflectivity, height, permeability, roughness). The problem for their calculation is that so far there is a law unique and comprehensive covering all possible situations, so the calculation should be carried out from proposed solutions to achieve specific approaches to the problem of different combinations studied (FEMA 2005).

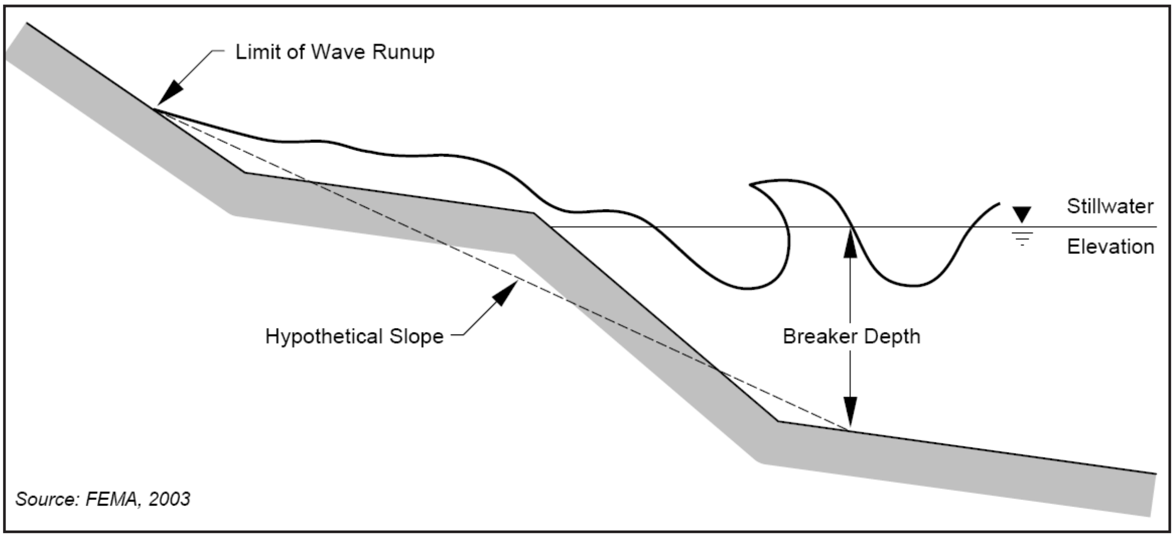


Figure 3.7. Runup (FEMA, 2003)

Due to the importance of the runup a lot of research has focused to perform measurements and analysis of data to identify its dependence on the conditions of waves or the morphology of the beach. At the same time, studies on the behavior of the runup on rigid structures of coastal protection (dikes, seawalls) are carried out, to establish criteria designs.

In the case of beaches, the number of studies and analysis is lower in comparison to the studies made in structures. So the existence of formulations or estimation methods are limited mainly to semi-empirical approaches based on results of laboratory tests, so their results applied to actual conditions should be regarded with caution, even though they may be used to estimate the order of magnitude of the process. Some results of these studies are equations that can obtain the value of the runup from the incident height wave or the Iribarren number. (Guza and Thornton 1982; Holman and Bowen, 1984; Howd *et al*.,1991; Raubenheimer and Guza 1996)

Stockdon and collaborators in 2006 proposed a new formulation that may be considered one of the most precise. Based on previous studies on runup and swash, which includes both wave-induced setup and swash (some of the studies work only with one at one time) and a greatest amount of field data analyzed combined with an analysis of empirical parameterizations.

This methodology was developed from statistical adjustments to a big set data of field data, which allows their use in different types of beaches and slopes. So, the calibrations are not necessary for each case as in other formulations (FEMA as example). The methodology of Stockdon *et al*., 2006, is based on the wave height (H_0), wavelength deepwater (L_0), period (T) and the slope of the beach (β_f). To calculate the runup Stockdon proposes:

$$R_2 = 1.1\left(0.35\beta_f (H_0 L_0)^{1/2} + \frac{\left[H_0 L_0 (0.563\beta_f^2 + 0.004)\right]^{1/2}}{2}\right)$$

and

$$R_2 = 0.043(H_0 L_0)^{1/2} \text{ if } \xi_0 < 0.3$$

Where ξ_0 is the Iribarren number so when ξ_0 (ξ_0 < 0.3) is small means 'very dissipative' beaches, and in the opposite case means a 'reflective' beaches.

Overtopping

Wave overtopping occurs when the barrier crest height is lower than the potential runup level (figure 3.8). Waves will flow or splash over the barrier crest, typically to an elevation less than the potential runup elevation (*R*). The exact overtopping water surface and overtopping rate will depend on the incident water level and wave conditions and on the barrier geometry and roughness characteristics. Moreover, overtopping rates can vary over several orders of magnitude, with only subtle changes in hydraulic and barrier characteristics, and are difficult to predict accurately.

Under random wave attack, overtopping discharges can change in several orders of magnitude from one wave to another, meaning that wave overtopping is a non-linear function of wave height and wave period. This time variation is difficult to measure and quantify in the laboratory and therefore overtopping discharges are most often given in terms of average discharge.

Due to the complexity of overtopping processes and the wide variety of structures over which overtopping can occur, wave overtopping is highly empirical and generally based on laboratory experimental results and on relatively few field investigations.

The wave overtopping on beaches and dunes is important because it helps in the calculation and prediction of sediment overwash, but has not been well studied. Most of these formulations have been developed for laboratory conditions where uniform slopes were used. On natural beaches, the profile is more complex and thus an appropriate equivalent slope for use in those predictive formulae is not straightforward. Different slope definitions can lead to substantial differences in overtopping estimates.

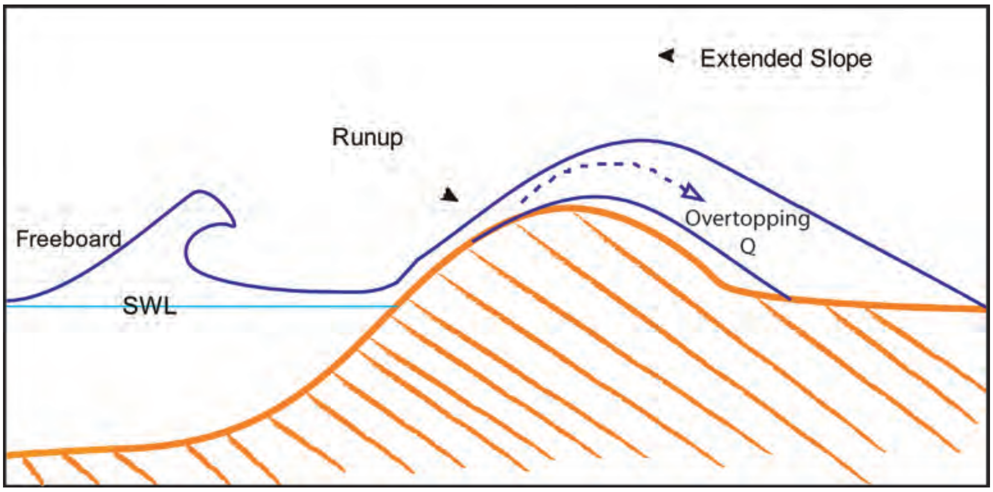


Figure 3.8. Overtopping

Overtopping guidance of FEMA (2003) is based largely on the work of Owen (1980) and Goda (1985). This formulation does not call for overtopping calculations in all instances. Instead it first calls for a comparison of the freeboard, F (the vertical distance between the base flood stillwater elevation and the crest elevation), and the mean runup height, *R. If F > 2 R*, then the guidance assumes that overtopping can be neglected. *If F < 2 R*, then the mean overtopping rate *Q* for a nonvertical slope is calculated according to:

$$Q = Q^* \left(\overline{gH_s^3}\right)^{0.5}$$

$$Q^* = 8 \bullet 10^{-5} \exp\left[3.1\left(rR^* - \frac{F}{H_s}\right)\right]$$

$$R^* = \left[\frac{1.5m}{\left(H_s / L_{op}\right)^{0.5}}\right]$$

where:

Q = dimensionless overtopping,*

R = estimated extreme runup normalized by*

r = the roughness coefficient,

F = freeboard,

Hs = incident significant wave height at toe of overtopped barrier,

g = gravitational constant,

m = the cotangent of the slope angle of the overtopped barrier, and

Lop = deepwater wavelength.

While this approach does not account explicitly for highly variable peak overtopping rates and does not offer a complete specification of overtopping hazards, its use is the best option for overtopping rate calculation. We decided work with FEMA formulation because it has been specified for unprotected areas or beaches, and tested in a high number of cases.

Pathways

Coastal Response

The impact of a storm on a beach is dependent not only of the storm magnitude of forced parameters, such as storm surge, waves and wave runup, but also dependent upon the geometry, particularly the vertical dimension, of the beach face.

In coastal sedimentary environments, the impact of the storm will induce a significant coastal response that will interact with the storm in such a way that the intensity of the flooding could be affected (enhancing or reducing).

Several physical factors can influence the type and magnitude of storm impacts. Those factors include the alongshore variability of storm processes geographic location relative to the storm center, prior storm history duration of beach inundation by waves, high wind speeds, flow regime of washover currents, morphology and elevations of the ground surface, grain sizes of the transported material, density of the vegetative cover, and human modification. Only a few of these variables are totally independent and several of them are closely linked such as pre-existing topography and washover flow regime (Morton 2002).

Morphological changes on beaches and barriers during storms are controlled primarily by the differences in elevations between the wave runup and adjacent land surface, and duration of backbeach flooding. These factors largely determine the coastal response (Morton 2002)

The induced change in beach morphology, i.e. beach lowering (decrease in the beach or dune height) and profile flattening (decrease in the beach slope) will affect the magnitude of the inundation in opposite terms when they are separately considered (see e.g. Jiménez *et al*., 2006). Thus, beach lowering will tend to increase the water discharge towards the hinterland because for a given water level the lowering of the beach/dune height will increase the freeboard. On the other hand, profile flattening will tend to reduce inundation because for given wave characteristics during the induced runup will decrease due to the decrease in beach slope. The dominant effect (inundation increase or decrease) will depend on the type and magnitude of beach changes during the storm. Under these conditions, not only the flooding is relevant for the manager but also the storm-induced response due to its intrinsic associated damage (coastal erosion hazard) and its potential synergic effect with coastal flooding.

As a practical consideration, forecast made as a storm approach the coast would be based upon the pre storm coastal geometry yet, in reality, the geometry can change during a storm which could in turn change the impact level. Hence, forecasts would be relevant to the initial impact of a storm, when geometry has not changed appreciably, and are valid as the storm progress does not change the geometry of the beach

A critical issue to map coastal areas prone to be inundated during storms is how to properly characterize the beach configuration. Beach configuration takes part in the process by controlling the magnitude of the runup (via beach slope) and, by controlling the overtopping (via beach/dune crest height). Thus, in contrary to the quasi-static case of dikes, beaches are continuously reacting to coastal dynamics and, especially during the impact of storms, they are significantly modified. This means that to properly map coastal flood hazard areas beach dynamics have to be incorporated to the analysis.

As part of this work, we have tested three different approaches to define the beach configuration during the storm impact on the inundation of the hinterland already outlined in Alvarado-Aguilar and Jiménez (2007).

The first approach uses a fixed beach profile. This should be equivalent to the case in which the only data available should be a pre-storm coastal configuration (taken at any moment and not necessarily just before the impact). This beach morphology is used throughout the analysis and this means that runup will be controlled by the corresponding beach slope and the overtopping by the beach/dune crest which are maintained fixed during the storm duration. This type of the approach is equivalent to consider the beach as fixed protecting structure. Figure 3.9

The second approach *Beach Envelope* introduces some information on the natural beach variability. In essence in this approach the beach is characterized by an envelope of the possible configurations instead of a single value. It can only be used when information about past beach morphologies are available. Thus, for each representative transect along

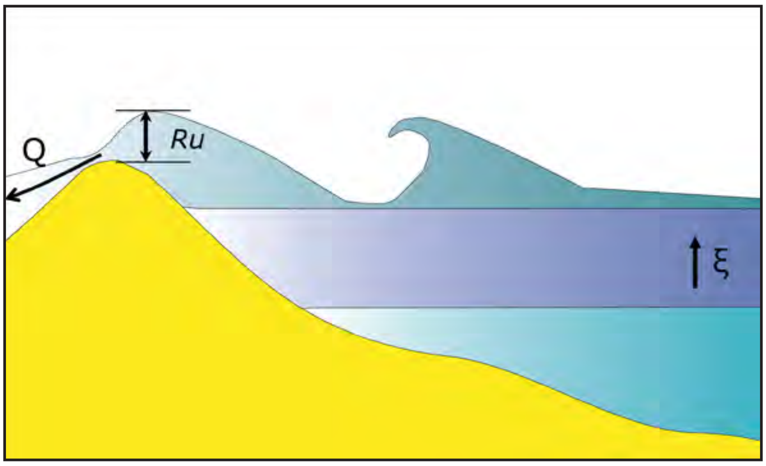


Figure 3.9. The beach is considered as a fixed protecting structure.

the coast, the morphology is represented by the envelope of all the existing data (ideally covering a period of several climatic periods and, thus, showing the natural changes in the beach morphology to wave action). This will permit to estimate all the relevant variables (runup and overtopping) for the different configurations - bounded by the maximum and minimum profiles –. This should be equivalent to add some kind of confidence band to the calculated floodwater and, in consequence, to the potentially flooded surface.

Figure 3.10 shows an example of beach profile envelope used in this study obtained from 4 years of beach profile data where a significant variation in the beach configuration is observed.

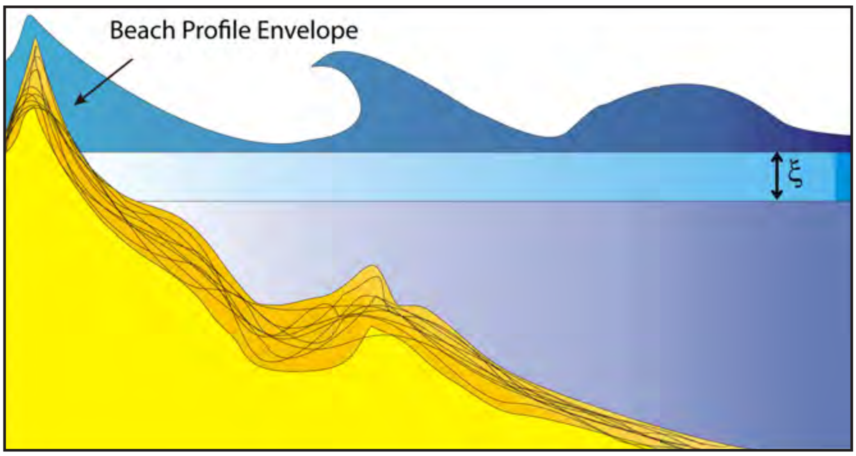


Figure 3.10. Envelope of beach profiles taken during a 4 years period in the Northern part of the Ebro delta.

In the table 3.3, we compare the key figures (height and slope of the beach) of these two approaches, and a difference can be seen when choosing between one approach or another. The variations may seem imperceptible, but the end results can vary widely

Table 3.3. Basic magnitudes on the initial approaches

	Beach Height (m)	Beach Tanβ
Static Beach	1.14	0.024
Beach Envelope	0.69 – 1.59	0.022 – 0.027

The third approach called *Beach Response* consists in simulating the beach profile response during the storm action recovering all the intermediate configurations from the pre-storm situation to the post-storm one. These intermediate configurations will permit to update the wave-induced runup and overtopping rates according to the time-dependent beach slope and crest height.

Beach profile evolution during the storm has been calculated by using the SBEACH modeling system developed by the United States Army Corps of Engineers Coastal Engineering Research Center (Larson and Kraus 1989). This model provides a semiempirical approach to determine time dependent cross-shore sediment transport processes for an arbitrary beach profile. SBEACH has been verified against a variety of physical model and field data and has been used extensively worldwide in planning studies and design of beach nourishment projects. This model has been previously used to simulate the dune lowering before the inundation of the hinterland during the impact of extreme storms (see e.g. Cañizares and Irish, 2008). The model simulates the beach profile response due to storm wave action by assuming sediment transport is due to cross-shore processes only.

An example of the application of the model to simulate beach profile changes is shown in figure 3.11. As it can be seen, if the beach evolution during the storm is incorporated, there is a significant difference in beach morphology –a decrease in beach height of about 1 m. If this knowledge is incorporated to the flood mapping, results significantly vary with respect to those obtained for the initial configuration.

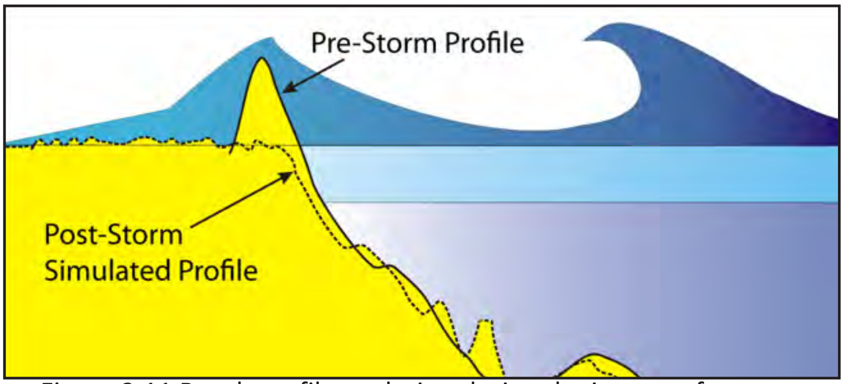


Figure 3.11 Beach profile evolution during the impact of a storm simulated by using Sbeach.

Receptor

The last steps in this methodology include first, to determine the area that could potentially be flooded due to the volume of overtopping, and second, once this is achieved the calculation of the values of vulnerability or impact on the area, besides the generation of maps

Inundation

Once water levels and the changes on beach configurations are known, the next step is to determine which part of the coastal plain is flooded.

To calculate the potential flood zone we used the LISFLOOD-FP inundation model (Bates and de Roo, 2000). This is a raster grid based model that has been successfully employed to simulate the inundation in fluvial and coastal areas (see e.g. Bates and De Roo, 2000; Bates *et al*., 2005). The model predicts water depths in each grid cell at each time step, and therefore can simulate the dynamic propagation of flood waves over fluvial, coastal and estuarine floodplains. In our analysis we specify the data input as a time series of water flow at the shoreline bordering the deltaic plain (calculated through the overtopping rates).

LISFLOOD-FP was originally developed by Bates and De Roo (2000). It is a coupled 1D/2D hydraulic model based on a raster grid. Where the flooding is modeled using a volume-filing process based on hydraulics principles and physical notions of mass conservation and hydraulic connectivity.

LISFLOOD-FP treat floodplain flows using a storage cell approach first developed by Cunge *et al*., (1980) and implemented for a raster grid to allow an approximation to a 2D diffusive wave and a momentum equation for each direction where flow between cells is calculated according to Manning's law, which can be described in terms of continuity and momentum equations as:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

$$S_0 - \frac{n^2 P^{4/3} Q^2}{A^{10/3}} - \left[\frac{\partial h}{\partial x}\right] = 0$$

where Q is the volumetric flow rate in the channel, A the cross sectional area of the flow, q the flow into the channel from other sources (i.e. from the floodplain), S_0 the down-slope of the bed, *n* the Manning's coefficient of friction, *P* the wetted perimeter of the flow, and *h* the flow depth.

As shown in figure 3.12, when bankfull depth is exceeded, water is transferred from the channel to the overlying floodplain grid. The model assumes that the flow between two cells is simply a function of the free surface height difference between those cells. The flow depth, (h_{flow},) represents the depth through which water can flow between two cells, and is defined as the difference between the highest water free surface in the two cells and the highest bed elevation.

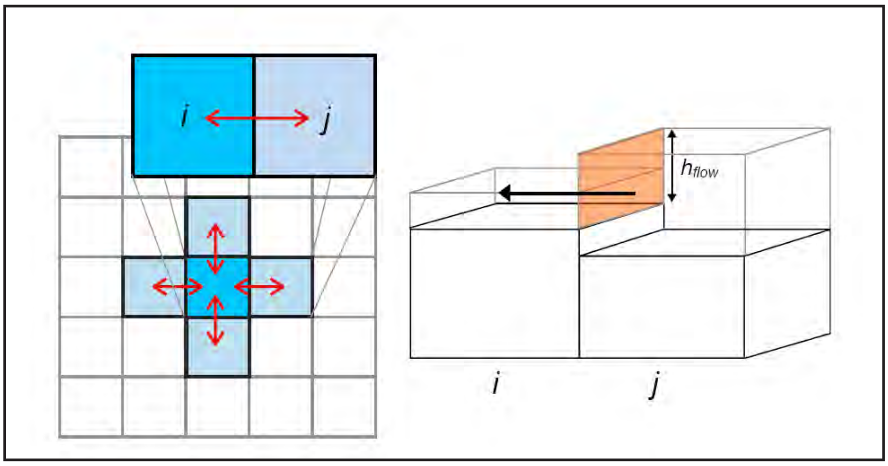


Figure 3.12. Representation of flow between cells in LISFLOOD-FP. (From Bates 2005)

This model is considered computationally simple, and although it may present problems in representing diffusive wave propagation, has been shown to give very similar results to a more accurate finite difference discretization models.

In order to represent overtopping or breach discharge correctly, a standard weir equation (British Standards Institute, 1981) was included in the model and if the breach development is known this is also relatively easy to include by varying the DEM topography with time. For more details on this model can be found on the vast literature produced by Bates and coworkers

The input data for the LISFLOOD-FP correspond to the values of overtopping a long the storm, and the DEM. Also it is necessary to determine the points of discharge and the time of the discharge, based on the DEM and in the data of runup and breach of the dune. The final result of the model is a group raster files that can be used and manipulated by GIS. In these files data about the flood extent, flood time and deep are collected.

Vulnerability and Damage Assessment

The vulnerability concept is central to the definition of a storm-related disaster, and acts as the conceptual bridge between changes in the external environment and the responses of the affected system. The nature of vulnerability only matters to the extent to which it produces insights that will help us to adapt to, or mitigate, external changes. Vulnerability concerns the susceptibility to substantial damage, disruption and casualties as a result of a hazardous event. The recent approach in terms of “coastal vulnerability” studies (since the 90s) is the main tool used nowadays to help managers to evaluate impacts of natural hazards on coastal zones.

The coastal vulnerability concept first appears in the International Panel on Climate Change works of 1992 (IPCC. 2001), where it is presented as essential for climate change adaptation. The use of aggregated vulnerability indicators (including geomorphology, hydrodynamics, climate change, etc.) is widespread (Boruff, *et al*., 2005). Those index-based methods propose a vulnerability mapping which visualizes indicators of erosion, submersion and/or socio-economic sensibility in coastal zones. This concept is a great tool for policy makers to help managing their action and taking into account climate change (McFadden, *et al*., 2006). However, in those approaches, vulnerability is the output itself (cost of effective impacts, geomorphologic impacts, etc.), but is not integrated it in risk analysis.

In order to make a Vulnerability assessment it is essential to make a systematic integration of factors such as topography, slopes, and morphological features, engineering characteristics of structures, and socioeconomic aspects and infrastructure facilities. The modern technique GIS, capable of assembling, storing, manipulating and displaying geographically referenced information can help us to integrate and value the vulnerability in the area of study.

Based on the previously discussed the first task for this study corresponded to the definition of events that could affect our study area and then the degree to which they affected the area. These events correspond to coastal storms induced responses, flooding and erosion. In table 3.4 we see the impact that it may cause our habitats.

Table 3.4. Degree of affectation to coastal storms (H=High, M=Medium, L=Low)

Habitat	*Erosion*	*Flood*
Beach & Dunes	H	L
Saltwater Wetlands	H	L
Saline vegetation	H	M / L
Riparian Buffer	L	M
Cropland	L	H

Once the events and their effect in the study area were defined, we observed that the erosion is the predominantly factor that can cause more high damage in habitats at the neighborhood. Where the main problem is the erosion of the shore, because in areas where the only protection is the beach itself, their loss have inherent risks for backbeach. While for the case of flooding, just the cropland could present high problems since being a habitat with a high degree of human intervention, has a low level of resilience that disables it to withstand flooding without damage.

Therefore, we focus first on determining the effects of erosion on the coast and then to assess the damage or impact of the floods on the backbeach, considering this two as the main coastal hazards in our area.

The evaluation of these costal hazards is a complicated task that requires reliable and quantifiable criteria to measure the changes occurring in the environment. Variables or criteria are a measure of the medium that allows us to estimate the extent of these effects. One way such criteria as it are structured through indicators. (Cendrero Uceda, 1997,).

Indicators are statistics or parameters that provide information and/or trends of environmental phenomena. A general indicator can be defined as a parameter or value derived from a number of parameters which gives information about a phenomenon. The indicator has a significance that goes beyond the properties directly associated with the parameter value (OECD, 1994 Gallopín, 1997; Kurtz *et al*., 2001).

Its significance goes beyond the same statistical information which aims to provide a measure of the effectiveness of environmental policies. The importance of the indicators is the need to provide decision makers and the general public a means by which information is presented concisely and scientifically based, so it can be easily understood and used. CoastView (2002) defines a coastal state indicator as: A reduced set of parameters that can simply, adequately and quantitatively describe the dynamic-state and evolutionary trends of a coastal system.

Ott (1978) describes a flexible general framework for classifying the type and structure of indicators, which can be adapted for multiple applications in their framework, an indicator is any measure to reduce a large amount of data to simplest form. More specifically define an indicator as an interpretive measure of relevant environmental parameters. Ott also uses the term index to refer to the interpretation or simple value obtained from the combination of two or more indicators through a mathematical function of aggregation. The indicators should provide three main functions: simplification, quantification and communication. In this sense, they are becoming an essential part of the communication process between scientists and managers and a way to reduce risk of failure of such a process. Indicators are increasingly recognized as a useful tool in many frameworks such as policy, sustainability, environmental analysis and they are considered to be crucial due to the important role they play in the decision making cycle (Gutiérrez-Espeleta, 1998).

The importance of the message transmitting an indicator is limited by the quality of data behind it, so it is necessary to establish criteria or guidelines to ensure that the information base is reliable (Bakker *et al*., 1994) and is possible to identify some basic criteria that the indicators must meet for them to be useful. According to Jiménez & van Koningsveld (2002) the indicator must meet the next criteria: Relevance, the proposed indicator must be conceptually related with the coastal function of interest. Easy to measure, the indicator should be straightforward and relatively inexpensive to be measured. Sensitive, the indicator should be responsive to stresses in the system. Have a known response to disturbances, anthropogenic stresses, and changes over time. Anticipatory, a change in the indicator should be measurable before substantial change in the targeted objective occurs. Integrative, the full group of indicators provides a measure of the key gradients across the analyzed change in the system state in time and space.

As the main factor of protection against coastal storm is the beach, it is necessary to assess their state and/or the vulnerability, to link this values with the flooding in the backshore. We propose the development of a physical coastal vulnerability indicator which quantifies the role of the beach as a protection buffer, taking into account the extreme storms and long-time erosion rates. This indicator is defined as the relationship between storm erosion and the horizontal beach width. The beach must present a width long enough before the impact of a storm to withstand the induced sea level change and protect the backbeach from flooding. In order to include the time factor, the range of annual erosion, which implies changes in beach width based on the annual level of erosion, was added, so the Vulnerability to Coastal Erosion for Extreme Storms (VuCEES), can be calculated as function of the time in our case for present time, 10 and 25 year.

The figure 3.13, and the formula below outlines the calculation of the vulnerability indicator by erosion, which is defined in terms of beach width, erosion associated with the storm and long-term erosion variability over time.

$$V_{cs} = \Delta x / (w + \partial w / \partial t)$$

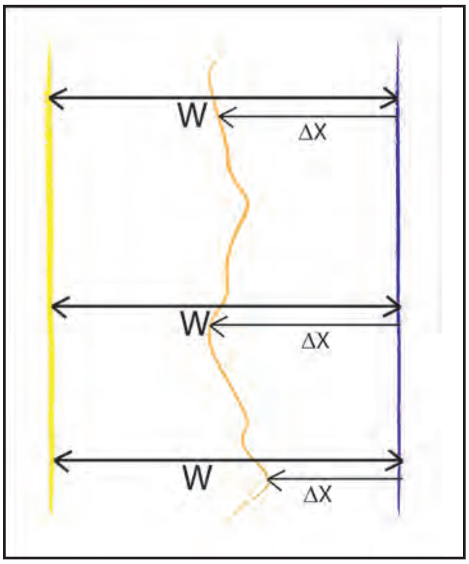


Figure 3.13. Schematic figure of the calculation of the VuCEE indicator

Where VuCEES is the Vulnerability Indicator, Δx is the erosion in the beach, w is the width of the beach, and the factor δw/δt corresponds to erosion rate. Once VuCEES is known, is scaled from zero to one following the rule represented in figure 3.14, this relation assigns values from low vulnerability in the cases where the erosion is lower than 25 % of the total width of the beach, medium and high values for rates of erosion between 25 and 75 % of the total beach, and very high vulnerability values over 75% of erosion.

Once we have assessed the vulnerability to erosion, these values are related with the habitats that are in the backbeach. This will be done measuring the kilometers of habitat associated with the level of VuCEES. With that we can connect the increase or decrease

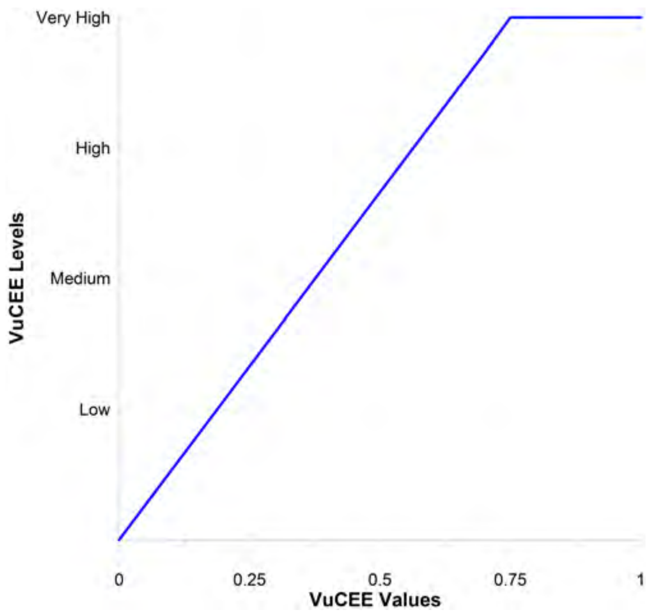


Figure 3.14. Scale for values of the VuCEES indicator.

of the VuCEES directly to the kilometers of habitat that were exposed. When changes in the beach width are present (reducing or varying) the protection of the backbeach is also affected.

After the assessment of above, the next step will be to account the loss or impairment of habitats due to flooding. To do that, the first step was to make a buffer in the study area (like a belt of approximately 500 meters long from the coastline), considering that most of the damage is concentrated in this area and case areas in which for the distance from the sea will not be flooded do not need to be included. After selecting the buffer, the total area and the flood potential area for the different storms was calculated. Once we know the areas affected we quantify the damage using the concept of ecological services and values. The flood damage calculated as values and ecological services, it gives us the value of the wounded only if we consider a total loss of the habitat, which occurs only in extreme cases.

It is necessary to take into account what kind of damage we are quantifying, for this work and based on the definitions given by FLOODsite (2006), we are talking about a *direct damage* that involves the immediate direct physical contact of flood water to humans, property and the environment and includes among other things, loss of standing crops and livestock in agriculture and loss of ecological goods. Direct damages are usually measured as damage to stock values. But here too are kind of *intangible damages*, which are basically ecological damages to goods and to all kinds of goods and services which are not traded in a market are far more difficult to assess in monetary terms.

Ecosystem valuation can be a difficult and controversial task, for trying to put a "pricetag" on nature. However, agencies in charge of protecting and managing natural resources must often make difficult spending decisions that involve trade-offs in allocating resources. These types of decisions are economic decisions, and thus are based, either explicitly or implicitly, on society's values. Therefore, economic valuation can be useful, by providing a way to justify and set priorities for programs, policies, or actions that protect or restore ecosystems and their services.

Ecosystem functions are the physical, chemical, and biological processes or attributes that contribute to the self-maintenance of an ecosystem. Thus, ecosystems, such as wetlands, forests, or estuaries, can be characterized by the processes, or functions, that occur within them. Ecosystem services are the beneficial outcomes, for the natural environment or people, which result from ecosystem functions. Some examples of ecosystem services are support of the food chain, harvesting of animals or plants, and the provision of clean water or scenic views. In order for an ecosystem to provide services to humans, some interaction with, or at least some appreciation by, humans is required. Thus, functions of ecosystems are value-neutral, while their services have value to society.

Ecosystem valuation can help resource manager's deal with the effects of market failures, by measuring their costs to society, in terms of lost economic benefits. The costs to society can then be imposed, in various ways, on those who are responsible, or can be used to determine the value of actions to reduce or eliminate environmental impacts.

Ecosystem values are measures of how important ecosystem services are to people. Economists measure the value of ecosystem services to people by estimating the amount people are willing to pay to preserve or enhance the services. Economists classify ecosystem values into several types. The two main categories are use values and non-use, or "passive use" values. Whereas use values are based on actual use of the environment, non-use values are values that are not associated with actual use, or even an option to use, an ecosystem or its services. Thus, total economic value is the sum of all the relevant use and non-use values for a good or service.

Brenner in 2007, made an evaluation of Ecosystem Services in the Catalan Coast, and proposed a set of values for the ecosystems or habitats. Based on these values was carried out the calculation of the environmental services provided by the study area and the potential economic losses in case of flood. In the case of cropland is considered the value proposed by Brenner plus the profit obtained per hectare of rice harvested by the farmers, this value is considered because the exclusive crop in the area of potential flooding are the rice field (Table 3.5). After the evaluation of the losses of ecological services due to flooding was assessed, we compare several scenarios to determine the contribution of each habitat and their importance.

The additional value added to cropland was calculated taken into account the annual yield per hectare of rice, based on data PIBDE 2006 from the yield per hectare is an average of eight tons for the Ebro Delta and the intervention price of it is € 299 plus € 53 for financial support, which transformed dollars for a total of €2610/ha/year.

Table 3.5. Values for ecosystem services in the habitat of the Delta Ebro.

Habitat	**Values for Ecosystem Services (€ Ha year)**
Beach and Dune	69778
Saltwater Wetland	10148
Saline Vegetation	2539
Grassland	154
Cropland	1434+2610
Freshwater Wetland	19152
Freshwater Lagoon	1266
Riparian Buffer	5601
Urban Green Space	4094
Urban	0.0

The flood damage calculated as values and ecological services, it gives us the value of the wounded only if we consider a total loss of the habitat, which occurs only in extreme cases. So in this work we do serve only to explain in an abstract way the damage and facilitate viewing and understanding

Areas below the targeted water levels, but not directly connected to the sea have not been considered hazard zones. In some cases, some of these areas could be classified as potentially vulnerable to inundation if we include the response to storms, especially in those cases where the coast has been previously breached.

The value of a future flood damage resulting from a single flood is called annualized flood damage. The amount from all possible future floods, ranging from the small frequent events (10 year) to the very large, rare events (500 year), is called the Average Annual Damage (AAD).

The AAD is calculated summing the annualized damages for a wide range of flood events. The average annual damage is mathematically the area beneath the curve, augmented by the intangible damages multiplier. This methodology is part of the Guidelines for Assessment of Floods Damage in New Zealand and Australia. (Berghan & Westlake 2001).

4. Study Area

A un certo punto il fiume, per stanchezza, perché ha corso per troppo tempo e troppo spazio, perché si avvicina il mare, che annulla in sé tutti i fiumi, non sa più cosa sia. Diventa il proprio delta. Rimane forse un ramo maggiore, ma molti se ne diramano, in ogni direzione, e alcuni riconfluiscono gli uni negli altri, e non sai più cosa sia origine di cosa, e talora non sai cosa sia fiume ancora, e cosa già mare...

Umberto Eco
Il nome de la rosa

4.1 Description of the Study Area

The Ebro Delta (ED) is located in the Spanish Mediterranean coast about 200 km southward of Barcelona. The ED has been formed due to the interaction between river and marine dynamics (Jiménez *et al*., 1997). The ED has been build up by the surplus of sediment discharge of the Ebro river (Galofré *et al*., 2002). The surface of the ED has expanded itself for several centuries. It has an approximate sub-aerial surface of 32000 ha and a coastline length of about 50 km excluding the inner coast in the two semi-enclosed bays. The ED is a microtidal environment with astronomical tidal range of about 25 cm although storm surges clearly exceeding such magnitude are not infrequent in the area (Jiménez *et al*., 1997). As many other deltas, it is an ecologically rich environment, with areas of high interest. The habitats are composed by freshwater, brackish and saline lagoons, salt marshes and coastal small dune sandy areas .

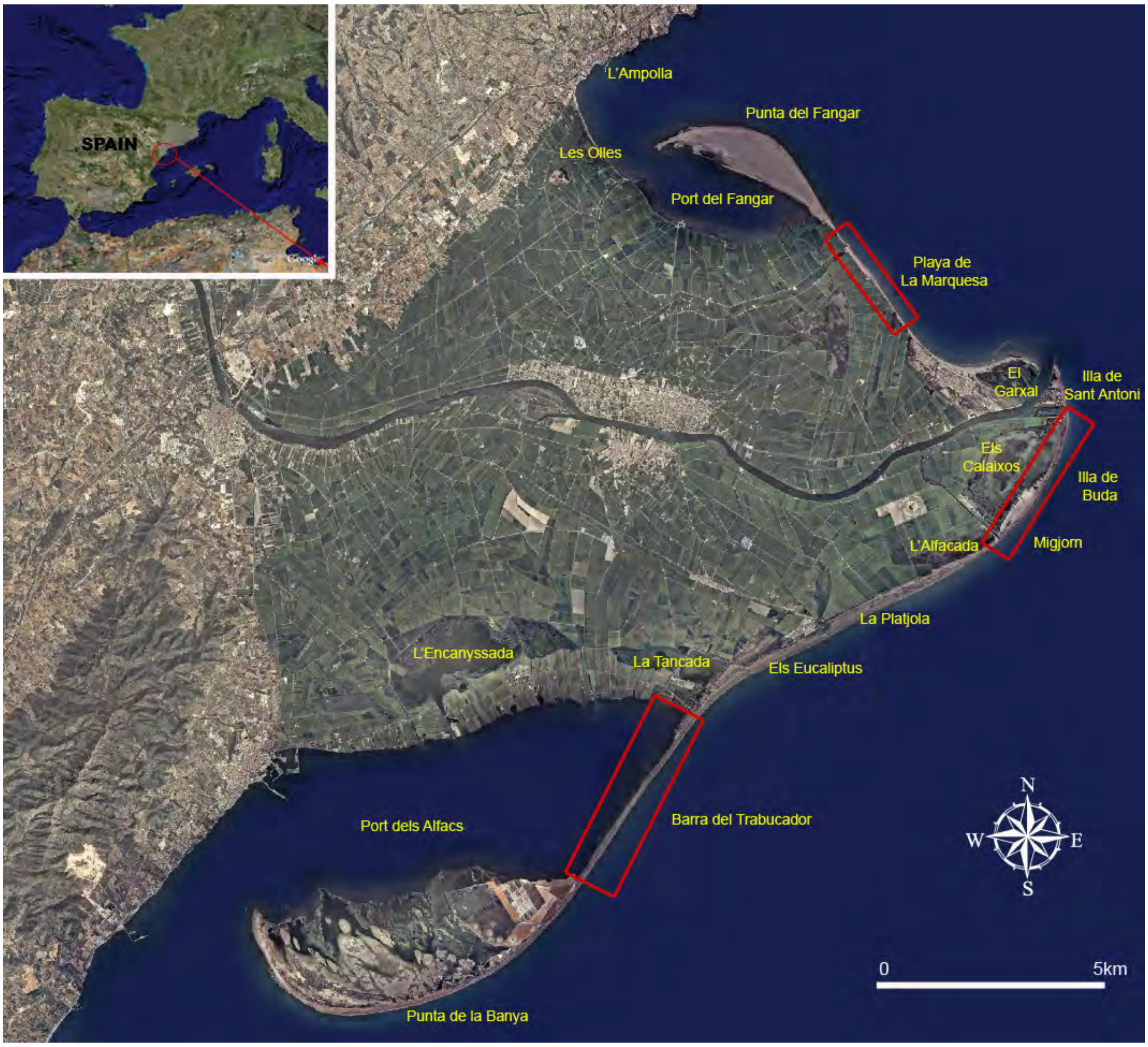


Figure 4.1. The Ebro Delta. Red polygons indicate most vulnerable areas to storm impacts

The ED does not have high elevations, about 10% of the delta lies below sea level and 45% of the Delta area has an elevation of less than 50 cm. (Jiménez *et al*., 1997, Day *et al*., 2006). Close to the beach there are some dunes, but these are not very high; the only protection against flooding is the beach itself.

The ED is one of the most important wetland areas in the western Mediterranean and is valuable both economically and ecologically. It is one of the most important bird habitats in the Mediterranean, and the second most important special protection area for birds (SPA) in Spain (SEO/BirdLife, 1997). Part of the delta (about 8000 ha) was designated as a natural park in 1986. The ED has international importance for breeding for at least 24 species and for migration and wintering for 13 species, and occasionally for 14 more (Martínez-Vilalta and Giró, 1996).

The international importance of the natural values of the ED has been widely recognized. In 1984, the delta was declared an area of special interest for conservation of halophytic vegetation by the Council of Europe. It has also been recognized as an area of European importance for conservation of aquatic vegetation. More recently (1993), it was included in the list of Ramsar areas and it is part of the Natura 2000 network. There are 18 habitats included in the 92/43/EEC Directive for the Conservation of Natural Habitats and Wild Flora and Fauna, from which 2 are of priority conservation and 8 are locally endangered (SEO/BirdLife, 1997).

The ichtyofauna is also very diverse with 55 species observed in the delta plain, not including marine species. It is remarkable that there are six endemic species of the western Mediterranean coast of the Iberian Peninsula (Sostoa and Sostoa, 1985; Elvira, 1995). In the lower river, there is also the last viable world population of globally threatened freshwater mussel (*Margaritifera auicularia*)(Altaba, 1990; Araujo and Ramos, 2000).

The main human transformations of the ED occurred in the 20th century. From 1900 to 1970 most wetlands and some lagoons were transformed into rice fields, and an intensive drainage system was built for their river water supply. Construction of dams, especially the large Ribarroja and Mequinença dams, resulted in great changes in the hydrology and sediment budget of the river. Sediment inputs to the delta have been reduced as much as 99%, and freshwater input has also been reduced dramatically (Guillén and Palanques, 1992; Ibáñez *et al*., 1996).

4.2 Values Relevance

Wetland areas have been steadily reduced from approximately 250 km^2 in 1900 to 80 km^2 in 1990 due to conversion to agriculture and other uses (SEO/BirdLife, 1997). Agriculture, fisheries, aquaculture and tourism are economic activities that are dependent on the delta, with a total annual economic value of about € 120 million. Agriculture accounts for a gross economic benefit of about € 60 million, tourism for about € 30 million, fisheries for about € 20 million and aquaculture for about € 10 million.

Rice agriculture represents the delta’s most important activity (60% of its surface), and rice fields play a crucial role in its economy and ecology. Rice gross production accounts for 120,000 metric tonnes per year, the third most important of the European Union, and represents 98% of the total production in Catalonia (Santalla, 2002, Day *et al*., 2006).

An extensive irrigation system delivers fresh water from the Ebro River to the rice fields. In addition to the grain harvest, rice fields play significant ecological roles for overwintering of migratory birds, preventing saline intrusion, and in biogeochemical transformations such as denitrification (Martínez-Vilalta, 1995; Ibáñez, 2000; Forés, 1989, 1992). Fish landings at ports influenced by Ebro River runoff are among the largest of the western Mediterranean, with an average of about 6000 metric tonnes per year. Aquaculture is an increasing economic activity, with a high production of mussels and oysters in Fangar and Alfacs bays of about 3000 metric tones per year, which is equivalent to 99% of the total production in Catalonia. Tourism has increased substantially since the creation of the natural park, and currently the number of visitors is estimated to be more than half a million people per year (Orellana 2005). Brenner (2007) conducted an assessment and valuation of ecosystem services in the Catalan coast and determined that the ED area presents from high to very high values of ecosystem services provision capacity.

4.3 State, Pressures and Risks

The Ebro River provides water, sediments and nutrients to the delta and coastal marine ecosystems. These fluxes of material and energy are the sustaining base of the main economic activities, landscape and cultural features of the lower Ebro. Rice cultivation, fisheries, aquaculture, and tourism, all of which are based on local natural resources, are the economic base of the delta (SEO/BirdLife, 1997). Moreover, rice cultivation, fishing and hunting have profound significance in the social and cultural features of the lower Ebro (way of life, literature, gastronomy, etc.), where water is part of the identity of the people.

Rice cultivation has an important environmental and economic value in wetland areas, in the sense that it is the best agricultural option. Any other non-flooded cultivation would imply stronger impacts, as dessication, salt stress, more rapid subsidence, and higher water pollution of surrounding wetlands. Moreover, because a rice field is an artificial wetland, it is a suitable habitat for feeding and reproduction of many aquatic birds and fishes (Ibáñez, 2000). These natural values are the base of an increasing tourism activity, since the delta and the lower Ebro River are visited by more than a half million people every year. Ecotourism and tourist river navigation are two economic activities that are increasing.

The ecological functioning of the ED at present days is largely dependent on and affected by human activities, especially rice production, as a result of the modification of the natural hydrological regime (Ibáñez *et al*., 1997a). These activities have already made sustainable management difficult. Under natural conditions, much of the water that flowed from the river into the delta plain went through wetlands. Nowadays much of the water flow in irrigation canals (about $45m^3/s$ from April to September) goes through rice fields and bypasses wetlands. High nutrient levels lead to eutrophication, and there exist pesticide problems (Comín *et al*., 1990; Camp *et al*., 1991; Menéndez and Comín, 2000). Over several decades, these conditions have led to decreased biological diversity, reduced submerged macrophyte production, and lowered fish and waterfowl populations (Ibáñez *et al*., 2000).

In addition, the decreased river discharge and almost complete elimination of sediment discharge lead to coastal retreat (Guillén and Palanques, 1992; Jiménez and Sánchez-Arcilla, 1993; Ibáñez *et al*., 1996), the waterquality deterioration in the river, estuary, lagoons and bays (Muñoz and Prat, 1989; Prat *et al*., 1988; Camp *et al*., 1991; Ibáñez *et al*., 1995), loss of wetlands and other natural habitats (Ibáñez *et al*., 1999a), salt water intrusion (Ibáñez *et al*., 1997b, 1999b), sinking of the delta plain and lack of accretion that is leading to lowering of the delta plain below sea level (Day *et al*., 1995; Ibáñez *et al*., 1997a).

Moreover, predictions of accelerated sea level rise of 40–60 cm within this century (IPCC, 2001) will make the lowering of the delta plain more critical, fisheries will decline (Aparicio *et al*., 2000; Sostoa and Lobón, 1989), and maintenance of socioeconomic welfare of local communities will be more difficult.

Because of this reduction in sediment input, subsidence of the delta plain, and eustatic sea level rise, considerable areas on the edges of the delta are now below sea level, and large-scale pumping is now in place. Again, about 40% of the emerged delta plain has an elevation of less than 50 cm, and about 10% is already below sea level. This results in drainage water being pumped directly to the bays, thus worsening eutrophication and leading to salinity intrusion in the lagoons. In addition, water draining from rice field contains nutrients and pesticides. Much of this drainage also bypasses existing wetlands and flows directly to lagoons and bays, contributing to water quality deterioration. There has been a reduction in fisheries linked to reduced river flow, habitat destruction, and poor water quality. The combined results of these problems threaten sustainability of rice farming and fisheries and maintenance of local communities (Day *et al.,* 2006).

The above considerations clearly show that the ED is not physically or geomorphologically sustainable at present. Due to the limited supply of sediments from the river there is now retreat of the active mouth of the river, and a general reshaping of the delta is taking place. The most important problem is the lack of sedimentation in the delta plain. Because most of the delta surface will be below mean high water within a century, it will become essentially isolated from the adjacent bays and sea.

In a near future, the ecosystem will switch from a system with two-way connections to the sea to one where there will only a one-way flow of water being pumped from the delta plain. Even more, a functioning deltaic ecosystem will no longer exist, and the system will be non-sustainable (Day *et al*., 2006). There is also the possibility that these problems will lead rice farming, to become economically unfeasible and will influence the decline of local communities. Examples of the future of the ED can be seen in the present status of the Colorado, Nile and Po deltas (Postel *et al*., 1998; Stanley and Warner, 1993; Scarton *et al*., 2002).

5. Results

• We sometimes talk as if "original research" were a peculiar prerogative of scientists or at least of advanced students. But all thinking is research, and all research is native, original, with him who carries it on, even if everybody else in the world already is sure of what he is still looking for. ~
John Dewey (born 20 October 1859)

5.1 Introduction

This chapter will discuss the results of this work. First of all, the scenarios or scales of this work are described in order to establish their scope. Then, the Long-Term Scenario results and the conclusions drawn from them are presented. After, on the Episodic Scenario results, the results associated with methodology selection are introduced and followed by field application. Thus, for both cases an assessment of damages associated with flood and consequences was undertaken.

5.2 Definition of scenarios

When morphological studies on the coast are carried out it is necessary to take into account time and spatial scales, since there is a combination of both on the active processes on the coast. Their definition should be based on the observed driving mechanisms and coastal response. In the Ebro Delta area, earlier works (Jiménez, 1996, Jiménez *et al*., 1997a, Sánchez-Arcilla *et al*.1998) show that the most "immediate" contributors to coastal morphodynamics and vulnerability can be "fixed" to three main spatial and temporal scales (large/long-term, medium and episodic ones).

This work focuses on long-term and episodic events, and was carried out with two well characterized scenarios based on temporal and spatial scales. Scenarios provide a plausible description of possible future conditions and their challenges, and are generally developed to inform decision-makers in conditions of uncertainty. Scenarios are different from assessments, models, and other decision-support activities, although they can provide important inputs to these activities. Scenarios can also be distinguished less sharply from other types of future statements used to inform decisions, such as projections, predictions, and forecasts. Compared to these, scenarios tend to presume lower predictive confidence, because they are based on processes in which causal relationships or longer time horizons increase uncertainty (Parson *et al*. 2007). For this work two scenarios were selected, associated to the coastal response in two scales of time and space. One scenario in a long-term scale with the Relative Sea-Level Rise as the principal agent, and a second scenario associated to extreme or episodic events where the coastal storms represents the principal forcings. The main difference between these scenarios is basically the nature of the flooding. The storm-induced inundation is merely temporary whereas the RSLR should be permanent. This temporality has a direct influence on the impact of the floods on the coastal area, and consequently in the responses of the coast, and therefore the stakeholder's actions.

5.2.1 Long-Term Scenario

The long term scenario for the Delta Ebro in this work will have as main forcing agent the RSLR. Large/Long-term coastal processes are associated with changes at a temporal scale of several decades and spatial scale that takes into account the whole delta. The RSLR will be assembled from the eustatic variations in sea level estimated by the IPCC in 2007 where three possible levels were selected, plus the local variation due to subsidence in the studio area. Different scenarios were build with these RSLR´s, and the flood and its effects on the Ebro Delta are discussed.

5.2.2 Episodic Scenario

The second scenario is associated to the episodic or extreme events that are related to processes with very large return periods, do not exhibit a periodicity in time, and in which the spacial scale is defined by the length of the coastal response. The main driving forces are defined by the presence of very energetic sea states (storm surges and storm waves) with an extreme coastal response. For this scenario, flooding areas associated to coastal storms with return periods of 10, 50,100 and 500 years, were identified and the morphodynamic coast response and how the flood is distributed in the backshore were studied.

The results from the flood due to RSLR and storms are presented. These results are divided into three different sections, the first one examines the RSLR events, the second one contains the application of methodologies that provide us with the “input data” for the episodic/extreme events, and a third section includes the results corresponding to the Flood mapping.

5.3 Inundation due to RSLR

As it was previously mentioned, processes acting at the long-term scale will mainly affect the deltaic dynamics in the vertical dimension, i.e. the relative elevation of the deltaic body with respect to the sea level. This has very important implications for a low-lying coastal environment, especially in a scenario of rising sea level because the only way to avoid direct inundation by the sea is the vertical accretion of the deltaic plain.

Due to the absence of sediment supplies to the Ebro deltaic plain, no vertical accretion is taking place and, as a consequence, RSLR (due to the combined action of subsidence and eustatic sea level rise) will increase the probability of flooding of low-lying areas, especially those directly connected to the sea or where a “passive” coastal fringe exists. We have to consider that sandy coastlines exposed to wave action will response following a Bruun’s rule-like response, i.e. they will move upwards and landwards following sea level (see figure 3.3). As a consequence of this, if the main barrier protecting the hinterland is given by the beach, its elevation will be the same with respect to the mean water level although it will be landward of the actual position after sea level rise. This will only occur in dynamically active (sandy rich) areas where no fixed inner boundaries (seawall, levees, etc) do exist.

RSLR was defined considering that it has two components, the eustatic and the local one. The Eustatic component corresponds to IPCC data, while the local component is related to the subsidence of the delta; Somoza *et al.,* in 1998 calculated a subsidence average value of 15 mm for year for the Delta Ebro, establishing an average subsidence of 15 cm to 100 years.

The IPCC constructed several scenarios to help to understand global average sea level changes. It is important to try to predict how much the sea will rise over the next century, so that coastal planners and engineers can prepare by implementing measures to enable entire regions to adapt to the effects of changing climate. The IPCC make The Special Report on Emissions Scenarios (SRES) that was a report prepared for the Third Assessment Report (TAR) in 2001. This contains future emission scenarios to be used for driving global circulation models to develop climate change scenarios. There are 40 different scenarios, each of them making different assumptions for future greenhouse gas pollution, land-use and other driving forces. Assumptions about future technological development as well as the future economic development are thus made for each scenario. The projected series of scenarios of sea level rise range from 18 cm (*low*) to 59 cm (*high*) for until the end of this century, with a central value of 33 cm (*medium*). The figure 5.1 shows the variation of these SRE scenarios. The region delimited by the outermost lines shows the range of all AOGCMs and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition, which for their uncertainty were not taken into account in this work.

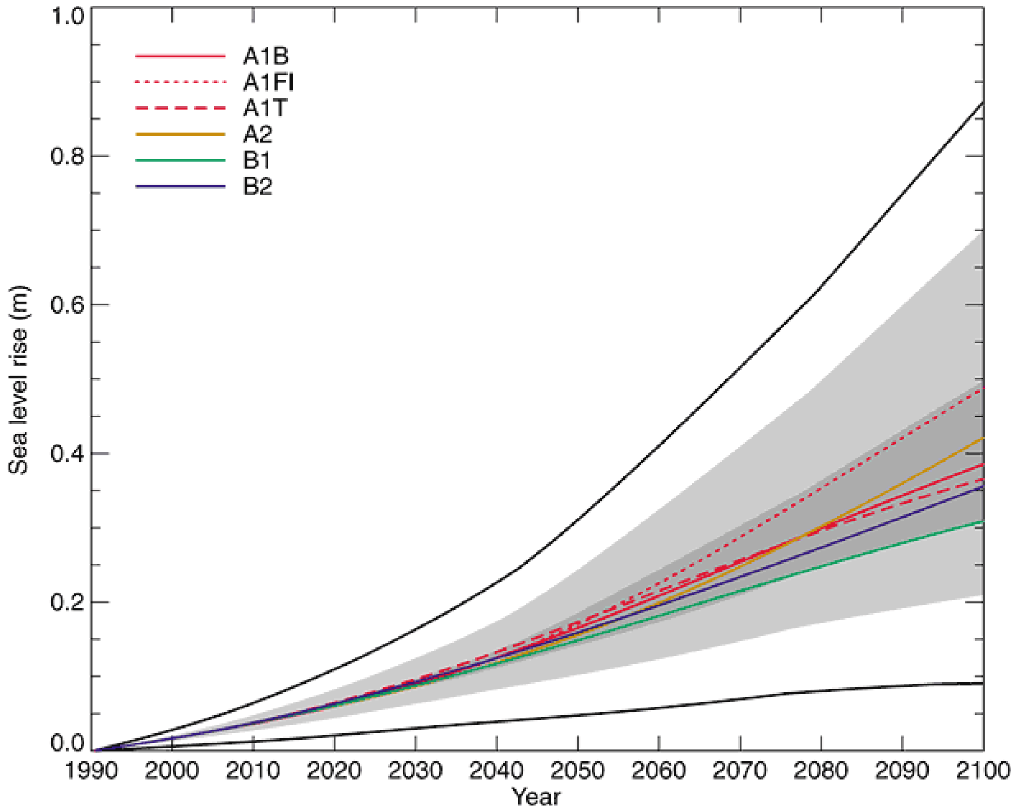


Figure 5.1 Global average sea level rise 1990 to 2100 for the SRES. Each of the six lines appearing in the key is the average of AOGCMs for one of the six illustrative scenarios. The region in dark shading shows the range of the average of AOGCMs for all 35 SRES scenarios. The region in light shading shows the range of all AOGCMs for all 35 scenarios. The region delimited by the outermost lines shows the range of all AOGCMs and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition (from IPCC 2001)

The inundation areas for the three scenarios of RSLR in Ebro delta were calculated. The areas potentially able to be inundated for RSLR levels were estimated taking into account the role of hinterland structures -such as levees, dikes and roads- in preventing flooding in impounded areas, because these structures associated with delta flat topography, can compartmentalize and limit the floods. The RSLR targeted water levels based on IPCC (2007) is presented in the table 5.1. Figure 5.2 shows the three different Inundation scenarios and the table 5.2 shows the data about the area flooded by RSLR.

Table5.1. Scenarios of RSLR to 100 years (to 2100)

	Lower (m)	Medium (m)	Higher (m)
SLR(IPCC)	0.18	0.38	0.59
Subsidence	0.17	0.17	0.17
Total RSLR	0.35	0.55	0.75

Table 5.2. percentages of flooded areas inside the Delta and the Natural park

Total Area	**Flooded Area**					
	RSLR 0.35 m		RSLR 0.55 m		RSLR 0.75 m	
	ha	%	ha	%	ha	%
Delta 31,066	9916	31.9	15,076	48.5	18857	69.7
Natural Park 6,733	4,490	66.69	5,747	86.01	6,127	90.15

Thus, the flood hazard area to a RSLR of 0.35 m has been estimated in 9916 ha, that increases up to 15,000 ha for a RSLR of 0.55 m and for the extreme case of 0.75 m it is close to 18,800 ha. These three scenarios correspond to approximately 31.9 %, 48.5 % and 69.7 % of the deltaic surface. This only includes areas to be inundated because they are directly connected to the sea. Areas below the targeted water levels but not directly connected to the sea have not been considered as hazard zones. In some cases, some of these areas could be classified as potentially vulnerable to inundation if previously is breached the natural protection given for the beach.

After carrying out calculations of the flooded areas in the Ebro Delta, we can confirm that due to its low profile, the Ebro delta is highly sensitive to changes in sea level and flooded areas normally correspond to ancient lakes, canals and river courses, that due to agricultural pressures have changed their original function, and when there is a rise in sea level they are easily flooded.

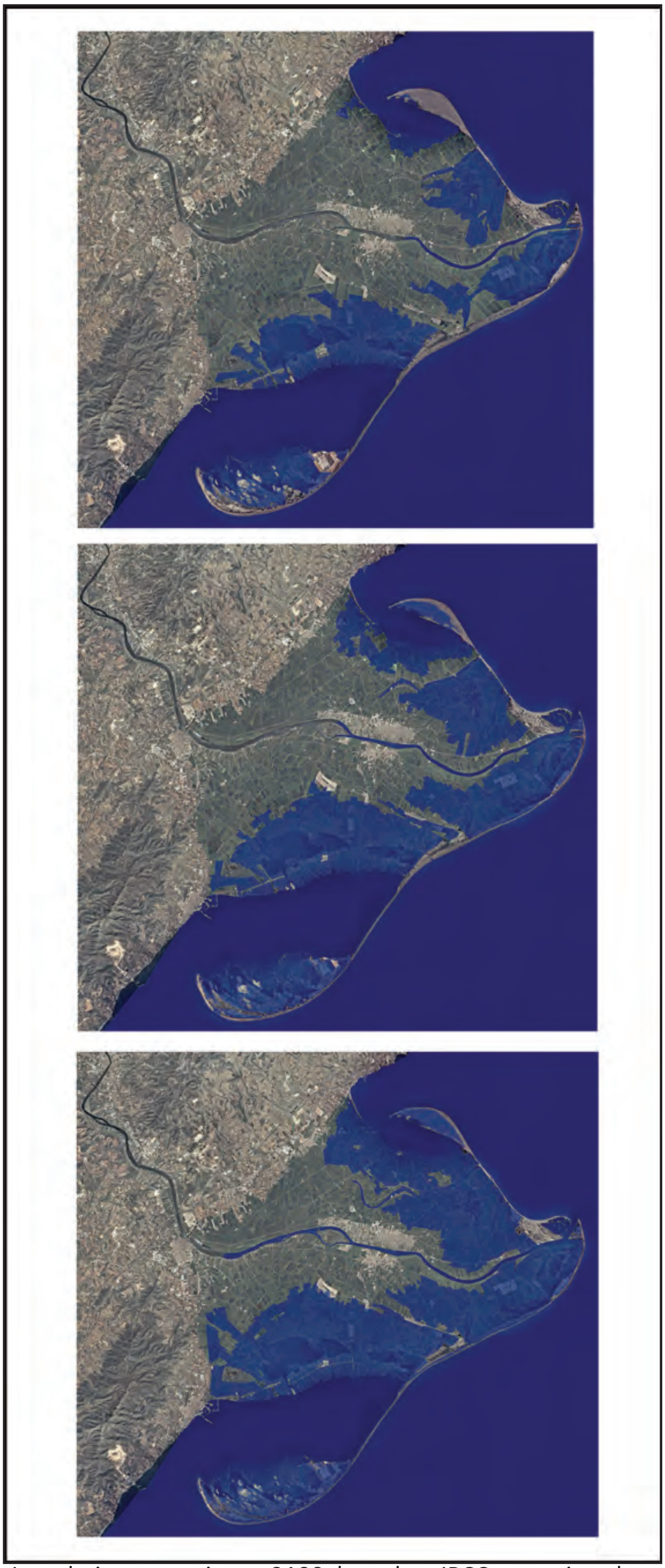


Figure 5.2. Inundation scenarios to 2100, based on IPCC scenarios plus subsidence.

The figure 5.3, illustrates the different flood hazard levels due to the different studied scenarios. The red area represents the zone of low scenario which may be termed as the most probable, assuming that when the sea level rises and at least this scenario is flooded, the green area represents the high scenario of RSLR. This provides us with the information on the areas to which more attention should be paid for future planning in the delta. When we use the word `probable´, we refer to the area that will be inundated in the three possible scenarios, and not to the statistical probabilities of occurrence of this event.

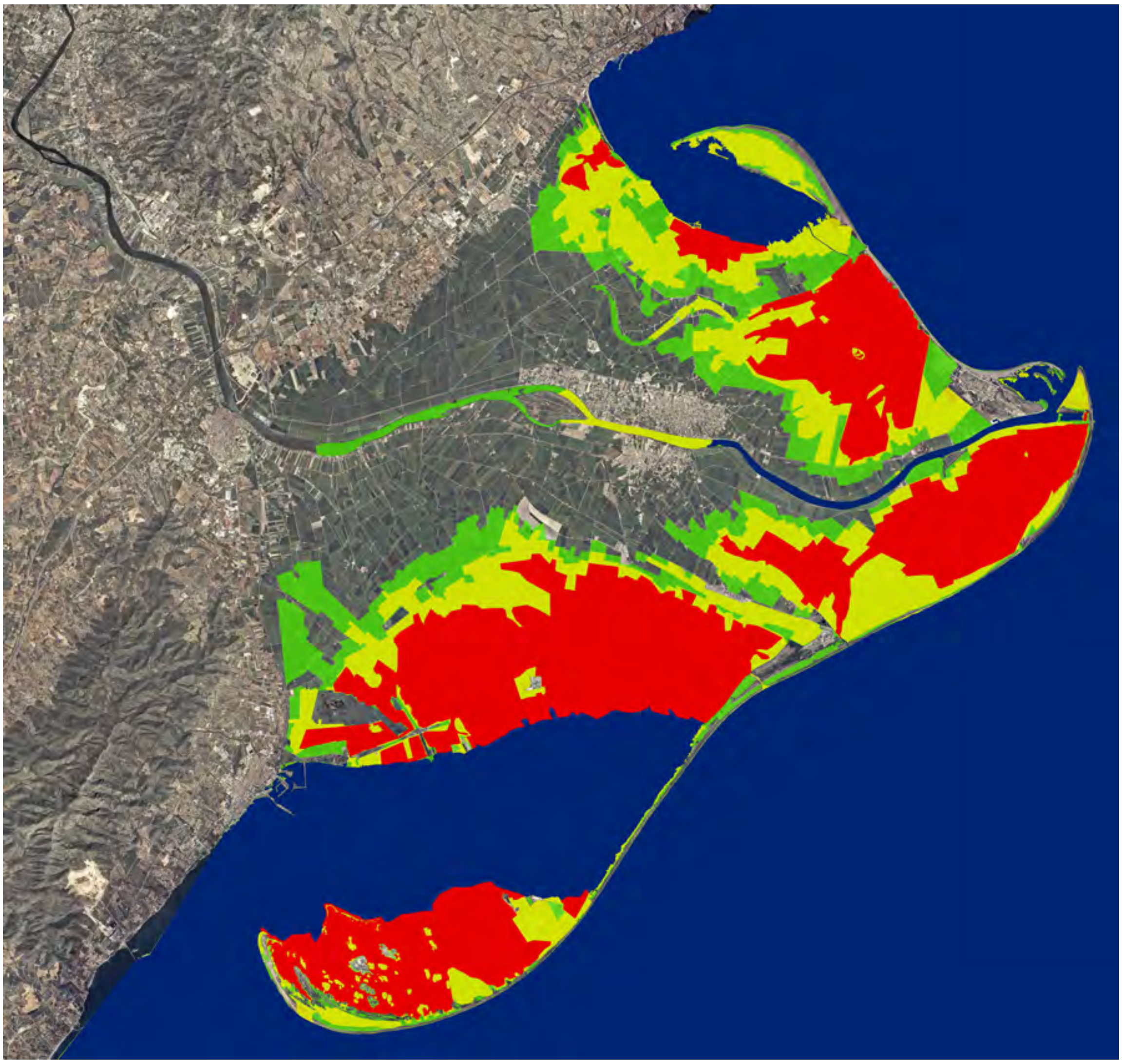


Figure 5.3 Hazard levels from RSLR in the Delta Ebro.

When sea level is raised, the main delta part flooded is the area in the vicinity of the bays, because these areas have no beaches or dunes that can offer protection. On the other hand this area is largely connected to the sea through the network of channels draining the rice pads. All these channels will transfer the rise of sea level to the delta plain. The southern part of the delta (around the Alfacs Bay) is the largest flooded area; this area is characterized by the existence of coastal lagoons that formerly covered a large area of south hemidelta. In the north hemidelta the largest flood is situated in the vicinity of the Bassa Del Canal Vell, in this case if the channels are strengthened or closed it is more feasible to keep the flood of direct communication with the sea. Other deltaic areas below targeted water level but not directly connected to the sea will be affected by other processes such as an increase in salt content in the soil and water.

One possibility, thinking in flood management strategies for the Delta is to close the channels that communicate the lagoons inside the delta. This would completely isolate the delta and avoid any exchange with the bays or the open sea. This only works for the *Low* scenario, because the channels are below the flood level of the following scenarios. In figure 5.4, we can compare these two results.

Figure 5.4. Comparison between two possibilities of 33 cm RSLR. The picture in the right exemplify the flood without closing the channels, the left- show what happen if the channels can be closed

The inundate area when the channels are closed, goes from 10,000 ha to 7350 ha and this implies a reduction of a third of the flooded area, which corresponds to 10% of the total area of the delta. This means, that if in this scenario we can take control of incoming water, we will be able to reduce the flooded area, albeit at the expense of having isolated parts of the delta.

It is possible to make an analysis of areas flooded by the three rising sea level scenarios in all delta, based on the type of habitat affected. The table 5.3 summarizes this data in percentage of the delta area flooded by the RSLR.

Table 5.3. Percentage of the habitats flood by the RSLR scenarios

	% Delta Area Flooded by RSLR		
RSLR	*35cm*	*55cm*	*75cm*
Beach & dune	3.30	39.40	69.90
Cropland	23.02	39.48	52.29
Grassland	0.00	0.00	0.00
Freshwater lagoon	32.48	62.98	62.98
Riparian buffer	76.03	79.95	84.90
Saltwater wetland	84.08	92.85	93.36
Saline vegetation	58.00	75.70	83.00
Urban	0.00	0.00	2.08
Total	31.9	48.5	69.7

In this case, we can observe that the most affected habitat by RSLR in the three scenarios is the saltwater-wetlands that lose more than 85%, followed closely by Riparian buffer with figures above 75% of flooded area and Saline vegetation with losses between 58 to 83 %. On the other hand, the less damaged is the urban “habitat” that is affected in only 2% of its total area (only in the worst scenario) and then the cropland, which loses between 30 and 50% of its surface. In ecological terms, the damage to the Dunes or the Riparian Buffer and Wetlands can be considered more severe than the damage to Urban and Cropland areas, but also that it is more likely to be a replacement or a realignment of habitats in adaptation to the changing sea level. Beach and dune, is a special case, since although largest losses are reported, these values can be overestimated, since we are considering a response to the beach as Bruun’s Law, so the beach can migrate or adapt to rising sea, and when these values are calculated, the GIS do not take into account this factor.

When the channels are closed, habitats or areas that would benefit if a so extensive flood did not exist, are mainly the open freshwaters that will reduce their flooded area from 31.9% to 8% and the cropland which has a variation of the affected area from 23% to 13%. The Riparian buffer and saltwater wetland are also benefited from the flood control that would reduce their flooded areas (9% in the first case and 10% in the second)

Once the flood area was estimated, the next step was to carry out an assessment of damage associated with RSLR scenarios, based on the economic values of the ecosystem services reported by Brenner(2007) and to calculate the “economic lost” in monetary terms due to loss or replacement of habitat (table 5.4).

Table 5.4. Damage or "economic loss" associated with RSLR, belonging to the values proposed by Brenner 2007

	RSLR 35 cm		RSLR 55 cm		RSLR 75 cm	
	Flooded Area (ha)	Economic Value (€)	Flooded Area (ha)	Economic value(€)	Flooded Area (ha)	Economic value(€)
Beach & dune	42	€3,059,700	504	€36,777,776	896	€65,306,084
Cropland	5631	€24,200,680	9659	€41,514,992	12791	€54,976,909
Grassland	0	€0	0	€0	0	€0
Freshwater lagoon	10	€12,915	19	€25,036	19	€25,036
Riparian buffer	906	€5,303,067	953	€5,576,375	1012	€5,921,762
Saltwater wetland	2007	€21,276,472	2216	€23,497,034	2228	€23,624,948
Saline vegetation	1320	€3,502,254	1725	€4,575,228	1891	€5,015,868
Urban	0	€0	0	€0	20	€0
Total	9916	€57,355,088	15076	€111,966,441	18857	€154,870,605

The biggest damage or economic losses are found in the habitat of Beach & Dunes, followed by that of Cropland and Saltwater Wetlands. That could happen only when it is considered the loss of the habitats as total loss, which in reality only happens with the Cropland. The other natural habitats, we suppose that can "adapt" to the new conditions, unless there is a sudden change or the boundary conditions do not permit this adaptation.

Divided by habitats, the cropland has the biggest losses and the freshwater lagoon present the lowest losses, mainly due to the location of the latter habitat, within the delta, which protect these from the RSLR flood. In the economic view, the largest loss is located on the beach and the lowest one on freshwater lagoon.

It should be mentioned that high values in the beach habitat are due to high unit values, whereas in the case of Open Freshwater, has an "average" value but the surface is very small. This does not imply that the loss of the beach is more important than the freshwater lagoons. It is also necessary to note that Beach & Dune, and brackish areas as mentioned above will not have problems to adapt to changes, while we consider that Open Freshwater adaptation will. I this is the case, there will be a need to change the evaluation method, from an absolute evaluation to a relative evaluation. Brenner uses values calculated in U.S, so it could be necessary consider studies for the Catalan coast, more specific for our study area.

Moreover a large part of the Ebro Delta nature reserve is located in the area near the coast or in low areas prone to flooding, so from 67% up to 90% of the park could be under water.

Based on the above, two possible responses or actions to solve the problem of flooding in the Ebro Delta can be addressed. The first “classical” response is the Total Protection (Hold the line), at all costs trying to keep the current use. The second would be to turn to the more sustainable system (“Adaptation” response) considering the gradual adaptation to the new profile of the coast.

5.4 Episodic/Extreme Events

5.4.1 Storm Scenarios

One of the goals of this work when assessing the coastal flooding, is to contribute to the European Directive (FD) for this type of events (2006/0005 (COD)) given the elements for its application. For this reason and based on the methodology for statistical analysis described in chapter three, a comparison between the two statistical methodologies (event and response was conducted), to determine differences and the usability for this type of assessments. Also he data for the construction of the simulated storm climate mentioned was obtained t by FD and was necessary to generate flood maps based on three assumptions or premises: High probability of flood (return period of 10 years), medium probability (return period of 100 years) and low probability of flooding (extremes).

Event Approach

Event approach involve the analysis of waves for its adjustment to an extreme distribution then the dependence with period and duration determined by nonlinear regression, since the extremes of potential flood elevations derive from these values.

At first step the wave height (H_s) was tried to fit into various extreme significant arrays (Figure 5.5). In this case the best fit was with a Weibull Distribution k=0.75 with a correlation of 0.9638

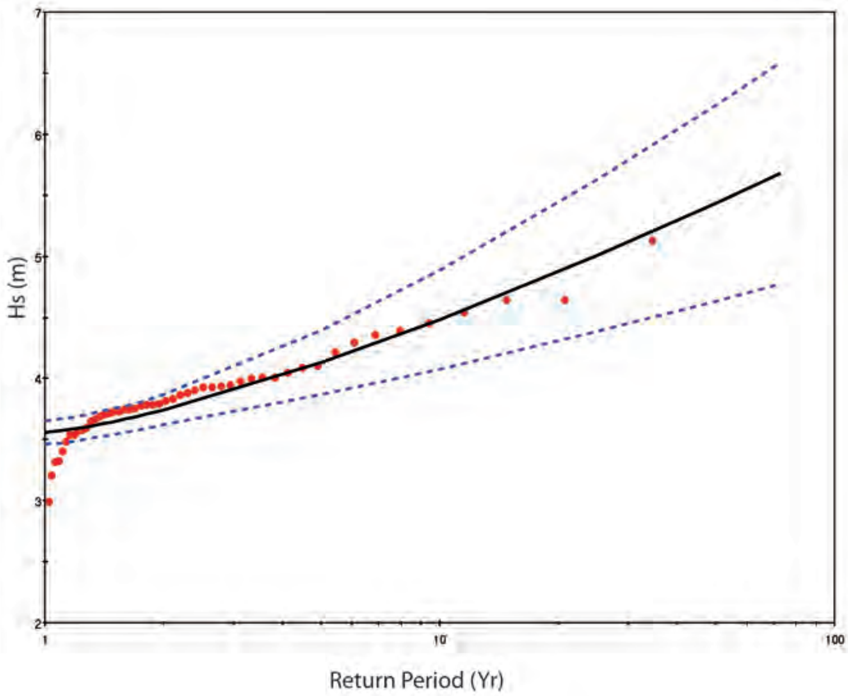


Figure 5.5. Fitted H_s to an extreme distribution (Weibull k=0.75) whit a correlation of 0.9638. The blue lines corresponds to 0.95 confidence band

Once we have the fitting to statistical distribution, we determine the dependence between the wave period (T_p) and H_s, by fitting the data by a nonlinear regression analysis, also between the Duration of the storm (ζ) and H_s. (Figures 5.6 and 5.7)

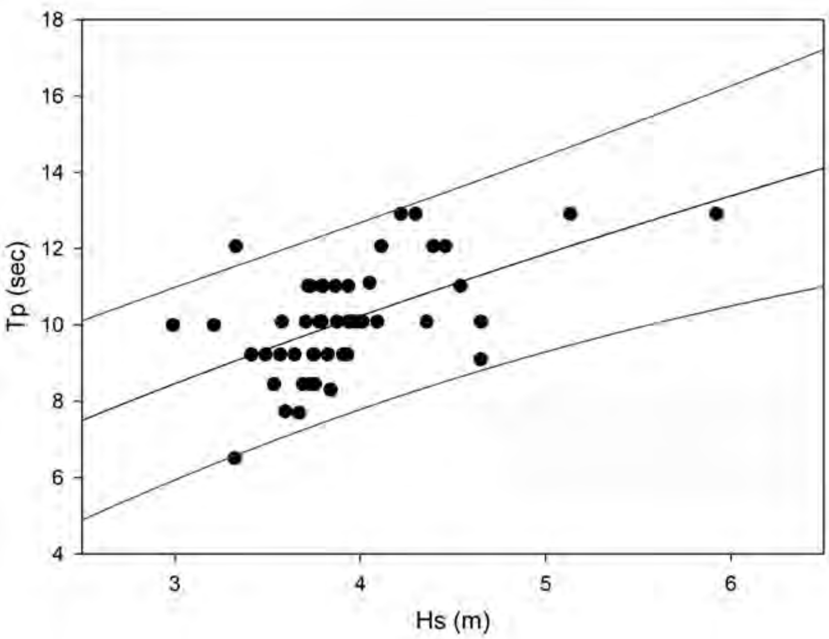


Figure 5.6. Dependence between T_p vs H_s .The black lines corresponds to 0.95 confidence band

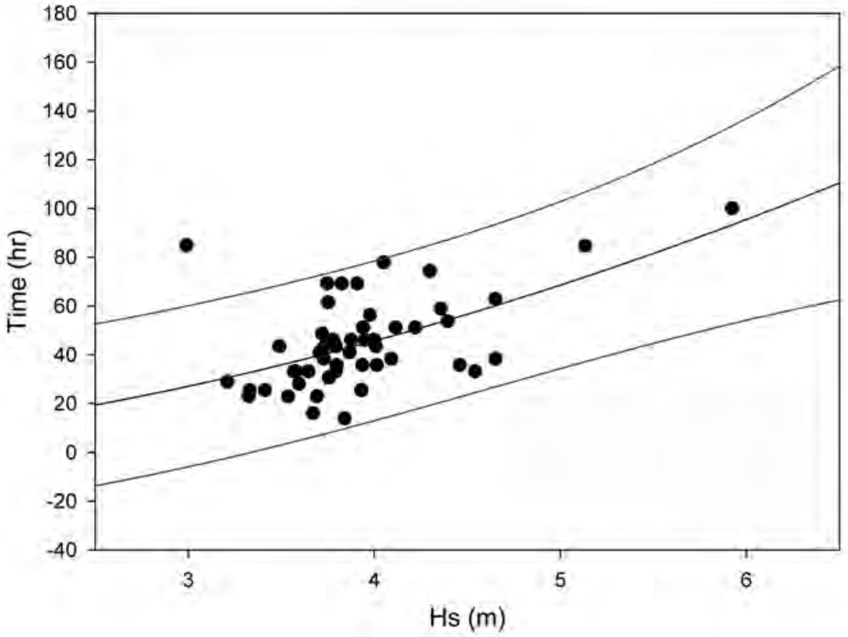


Figure 5.7. Dependence between ζ vs H_s. The black lines corresponds to 0.95 confidence band

From the previous fittings and dependences is possible to calculate the runup for specifics return periods. In this the case the runup acted as Total Water Level (Table 5.5) . The runup was calculated by Stockdon (2006), and considering an average beach slope of 0.02.

Table 5.5. Fittings, dependences, and calculate Runup for specific Tr

T_r	H_s (m)	T_p (s)	ζ (hr)	***Ru***(m)
2	3.74	9.78	41	1.03
5	4.13	10.45	48	1.15
10	4.48	11.03	56	1.26
25	5	11.86	69	1.44
50	5.43	12.52	80	1.58
73	5.68	12.90	87	1.67
100	5.89	13.22	92	1.74

In this case we get as final data, the runup values derived from the calculation of probabilities and dependences of the various phenomena and process that are part and influence the final result, but the problem here is as mentioned in the previous chapter the accuracy error due to joint probabilities of the several processes.

Response Approach

The response approach is the analysis of the final process in this case the runup, considering that the physics and statistics of the components of the event are implicit in the observer data.

Considering an average beach slope of 0.02, the runup (based on Stockdon 2006), was calculated and these results were fitted to extreme distributions. In this case the best fit was to the Fisher-Tippett distribution with a correlation of 0.9923. (figure 5.8).

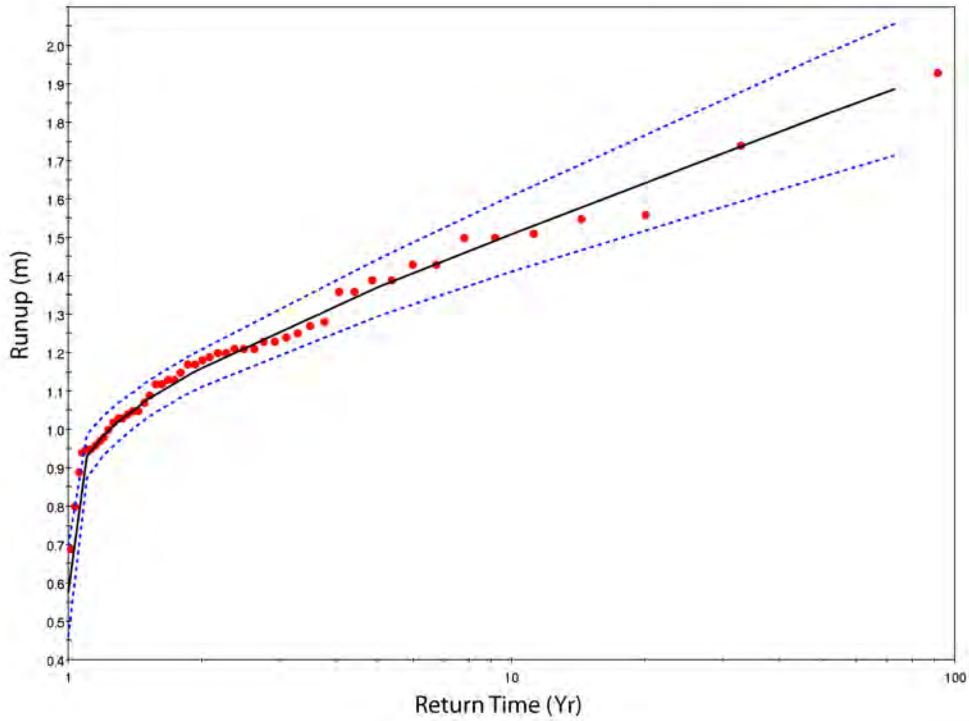


Figure 5.8. Fitted Runup to an Extreme distribution (Fisher-Tippett) whit a correlation of 0.9923. The blue lines corresponds to 0.95 confidence band

From this distribution we obtain the runup values for the specific return periods. Comparing the two methodologies, it is possible to observe that the Response method provides highest values, and would be the most suitable method for application in this type of work. This is because based on the discussion of the previous chapter, the event approach may present problems associates to uncertainty; also the estimations given by the response approach are more conservatives and therefore tend more to security (Table 5.6 & figure 5.9)

Table 5.6. Comparison between runup height
with same return periods for the two approaches

T_r	***Ru Event*** (m)	***Ru Response***(m)
2	1.03	1.16
5	1.15	1.37
10	1.26	1.51
25	1.44	1.68
50	1.58	1.81
73	1.67	1.89
100	1.74	1.94

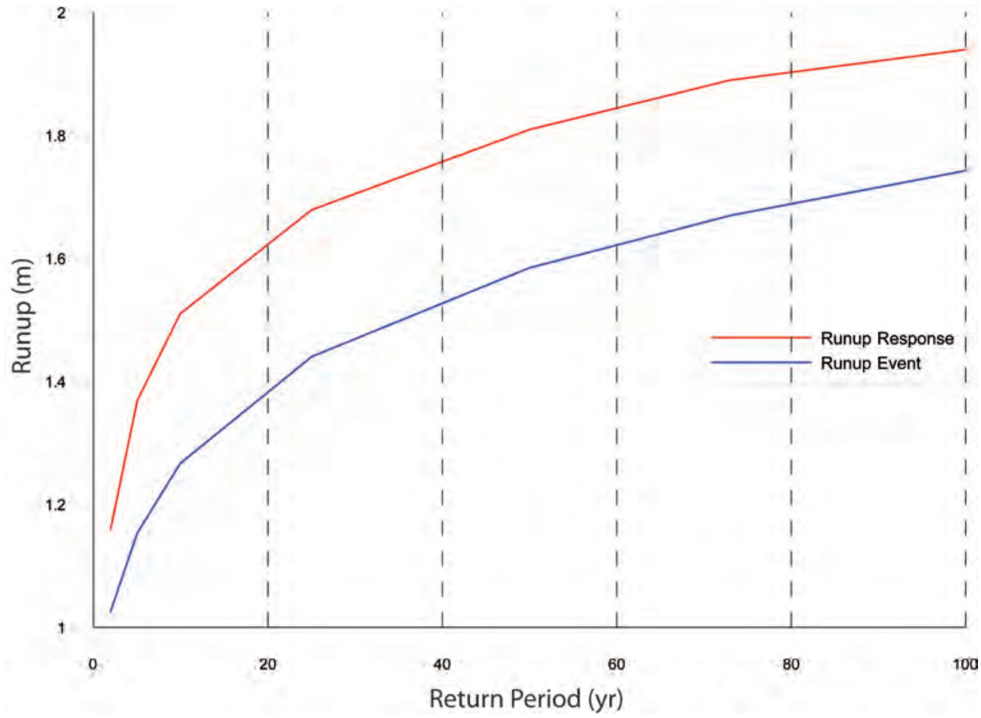


Figure 5.9. Graphic comparison, the differences are at least 25 cms

As we can see from these results, the final values can differ in more than 20 cm, and considering that the runup, is not the final response, since it represents only the TWL, but does not involve beach erosion. The final flood depends entirely of the overtopping, that is due to the combination of the TWL and the beach height. Therefore a third approach was proposed, in which the value obtained by the subtraction of minimum height of the beach profile from the maximum runup height is considered proportional to the final overtopping; therefore we have the final response that causes the flood. This is condensed in the next formula

$$Q \approx \Delta z = (Ru + StormSurge) - Z_{beach}$$

These values fitted a Weibull k=2 distribution with a correlation of 0.9864. So we have as final result an extremal distribution in which the return period of the storms can be associated to the overtopping (figure 5.10).

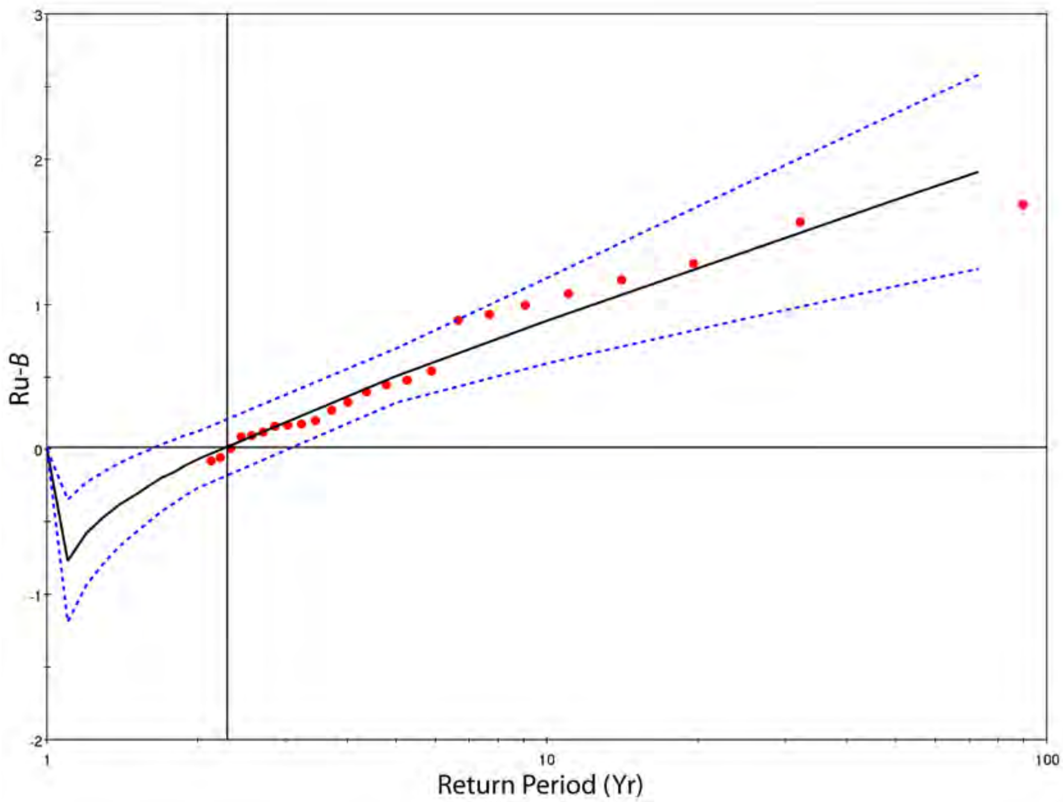


Figure 5.10. Fitted ΔZ to an Extreme distribution (Fisher-Tippett) whit a correlation of 0.9864

From these results it is clear that events associated to return periods of less than or equal to 1.5 years, the beach would not be exceeded, while for larger values, the excess of runup and hence, the volume and overtopping and water entering the hinterland would increase, at the same time as the return period increases.

The last step is the reconstruction of the simulated storm climate from the previous data. To do this we calculate the variation of these values in order to fit a triangular shape, starting from values of 2 meters of wave height and a 5 seconds wave period. This is done in order to obtain a simulated storm climate in which the growth and decline of the values of wave height and wave period are in a linear and continuous way

The table 5.7 resumes the information upon which the simulated storm climates were generated. The 500 years return period storm, was also calculated in order to define a very extreme episode. Also is included the storm from November 2001, as is the most significant storm recorded in the study area.The figure 5.11 illustrates the storm climates that were used for this work.

Table 5.7 Simulated Storm Climates.

T_r	*Year*	H_s (m)	T_p (s)	ζ (hr)
10	*1984*	*3.60*	*7.73*	28.15
50	*1980*	*5.13*	*12.92*	*84.71*
100	*2001*	*5.92*	*12.92*	*100.14*
500		*7.05*	*14.84*	*129*
Nov 2001	2001	*5.95*	*15.5*	*160*

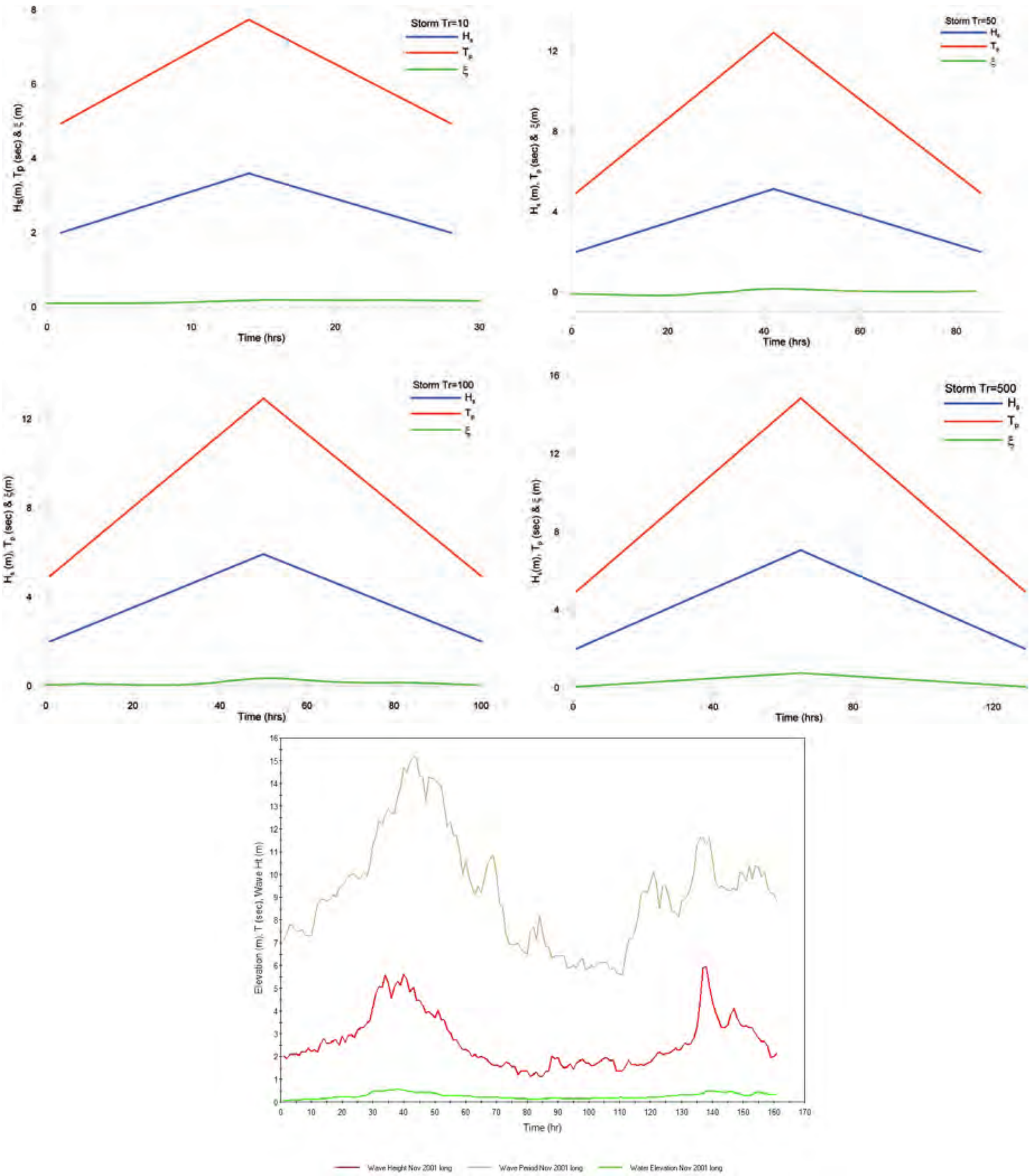


Figure 5.11. Simulated storm climates obtained from response-approach, with return periods of 10, 50 and 100 years.And November 2001 storm. All storms begin with an H_s of 2 m and T_p 5 seconds

5.4.2 Profile Response

Traditionally the coastal response was considered almost zero and implicitly has been assumed that the coast is a solid basement. But the truth is other; the coastal zone is protected by a cordon of beach that does not have these features. The beach reacts to the force of waves during extreme events and changes rapidly its dimensions and profile, and this may affect the storm-induced inundation. To test the proposed methodology and know how this coastal response affects to subsequent conditions, such as flooding and how the selection of a morphodynamic affects our final results, several analysis to compare the profiles suggested in Methodology Chapter 3 were carried out.

The main objective of the section is to test the different coastal morphodynamics approaches. For this study we have restricted the analysis to the simulation of flooding to the northern part of the Ebro delta to reduce computational cost. In this area we observed significant overwash during the simulated storm, and is one of the most sensitive areas to the impact of storms and “frequently” experiences temporary inundation of the deltaic plain (Jiménez *et al.*, 2005; 2008)(see figure 5.12)

Figure 5.12. Northern part of the Ebro delta coast (La Marquesa beach) just after the impact of the storm of November, 2001. The Photo correspond to the area of Gorg del Bou and Casa del Prats

Along this coastal stretch we have information on the natural variability of four representative beach profiles. The available data covers the evolution of these four profiles (named as 31 to 34 from south to north, see locations in figure 5.13) during four years during which a significant storm with a return period of about 100 years impacted the coast. This information is usefull to characterize the statistical approach and reinforce the notion of variability. The profile characteristics are summarized in table 5.8.

Figure 5.13 Marquesa Beach. Delta Ebro. The red lines represents the beach profiles, named as 31 to 34 from south to north

Table 5.8 Characteristics of beach profiles

Beach profile	Average Height	Maximum Height	Minimum Height	Average Slope (tanB)
31	1.41	2.11	0.85	0.011
32	1.14	1.59	0.26	0.019
33	1.14	1.52	0.77	0.015
34	0.77	1.54	0.15	0.022

The selected event to test the described methodology was the one associated to a return period of about 100 years. This was selected because it is extreme enough to produce a significant flooding and especially because it is expected that under these conditions there is a significant morphodynamic response, additionally we have a detailed record of a storm of such characteristics. This storm was recorded in November 2001 and produced a significant erosion and inundation along the Ebro delta coast (see Jiménez *et al.*, 2005; 2008). This storm had a duration of 161 hours, a maximum wave height of 5.95 meters, 15.2 second of wave period, and the storm surge associated reached 0.54 cm.

The first task to test the influence of the beach morphology on the different parameters controlling flooding was to obtain for each beach profile three representative states: mean, maximum and minimum. These states will be herein after called as *profile scenarios* and they have been obtained by statistical analysis of all the existing data for each profile. Thus, the *mean* corresponds to a simple averaging of all the existing data of a given profile; the *maximum* is a hypothetical configuration given by the upper limit of the envelope of all the data of the corresponding profile and *minimum* is the hypothetical configuration given by the lower limit of the envelope. Teorically, the *maximum* would produce a configuration that protects most the hinterland from flooding and the minimum which gives less protection.

Once we have the different scenarios defined in terms of beach profile configurations, first we estimate the variation in the period of beach overtopping during the storm due to definition of pre-storm beach morphology. Table 5.9 shows the obtained exceedance times for the different profiles, defined as the storm time period during which the total water level (here limited to the wave runup, $R_{2\%}$) exceeded the beach height. It is necessary to consider that was assumed that no variations exist between the slope profiles and therefore the only source of variation is due to changes in elevation of the profile

Table 5.9. Periods of effective beach overtopping (R2% > beach height) for the different profile scenarios along the Northern part of the Ebro delta coast for 2001 storm.

Profile	Max (hours)	Min (hours)	Mean (hours)	Variation Coefficient (%)
31	10	160	38	395
32	29	114	69	123
33	29	111	70	117
34	29	160	100	131

Thus, by measuring the differences in overtopping conditions in terms of a pseudo-coefficient of variation ([*Tmax-Tmin*]*100 / Tmean*), we find that the uncertainty introduced in the flood analysis due to coastal geomorphology (only referred to the duration of overtopping conditions) should vary from a minimum value of 117 % (profile 33) up to a maximum of

395 % (profile 31). Taking into account that this time duration is a critical issue to calculate the total volume of water entering the hinterland. The impact that the proper selection of the pre-storm profile will have in the final results is evident.

These calculated variations are strongly dependent on the natural profile variability, decreasing in importance for low-response coasts. Also there will be a range of storms in which this response will be more visible. In extreme conditions (minimum or maximum) the changes will be smaller than average conditions. However, low-lying sandy coasts, as the one studied here, are highly dynamic environments and, in consequence, although obtained values are strictly valid for analyzed conditions; they can be used as an order-of-magnitude of the expected variations. With respect to the spatial variations along the studied coastal stretch, obtained results show a relatively low variability. Thus, obtained coefficients of variation for each scenario range from a minimum value of 20.1% for the worst scenario (profiles defined with the minimum shape) to 39.2 % for the safest one (profiles defined with the maximum shape).

This should indicate that the morphological consequences of coastal dynamics on beach configuration are relatively alongshore uniform, especially when high energetic events (those determining the minimum profile scenario) are considered. Moreover, for our study area these results should also indicate that the uncertainty introduced in the analysis due to the use of a single profile to represent the entire coastal stretch should be much lower than the associated to the selection of the configuration of such profile.

Once the duration of overtopping events was determined, the next step was to compare the magnitude of such events. Table 5.10 and figure 5.14 show calculated mean overtopping rates (averaged during the duration of the storm) for each profile scenario.

Table 5.10 Mean overtopping rates (averaged along the storm duration) estimated for the three beach profile configurations in the Northern part of the Ebro delta coast for november 2001

Profile	Max Q (10^{-3} $m^3/m/s$)	Min Q (10^{-3} $m^3/m/s$)	Mean Q (10^{-3} $m^3/m/s$)	Variation Coefficient (%)
31	0.292	14.356	1.038	1355
32	0.733	3.947	1.978	162
33	0.853	2.918	1.796	115
34	0.811	5.345	2.506	180

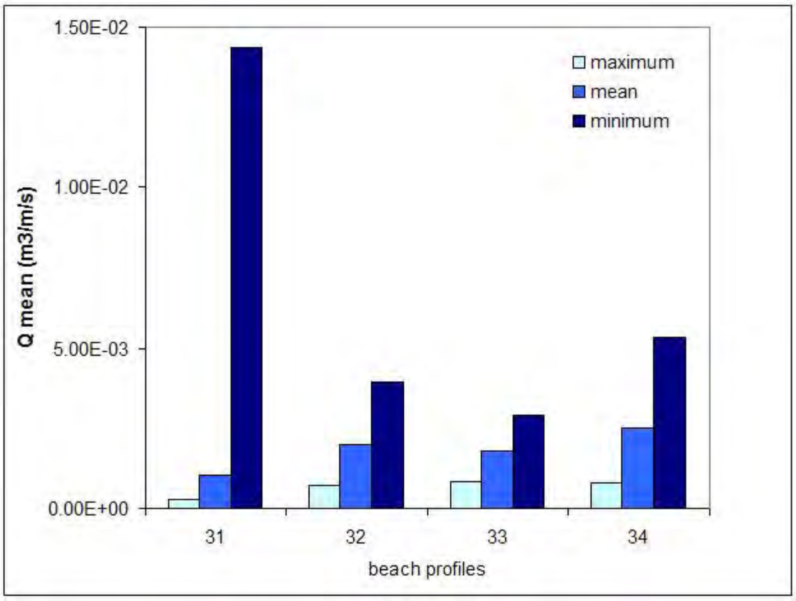


Figure 5.14 Mean overtopping rates (averaged along the storm duration) estimated for the three beach profile configurations in the Northern part of the Ebro delta coast for Novembre 2001

Obtained results show a similar behavior to the calculated for the overtopping periods. Thus, when different profile scenarios are compared, a large variability is again detected, with the pseudo coefficient of variation ranging from a minimum value of 115 % (profile 33) to a maximum of 1,355 % (profile 31). This huge increase in the variation for profile 31 is due to dependence of the overtopping formula on the beach height (freeboard). Because the worst scenario (minimum configuration) for profile 31 corresponds to a really eroded and low profile, overtopping rates dramatically increase.

This indicates that the above estimated uncertainty for the overtopping period could be significantly amplified when converted to volume of floodwaters.

When mean overtopping rates are compared along the coast for a given scenario, they also show a similar behavior to the ones observed for overtopping periods, i.e. a much lower variability than the observed as a function of the profile configuration. Thus, calculated coefficients of variation are of the same order of magnitude with a minimum value of 33.31 % to a maximum one of 78.86 %. Again, there is an increase for the worst scenario (minimum profile) due to the already mentioned sensitivity of the overtopping formula to beach height.

In practical terms, these results show that, similarly to the case of overtopping periods, the uncertainty introduced in the analysis due to the use of a single representative profile for the entire coast will be much lower than the associated to the selection of the beach profile shape.

Moreover, it has also to be stressed that for the same conditions, the uncertainty in overtopping rates will be larger than in the period of exceedence for overtopping. Based on the above, coastal managers could make the selection of the different approaches and know the expected variability. We recommend the most conservative approach thinking in security .

The following task in this section, was to evaluate the previous two variables (period of exceedence for overtopping and overtopping rates) for one location along the coast (profile 32) including the simulated beach response during the event (table 5.11). In addition to the mean overtopping rates (averaged during the event), we have included the peak discharge during the event.

Table 5.11. Calculated overtopping rates during the storm of November 2001 along the Marquesa beach for the different scenarios (peak: at the storm peak; mean: storm-averaged; Flooded area: after 10 hours of continuous overtopping).

Profile scenario	Q peak (10^{-3} $m^3/m/s$)	Q mean (10^{-3} $m^3/m/s$)	Flooded area (ha)
Mean	16.811	1.978	43
Maximum	6.653	0.073	26
Minimum	32.717	3.947	57
Evolving Beach response	55.736	7.403	74
Variation Coefficient (%)	291	370	112

As it can be seen and as it was expected, the inclusion of the beach evolution during the event results in an increase of overtopping rates, from 0.073 in the maximum profile to 7.403 in the beach response. The magnitude of the calculated overtopping is increased about 1.7 times the value for the previously defined as the worst scenario (minimum configuration). These variations are reflected in the flooded area, which go from 26 ha to 112 ha (112 % of area variation). The overtopping rates can have variations of 370% between approaches in the overtopping mean, and 290% in the peak. This means that even selecting the worst scenario for static-oriented (fixed beach profile) FHM in low-lying coasts, the volume of floodwater entering the coastal plain would be significantly underestimated. This is illustrated in figure 5.15 through the comparison of the runup during the storm (assuming beach slope changes are small enough to modify it) taking into account beach height for both the static (a given profile maintained fixed throughout the analysis) and the dynamic (simulated beach evolution) approach.

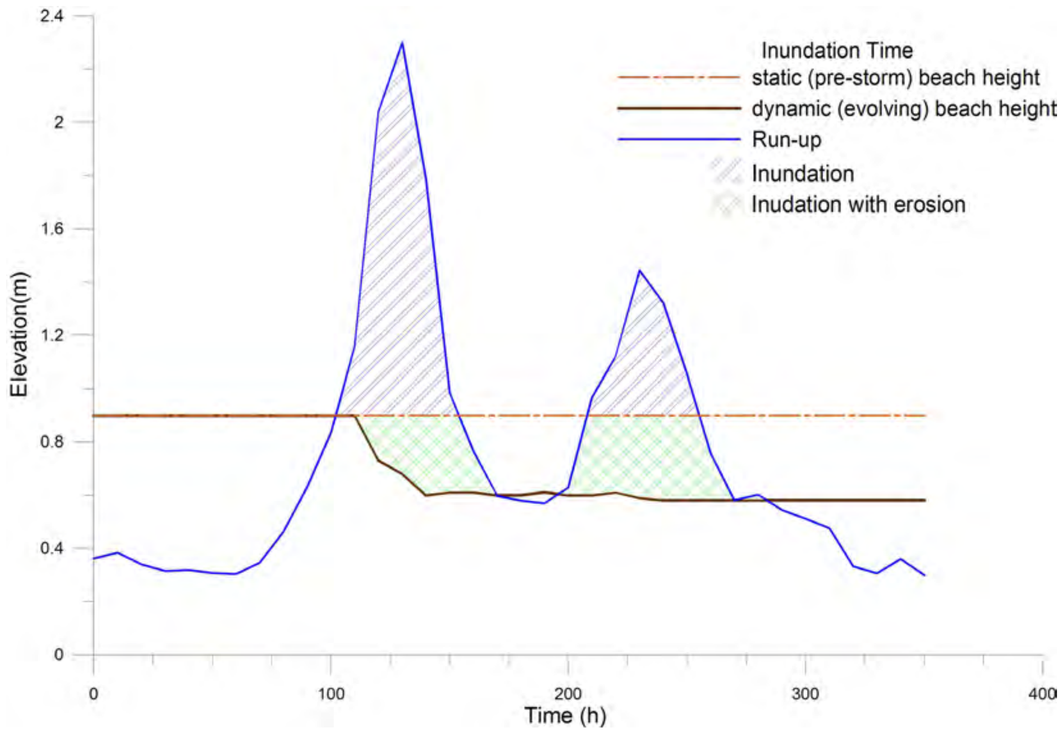


Figure 5.15. Runup vs beach elevation during the target storm for static and dynamic beach configurations.

Figure 5.16 shows the importance of the proper selection of the pre-storm morphology, this result stresses the importance of including the morphodynamic feedback in coastal FHM. In this case, the inclusion of coastal response during the event determined a significant increase in the volume of water entering to the deltaic plain. In consequence, the potentially affected surface also increased (74 ha) with respect to the calculated worst scenario (57 ha). The red area represents the flooding that occurs when *maximum* profile is used for the calculation (26 ha), yellow area corresponds to *mean* profile (43 ha), *minimum* profile match up to orange areas (57 ha) and green area depicts morphodynamic feedback (74 ha). The variation coefficient is about 112%, and the variations among approaches range from 285% between beach response and maximum profile, to 129 % between beach response and minimum profile. The variation between maximum and minimum amounts to 220 %.

We can say that the best option to use in the analysis of flood and coastal response is the morphodynamic response. The subsequent results of flooding and the rest of the work was obtained using this representation of coastal fringe. To illustrate the application of this technique, a SBEACH implementation is presented with the simulated storm climates and data from profile 33.

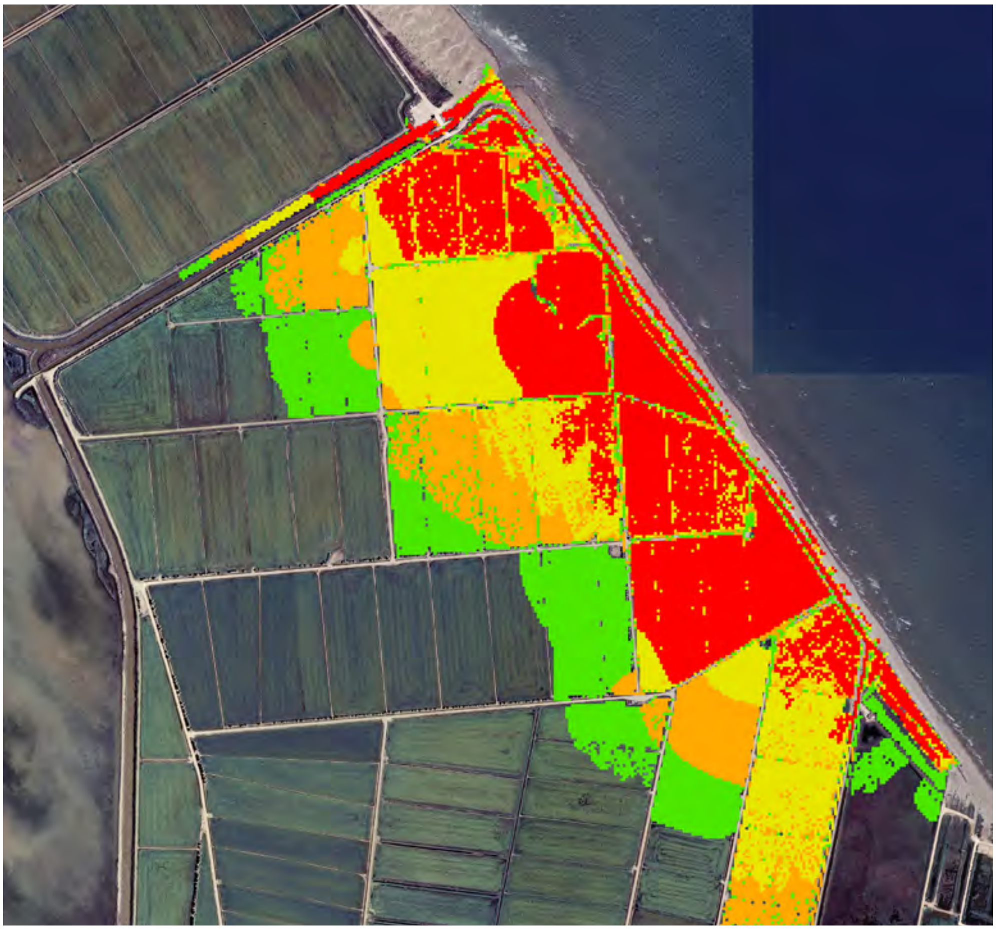


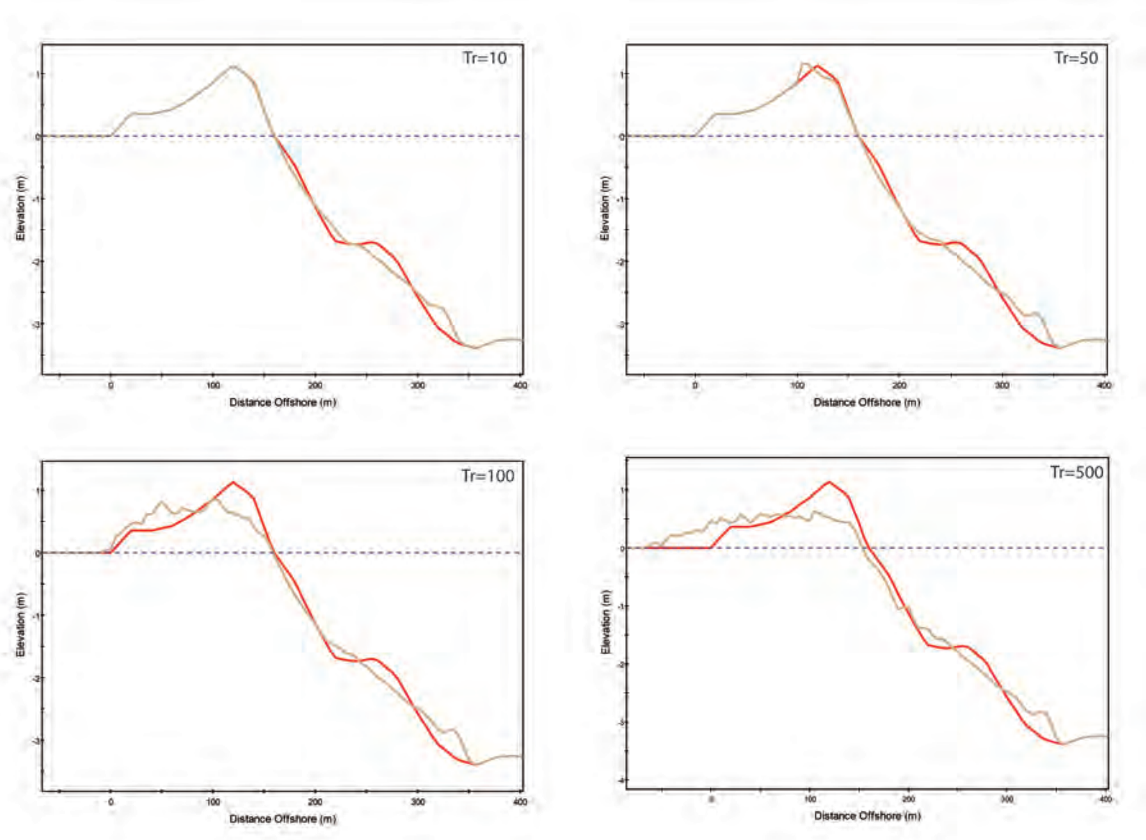
Figure 5.16. Delineation of flood hazard areas as a function of the definition of the beach morphology.

The characteristics of this coastal response (beach height) are summarized in table 5.12 where it can observed that for storms with a low return period, the erosion is nil or minimal, also for the 50 years return period storm a small accretion exists. For storms with long periods, there is a greater variation at the beach height, which means a decrease in natural protection, coupled with a beach line regression by erosion. Probably this variations would be greater, and many of the changes in height would vary due to the overwash transport model used, since this process is not very well represented, given the difficulty of finding a specific model or formula for this process. Only in case of total flood the model gives more realistic results. Figures 5.17 illustrates the above results.

Table 5.12 Coastal responses to Simulated Storm Climates

Storm (T_R)	Vertical variation (m)
10	0
50	0.02
100	0.26
500	0.60
Nov 2001	0.76

As can be seen from the results obtained from the responses to simulated storm climates, the storms with a small return period (10 and 50 years) do not generate remarkables changes in the configuration of the beach (in the emerged beach because the stronger variations are in the submerged beach). These changes in the inshore can induce changes in the slope, which would affect the attack of waves. The latter would change the range of the runup and cause variations in the final overtopping, hence it should be taken into account. In our case, this was considered during calculations to determine the overtopping values. The model used to determine the shoreline response allowed us to obtain intermediate beach profile values (from both emerged as submerged) from which slope variations were further calculated. Furthermore storms with longer return periods present variations in both emerged and submerged beach. A point to stress is that the November 2001 storm caused major changes, this can be attributed to the increased storm duration.



Figures 5.17. Morphodynamic response of the profile 33 to the simulated storm climates

5.4.3 Inundation

After testing the different methodologies and selecting both the most appropiate methodology and the input data to be used in this work, we proceeded to calculate the areas of the Ebro Delta which could potentially be flooded in case of coastal storms. The input data for this will be the simulated storm climates that corresponds to forcings that cause the floods. When determining the receptor area inundation, beach profiles representative of the study area and DEM are employed. Therefore from this information the water flows that may enter the hinterland and cause the flood are determined.

The first task was to extend along the coast the runup and overtopping calculations done for representative profiles. To do this and according to the site characteristics and existing knowledge about spatial variability of morphodynamics process in the area (Sanchez-Arcilla *et al.*, 1988), we have assumed the existence of an alongshore semi-uniformity in morphology and response. Thus, each profile is considered to be representative of a coastal stretch of about 1 km. With this assumption, the total floodwater entering the hinterland across the beach will be the overtopping rates estimated for a given profile extended along the corresponding stretch. Although there are morphological evidences of alongshore uniform response of the study area under the impact of extreme storms (Jiménez *et al*., 2008), this introduces some uncertainty in the final extension of the flooded area. This is inherent to coastal flood analysis in sedimentary environments (coasts naturally protected by natural beaches/barriers) since (accurate) morphodynamic modeling of overwash and breaching processes is still an open question (e.g. Kraus and Hayashi, 2005; Donelly and Sallenger 2007; Tuan *et al*., 2008; Cañizares and Irish, 2008).

These spatially-integrated overtopping rates need to be also time-integrated over the duration of the storm. When the main source to induce flooding is the wave-induced *runup*, there is some uncertainty about how to extend this pulsating process during a large period.

Once floodwater at the shoreline was estimated for the different scenarios, the remaining step was to delineate the part of the deltaic plain prone to be flooded during the event. In this step the areas or entry points where the height of the dune is less than the runup and therefore the overtopping can enter and flood the backshore (figure 5.18) were identified. These points represent places where the height of the beach or the dune is smaller than the runup, or could be eroded under the runup level.

Figure 5.18. Entry points for the overtopping. This points represent places where the high of the beach or the dune is less than the runup, an also for the coastal response could be erode under the runup level.

After the integration of the overtopping we know the amount of water that came through the storm but we also need to know when the overflow covers the dune and thus the flood happens. Figure 5.19 summarizes in a graph the timing and intensity of flooding due to overtopping along La Marquesa beach; where the dune height and the runup, were taken into account. If dune height is less than the wave runup, a flood will take place. Finally the intensity will depend on the overtopping and it is related to the two previous agents. It is possible to observe that in the profiles between 220-250 (at the south part of the beach) the flooding is much lower due to the own beach protection (dunes).

The above data give us the knowledge about "how much" and "when" does the water enters the delta during the storm, the next step is to determine "where" (the area) this volume of water could fill the backshore. This feasible distribution is calculated by LISFLOOD-FP.

As mentioned previously, LISFLOOD-FP is a two-dimensional model that was selected to simulate the flood on the coastal plain. The fluxes integrated before were introduced as boundary conditions in LISFLOOD-FP, and consisted of time series of water levels in each of the 255 cells marking the seaward edge of the computational domain.

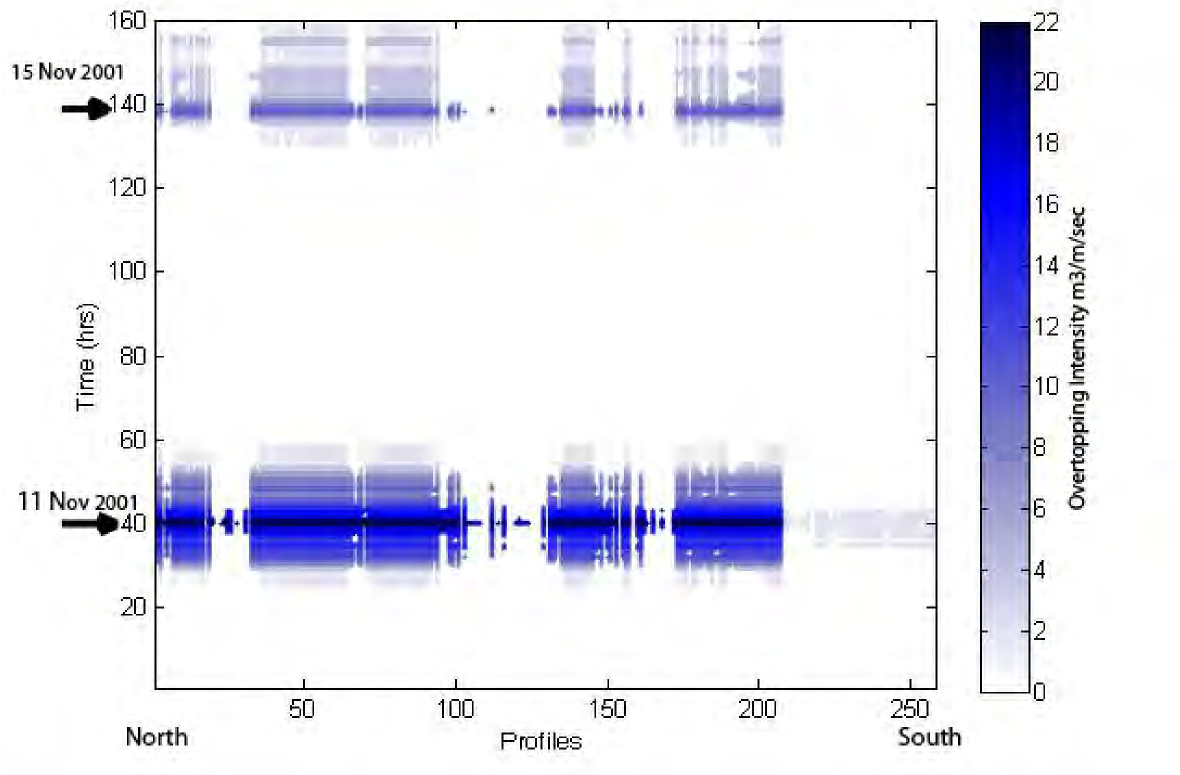


Figure 5.19. Time and intensity of the storm along the La Marquesa beach for the November 2001 storm. The X axis represent the profiles from north to south, the y axis represent the duration of the storm. Is possible observe the two peaks of the storm and the intensity of overtopping

In practice, the resolution of the DEM obtained through LIDAR is often different from the optimum resolution required for computational analysis in hydraulic flood modeling. Commonly relatively large DEM grid elements make up the model domain in order to reduce the computation time. This allows quick model calibrations and model sensitivity analysis but also, in operational mode, it allows flood forecasting in real time. A major disadvantage of the use of low resolution input data is the loss of important small-scale features that affect flood propagation. During the transformation or re-sampling of the original DEM data of relatively high resolution to a lower model resolution, important topographic details are lost mainly as a result of averaging. Therefore, there is a need to quantify the effects of averaging on model performance and, more importantly, the reliability of simulation results. Horritt *et al.,* (2001) performed such study and used topographic information provided by LIDAR survey and concluded that the spatial aggregation can affect the accuracy of modeled output. Chow (2005) investigated the impact of scale by conducting the study at varying spatial resolutions. The author found that modeled peak discharge and modeled error are affected by observational scale. At very coarse resolutions the variation of modeled discharge was less evident.

In the LISFLOOD-FP the computational cost is primarily a function of the number of wet cells and the adaptive time step. Optimum time steps varied between 5 and 2 second depending on the flow depth and water surface slopes, and showed relatively little variability between events. Computational costs were therefore largely a function of the number of wet cells (i.e. event magnitude) and the length of time taken to complete an individual simulation varied for us between 45 hr and 70 hr (for the storm of 10 years and 500 years), with a resolution of 5 meters, for the entire study area .

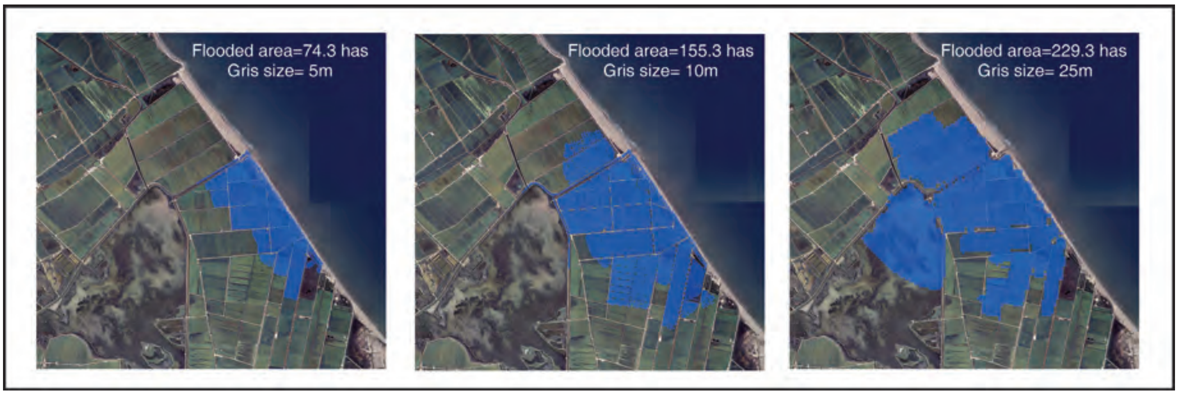
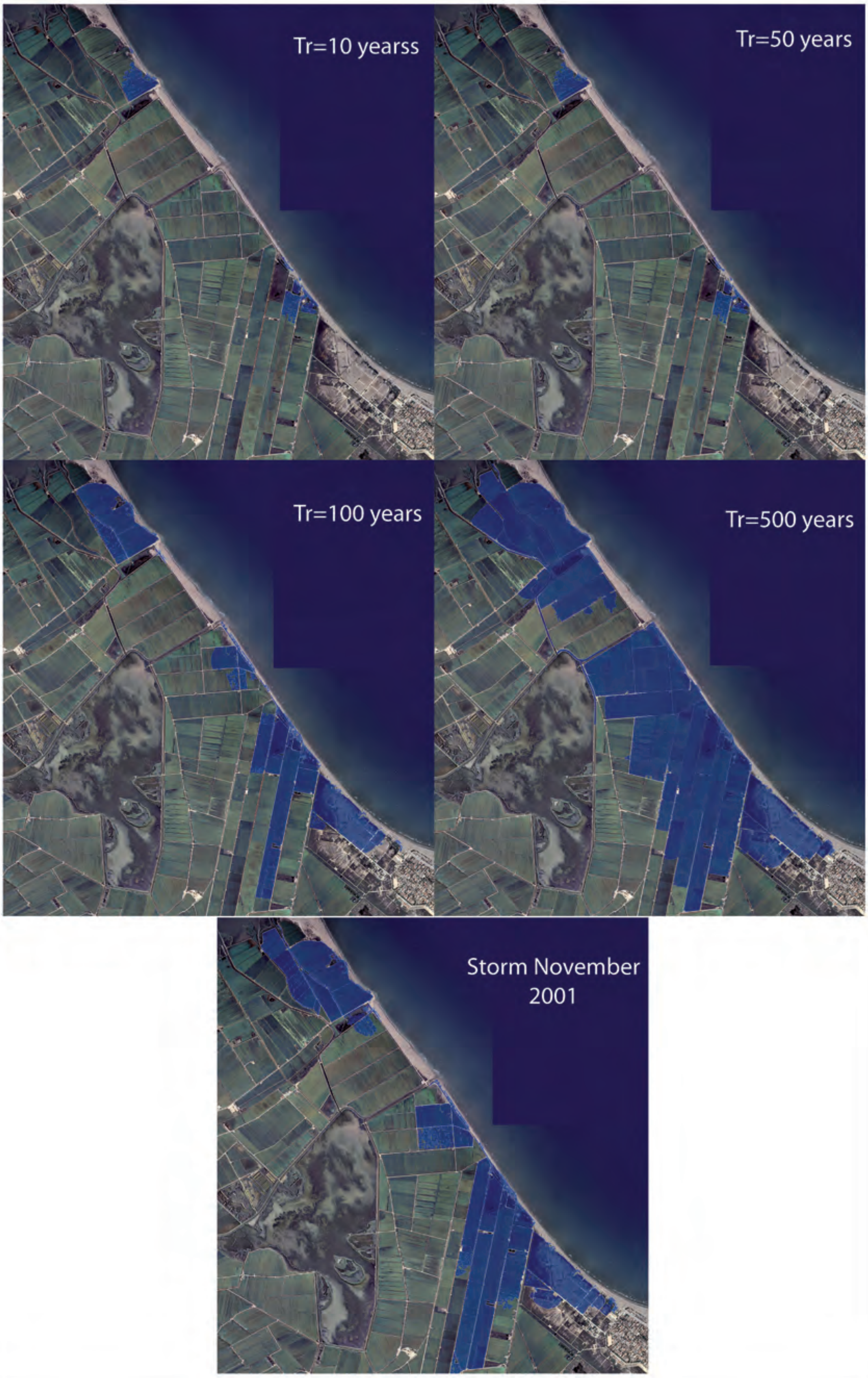


Figure 5.20 Three different DEMs resolution and the differentials in flooding areas

In Figure 5.20, we illustrate and compare the results of using different resolutions DEM`s (25, 10 and 5 meters). Using different resolutions, variations in the flooded area were found to be between 229.3 ha in 25 m and 74.3 ha in 5 m (more than 3 times in area) and for execution time between 2 hr for the 5 m resolution and 30 minutes for the 25m. It is also convenient to note that due to the nature of the model, an increasing of resolution of the DEM, can produce instability problems. To avoid this, it is necessary to implement a very small time step that gives time to the model to resolve the shallow water equations. The time step selected for this case was of 2 seconds. To reach a compromise between resolution/ precision and speed of calculation (reasonable computational cost) of the inundation of the delta, the DEM resolution was set to 5 m. This size was selected after testing the effects of the cell size in masking the effects of the presence of canals and small dikes separating rice pads.

LISFLOOD-FP outputs are in raster images, these are processed with the aid of ArcGis 9.2 (http://www.esri.com/). These files are converted to polygons and overlapped with information of the Ebro Delta (habitat, protected areas), giving the area flooded by habitat and the corresponding percentage. The final result of this phase are the maps of the study area, which provide information about the flooded area, the type of habitat affected, and its characteristics. The figures 5.21 and table 5.13 exemplify this.



Figures 5.21. Inundation in the Marquesa area due to the simulated storm climates.

Table 5.13. Flooding in the area of La Marquesa. Habitats affected and corresponding percentage of north hemidelta.

		Beach & Dune	Cropland	Riparian Buffer	Saltwater Wetland	Saline Vegetation	Total
T10	He	0.24	14.96	0	1.48	0	16.68
	%	0.04	0.14	0	0.45	0	0.14
	%PN	0.02	0.58	0	0.32	0	0.22
T50	He	0.57	78.36	0	4.11	21.79	104.83
	%	0.10	0.75	0	1.24	8.13	0.85
	%PN	0.03	2.88	0	1.31	0	1.02
T100	He	1.22	111.96	0.08	4.63	32.70	150
	%	0.20	1.08	0.04	1.39	12.20	1.22
	%PN	0.03	3.11		1.45	0	1.10
T500	He	1.406	405.82	4.9	5.66	57.94	475.74
	%	0.23	3.90	2.56	1.71	21.62	3.86
	%PN	0.17	6.52	2.88	1.62	0	2.32
Storm Nov 2001	He	1.407	202.17	1.729	5.065	41.98	252.35
	%	0.23	1.94	0.90	1.52	15.66	2.05
	%PN	0.04	4.81	0.85	1.52	0	1.63

After the coastal storms flooding analysis in the La Marquesa area, we found that there is a change in potentially flooded area ranging from 16.68 ha for the storm of 10 years to 476 ha in the storm of 500 years. Consequently, the most vulnerable area to be flooded most of the time (high probability) are the zones adjacent to Los Vascos and the saline Casa dels Prats. While the area with the least probability to be flooded will correspond to outlying areas near the urban Riumar.

The most affected habitats due to floods are the cropland and saline vegetation followed by saline wetland, beaches and dunes, in last place and with less affectation we have the Riparian buffer (see table 5.13). This degree of affectation is mainly due to the predominance of cropland as a major habitat of the delta, and the smallest area occupied by the other habitats. Also, the Natural Park area damaged by flooding is not serious, when compared to the total area of the park. Additionally, beaches and dunes, with the capacity of withstanding the inundation process have been taken into account.

At hemidelta level the flooded zone does not represent more than 4% of total area, but the area near the coast (a buffer of 500 meters wide was taken into account, to include the influence area of the storms in the delta) may represent more than 90% in case of flooding due to Tr = 500.

When combining the information of the all scenarios of return time storms and put together in a map, is possible to delineate the range of potential areas of flood risk based on the return period. The red area represents the most probable area that can be inundated, and the green represents the least probable. Figure 5.22 illustrates this.

Figure 5.22. Superposition of Potential flood areas, for different return periods.
Red color correspond to 10 year, Orange to 50 year, Yellow to 100 year, and Green to 500 years.

The range of flood hazard areas should allow to estimate the uncertainty in the calculations associated to the selection of the storms. The hazard area can be drawn not only as a single surface but, as an area with confidence bands. The decision on what surface has to be selected would depend on the purposes of the analysis and in the level of "safety" to be imposed.

The possibility of conducting a cross between scenarios of RSLR and storms was raised, but because the area presents a very low-lying coast as seen in chapter 5.3, only considering RSLR this area was flooded for any RSLR exceeding 35 cm, so the storms would not affect the area. The only possible variation is that in a scenario of permanent inundation, the storms can impact more inward and affect also the flooded area.

5.4.4 Vulnerability to Coastal Erosion for Extreme Storms.

The flooding in the coastal zone is not only related to variations in the height of the coast, but also with the width of the beach. This measure combined with the erosion lets us know the resilience that has the beach. The state of the beach is directly related to its flood protection capacity of the hinterland. An indicator of Vulnerability to Coastal Erosion for Extreme Storms is proposed, this indicator give us the posiblity to relate to beach state or beach resilience with the inundation of the hinterland.

As mentioned earlier in the chapter of methodology, the calculation of the vulnerability indicator by erosion is defined in terms of beach width, erosion associated with the storm and variability over time. The graphic results of this indicator and also its association with the backbeach habitats are show below.

For the calculation of the vulnerability indicator, the input data were taken from: the orthophotos of ICC 2008 (beach width for La Marquesa area (W)), the DEM (beach profiles data), and also the SBEACH model in which was measured the shoreline retreat for the simulated storm climate with a return period of 10, 100 and 500 years (Δx). In addition, it is considered that a retreat of the coastline from erosion at a rate of three meters per year (δw / δt) exists, and it does not change along time (Jiménez & Sánchez-Arcilla, 1993). An extra consideration is that the beach width associated to the representative profiles measured used in the SBEACH behave in a similar manner.

The VuCEES is calculated for different scenarios of erosion (same rate of erosion, but different intervals of time). The results for the storms with returns periods of 10, 100 and 500 years are presented here. The next figures show the combination between storms and the erosion rate scenarios. Figure 5.23 summarizes in graphical form the VuCEES values for the different stage of coastal erosion. Then, the figures 5.24, 5.25 and 5.26, transfer these values to the field for their association with the corresponding beaches

The figure 5.24, presents the vulnerability levels to the storms of 10, 100 and 500 years of return period of the actual beach configuration. In general, is possible to say that this scenario presented a range of low to high values. Only three areas are considered to exhibit high vulnerability to coastal erosion, two in the beach of Bassa de l'Arena, situated in Gorg del Bou and Muntell de l'Ordi, and also the one located in the northern part of Los Vascos. For the largest storm, the beach that presents the highest levels of vulnerability to coastal erosion is Bassa de l'Arenas, while the beaches Riumar and Marquesa have the lowest levels of this range.

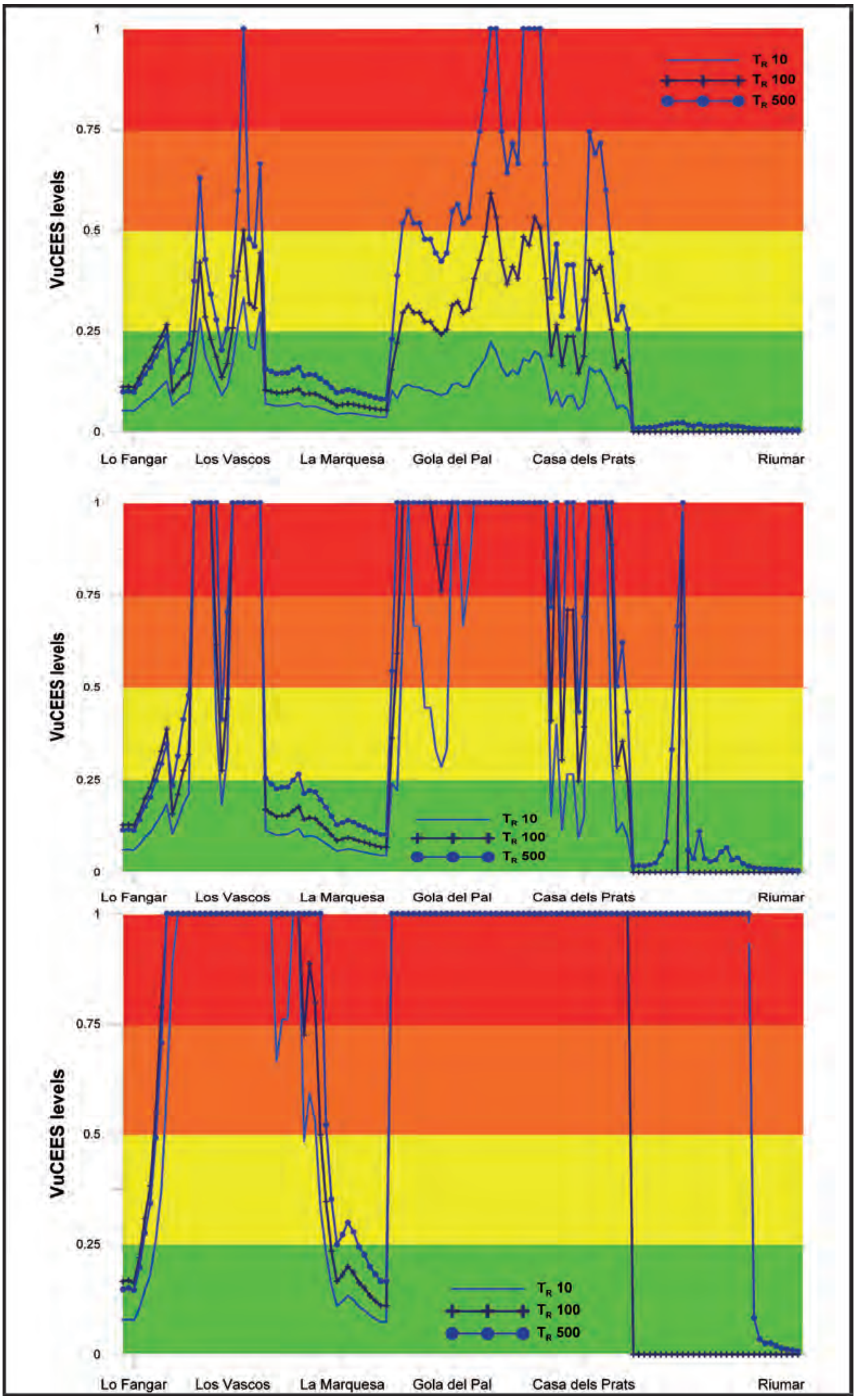


Figure 5.23 VuCEES Levels for the storms with 10, 100 and 500 years of return period. Actual Beach configuration in the top, Beach with 10 year of erosion in the middle, and Beach with 25 year of erosion on the bottom.

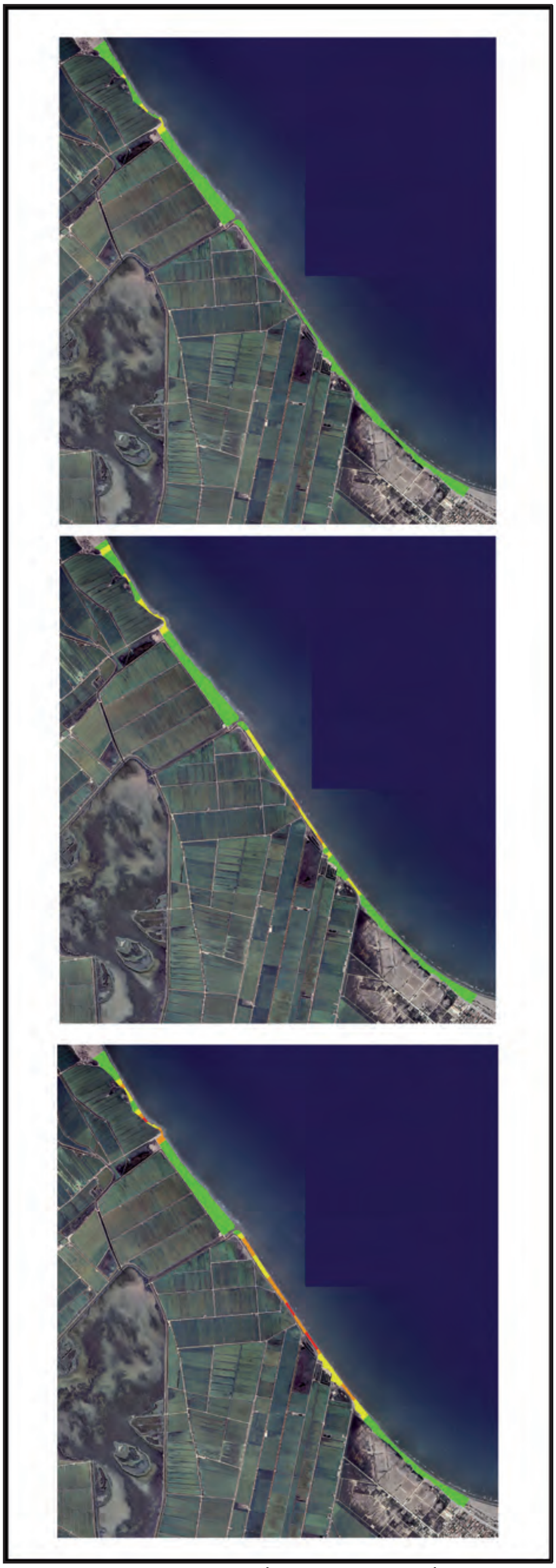


Figure 5.24. VuCEES Levels to storms with 10, 100 and 500 year of return period. Beach at present time.

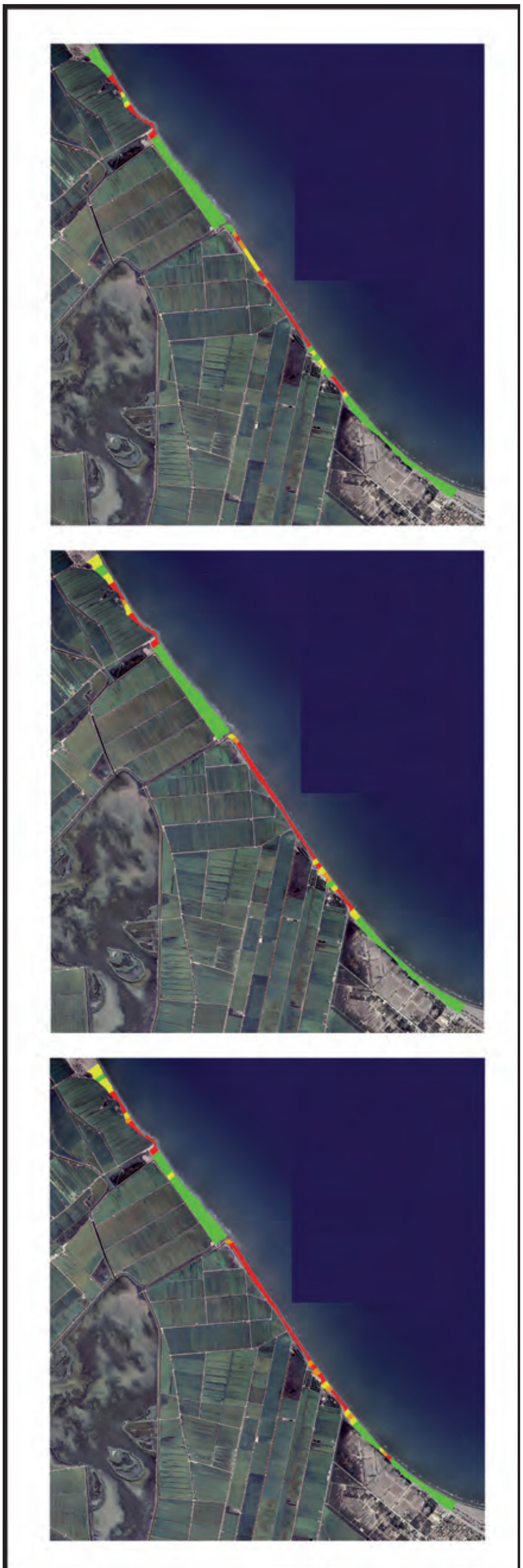


Figure 5.25. VuCEES Levels to storms with 10, 100 and 500 year of return period. Beach at 10 years of erosion.

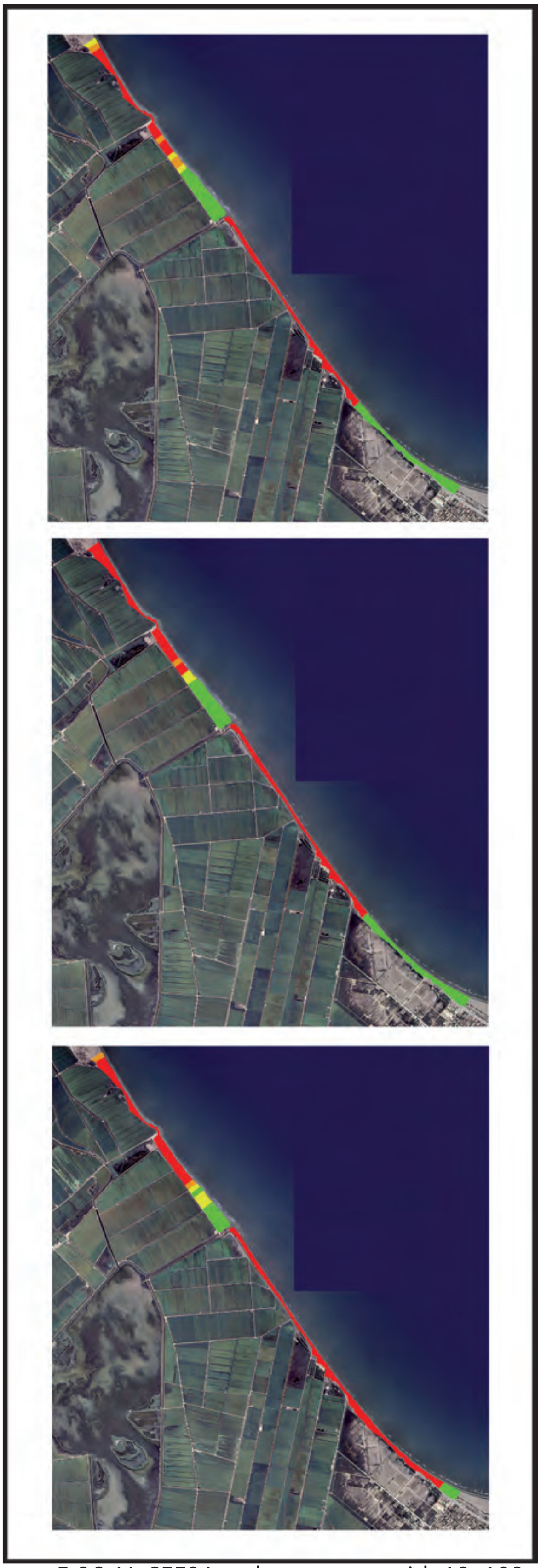


Figure 5.26. VuCEES Levels to storms with 10, 100 and 500 year of return period. Beach at 25 years of erosion.

The figure 5.25 shows the vulnerability to coastal erosion levels if we have a retreat of the shoreline equivalent to 10 year of erosion. Which implies a reduction in the capacity of the beach to withstand the storms, and in some areas almost the total disappearance of the beach. In this case, the three scenarios present areas of high to very high vulnerability to coastal erosion. Very high values are concentrated in the beach Bassa de l'Arenas, and north of Los Vascos, while the beaches Marquesa and Riumar still present low levels of vulnerability

To end with this series, the figure 5.26 shows the scenario of 25 years of retreat, and the levels of vulnerability associated to the response to storms. In this case, as expected by the large regression on the beaches, vulnerable areas are located throughout the study area. The very high vulnerability levels due to the storm of 10 years are found in the area of the Bassa de l'Arenas, and the area between Los Vascos and Lo Fang. Marquesa beach which in previous cases had low vulnerability levels, in this case, its northern part presents medium to high VuCEES level. In the extreme case of 500 years, only the south area, close to Gola del Pal, have low VuCEES levels. Riumar on the other hand, goes from low to very high levels, and it is in the northern part near Casa del Prats where very high levels are present. In the maximum event, the only area with low values levels for Riumar Beach is located in the extreme south.

Summarizing the results of VuCEES in the area, we have that beach area between Lo Fangar and north of the Los Vascos, presented a higher level of vulnerability to coastal erosion for the three storms. In the next rank with high vulnerabilities was the beach area between la Bassa de l´Arena and Casa dels Prats. It should be noted that when the analysis to determine the entry points for the LISFLOOD-FP model was performed, a big fraction of these points were located in these areas. On the other hand, the beaches located between Los Vascos and Gola del Pal, and the Riumar beach are those with the lowest VuCEES.

The beaches with low level of VuCEES, that could be more secure against flood, are located in the north of the Gola del Pal and south of Riumar beach. This low level is mainly due to the beach width because having a wide beach, allows resilience to erosion to be increased, and therefore flooding associated with erosion, goes also down. These lower levels of VuCEES do not imply that the area at backbeach is unable to present problems due to flooding, since there is a flood risk for less protected neighboring areas.

To associate values of VUCEES with habitats in the backbeach, kilometers of each habitat, either associated or adjacent to each level of VUCEES, were measured. With the foregoing we can establish what habitats may be exposed or may be susceptible to be damaged by coastal flooding; being the main protection the beach itself. In the table 5.14 the results for the three VuCEES scenarios with the storm of 100 years are summarized. This storm was considered the midpoint for erosion and damage (the 10 year does not cause too much disaster, and the 500 years the damage is extremely large)

The capability to determinate zones with levels of vulnerability to erosion, which is directly related to flooding due to coastal erosion, allows us to have a synergistic analysis of the flood and its relation to coastal erosion. So we can know in advance the risks present in the area, which we must fight for an efficient management of the environment today and in a long-term planning. For this analysis the VuCEES indicators levels were combined with the flood maps in the backbeach, so we obtained maps that cover the area of flooding for a given storm. The beach was considered to be a protection for the backbeach or the main entrance of flood water. It is possible to associate the levels of VuCEES in the beaches, with the inputs of water for the flood.

The following figures represent the flooding for storms with a return period of 10,100 and 500 years, and the color bars are the levels of VuCEES for the current time, 10 and 25 years (located from the beach to the sea)

In the following figures (figures 5.27) we can see that in general, the VuCEES high levels for this scenario match with the input points or the breach areas were the flood star. We must consider that the flooding methodology involves the coastal response inside the final calculation of the flooding areas. And for this scenario (present time), the sum or integration of the flood with the VuCEES was not taken into account as it would be repetitive.

In addition when we link the inundation areas with the breach points, we have that even though there are areas with low levels of VuCEES (consequently protected), those areas could undergo flooding, if are near or adjacent to other areas with high levels of erosion and consequently a entrée of high quantities of water.

On the other hand, we can use the scenarios of VuCEES corresponding to 10 and 25 years of potential erosion, and based on the high levels of VuCEES, locate the areas of the beach that will have less protection to the backbeach.

Table 5.14. Kilometers of habitat for VuCEES level

		VUCEE Levels on the adjacent beaches			
Habitats in Beach (kms)		Low	Medium	High	Very High
Present & Tr 100	Cropland	1.92	1.50	0.10	
	Saline Vegetation	1.43			
	Saltwater Wetland	0.17	0.15	0.10	
	Riparian Buffer	0.04	0.06		
t=10 & Tr	Cropland	1.17	0.38	0.11	1.86
	Saline Vegetation	1.33	0.10		
	Saltwater Wetland		0.10	0.09	0.23
	Riparian Buffer	0.04		0.06	
t=25 & Tr	Cropland	0.50	0.10	0.04	2.88
	Saline Vegetation	1.29			0.15
	Saltwater Wetland				0.42
	Riparian Buffer				0.10

VuCEES Scenarios linked to the flooding scenarios, give us information of the areas of breaking or inflowing for a flood. This knowledge allows the coastal manager to consider long-term areas where to put more attention, in the management of protection or retreat of the coast line.

We can mention the existence of a feedback between VuCEES and floods, since a high VuCEES levels increases the possibility of flooding. Since strong erosion, can modify the coastal morphology and decrease the protection that this area gives to the backbeach, the flood areas could increase. It is desirable to develop a methodology that takes into account the rates of coastline retreat to long-term in the calculation of the storm flooding.

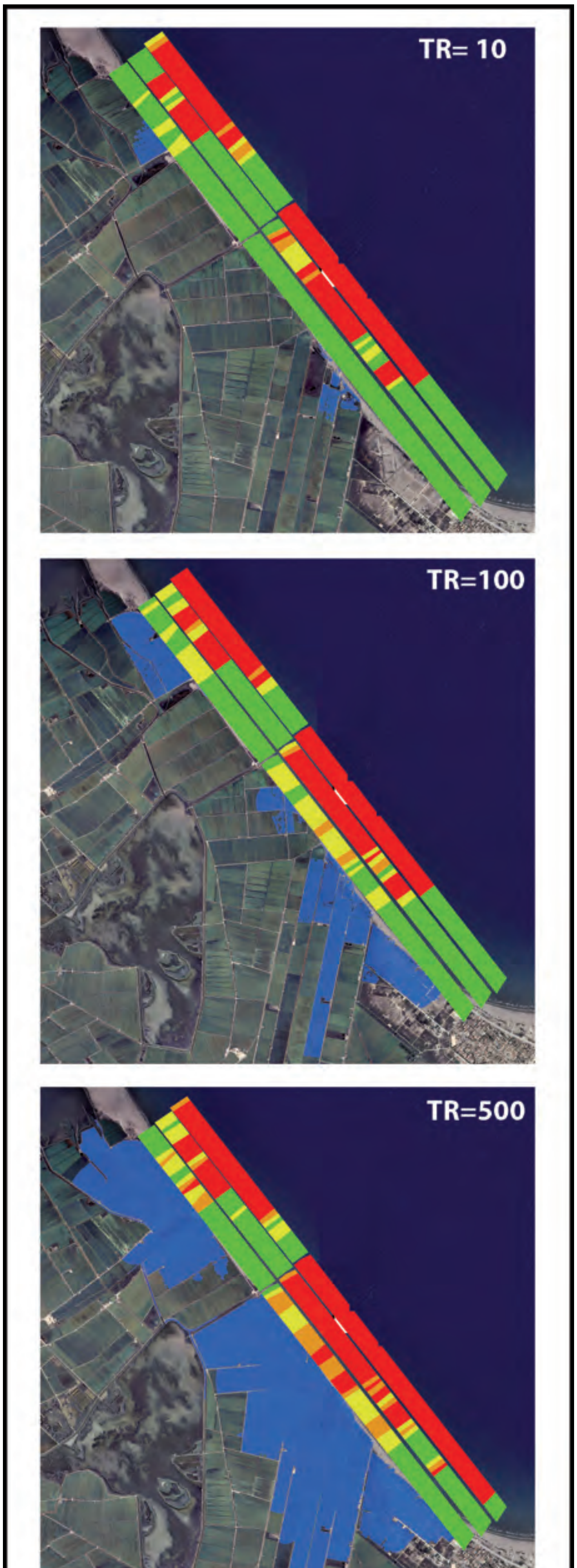


Figure. 5.27 VuCEES plus Inundation. Flooding for storms with a return period of 10,100 and 500 years. Color bars are the levels of VuCEES for the current time, 10 and 25 years (from the beach to the sea)

5.4.5 Damage Assessment

Economic Damage Assessment

To assess the damages associated to floods in our study area, three different scenarios of "damage or loss" were considered. The first scenario considers a "total loss". This imply the destruction of the habitats presents in the area, to an extent that is considered a total loss, so it is necessary to take into account all ecological services values of the area.

A second scenario considers that cropland is not cultivated at the time of the flooding because it is very usual that the growing season (April to September) does not match with the storm season. It has to be considered that most of the extrem storms impact on the Ebro delta have been recorded in late autumn, later than the end of the collection of the crop (Jiménez *et al.,* 2009). The main loss occurs by the salinisation of the land, therefore we just add the cost of cleaning up the cropland after the flood, and in this case we consider that this is equivalent to a 10% of the total value of the crop.

A third scenario proposes damages only for cropland, considering only the ecosystem services value without addening the rice value. As it was discussed in previous chapters, it is important to stress that due to their resilience, the other habitats remain undamaged, there will be no losses. According to this final value of the losses will only be due to cropland (as this is an habitat with high human intervention is the most sensitive to external phenomena). These three scenarios are summarized in table 5.15.

Generally speaking, we can say that when the calculation of economic loss or damage associated with flooding was maked, the largest contribution is given by the of this damage is the cropland. This contribution give us values from €63,000 in the third scenario on the storm of 10 year equivalent to 80% of the damage to almost € 2 millions on the first scenario on the storm of 500 years that contribute 88% of the damages. This contribution is mainly due to the wide area covered, and their economic value associated with the rice crops. After the cropland, the most damaged habitats are the Riparian buffer with a minimum contribution in percentage (0.08 to 2.5 %), saltwater wetland that contribute to the total damage with 3 to 23 % and economically from €15,700 to €60,000, and finally the saline vegetation that has a contribution of 7 to 23 % that represents in economic values between €86,000 to €153,000. The damage in these habitats is significant, but is diluted when the damage of the cropland is taken into account. For their large size the cropland covers a percentage over 68% in almost all cases and in some one more represents the 100%. If the cropland damage was not taken into account the Total Damage value decrease drastically.

Table 5.15 Economic Damage for Flood associated to Coastal Storms.
Values in €/ha/year

	Scenarios & contribution to damage	Beach & Dune	Cropland	Riparian Buffer	Saline Vegetation	Saltwater Wetland	Total
Tr=10	Sc1	0,0	€63,250	0	0,0	€15,700	€78,950
	% CtD	0.0	80	0	0	14	
	Sc2	0.0	€26,500	0	0	€15,700	€42,200
	% CtD	0.0	68	0	0	23	
	Sc3	0.0	€22,400	0	0	0	€22,400
	% CtD	0.0	100	0	0	0	
	Damage	0.01	1	0.0	0.0	0.09	
Tr=100	Sc1	0	€473,370	€470	€86,730	€49,100	€609,670
	% CtD	0	78	0.08	14.23	8.05	
	Sc2	0	€166,800	€470	€86,730	€49,100	€303,100
	% CtD	0	64	0.12	22.8	12.9	
	Sc3	0	€167,700	0	0	0	€167,700
	% CtD	0.0	100	0	0	0	
	Damage	0.0	1	0.31	0.28	0.03	
Tr=500	Sc1	0.0	€1,716,000	€28,600	€153,700	€60,000	€1,958,300
	% CtD	0.0	88	1.46	7.85	3.06	
	Sc2	0.0	€718,700	€28,600	€153,700	€60,000	€961,000
	% CtD	0.0	79	2.54	13.64	5.32	
	Sc3	0.0	€608,000	0	0	0	€608,000
	% CtD	0.0	100	0	0	0	
	Damage	0.0	1	0.08	0.13	0.01	

If we make comparisons between scenarios we observe that the damage values of the 1st scenario are almost the doubled that the values of the 2nd scenario. This reinforces the ideas that the cropland suffers the greatest losses by flood, clarifying that the crop production can have a great contribution to the losses.

As mentioned before, the highest damage values for the Cropland can be attributed, to its extensive coverage. Furthermore is an artificial habitat, and does not possess a level of resilience sufficiently high to recover it from the flooding. An important point to consider is that if in this area there were no farmlands, but instead the original coastal lagoon (Bassa de las Arenas), if it existed a total damage, it would drop by several orders of magnitude.

We can consider that the remaining habitats flooded in the study area, do not show permanent damages or losses, otherwise the level is low compared to the cropland. This is because by nature these habitats are prepared to withstand such events, and only in very extreme cases one could speak of a total loss.

With the foregoing one should not trivialize the damage to natural habitats, unless the contrary is to be noted that the cropland is an habitat that have a high risk of damage and this location area, near to the coast, makes that potential of damage greater. This damage is also associated the goodness of natural habitats that will be the role of buffer and cropland protection. By not paying attention to the state of beaches, dunes, and wetlands adjacent to agricultural fields, and promote their degradation, we will increase the possibility of direct damage to crops.

It is important draw attention to the progression of the damage, related to storms return period because that increment is not lineal, and each habitat has its own answer. So the damage produced to the cropland has increased close to 30 times, at the same time the damage produced to the saltwater only goes up fourth times (from the storms of 10 and 500 years in this example). This can be attributed to the fact that the damaged habitats on the coast does limited by the area, and do not have high values as those located more inland. Also, as mentioned earlier, the beach and dunes are able to withstand the impact of storms and they do not present losses like the cropland.

Annual Average Damage

Floods affecting a susceptible area will vary in intensity and effect. More frequent floods will be less severe and cause less damage than infrequent events. The Annual Average Damage (AAD) is a useful tool to compare these effects. Examining a range of floods and estimating the potential and actual damages is the method used to determine the AAD (Berghan & Westlake 2001). This methodology is part of the Guidelines for Assessment of Floods Damage in New Zealand and Australia.

The Average Annual Damage is calculated summing the annualized damages for a wide range of flood events and for the different damage scenarios rose before. The AAD is mathematically the area beneath the curve and can be augmented by an multiplier value relate to intangible damages. For this case was not consider intangible damages. The AAD was calculated only for the scenarios where were the values of all habitats was taken into account. This has been completed for the Marquesa Beach with the results plotted in Figure 5.28. Details of this figure are summarized in Table 5.16.

From the above results we can conclude that if in one year we have an coastal storm event when the cropland is cultivated, the AAD can be up to € 0.186 million. While if the fields are out of season, and the harvest is not lost (it is only necessary clean the area) the AAD only reaches € 0.118 million. Finally, when considering only the cropland as a habitat and is not added the value of the rice-crop, the AAD value is less than € 0.0.86 million. The differences in these values are due primarily to the fact that when the loss is annualized, the damage values are proportional to their probability of occurrence. Therefore the high values of damage of the 500-year storm will be diminished by their low probability and in opposite the low values of storm damage of 10 years will be increased.

The AAD is a useful figure as it provides a measure of how much damage associated to coastal floods we can have in the area. We can see that the greatest losses can be related to the cropland, as when we introduce changes in this value, the associated damage present changes.

Table 5.16. AAD values for the three scenarios of flood

	Storms	Total Damage	Probability of Flood in One Year	AAD calc
1rst Damage Scenario	10	0.08	0.1	0.015
	50	0.43	0.02	0.036
	100	0.61	0.01	0.041
	120	1.03	0.0083	0.042
	500	1.96	0.002	0.052
	total	Millions Euro		*0.186*
2nd Damage Scenario	10	0.05	0.1	0.010
	50	0.27	0.02	0.023
	100	0.38	0.01	0.026
	120	0.62	0.0083	0.027
	500	1.13	0.002	0.032
	total	Millions Euro		*0.118*
3rd Damage Scenario	10	0.04	0.1	0.007
	50	0.22	0.02	0.017
	100	0.30	0.01	0.020
	120	0.48	0.0083	0.020
	500	0.85	0.002	0.025
	total	Millions Euro		*0.089*

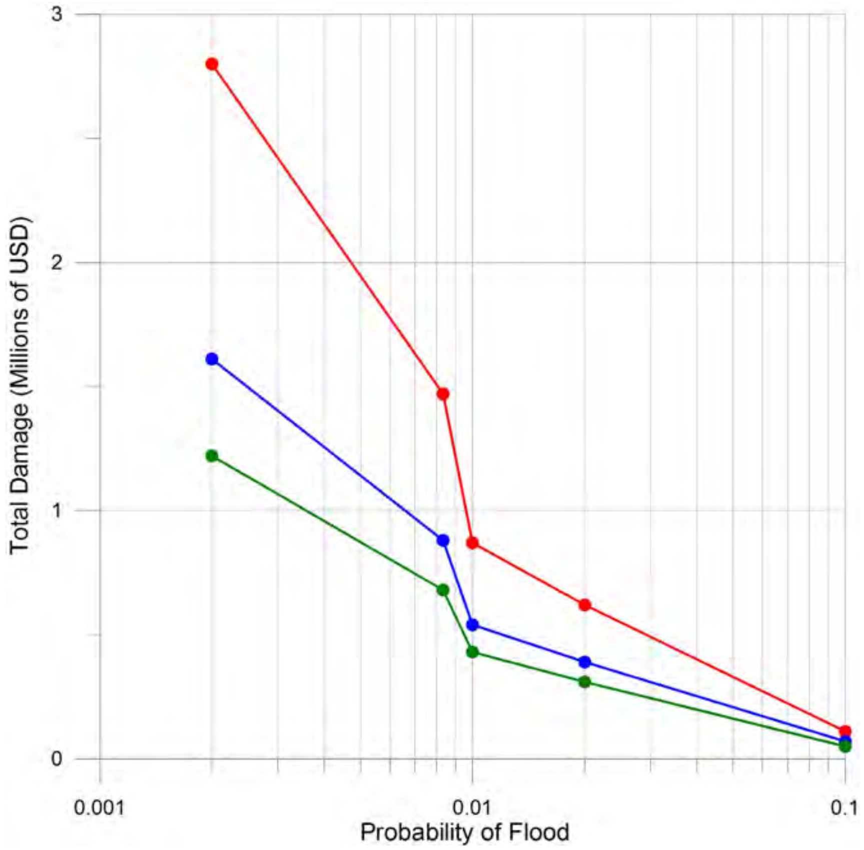


Figure 5.28. Average Annual Damage for the Marquesa area in three different scenarios