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The Coastal Risk Landscape

Application on the Catalan Coast

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Abstract

Coastal zones are among the most productive yet highly threatened systems in the world (EEA 2006; Finkl 2012; Kron 2013). These areas concentrate an elevated number of values both natural and socio-economic, making them very vulnerable to the potential effects of natural hazards (EEA 2013a). Therefore, effective risk management requires a holistic analysis in which the multiple components that determine risk are taken into account. This has been addressed with use of *The Coastal Risk Landscape* concept, which can be defined as the integrated risk of coastal areas resulting from the action and interaction of natural and/or human induced hazards on existing values and assets.

A methodology to assess coastal erosion and flood risk at a regional scale is presented. This uses an integrated analysis of the main processes associated to forcings that induce erosion and flooding at different temporal scales (episodic, medium and long-term) as well as an analysis of the socio-economic consequences. This has been framed within the Source-Pathway-Receptor-Consequences (SPRC) model, in which the “pathway” has been adapted to represent each hazard by considering the different related processes acting at different timescales.

To this end, each component (process) is first evaluated individually and classified into an intensity scale which allows an integration and comparison of their relative importance along the coast. An intensity scale associated with erosion components (episodic, medium and long-term) has been defined considering how the beach is affected, in terms of providing relevant functions for the area, i.e. recreation and protection (Valdemoro and Jiménez 2006). Then, selected variables are used to assess the flooding components (flash floods, marine floods and inundation by sea level rise), related to the characteristics of their processes, and classified into an intensity scale. In this case, an absolute and average value is obtained depending on whether the total affected area is considered or not. This permits an assessment of their individual contribution in order to analyse their relative contribution to the total risk.

The consequences of erosion and flooding have been determined separately taking into account the most relevant impacts. In the case of erosion, socio-economic values of

the two coastal functions analysed at a management scale (the municipality) have been considered. Then, the erosion components are combined in a risk matrix, providing risk values for different coastal management targets (i.e. recreation and protection). In the case of flooding, the consequences are assessed by characterising the values at exposure based on an indicator that encompasses five categories (land use, population and social vulnerability, transport system, business settings and utilities). The total risk is expressed as the combination of the hazard and the exposure. All of this is integrated at a management scale, represented by the municipality.

This methodology has been applied to 219 km of beaches along the Catalan coast (NE Spanish Mediterranean). Results obtained indicate that despite the generally good condition of the coast to provide recreation and protection functions at present, a future projection at 2035, which considers the medium and long-term erosion components (background erosion+ SLR-induced erosion), shows an increase in the risk to provide such functions. Thus, most of the municipalities with a tourism focus will be unable to support a recreational use, and the Maresme *comarca* will barely provide the required level of protection by 2035. Moreover, episodic flood components (marine and flash flooding) can be considered the most relevant along the coast, with generally medium risk values, rising to high risk in some northern municipalities for marine floods. The long-term flood component (SLR) only affects low-lying areas, with the Ebro delta being the most important. Results indicate that the Maresme *comarca* is the most sensitive region to storm-induced components in the Catalan coast.

Resumen

Las zonas costeras son unos de los espacios más productivos y altamente amenazados del mundo (EEA 2006; Finkl 2012; Kron 2012). Estas áreas concentran un elevado número de valores tanto naturales como socio-económicos que las hacen muy vulnerables a los efectos potenciales de los riesgos naturales (EEA 2013a). Por ello, para llevar a cabo una gestión adecuada del riesgo se requiere un análisis holístico en el que se tengan en cuenta las múltiples componentes que determinan el riesgo. Esto se ha abordado con el uso del concepto de *El Paisaje del Riesgo Costero*, que puede definirse como el riesgo integrado de las zonas costeras del resultado de la acción e interacción de los riesgos naturales y/o humanos inducidos sobre los valores y bienes existentes.

En este trabajo se presenta una metodología para la evaluación del riesgo de erosión e inundación costera a escala regional. Para ello, se considera el análisis integrado de los principales procesos asociados a forzamientos que inducen erosión e inundación a diferentes escalas temporales (episódica, medio y largo plazo) así como un análisis de sus consecuencias socio-económicas. Esta metodología se ha enmarcado dentro del modelo Source-Pathway-Receptor-Consequence (SPRC) en el cual el “pathway” se ha adaptado para representar cada riesgo considerando los diferentes procesos relacionados que actúan a diferentes escalas temporales.

Para ello, cada componente (proceso) es evaluada individualmente y clasificada en una escala de intensidad que permite una integración y comparación de su importancia relativa a lo largo de la costa. Así, se define una escala de intensidad para las componentes de erosión (episódica, medio y largo plazo), considerando como se ve afectada la playa para proveer dos de las funciones más relevantes, recreación y protección (Valdemoro y Jiménez 2006). Para la inundación se utilizan diferentes variables que permiten evaluar cada una de sus componentes (riadas, inundación marina e inundación por la subida del nivel del mar SNM) considerando las características de los procesos y clasificándolas en una escala de intensidad. En este caso, se obtiene un valor del riesgo absoluto y medio en función de si se considera o no el área total afectada. Esto permite la evaluación de la contribución individual así como la relativa al riesgo final.

Las consecuencias de erosión e inundación se determinan por separado teniendo en cuenta sus impactos más relevantes. En el caso de erosión, se consideran valores socio-económicos de las dos funciones costeras analizadas a una escala para la gestión (municipal). Luego, las componentes de erosión se combinan en una matriz de riesgo, que proporcionan valores del riesgo para diferentes objetivos de gestión costera (i.e. recreación y protección). En el caso de la inundación, las consecuencias se evalúan mediante la caracterización de valores en exposición basados en un indicador que abarca cinco categorías (usos del suelo, población y vulnerabilidad social, sistema de transportes, negocios y servicios públicos). El riesgo total se expresa como la combinación de la amenaza y el valor de exposición. Todo ello es integrado a una escala adecuada de gestión, representada por el municipio.

Esta metodología se ha aplicado en 219 km de playas a lo largo de la costa catalana (NE Mediterráneo español). Los resultados obtenidos indican que, a pesar del buen estado general de la costa para proveer las funciones de recreación y protección en la actualidad, considerando una proyección futura para el 2035 con las componentes de erosión a medio y largo plazo (erosión de base + erosión por SNM), el riesgo para proveer estas funciones incrementa sustancialmente. Así, los municipios que en la actualidad tienen un desarrollo basado en el turismo, tendrán problemas para proveer un uso recreativo, y en la comarca del Maresme difícilmente se podrá proporcionar el nivel requerido de protección para el 2035. Además, las componentes episódicas de la inundación (riadas e inundación marina) pueden ser consideradas las más relevantes a lo largo de la costa con valores en general de riego medio, elevándose a valores de riesgo alto por inundaciones marinas en municipios del norte. La componente de inundación a largo plazo (SNM) solo tiene efectos en costas bajas, siendo el delta del Ebro el más importante. Los resultados indican que la comarca del Maresme es la región más sensible a las componentes provocadas por tormentas en la costa catalana.

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Chapter 1
Introduction

1.1 Background

Coastal zones are among the most productive yet highly threatened systems in the world (EEA 2006; Finkl 2012; Kron 2013). Here, populations tend to be concentrated, as these zones are the most favourable for developing human activities (EEA 2013a). As a consequence of this, the potential for damages of natural and human-induced hazards increases (Elliott 2014).

The Catalan coast, located in the NE Spanish Mediterranean, can be characterised as a high-risk area in which the presence of urban infrastructure and socio-economic developments, such as for tourism, combined with the effects of natural hazards leads to high levels of exposure. Here, coastal erosion and flooding represent two of the most relevant hazards due to their induced impacts (Barnolas and Llasat 2007; CAD 2008; Jiménez et al. 2011). Thus, it has been reported that in the absence of a general increase in marine storm-induced hazards, damages at the Catalan coast have increased at a rate of aproximately 40% per decade over the last 50 years (Jiménez et al. 2012). This is the result of an increasingly occupied coast and a progressive coastal retreat where approximately 72% of the beaches are subject to erosion, at an average retreat rate of about 1.0 myr^{-1} (CIIRC 2010).

Given the combined effects of human pressures on the coast and climate change impacts, coastal erosion and flooding are problems of increasing intensity (Marchand 2010). Although traditionally they have been managed with the use of physical infrastructures, it has been recognized that absolute mitigation is both unachievable and unsustainable due to the high costs and inherent uncertainties involved (Schanze 2006).

As a result of this, there is a clear and increasing need for including coastal risk management within general coastal zone management policies. Within this context, the Protocol on Integrated Coastal Zone Management in the Mediterranean (ICZM)

(PAP/RAC 2008) advise countries to undertake risk assessments to consider prevention, mitigation and adaptation measures in order to cope with the impacts of natural hazard in general, and climate change in particular. Also related to this and, specifically devoted to flood hazards, the EU Floods Directive 2007/60/EC (EC 2007) establishes a framework for the assessment and management of flood risks, aiming for a reduction in the adverse consequences for human health, the environment, cultural heritage and economic activity. The Directive urges flood risk analysis and flood risk management at the community level, based on local circumstances and the specific types of flooding (river floods, flash floods, urban floods, and flooding from the sea in coastal areas) which may be present.

In order to assess and mitigate the effects of natural hazards in a given area, it is necessary to develop new methods which allow for the consideration of multiple hazards and their consequences. This is a key factor in achieving a sustainable environment, and for adequate land use planning (Durham 2003; Marzocchi et al. 2009). Although new approaches, which consider multiple hazards, are emerging (e.g. De Pippo et al. 2008; Thierry et al. 2008; Lozoya et al. 2011; Marzocchi et al. 2012; FEMA 2013) challenges remain due to the multitude of factors involved in the assessment of risk. One of the major difficulties arises with the consideration of different time and spatial scales in which hazards act, as well as the range of consequences.

To address all of these challenges, this work presents the *Coastal Risk Landscape* concept, which is defined as the integrated risk of a coastal area resulting from the action and interaction of natural and/or human induced hazards on existing values and assets. From this, a methodology has been developed which considers both coastal erosion and flooding, these being the most significant hazards for the study area (Barnolas and Llasat 2007; CAD 2008; Jiménez et al. 2011), and their induced impacts. Here, these two hazards are considered to be the resultant processes induced by forcings acting at different temporal and spatial scales.

1.2 Objectives

Within this context, the main objective of this study is to develop a methodology to assess coastal erosion and flood risks associated with different processes acting at different temporal scales and to apply this to the Catalan coast.

In order to achieve this, three partial objectives have been defined:

1. To develop a conceptual framework for the assessment of multiple coastal risks.
2. To develop methodologies in the assessment of different hazards at different temporal and spatial scales and their consequences at a regional scale.
3. To assess coastal erosion and flood risk associated with processes of different temporal and spatial scales in the Catalan coast.

1.3 Outline

The document is organised in seven main chapters and three appendices as follows:

Chapter 2 describes the study area and the data used.

Chapter 3 provides an overview of the risk analysis framework for the proposed methodology.

Chapter 4 presents the methodology developed for erosion risk analysis and the results obtained from its application at the Catalan coast.

Chapter 5 presents the methodology developed for flooding risk analysis and the results obtained from its application at the Catalan coast.

Chapter 6 analyses the implications of erosion and flooding risk methodologies and their integrated results along the Catalan coast.

Chapter 7 gives an overview of the main conclusions and the implications for coastal management.

Appendix A shows the maps used for the calculation of the FFPI'. These maps provide geomophological and climatic characteristics of the study area.

Appendix B indicates the importance of the variables used in the calculation of a Social Flood Vulnerability Index (SFVI), the corresponding data for Catalonia and the standardization methods used.

Appendix C provides a list of scientific contributions during this doctorate.

Chapter 2
Study area and data

2.1 The Catalan coast

Catalonia is an autonomous region located on the NE Spanish Mediterranean coast (Figure 2.2). It occupies 32,105 km^2 with a coastline of around 600 km, of which 270 km are beaches (CADS 2005). The coast comprises an extensive variety of geodiversity and biodiversity represented in different coastal systems, such as cliffs, rocky coasts, sandy beaches, estuaries and river deltas.

Along the coast, beach typology can be divided into two geographical areas. In the northern part, beaches mostly correspond with small pocket beaches nestled between cliffs, with course sand and high slopes. The rest of the northern coast is made up of the low-lying area of the Gulf of Roses and the long narrow beaches of the Maresme region. In contrast, in the southern part (south Barcelona) beaches can be characterised as having very fine sand and soft slopes (Figure 2.1) (see Appendix A for geomorphologic and climatic characteristics).

An important geomophological feature located parallel to the coast, and the source of sand for its beaches, is the Littoral range and the Pre-littoral system, reaching above 700m and 1700m respectively. The hydrographical network covers the tributary waters of the Ebro basin and the Internal Basins of Catalonia (IBC), which include rivers that rise in Catalonia and flow into the Mediterranean Sea. The proximity to the Mediterranean Sea and its complex orography plays an important role in rainfall and flood production (Barnolas and Llasat 2007). Moreover, local topography also exerts a significant control over the wind climate which is characterised by low average winds although some events, especially those synoptic in nature, are responsible for strong winds and gales in the Catalan Sea (Sanchez-Arcilla et al. 2008). The storm-associated with a mean climatic year can be defined by the storm season between October-April and the calm season between May-September (Jiménez et al. 1997). The precipitation regime is characterised by a yearly distribution, with two maximum peaks in autumn and spring (Barnolas and Llasat 2007). However, high rainfall precipitation produced by convective events shows only one peak between the end of summer and autumn (Llasat 2001).

In many cases, permanent rivers form deltas at their mouth, with the most relevant being the Ebro delta, an ecologically rich environment, barely controlled by human activity and very vulnerable to wave action and varying sea levels (Alvarado-Aguilar et al. 2012) (Figure 2.1). Additionally, ephemeral dry streams are also found along the coastal fringe characterised by short and steep slopes, which after an intensive rainfall, typical of Mediterranean regions, causes immediate high-energy water runoff toward the sea.

Socio-economic development is based on typical coastal activities, such as commerce, agriculture, residential developments and tourism (Sardá et al. 2005) with the latter being one of the main economic activities contributing around 11 % of the Gross Domestic Product (GDP) (Duro and Rodrígez 2011). Tourism has significantly influenced a secondary residence urbanization process which has contributed greatly to the artificialization of the coastline, and consequently, in the reduction of natural areas along the coast. In Figure 2.1, the natural and the urban areas are presented. The most relevant natural areas are largely located in the northern (Cap de Creus and the Gulf of Roses) and southern regions (Ebro delta). Among the total coastal land, 46 % is urban, 5.7 % is protected against urbanization (but is not protected for other uses, such as agriculture) 8.2 % is non-urban and 39.6% is protected under the regional Plan of the Spaces of Natural Interest in Catalonia (PEIN) (Brenner 2007).

61.9 % of the population of Catalonia (4.68 million people in 2014, (IDESCAT 2015)) are concentrated in the coastal *comarcas*, which represent 22.8% of the total territory. This results in an average population density of 509.7 people/km^2 (without considering Barcelonès- see Figure 2.2), which is considerably higher than the total Catalonia average of 235.3 people/km^2 (IDESCAT 2015). Furthermore, these values can be tripled in some municipalities during the summer season.

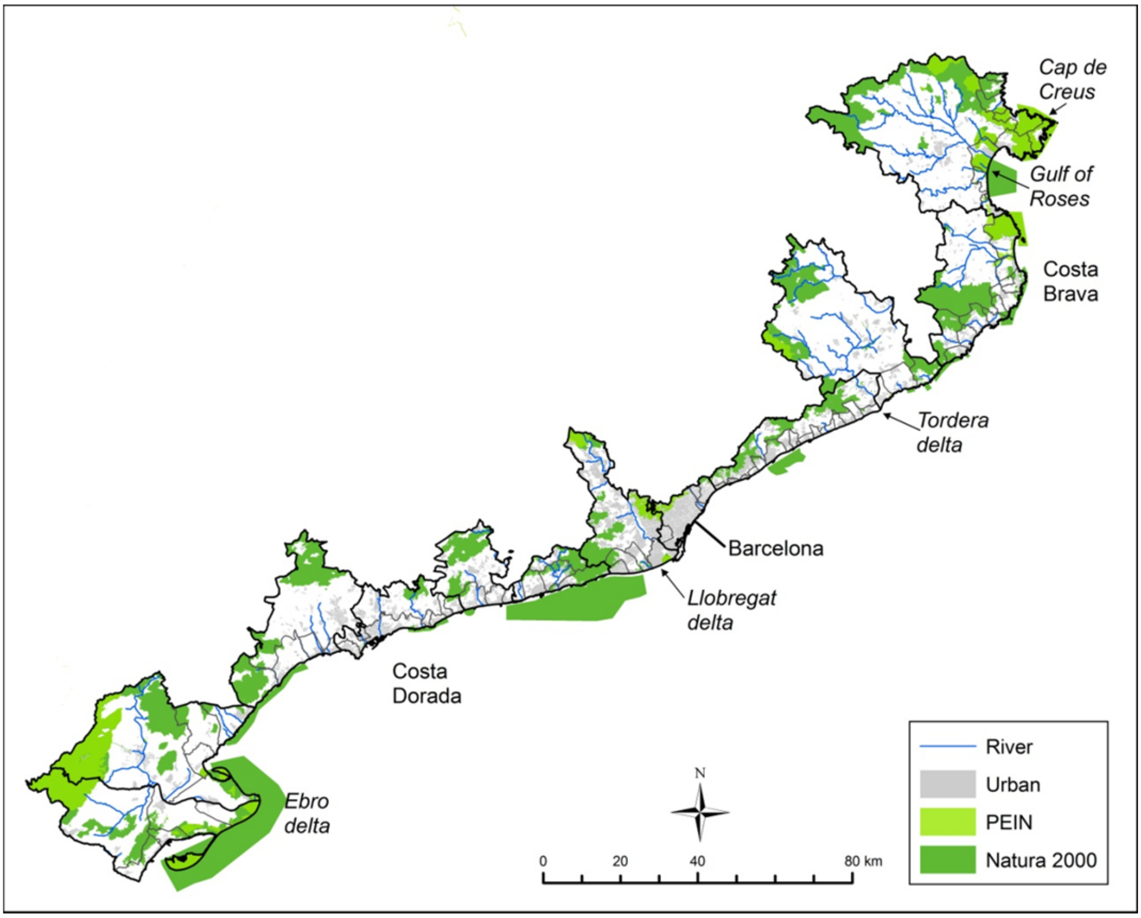

Figure 2.1 Natural and urban areas represented within coastal administrative boundaries (coastal *comarcas* and municipalities).

Administratively, the Catalan coastal zone is divided into three administrative levels which represent different management units (Figure 2.2). With a total of 70 coastal municipalities, this level typifies the smallest administrative unit. These municipalities are grouped within a second level, termed *comarcas* (similar to a county) of which there are 12 in the coastal area. Finally, the first and the largest level includes the aforementioned levels grouped within 3 provinces. Their spatial distribution along the Catalan coast can be seen in Figure 2.2, complemented by Table 2.1 in which the codes used are presented.

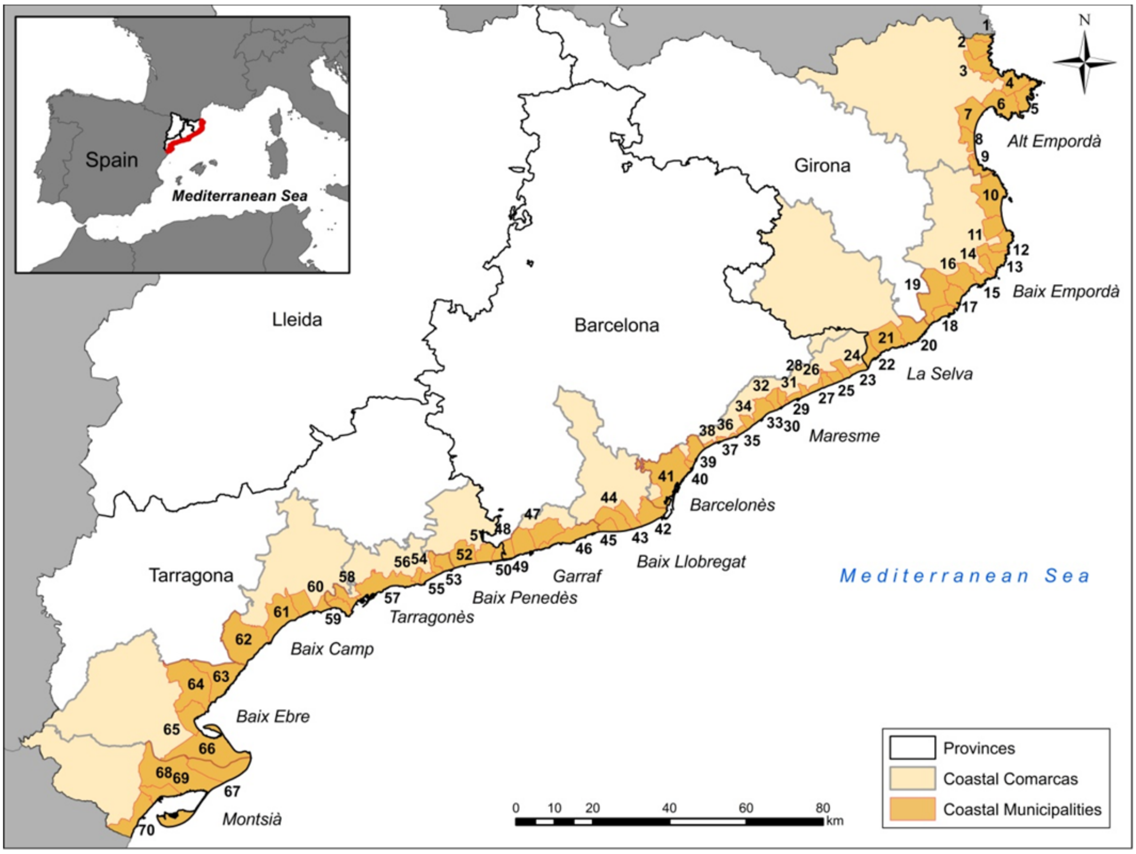

Figure 2.2 The study area, showing the coastal administrative boundaries: Province, coastal *comarcas* and municipalities (numbers explained in Table 2.1)

Table 2.1 Coastal administrative division code.

	Municipality	*Comarca*	Province
1	Portbou	Alt Empordà	Girona
2	Colera		
3	Llançà		
4	El Port de la Selva		
5	Cadaquès		
6	Roses		
7	Castellò d'Empúries		
8	Sant Pere Pescador		
9	l'Escala		
10	Torroella de Montgrí	Baix Empordà	
11	Pals		
12	Begur		
13	Palafrugell		
14	Mont-Ras*		
15	Palamòs		
16	Calonge		
17	Castell-Platja d'Aro		
18	Sant Feliu de Guixols		
19	Santa Cristina d'Aro		
20	Tossa de Mar	La Selva	
21	Lloret de Mar		
22	Blanes		
23	Malgrat de Mar	Maresme	Barcelona
24	Santa Susanna		
25	Pineda de Mar		
26	Calella		
27	Sant Pol de Mar		
28	Canet de Mar		
29	Arenys de Mar		
30	Caldes d'Estrac		
31	Sant Vicenç de Montalt		
32	Sant Andreu de Llavaneres		
33	Mataró		
34	Cabrera de Mar		
35	Vilassar de Mar		
36	Premià de Mar		
37	El Masnou		
38	Montgat		

	Municipality	*Comarca*	Province
39	Sant Adrià del Besos*	Barcelonès*	Barcelona
40	Badalona*		
41	Barcelona*		
42	El Prat de Llobregat	Baix Llobregat	
43	Viladecans		
44	Gavà		
45	Castelldefels		
46	Sitges	Garraf	
47	Sant Pere de Ribes*		
48	Vilanova i la Geltrú		
49	Cubelles		
50	Cunit	Baix Penedès	Tarragona
51	Calafell		
52	El Vendrell		
53	Roda de Barà	Tarragonès	
54	Creixell		
55	Altafulla		
56	Torredembarra		
57	Tarragona		
58	Salou		
59	Vila-seca		
60	Cambrils	Baix Camp	
61	Mont-Roig del Camp		
62	Vandellòs i l'Hospitalet de l'Infant		
63	L'Ametlla de Mar	Baix Ebre	
64	El Perelló		
65	L'Ampolla		
66	Deltebre		
67	Sant Jaume d'Enveja	Montsià	
68	Amposta		
69	Sant Carles de la Ràpita		
70	Alcanar		

*Municipalities not considered in the analysis, as they have no beaches (Mont-Ras and Sant Pere de Ribes) or their socio-economic data may distort the results for the entire region (Barcelonès *comarca*)

2.2 Data

2.2.1 Forcing data

Wave data used to characterise storm-induced erosion and flooding have been obtained from the hindcast SIMAR-44 database. To obtain a reliable extreme distribution representative of the climatic characteristics of the study area, long time wave series data are required. For this purpose, the hindcast SIMAR-44 database represents the longest existing datasets for the study area. This database was generated from high resolution modelling of the atmosphere, sea level, and waves developed by Puertos del Estado within the HIPOCAS project (Guedes-Soares et al. 2002; Ratsimandresy et al. 2008). The data used covers the period from January 1st 1958 to December 31st 2001, providing a time series of meteorological tide level, significant wave height H_{m0}, peak period T_p and the mean wave direction every 3 hours.

In order to characterise flash floods, the annual maximum daily precipitation for a return period of 10 years (INM 2007) was selected as being representative of an extreme precipitation event. This information yields 2.5 x 2.5 km-sized cells for all of Catalonia.

Finally, to characterise sea level rise (SLR) due to climate change, two climatic scenarios have been considered: scenario RCP 8.5, as presented within the last AR5 report (IPCC 2015) (a rise of 0.75 by 2100), and a High-End scenario (a rise of 1.75 m by 2100) taken as the worst case, which is relevant for coastal management (e.g. Hinkel et al. 2015). This last scenario was created by Jevrejeva et al. (2014), and it was obtained with a projection of sea level at 95% probability of the upper-limit scenario using the RCP 8.5 steric component.

2.2.2 Geomorphological data

To characterise the shoreline evolution pattern dominated by alongshore gradients in the longshore sediment transport, aerial photographs provided by the Institut Cartogràphic i Geològic de Catalunya (ICGC 2014) from the period 1995-2010 have been analysed. It is considered that the period of analysis properly represents the evolution of the system under current conditions since most of major perturbations (harbours, coastal engineering works, and artificial nourishments) were implemented before 1995. This data reflects the shoreline behaviour at decadal scale and can be used to estimate future beach configurations provided conditions do not change (i.e. in the absence of any new coastal engineering measure). For the analysis of current beach features, such as the beach width, longitude and sediment type, aerial photography (ICGC 2014) has been used alongside data provided by CIIRC (2010).

To obtain information about the coastal surface topography, a Digital Terrain Model (DTM) of 5 x 5 m-sized cells, supplied by the Institut Cartogràphic i Geològic de Catalunya (ICGC 2014), has been used. Other physical-geomorphological features, used in the assessment of flash flood risk, are provided in raster format for the Maximum Green Vegetation Fraction by the USGS Land Cover Institute (Broxton et al. 2014) and the Soil Texture, developed by the European Soil Data Centre (EC 2015) with a spatial resolution of 1 x 1 km cell size.

2.2.3 Socio-economic data

To evaluate the socio-economic consequences, different data provided by various institutions have been consulted.

To estimate the importance of tourism within the coastal municipalities, data based on taxes generated from tourism was acquired from La Caixa Bank (2013). Although this data represents a value for the entire municipality, in coastal municipalities tourism based on coastal activities is the major contributor.

Data used in the assessment of indicators such as population, non-home ownership, single parents, car ownership, overcrowding households the unemployed has been obtained from the Institute of Statistics of Catalonia (IDESCAT 2016) which provides data from the latest census (2011) and administrative municipalities registration.

In order to define physical territorial exposure values, data in vector format has been employed. Urban settlements and infrastructure have been identified with data provided by the Mapa Urbanístic de Catalunya (MUC) from the Departament del Territori i Sostenibilitat (Generalitat de Catalunya 2016). Other territorial land uses have been characterised with information from the MCSC-4th edition (2009) (Mapa de Cubiertas del Suelo de Catalunya) provided by the institute CREAF (Ecological and Forestry Applications Research Centre), which supplies a high resolution thematic cartography (from aerial photography with a scale of 1:2500 and pixel resolution of 0.25 m) of the main land cover in Catalonia (Ibàñez and Burriel 2010).

Chapter 3
Risk Analysis Framework

3.1 Coastal risk landscape concept

Coastal areas are subjected to the impacts of multiple natural and anthropogenic hazards making them especially sensitive given the elevated number of receptors at exposure. To manage risks effectively and to build resilience to their impacts, it is necessary to understand, measure and predict the evolution and interdependencies between them (WEF 2014). Thus, risk assessment must include each of the risk components (hazard and consequences) taking into account a number of variables and quantities from physical to socio-economic aspects (Kron 2013). To this end, a combined assessment of all the anthropogenic and natural risks affecting a territory is a key factor in developing a sustainable environment, and for adequate land use planning (Durham 2003; Marzocchi et al. 2009). However, one challenge related to analysing multiple components is associated with the fact that while for single processes a multitude of well-established approaches are available, far fewer studies analyse multiple components together (Kappes et al. 2012). Moreover, difficulties particularly arise due to differences in spatial and temporal scales. In recent years, new approaches are emerging where, in some cases, multiple coastal risks are considered for coastal management (CADS 2008; ANCORIM 2010; Saxena et al. 2012; Elliot 2014) and, in others, multi-risk methodologies are developed to consider different hazards acting in a given area (e.g. De Pippo et al. 2008; Thierry et al. 2008; Lozoya et al. 2011; Marzocchi et al. 2012; FEMA 2013).

Given the intrinsic characteristics of the coast, which can be considered a multi-component system, and recognizing the multi-dimensional assessment of the term “risk”, use is made of the *risk landscape* concept. There are several definitions of “landscape” depending on the context (e.g. De Bolos 1992; Olwig 2005). According to the European Landscape Convention, landscape is defined as “an area perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (Council of Europe 2000). Within the context of this work, *The Coastal Risk Landscape* is defined as the integrated risk of a coastal area resulting from the action and interaction of natural and/or human induced hazards on existing values and assets.

Although it is a relatively new term, one example of its applicability can be found in Kamppinen (2001) to address future social risk perceptions. Another of the most relevant examples is introduced by the World Economic Forum in their annual report "Global Risk" where "The Global Risks Landscape" is included (WEF 2014). One of the characteristics of "landscape" is the concept of perception, which is also included when assessing the Global Risk Landscape in terms of perceived likelihood and impacts. In this work, the analysis has been limited to an "objective" approach by assessing the impacts without introducing the perception component. However, the final risk assessment is compared with local perceptions on local coastal risks to provide some indication of how close objective and subjective assessments are.

One difficulty inherent in multi-risk assessments is that different disciplines do not use a common terminology, and definitions usually change according to the context for which they are created (Schneiderbauer and Ehrlich 2004). Table 3.1 presents the definitions of the different components of the risk analysis used in this work.

Table 3.1 Terminology used.

Risk	The probability of harmful consequences or expected losses resulting from a given hazard to a given element over a specified time period. (Schneiderbauer and Ehrlich 2004). Throughout this work the risk components are characterised as Risk = Hazard x Consequences
Hazard	Process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage. This can be characterised by their magnitude or intensity, speed of onset, duration and area of extent (UNISDR 2009).
Consequences	Potential socio-economic values and services at exposure.
Vulnerability	The potential for casualty, destruction, damage, disruption or other form of loss (Alexander 2000).

In the context of this work, the analysis is restricted to the most relevant hazards affecting the physical state and stability of the Catalan coast; erosion and flooding. Hence, a specific methodology adapted to the characteristics of each hazard, contributing forcings and induced impacts has been developed. To this end, each hazard (erosion and flooding) is considered to be composed of different components induced by forcings acting at different timescales (see section 3.3.1). The consequences are evaluated taking into account the implications of the different processes acting on the coast in terms of services provided by beaches and socio-economic values. The combination of hazard and consequences determines the risk associated with each component, which is later integrated at different (management) scales (see section 3.3.2). Although each hazard and consequence is assessed in terms of their respective magnitude, obtained values are later standardised using selected risk indicators. This permits a selection of common units for all components to compare and to integrate them. The development of comparative indicators has been used extensively to measure risk in a quantitative way and to enable a comparison of different areas (Birkmann 2007). This also facilitates the task of communicating results in a format that can be understood by the non-specialist, which is especially important for coastal zone management objectives (Cooper and McLaughlin 1997).

3.2 Source-Pathway-Receptor-Consequence model

The basic conceptual framework used to analyse risks is the well-known Source-Pathway-Receptor-Consequence model (SPRC) (Figure 3.1). This model was first used in natural science for pollutants (Holdgate 1979) and has been subsequently used for different kinds of risk analysis. Particularly, it is widely used in flood risk assessment (Evans et al. 2004; Gouldby and Samuels 2005; Narayan et al. 2014) and has become a well-established framework in coastal risk management (Sayers et al. 2002; Evans et al. 2004; MfE 2008; Narayan et al. 2014).

An example of the application for coastal hazard risk is presented in Figure 3.1. The basis of this model is that for a coastal hazard risk to occur, there needs to be a ‘driver’ (such as a storm), a ‘receptor’ (such as property within the coastal margin), and an erosion or inundation pathway between the two, created by the driver (MfE 2008).

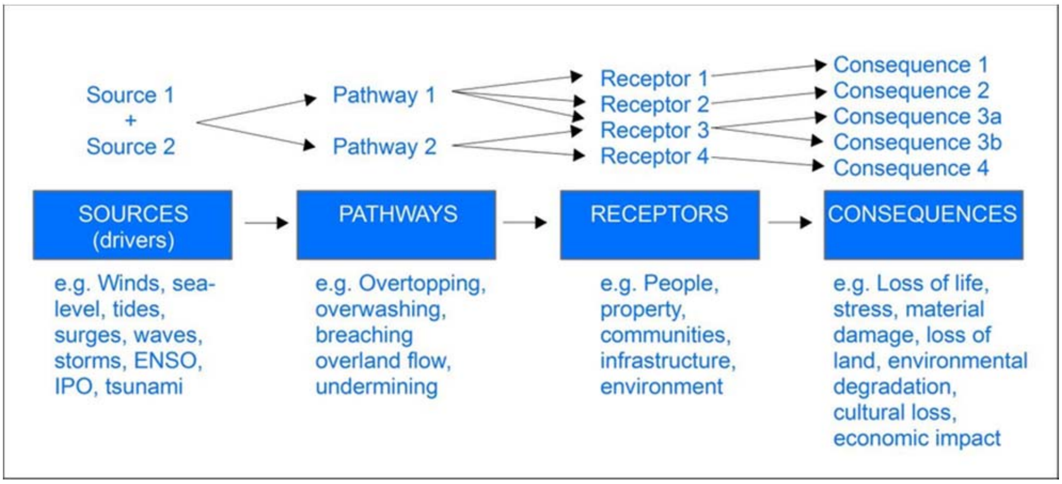

Figure 3.1 SPRC model. An example for coastal hazard risk (MfE 2008).

Here, the model is adapted for erosion and flooding risk analysis. In each case, the presence of multiple sources inducing a hazard (pathway) are considered and presented at different timescale. Thus, the hazard (pathway) is divided into different components or processes associated with different timescales. This division permits to clearly see the linkages between the sources and the "divided" pathways. The model also represents the linkages between the pathways and the receptor and consequences. This is presented in more detail in section 4.2 for erosion risk and section 5.2 for flooding risk.

3.3 Scales

3.3.1 Temporal and spatial scales of processes

The temporal and spatial scales over which hazards can impact upon the natural environment cover many orders of magnitude and are related to the forcing forms inducing them (Gill and Malamud 2014). In this work, the analysed hazards (i.e. erosion and flooding) are considered to be induced by different forcings acting at different temporal and spatial scales. In this sense, although a single denomination for each hazard is used, they refer to different processes. Thus, the erosion hazard is considered to be composed of three components: (a) a storm-induced erosion, (b) a mid-term (decadal scale) erosion mainly due to gradient transport along the coast and (c) a long-term SLR-induced erosion. The flooding hazard is also considered to be composed of three components: (a) a coastal storm-induced flooding, (b) flash floods and (c) a long-term SLR-induced inundation. The associated temporal and spatial scales of each component are shown in Figure 3.2.

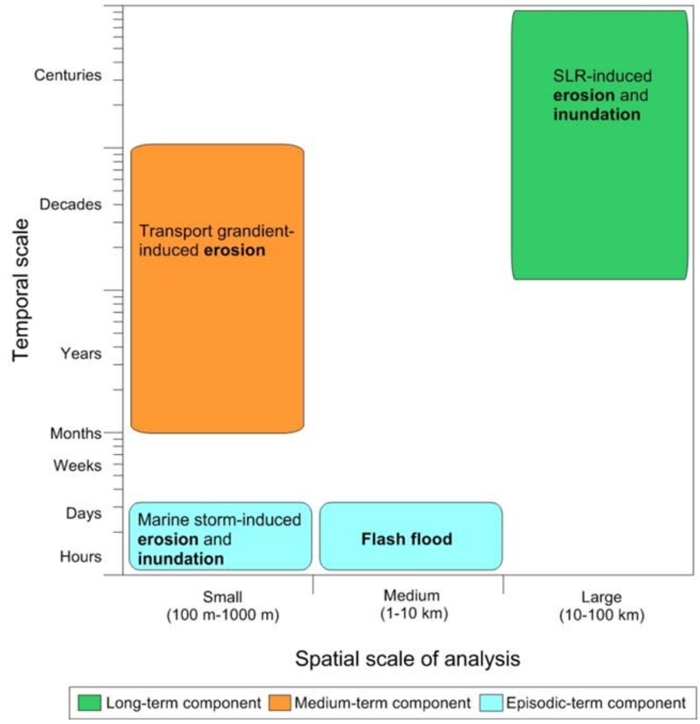

Figure 3.2 Temporal and spatial scales of analysis of coastal processes.

The storm-induced component is caused by processes taking place at a short time scale, from hours to a few days, i.e. the duration of the storm. However, due to the stochastic nature of the forcing, this component is identified as being representative of the episodic timescale and usually is defined in terms of probability of occurrence. Although storms usually impact large coastal stretches, their effects are assessed locally, since local morphology can significantly modulate their magnitude. Due to this, the associated spatial scale is considered to be small (few 100s m).

Flash flooding is also associated with the impact of storms and, in consequence, has a similar timescale. Due to the specific nature of this hazard, its spatial scale is associated with the river basin where this takes place.

The mid-term erosion component is associated with the cumulative effect of littoral dynamics acting on a scale of years to a few decades. This is mainly induced by alongshore gradients in sediment transport, and has an associated spatial scale from 100s of metres a few kilometres.

Finally, the long-term hazards are identified here as those induced by SLR. In this sense, they can be considered as the result of the continuous and cumulative action of a slow process. Thus, a minimum time of integration is required to perceive their impacts, and so the associated temporal scale is from decades to centuries. With respect to the spatial scale, their action takes place along the entire coast and in this sense they are representative of the large scale (up to 100s km).

3.3.2 Scale of integration

As mentioned, the area of study in this work is the Catalan coast. Since the main objective of the proposed methodology is to help in the process of risk management from the perspective of a coastal manager, the scale of application/integration of the risks has been selected based on administrative/management considerations.

The basic scale of integration is the municipality. It constitutes the smallest official geographical administrative unit where activities that influence the structure and dynamics of the shoreline are managed. Therefore, municipalities represent the most effective planning unit for an Integrated Coastal Zone Management (ICZM) (Sardá et al. 2005). The study area comprises 70 coastal municipalities (Figure 3.3) from which 5 are not considered in this work (see section 2.1).

The second management level corresponds to the province. This represents a territorial division with its own legal jurisdiction composed of a set of municipalities. The study area comprises three coastal provinces (Figure 3.3).

An intermediate management level between the municipality and province is the *comarca*. This unit integrates different municipalities with a common interest, which require a coordinated management. In order to introduce an additional value to this management unit, use has been made of the work of Brenner et al. (2006) regarding the characterisation of the Catalan coast. These authors analysed socio-economic and environmental variables to identify Homogeneous Environmental Management Units (HEMUs). These HEMUs are parts of the territory with similar environmental and socio-economic conditions that deserve a specific management orientation. HEMUs, aggregate several *comarcas* provided they present similar values. In the study area, three different HEMUs classified as highly natural areas (A), seminatural areas (B), and semiurban areas (C) are identified in addition to the Barcelona area with a high socioeconomic development (D) which is not covered in this work (Figure 3.3).

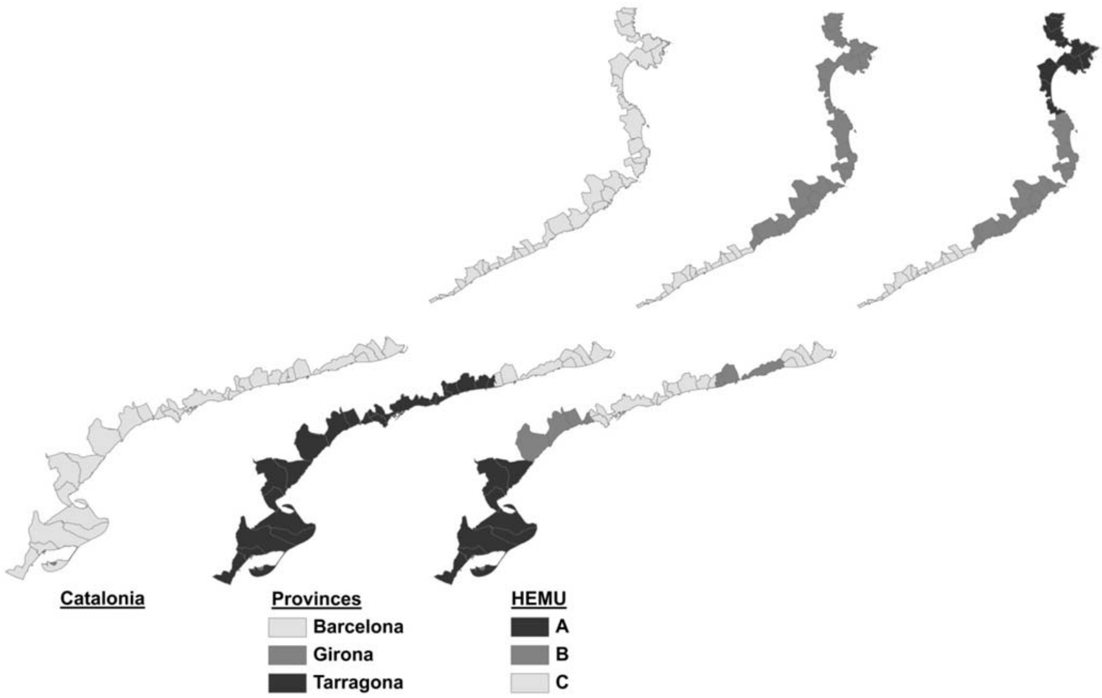

Figure 3.3 Scales of integration.

Chapter 4
Erosion risk analysis*

4.1 Introduction

Coastal erosion has become an important environmental concern as recent decades have seen significant economic losses, ecological damage, and social problems (Roca, Gamboa et al. 2008; Marchand 2010; Jiménez et al. 2012). Climate change and continuing urban sprawl will likely cause this tendency to grow (IPCC 2015). In Europe, it has been estimated that about 20,000 km of its coastline (corresponding to 20%) faces serious coastal erosion impacts (EC 2005). As a result, over the last decade, the cost of coastal adaptation against flooding and erosion has been an average of 0.88 billion Euros per year (EC 2009). In the Catalan coast about 72% of the beaches are subject to erosion, at an average retreat rate of about 1.0 myr^{-1}, with more than 50% of the coastal municipalities having reported damages in existing beach infrastructure (CIIRC 2010). However, beach erosion not only poses risk to existing assets, but also causes a significant setback to recreation and tourism activities, and, consequently, threatens one of the most important sources of income for coastal economies (Phillips and Jones 2006; Houston 2013).

Due to this fact, the need for including coastal hazards management within general management policies in the coastal zone is clear. Within this context, the Protocol Integrated Coastal Zone Management in the Mediterranean (PAP/RAC 2008) includes a specific chapter on natural hazards where the signed parties (countries) are mentored in "preventing and mitigating the negative impact of coastal erosion more effectively, and should undertake to adopt the necessary measures to maintain or restore the natural capacity of the coast to adapt to changes, including those caused by the rise in sea levels."

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* Edited version of Erosion Risk Analysis in the Maresme coast (NW Mediterranean,Spain) by Ballesteros C, Jiménez JA, Valdemoro HI and Bosom E (2017) accepted (in review) to the journal Natural Hazards.

Athough an important amount of data on coastal erosion is currently available, there is still a gap between its existence and its use by coastal managers (EC 2005), and this shortfall results in deficient or uninformed decisions.

Moreover, understanding coastal erosion involves an insight into all the factors that interact along the coast and an awareness of different timescales (Marchand 2010). In this context, erosion is a process that operates at a wide variety of temporal scales. Due to this fact, and in order to tackle erosion, an holistic approach of processes at multiple scales is required (Fekete et al. 2009). This approach should include practical measures and principles that are also important for coastal erosion management, such as local specificity and a long-term perspective (EC 2005).

In the Catalan coast, as in other Mediterranean coasts, coastal erosion has important consequences over two main coastal function; protection and recreation (Jiménez et al. 2011). Coastal protection can be defined as the natural function provided by the beach in safeguarding the hinterland (infrastructure and/or socio-economic receptors) from the direct wave action, whereas recreation makes reference to the space provided by the beach for leisure purposes.

Within the SPRC framework, a methodology is presented here to assess erosion risk at a regional scale considering the implications of different erosion processes associated with different timescales affecting coastal functions. The methodology also includes an assessment of the resulting consequences, by taking into account socio-economic indicators that determine the relative importance of each function. This information is integrated at the most adequate spatial and temporal management scale, and is combined within a risk matrix that will permit coastal managers to make decisions for specific management targets.

4.2 Methodology

Risk can be defined as the probability of harmful consequences or expected losses resulting from a given hazard to a given element over a specified time period (Schneiderbauer and Ehrlich 2004). In this part of the work, the considered hazard is coastal erosion, which is evaluated at three timescales. The expected negative consequences (or potential losses) are evaluated by assessing how two specific beach functions, i.e. recreation and protection, are affected by this hazard. The decrease of the beach recreational carrying capacity leads to economic losses for tourism-dependent businesses. It will also have social consequences, because the local population will be affected by the disappearance of leisure spaces (beaches). The decrease in the protection provided by beaches will expose existing coastal infrastructure to the direct action of waves leading to its damage or loss. These consequences are represented in terms of socio-economic indicators valuing the relative importance of each component (recreation and protection). Finally, the period of time in which the risk is evaluated is selected taking into account the perspective of the coastal manager. Thus, the risk is evaluated at current conditions to help make decisions now, and at decadal scale (25 years forecast) to help make future-decisions.

The methodology presented for erosion risk has been framed within the SPRC model (Figure 4.1). Sources represent all forcings determining or conditioning the erosion process in the coast. They cover all scales, and range from those acting at very large spatial and long-term scales, as is the case for changes in sediment supply and the effects of SLR, to those associated with the episodic scale such as storm events (Figure 4.1). These sources determine the pathway, which although known as "erosion" in generic terms, is decomposed here into three components (episodic-term, medium-term and long-term), each one associated with a specific timescale. These three erosion components characterise the hazard, and are separately evaluated by considering the relevant process controlling its magnitude. They are subsequently integrated in order to assess how the beach ("receptor") is impacted in terms of providing relevant functions for the area, i.e., recreation and protection. In order to measure the changes in the beach state affecting a given function, the concept of *beach functional vulnerability* (*BFV*) is introduced. This is a measure of the lack of capacity of the beach to properly provide a given function and which can be affected by coastal hazards (here restricted to erosion). Finally, the practical consequences of these socio-economic changes are measured in terms of a series of indicators representing relevant aspects of the analysed functions. These last two components, represented by the *BFV* and the consequences are jointly considered to assess the effects of the analysed hazard for coastal management. To do this, both components are combined within a risk matrix, where their values are spatially integrated at the management scale, and are then compared to identify and rank the most sensitive areas along the coast.

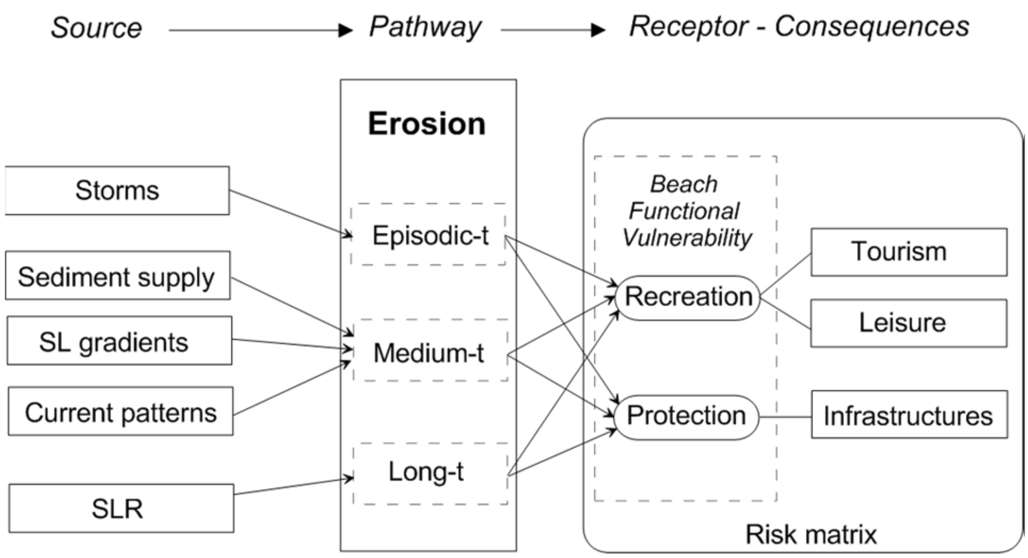


Figure 4.1 SPRC for erosion risk analysis.

4.2.1 Erosion hazard assessment

As mentioned, erosion is considered here as the "integrated" hazard of the action of three components which are the result of different processes acting at different timescales.

Episodic-term component

The episodic component corresponds to the instantaneous beach erosion induced by the impact of a storm on the coast. Although the induced beach erosion takes place at a timescale of hours and days (the duration of the storm), it is considered as representative of the episodic scale due to the stochastic nature of the forcing, the storms. Due to this, the characterisation of this hazard component is done in probabilistic terms, i.e. the magnitude of the hazard associated with a given probability of occurrence.

To characterise the magnitude of the storm-induced erosion, the extreme probability distribution of the shoreline retreat has been obtained for the study area following Bosom and Jiménez (2011). The procedure is as follows, first the maximum annual storm in the 44-year wave time series is identified. Then, the expected induced beach erosion using the bulk erosion model of Mendoza and Jiménez (2006) is calculated. This model predicts the storm-induced beach erosion as a function of storm properties (wave height, period and storm duration) and beach characteristics (sediment grain size and beach slope) and is applied to selected representative profiles along the study area (as a function of their sediment and profile shape). Finally, obtained sets of erosion magnitudes are fitted by a Generalized Extreme Value (GEV) probability distribution (one per each representative profile type) in order to know the expected storm-induced erosion at any probability of occurrence.

Medium-term component

The medium-term erosion component is that associated at a timescale from years to few decades. At the study site, it is driven by alongshore gradients in longshore sediment transport rates which are due to the presence of different marinas and coastal structures acting as barriers for the net longshore sediment transport directed southwards. This component has been empirically derived by analysing shoreline data to obtain representative shoreline rates of displacement. This has been done by applying a least-squares linear regression analysis of shoreline data over time. This method filters out short-term shoreline fluctuations and retains the main shoreline evolution trend (e.g. Dolan et al. 1991; Fenster et al. 1993), which is the medium-term evolution (erosion when negative) component.

This component has been evaluated through an analysis of the shoreline evolution over a period of a few decades using aerial photography from 1995 to 2010. As previously mentioned, this period can be considered as representative of the system behaviour under current conditions since most of major perturbations (harbours, coastal engineering works and artificial nourishments) were completed before 1995. The analysis has been applied to control points along the coast with a spacing of 100 m. The timeframe of the analysis can be considered as representative of this timescale because, in areas where the littoral dynamics is strongly dominated by the longshore sediment transport, shoreline evolution rates calculated using this technique require relatively short periods to reflect the dominant trend. This is the case for the study area, where, as discussed, mid-term shoreline changes are driven by the southwards directed net longshore sediment transport rates (CIIRC 2010; CEDEX 2014). Obtained shoreline evolution rates can be used to estimate future (decadal) beach configurations provided conditions do not change (i.e. in the absence of any new coastal engineering measure).

Long-term component

The long-term component of the erosion hazard is that associated with a timescale of several decades. This component is driven by processes acting at the long-term scale such as SLR, as well as by the cumulative effect (residual) of shorter-term processes such as alongshore gradients in sediment transport rates. Since the latter are directly characterised at the corresponding timescale, in this study the SLR-induced erosion is considered the intrinsic long-term component.

To evaluate this component, it is assumed that the SLR-induced response on sedimentary coasts can be modelled using the Bruun model (Bruun 1962). This model is based on the assumption of the existence of an equilibrium beach profile under current maritime climate. A change in the position of the mean sea level (MSL) will not affect the shape of the equilibrium profile which will only react to maintain its constant shape with respect to the new MSL. To do this, the model predicts a landwards and upwards movement of the beach profile, which results in a shoreline retreat. In spite of the fact that the Bruun rule is the most common way to assess SLR-induced shoreline retreat (e.g. Le Cozannet et al. 2014), there is a disagreement about its validity at the local scale. Many researchers use it to estimate an order of magnitude of the expected shoreline retreat (e.g. Nicholls and Cazenave 2010; Le Cozannet et al. 2014; Jiménez et al. 2016), whereas others claim that it should only be applied on a small number of coasts due to its simplicity and assumptions (e.g. Cooper and Pilkey 2004). In the absence of a generally accepted morphological model, it is assumed that the Bruun rule can be used to estimate an order of magnitude of SLR-induced shoreline retreat at the regional scale. In consequence, the model is applied to compute the expected regional long-term erosion rate along the area of study, i.e. a unique value of the shoreline retreat for the entire study area.

4.2.2 Beach Functional Vulnerability (BFV)

As previously described, beaches in the Mediterranean coast provide two main functions: protection and recreation. Erosion induces changes in the available beach width, which affects the aforementioned functions. In order to evaluate these effects, the necessary beach configuration to ensure these functions has been considered. Therefore, in order to classify the hazard in terms of its impacts, an optimum and a failure state have been established for each function (protection and recreation). Thus, an optimum state will correspond to a beach configuration which is fully able to support/provide the function of interest, whereas a failure state will be given by a beach configuration which is unable to provide such a function.

For a recreational beach configuration, these limits will be fixed depending on the density of use for the analysed beach (Jiménez et al. 2011). According to studies on user perception and characteristics of the study area (Yepes 1999; Valdemoro and Jiménez 2006; Roca, Riera et al. 2008; Sardá et al. 2009), it can be assumed that the optimum beach width is 35 metres. Assuming a steady affluence of users, the failure state of the beach is selected when the beach width is 1/3 of the optimum width, which results in an excessive density of beach users and, in consequence, in a poor recreational capacity.

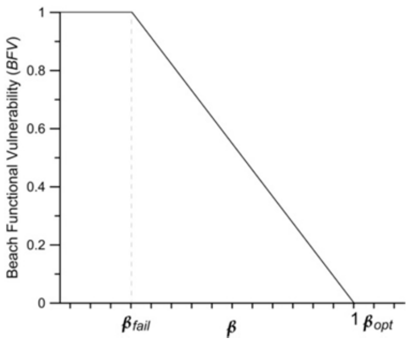
Protective beach configuration will be dependent on the characteristics of the storm and on the beach morphology at the time of impact. Beach configuration related to the protection function is determined by the beach width required to dissipate the energy of a storm for a given probability of occurrence (Bosom and Jiménez 2011; Jiménez et al. 2011). This is equivalent to a beach wider than the storm-induced erosion associated to such probability. In order to select the probability of interest, coastal managers have to define a safety level of analysis. This level should be determined by taking into account the characteristics and values of the hinterland. In this case, a beach wider than the erosion induced by a storm with a 50 yr return period is considered the most appropriate for the study area (see e.g. Bosom and Jiménez 2011). Therefore, in order to define the optimum beach width, the 50 yr return period storm-induced shoreline retreat plus an additional six metres has been considered. These six metres represent the minimum beach width required to safely maintain beach operations after the storm, in order to carry out reconstruction activities and to avoid the full exposure of the hinterland to direct wave action. The failure state is fixed by the beach width determined by the storm reach associated with the impact of a frequent storm, which here is defined as the 10 yr return period. In any case, these limits can be modified taking into account the importance of the values at exposure along the coast of interest, as well as, the safety level fixed by local stakeholders.

Hence, in order to assess coastal erosion regarding a given function, the actual and the future status of the beach induced by the medium and the long-term erosion components is evaluated with respect to the optimum beach status required for the functions of interest. To this end, the future status of the beach has been calculated according to two possible scenarios by 2035, with this future projection considered suitable to provide useful information to decision makers while maintaining the analysis within reasonable uncertainty bounds. Therefore, one scenario has been defined by the 25 year projection of the beach width using evolution rates given by the medium-term component. The second scenario corresponds to the same beach width projection plus the shoreline retreat induced by the long-term component (SLR) (Table 4.1).

To measure the ability of the beach to provide a given function an indicator, the *beach functional vulnerability, BFV,* is defined, which is computed taking into account the beach status at a given time (β) as a function of the optimum and failure states (see Table 4.1). It varies between 0 (representing a beach status able to properly provide the selected function) and 1 (a beach without any capacity to provide the target function). This indicator is calculated every 100 m along the study area to characterise local beaches.

With this approach, the erosion hazard is computed not only by the physical consequence, i.e. induced shoreline retreat, but also by the practical (end-user oriented) consequences, i.e. capacity to provide a given function.

Table 4.1 Methodology to assess the beach state (β) and functional vulnerability (*BFV*) for each function at selected scenarios.

β	***BFV***	**current**	**2035 scenario 1**	**2035 scenario 2**	**function**	**state**
$\beta = \frac{beach\ width\ at\ t}{optimum\ beach\ width}$		$\beta = \frac{beach\ width\ 2010}{Wop}$	$\beta = \frac{beach\ width\ 2035}{Wopt}$ *beach width 2035* = *beach width* 2010 + [medium-term evolution rates · 25]	$\beta = \frac{beach\ width\ 2035}{Wopt}$ *beach width 2035* = *beach width* 2010 + [(medium-term +long-term evolution rates) · 25]	***recreation***	optimum *Wop* = 35 m failure *Wfail* = *Wop* / 3
					protection	optimum *Wop* = Δ*X* (*Tr* = 50 yr) + 6 failure *Wfail* = Δ*X* (*Tr* = 10 yr)

4.2.3 Consequences

Many approaches exist for assessing the consequences induced by coastal hazards (e.g. Cooper and McLaughlin 1998; McLaughlin et al.2002; Boruff et al. 2005; Del Rio and Gracia 2009). However, although there are well-established approaches (e.g. Messner et al. 2007; Green et al. 2011; FEMA 2013; Penning-Rowsell et al. 2013), in many cases, they depend on the type of hazard analysed and their implications for the applicable socio-economic and natural systems. Erosion is a process that can clearly be reflected in a direct impact that results in beach retreat. However, beach functions can have indirect consequences that can go beyond the direct impact, resulting in important losses to the local economy. In this work, these consequences are addressed by selecting a set of socio-economic indicators related to the function of interest. In order to define these, indicators must be easily quantifiable, they must be integral at a proper management unit scale, and need to be acceptable/understandable to coastal managers. In this sense, indicators have been developed and selected to characterise the importance of the main coastal functions: protection and recreation within the study area and they are represented at the minimum management scale, that is, at the municipality level.

Focusing on the recreational function of the coast, two differentiated typologies can be distinguished: a) beaches with a tourist focus, representing one of the most important sources of income for the local economy, and b) a recreational use of beaches by the local population.

It should be pointed out that in the analysis of the consequences, a temporal scale is not considered given the uncertainty associated with socio-economic scenarios. Rather, and in contrast to the erosion hazard components, they represent a variable which is steady at the present time. However, in order to replicate the methodology presented here in other regions, if further data is available, future socio-economic indicators can be implemented in the analysis.

The construction and socio-economic importance of coastal uses are represented in the following indicators.

Tourist Index

In order to obtain a representative value of the importance of coastal tourism, a direct economic value of the beaches should be considered (Ariza et al. 2012; Houston 2013). However, this evaluation requires a thorough analysis of the many factors which should be considered in order to obtain reliable information. In the absence of this direct economic value, a representative indicator of tourism at municipality level is used here. The tourist index developed by La Caixa Bank (2013), is a relative index based on tax revenues (Business Activities Tax), which takes into account the number of rooms, the annual occupancy rate and the category of tourist establishments (budget hotel, campground, etc.). The index value is the percentage share of each municipality relative to the entire nation, which can be expressed as:

$$\textit{Tourist index} = \frac{\text{Municipality tax rate}}{\text{Total tax rates in Spain}} \times 100{,}000 \qquad (4.1)$$

In order to carry out an assessment at different scales the absolute tourist index value has been relativised obtaining a value for each municipality from 0 to 1 at the three spatial scales of analysis proposed in this study. It should be noted that although this index represents a value for the entire municipality, in the study area as in many other coastal Mediterranean regions, tourism based on coastal activities is the major contributor.

Leisure Index

In order to consider the role played by the local population in the recreational use of the coast, an indicator which expresses the user density of locals “served” by the beaches has been developed. Consequently, it is assumed that beach use will be proportional to the total municipality population, and therefore, it can be said that the higher the population, the larger the beach use demand. The index is expressed as follows:

$$\textit{Leisure index} = \frac{\text{Total municipality population}}{\text{Length of municipality coastline (m)}} \qquad (4.2)$$

The leisure index has been built considering the total municipality population at 2016 (IDESCAT 2016) and the total coastline classified as beaches by the CIIRC (2010).

Infrastructure Index

Regarding the protection function of the beach, an index to quantify the main infrastructures at the coast has been developed. The rationale behind this is that this function will be especially relevant in those places with important elements to be protected. To do this, and taking into account the characteristics of the study site, three components have been considered behind the beach within a buffer area: built-up urban areas, roads, and the railway. In order to obtain a value at the municipality level, these three components have been relativised with respect to the total buffer area (built-up areas) and to the coastline length (roads and railway).

To define the buffer area, the scope of the hazard should be considered. In this case, with a focus on erosion and the characteristics of the study area, damages in the hinterland occur in a narrow fringe along the shoreline, and therefore, a buffer area of 100 m inland is considered.

To aggregate the three components measured in the index, it is considered that damages reported for each component (roads, railway, and built-up areas) can be similar in consequence, and so an additive aggregation method, assuming a linear relationship, is taken into account as expressed in Eq. 4.3;

$$\textit{Infrastructure index} = \frac{\frac{\text{Urban surface (km}^2\text{)}}{\text{Buffer area (km}^2\text{)}} + \frac{\text{Roads (km)}}{\text{Coastline (km)}} + \frac{\text{Railway (km)}}{\text{Coastline (km)}}}{3} \qquad (4.3)$$

Thus, a value from 0 to 1 will be obtained for each municipality. Although the information stated by this index does not specially represent the direct damages, this index characterises the coast in terms of the number of infrastructures exposed and potentially damaged if the natural protection function of the coast fails.

4.2.4 Spatial integration

In order to provide a management-oriented value, *BFV* values locally obtained (every 100 m along the coast) are spatially aggregated at the municipality scale. This scale represents the smallest administrative level where coastal managers can undertake risk management measures. Because the main objective of the management is to reduce/mitigate risks (negative responses) and, to avoid compensatory results among erosive and accretive stretches in a given municipality when a linear aggregation method is performed (average), a weighted averaging to characterise the aggregate impact has been adopted (Table 4.2). The underlying hypothesis is that eroding beaches which will result in an exposition of existing infrastructure and/or decreasing carrying capacity of the beach will not be compensated by wider beaches in areas already well protected or wide enough to support recreation. This replicates the observed preference of users to concentrate in a narrow fringe close to the shoreline, even in very wide beaches. A decreasing linearly weighting scale (Table 4.2) has been selected to give more importance to those stretches with larger *BFV* values (narrowing beaches) than stretches with lower *BFV* values corresponding with stable or wide beaches. This method highlights stretches at risk in order to obtain a final value at the municipality level.

Thus, the integrated beach functional vulnerability (*BFV'*) at the scale of interest is given by;

$$BFV' = \sum_{i=1,n} \alpha_i \, BFV_i \, l_i \Big/ \sum_{total} l_i \qquad (4.4)$$

where *BFV* represents the beach functional vulnerability of a given stretch, α_i the corresponding weights and l_i the length of the coastal stretch.

Table 4.2 Weights assigned.

Intervals (*BFV*)	Weights (α)
[0.0-0.2]	0.125
[0.2-0.4]	0.25
[0.4-0.6]	0.50
[0.6-0.8]	0.75
[0.8-1.0]	1

4.3 Results

The results obtained for the erosion assessment are presented in this section for the entire Catalan coast. Results for each erosion hazard component are only illustrated for one coastal sector, the Maresme coast. This analysis has been done for all sectors along the Catalan coast and they are directly included in the evaluation of the erosion risk matrix (section 4.3.5).

4.3.1 Episodic-term component

As previously mentioned, this hazard component is represented by the storm-induced shoreline erosion. This is symbolised here by an extreme probability distribution of the shoreline erosion which has been computed for the different beaches along the study area. As an example, Figure 4.2 shows the obtained extreme erosion climates for all beach types along the Maresme coast (dashed lines) in function of their sediment size and beach profile together with the representative erosion climate (solid line), provided by the weighted average of the individual beaches taking into account their relative contribution to the total coastline. As can be seen, although it can be assumed that incident wave climate is uniform along this coastal sector, there will be differences in erosion due to variations in beach morphology. This has been done for the entire coast using the sectorization and classification of beach types of Bosom (2014).

According to the obtained probability distribution, the average storm-induced shoreline retreat along the Catalan coast associated to a return period of 50 years is about 20 m.

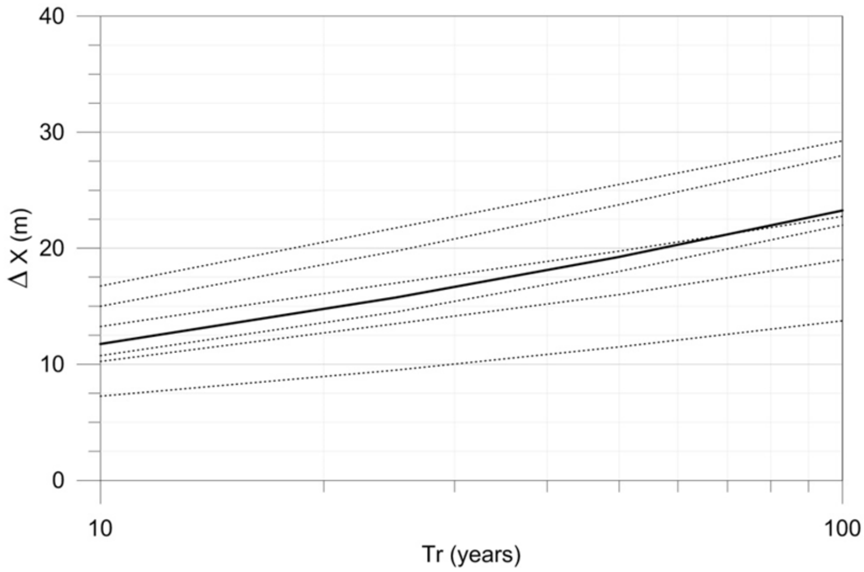


Figure 4.2 Representative extreme probability distribution of storm-induced shoreline erosion in the Maresme coast.

4.3.2 Medium-term component

Figure 4.3 shows the obtained medium-term shoreline displacement rate every 100 m along for the Maresme coast. This coastal area displays a clear spatial pattern representative of the majority mid and southern beaches along the Catalan coast showing the importance of longshore sediment transport gradients in driving the observed changes. In general, the coast presents a generalized retreat with the exceptions of areas just upcoast of existing barriers (harbours) where accretion is observed. Moreover, the stretches just downcoast from these barriers are the areas with the largest recession rates. Overall, for the 1995-2010 period, the average evolution rate for the Maresme is -0.97 m/yr with a maximum retreat of 7.97 m/yr, which was obtained at the municipality of Malgrat de Mar (23) corresponding with the low-lying area of the Tordera delta.

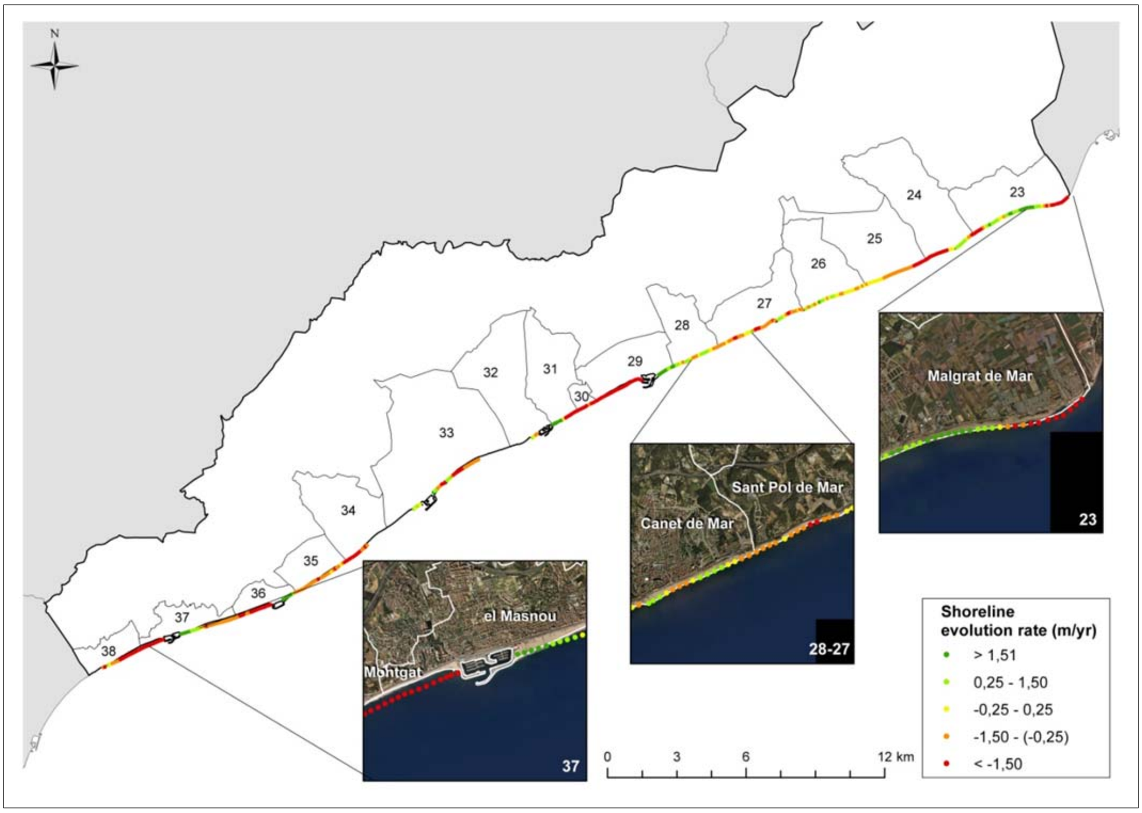


Figure 4.3 Shoreline evolution rate along the Maresme coast

The average evolution rate for the Catalan coast is -0.7 m/yr with the maximum shoreline retreat found in the deltaic zones such as the Tordera delta, as presented previously, and the Ebro delta, the most susceptible area to erosion. In this region the average shoreline evolution indicated maximum rates of -22.47 m/yr and -13.75 m/yr for the Sant Antony beach within Deltebre (66) municipality and for the Platja de Buda within Sant Jaume d'Enveja (67) municipality respectively. Although deltaic zones represent the areas with the most important shoreline retreats, large shoreline retreats along the Catalan coast are also presented in the Maresme *comarca*, within the municipalities of Arenys de Mar (29) (-3.95 m/yr) and el Masnou (37) (-3.57 m/yr) among others.

4.3.3 Long-term

The long-term component is provided by the computed SLR-induced shoreline retreat for the RCP8.5 scenario up to the year 2100. This component is calculated by applying the Brunn equilibrium model for different sedimentary coastal sectors which represent homogeneous geomorphologic characteristics (similar grain size and shoreface slope) (Figure 4.4). Obtained values indicate the Ebro delta as the most erosional sector. Due to its very mild shoreface, and considering that this area is also affected by subsidence, SLR-induced shoreline retreat determines an order of magnitude between two and three times greater than the rest of the Catalan coastal sectors. In contrast, the Maresme represents the less sensitive area to erosion by SLR given its steep slope. In general, results along the Catalan coast (excluding the Ebro delta), show a background erosion of about 0.57 m/yr with an increase in erosion rates by the year 2050 due to the acceleration of SLR (Figure 4.4). Expected shoreline retreats by 2050 are 19 m in the Maresme, 22 m in Costa Brava and 25 m in Llobregat-Costa Dorada (see Jiménez et al. 2016).

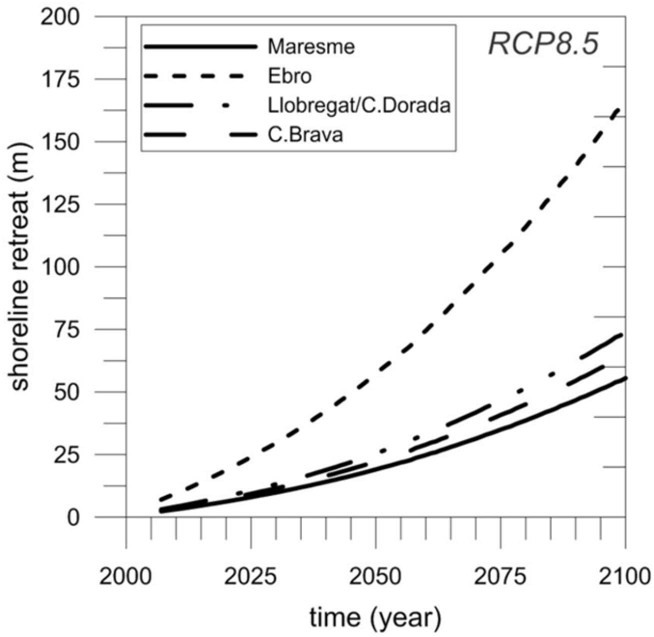


Figure 4.4 SLR-induced shoreline retreat (RCP 8.5 scenario) along the Catalan coast.

4.3.4 Consequences

Figure 4.5 shows the socio-economic indicators used to measure the degree of exposure and importance of the two analysed coastal functions; recreation and protection. It should be noted that although the results presented here have been relativised considering the whole Catalan coast, the indicators have also been re-scaled at province and HEMU levels (for the tourist and leisure indices) for analysing the effect of scaling on the assessed impact. In general, results show a different spatial pattern along the coast for the three indicators assessed. The tourist index highlights the two main tourist destinations (with the exception of Barcelona); *Costa Dorada* in

Tarragona with Salou (59) having the highest value and *Costa Brava* in Girona with Lloret de Mar (19) presenting the highest value. Both locations present a magnitude considerably larger than the other municipalities. To avoid an excessive weight of these two municipalities on the scaling of the tourism-based economy for the rest of Catalonia, the remaining municipalities have been relativised with the next highest value (i.e. Cambrils (60) at the Catalan level). This is illustrated in Figure 4.5, where the importance of other tourist municipalities, such as Roses (6), Tossa de Mar (20), Santa Susanna (24), Calella (26) and Sitges (46), among others, are also highlighted.

With respect to the level of the local population served by beaches, the leisure index shows that Mataró (33) and Tarragona (57) represent the highest values. Both municipalities correspond to important urban areas, Tarragona being a provincial capital. For this reason, Tarragona has been considered in the analysis at the Catalan level but not in the analysis at other scales (province and HEMU levels) as this would distort the results of the analysis. Other municipalities with high index values are St. Andreu de Llavaneres (32), Viladecans (43), Cubelles (49) Palafrugell (13). In some cases, the coastal configuration of the municipality, with small coastlines and/or bays, can influence the final index value, whereas in other cases it is the elevated municipality population.

The infrastructure index shows a clear distribution, where the highest index values are presented in the Maresme *comarca*. Also, the municipalities of Portbou (1) and Colera (2) in the north present high values although they are concentrated in a small portion of the territory. It should be noted that although the map gives a total value for the whole municipality area (Figure 4.5), the infrastructure index has only been assessed in the sedimentary part of the municipality coastline. In this sense, the municipalities of Portbou and Colera can generate a false impression as their coastlines are mainly formed by a rocky coast with natural areas. In the case of the Maresme coast, characterised by the presence of a quasi-continuous sedimentary coastline, there is an important level of infrastructure development very close to the shoreline as this region represents a metropolitan extension of Barcelona, with excellent communication routes to the city (the railway and a motorway) and the expansion of new residential areas. The rest of the coastal municipalities present similar values due to the coastal zone having been uniformly developed, with the exception of natural areas, such as the Ebro delta (south) or the Gulf of Roses (north) with very low or no development at all.

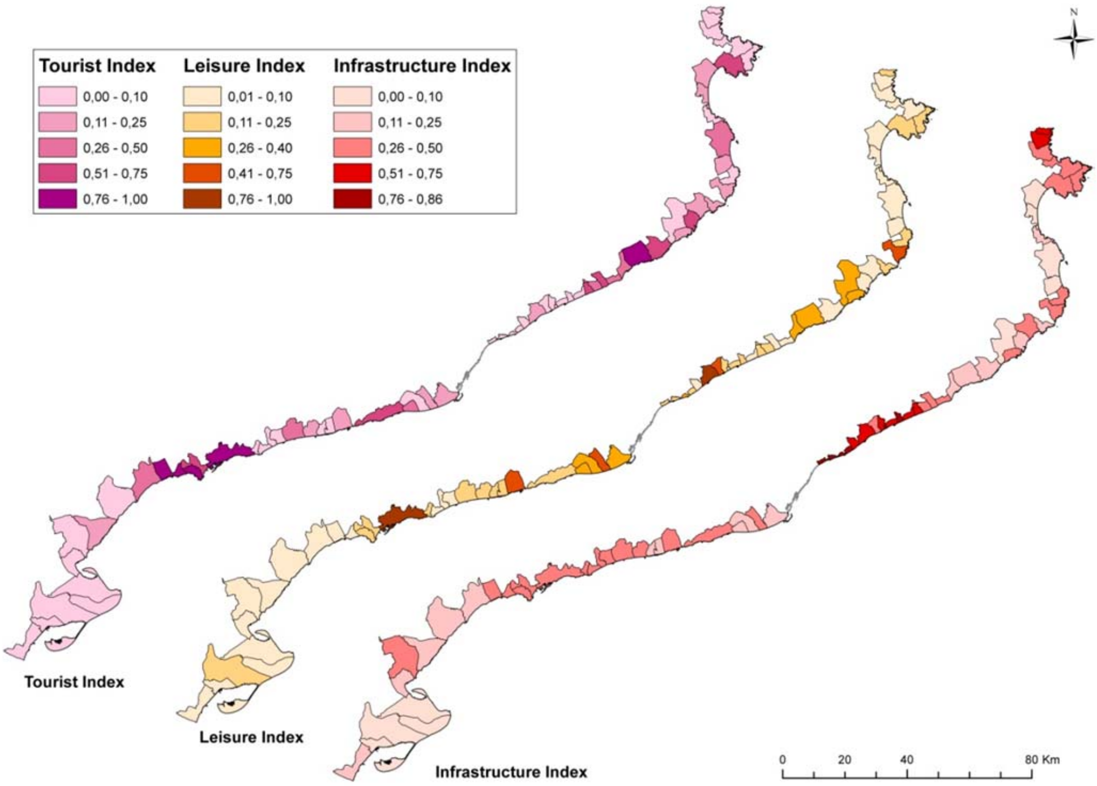


Figure 4.5 Consequences represented by socio-economic indicators. Leisure and infrastructures indices are evaluated only for the part of the municipality coastline composed of beaches.

4.3.5 Erosion risk matrix

The computed erosion components (hazard) and consequences have been integrated to obtain the erosion risk matrix. As previously mentioned, the hazard component is evaluated to account for each analysed function in terms of the *beach functional vulnerability*, *BFV'*.

The risk matrix enables the presentation of two components, hazard and consequences, and in this way, to illustrate their importance separately. Moreover, this approach permits, when more than one hazard component is considered, to easily show their time evolution.

Figure 4.6 and Figure 4.7 show risk matrices obtained for analysed coastal functions scaled using the HEMU and province levels. In the analysis of the recreational function, only the mid and long-term erosion components have been included because in the region, storms usually take place in autumn and winter, while the beach is only used for recreation in summer (Valdemoro and Jiménez 2006). Thus, during “normal climatic years”, beaches are generally able to recover after seasonal storm-induced erosion. Although the hazard is the same (the same *BFV’* considering the recreational function), the resultant risk is different as the consequences are measured taking into account different recreational interests. Moreover, when considering different scales, it can be observed how the erosion risk for recreational uses changes since the socio-economic indicators are relativised at such scales.

When the scaling of the risk is done using parts of the territory (HEMUs or provinces, Figure 4.6 and Figure 4.7) obtained results have to be interpreted individually. As an example, obtained results for HEMU A (Figure 4.6) indicate that with the exception of a single municipality (Roses (6)), the expected potential damage on tourism should be very low because this HEMU corresponds to areas dominated by natural values and where tourism development is usually low. However, if the same area is evaluated just in terms of leisure (potential use of beaches by the local population) additional municipalities emerge as areas at-risk showing some kind of clustering in two big groups in terms of population.

Results obtained for tourism use along the Catalan coast as a whole (Figure 4.11), show that the erosion risk is, in general, low and very low at present, with the exception of two municipalities, Sitges (46) and Tossa de Mar (20) which present medium risk values. In spite of these current generally good conditions, the projection by 2035 indicates an increasing risk due to background erosion rates, which increase further if the long-t component (SLR-induce erosion rates) is also considered. The municipalities most affected are Blanes (22), Santa Susanna (24) Tarragona (54) and Lloret de Mar (21).

When considering leisure (Figure 4.11), Mataró (33) and Tarragona (57) are principally the two municipalities with the highest risk level. Both municipalities are important urban areas, with an elevated population which determines the highest index values. Other municipalities with very high levels considering the projection by 2035 are St. Andreu de Llavaneres (32), Castell-Platja d’Aro (19) and Palafrugell (13).

Figure 4.8 and Figure 4.9 show the spatial distribution of values presented in risk matrices (Figure 4.6 and Figure 4.7) for the HEMU and province aggregation scale along the Catalan coast. As can be observed, under current conditions the Catalan coast can be considered as generally safe, but when future evolution is included some hotspots appear, especially when SLR is considered. This type of aggregation results in the appearance of these sensitive areas in all territories since each HEMU type or province will have their own critical areas.

Focusing on province level (Figure 4.7 and Figure 4.8), erosion risk at present for tourist use is low in Tarragona and Girona while high in Barcelona for the municipality of Sitges (46). However, when considering the medium component (longshore sediment transport) the level of risk significantly increases in those municipalities with high tourist index values (i.e. 6, 20, 22, 46, 24, 25, 58). Moreover, when the long-term component is taken into account, risk increases considerably to very high, especially in Girona for Lloret de Mar (21) and Roses (6). At HEMU level (Figure 4.6 and Figure 4.8) results show a risk distribution quite similar to the provincial one. However, at this scale of analysis and considering the medium and the long-term components, some municipalities such as Sitges (46) and Santa Susanna (24) present high risk values instead of very high, whereas other municipalities such as Cambrils (60) and Vila-seca (58) increase their risk level.

Regarding leisure use (Figure 4.7 and Figure 4.9), the risk at the present time is medium for Barcelona, presented in Mataró (33) and Castell-Platja d'Aro (19), and Palafrujell (13) within Girona. In these municipalities, the level of risk rises when the medium and long-term components are considered. In the case of Tarragona[2], although risk levels at present are low and very low, these significantly increase by 2035 in Calafell (51) and Altafulla (56). As is the case for tourist use, erosion risk changes for leisure use considering different scales of analysis (Figure 4.6 and Figure 4.9). Major changes are found in HEMU category A where municipalities such as Portbou (1), Cadaquès (5), Roses (6), l'Ametlla de Mar (63) and el Perello (64) present very high erosion risk values for the local use of beaches.

[2] It should be noted that the Tarragona municipality is not considered in the analysis at province and HEMU level given that it represents a provincial capital with a significant population which can distort the results for the rest of municipalities.

As expected risk conditions significantly change when future projections include background erosion rates plus SLR-induced retreat are considered.

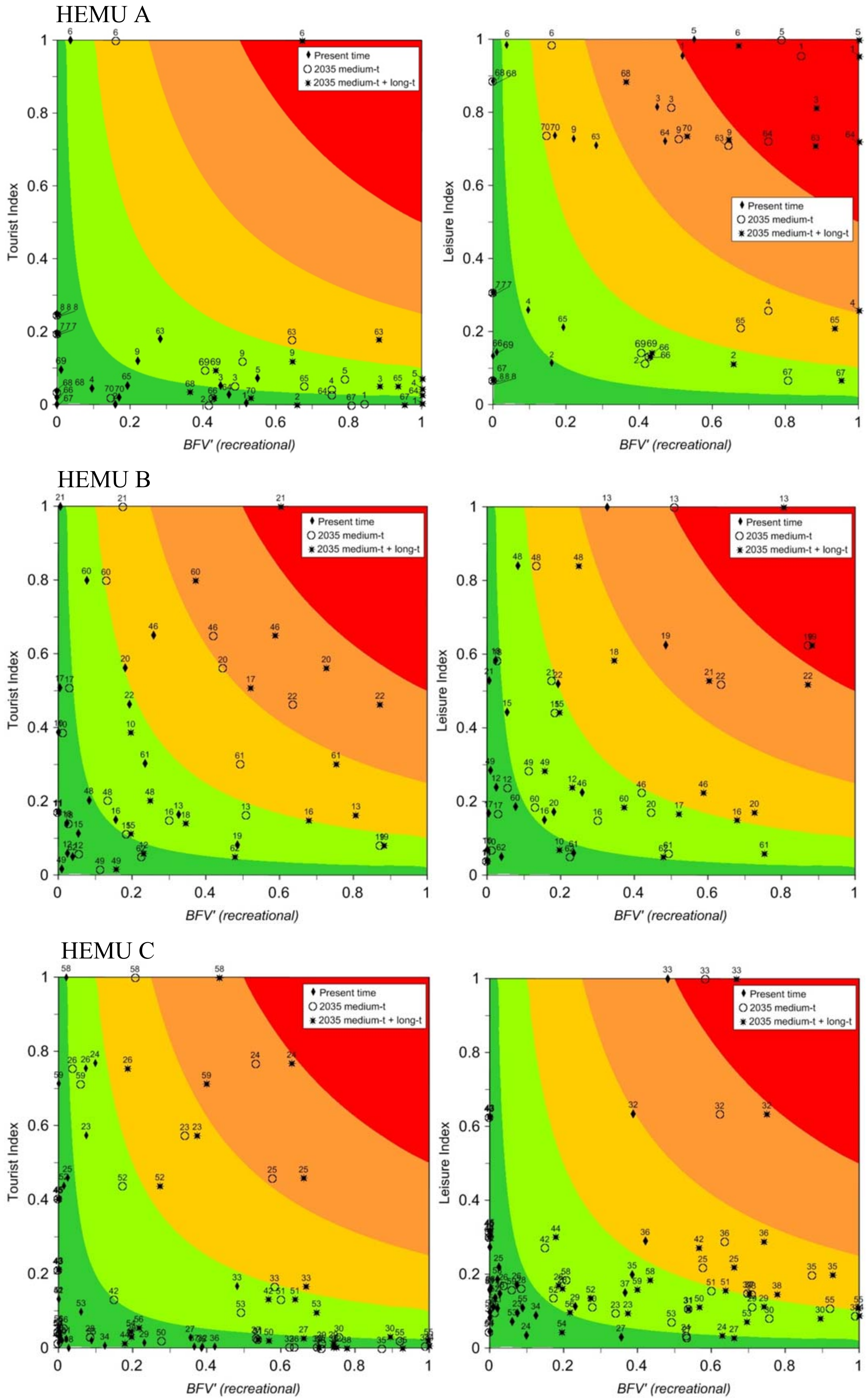


Figure 4.6 Erosion risk for recreation- HEMU level (tourist use / leisure use).

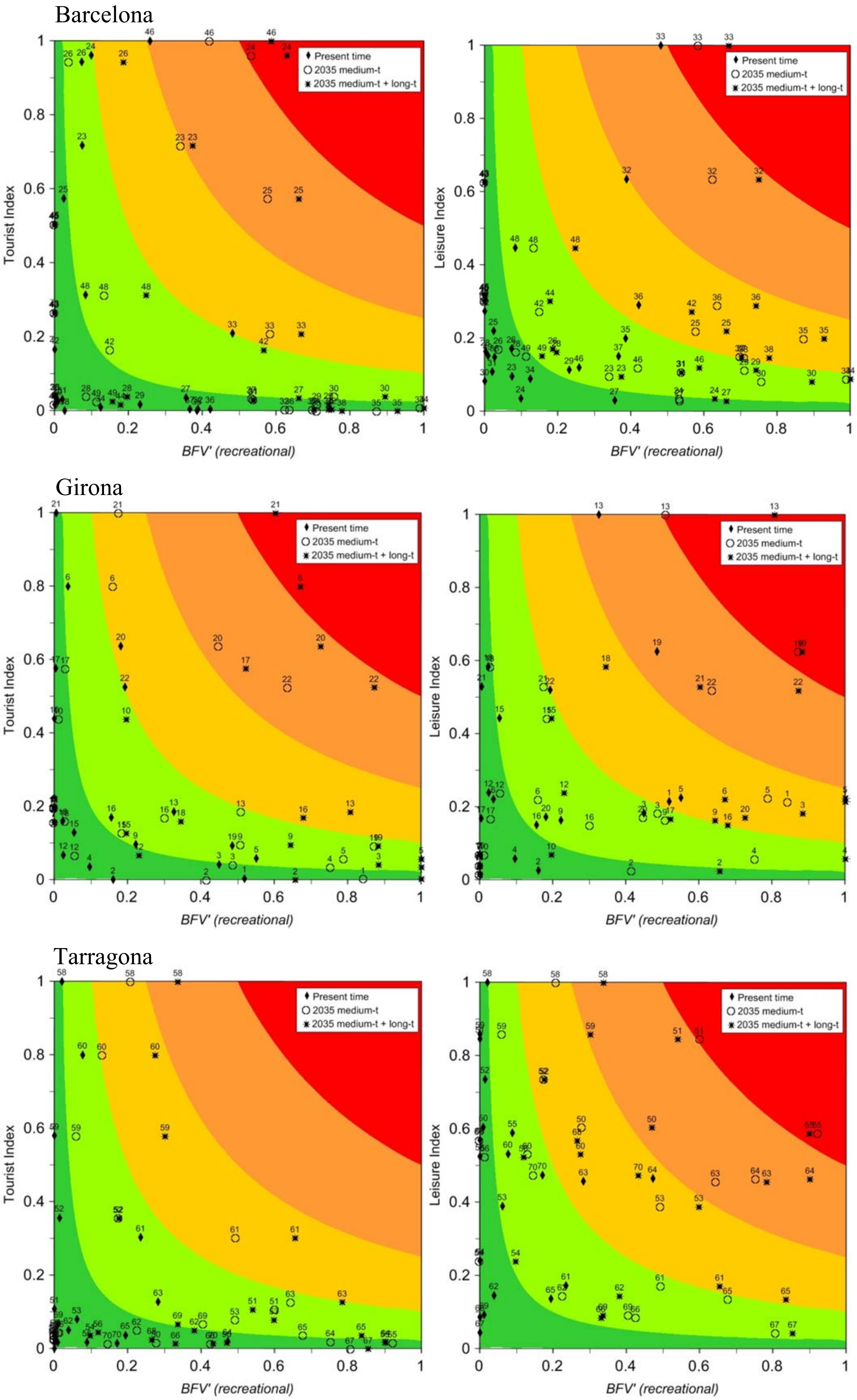


Figure 4.7 Erosion risk for recreation-Province level (tourist use / leisure use).

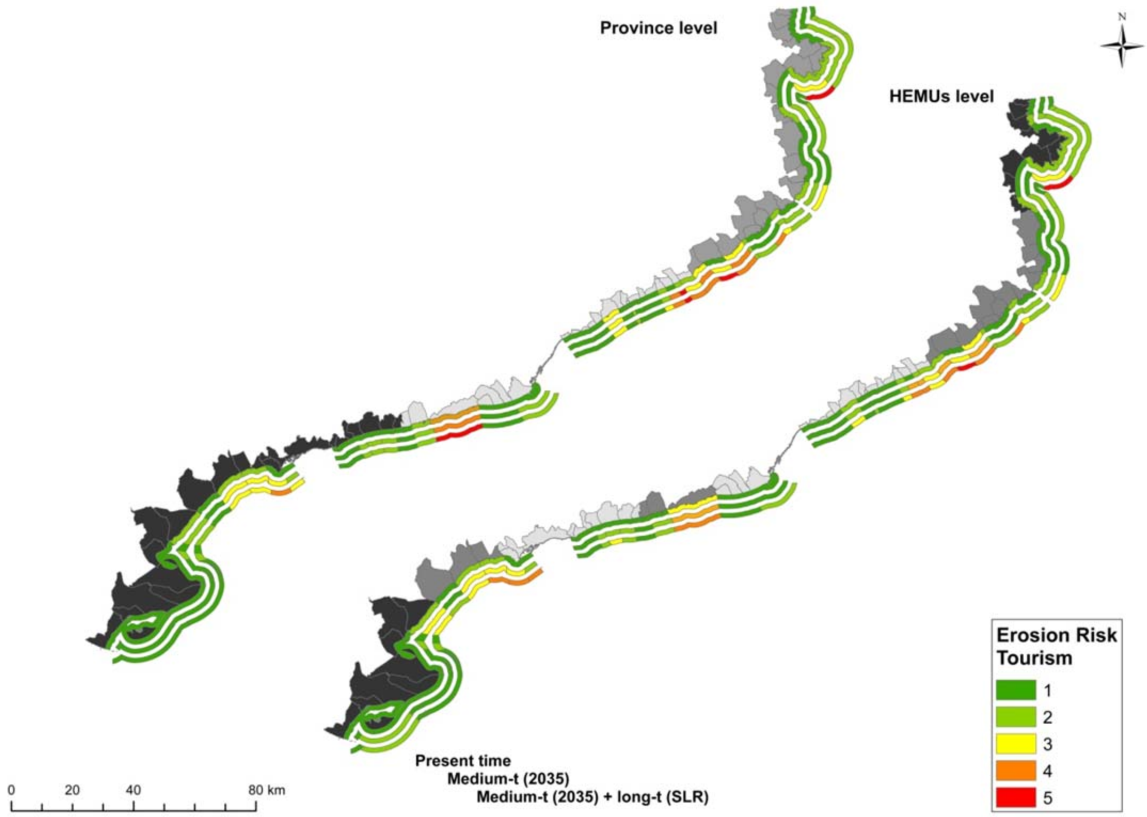


Figure 4.8 Erosion risk for tourism considering province and HEMU level.

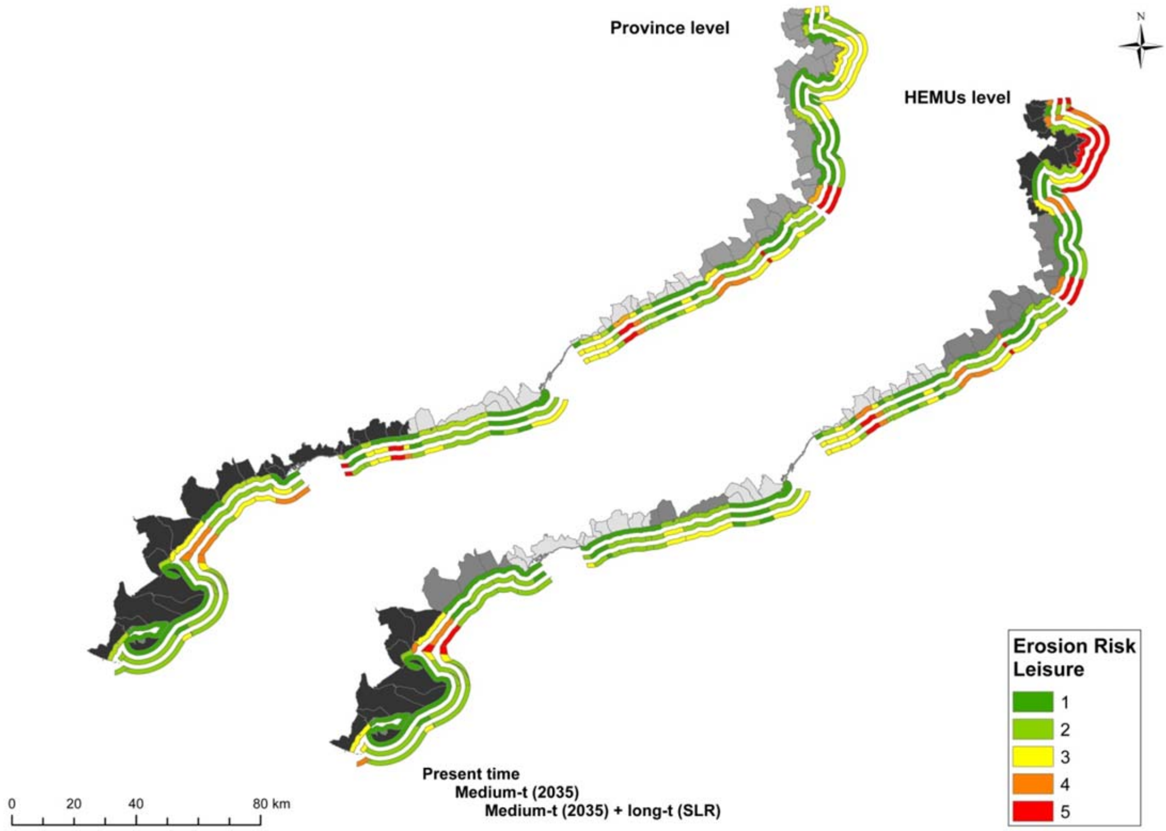


Figure 4.9 Erosion risk for a leisure use considering province and HEMU level.

Figure 4.10 shows the erosion risk matrix for a protection function of the beach. In this case, the function will be determined by the impact of storms that usually occur in winter when there is no recreational use (Valdemoro and Jiménez 2006). Thus, in this case, all the erosion components are considered in the analysis.

As a result of this, and although background erosion rates for all municipalities controlled by the medium-term erosion are the same as before, their associated *BFV'* are different, since the optimum and the failure beach function states will be fixed considering the episodic-term erosion component.

Figure 4.10 presents the results obtained at province and HEMU level. However, it should be noted that as the infrastructure index is not scaled (as it represents an absolute value), the risk associated to a given municipality is the same in both scales. Figure 4.11 shows the spatial distribution of the erosion risk for a protection function associated to each municipality along the Catalan coast. As can be observed, in general and, at present, the coast is relatively safe with the exception of some medium to high risk areas mostly in the municipalities located within the Maresme *comarca* (i.e. 32, 35, 36) and the municipality of Roda de Barà (53) within the Tarragonès *comarca* where a large density of infrastructure and narrow beaches exist. By 2035, background erosion rates will substantially increase the level of associated risk in these municipalities to the highest level, also raising risk levels in municipalities such as El Port de la Selva (4) and Santa Susanna (24), Sant Pol de Mar (27), Arenys de Mar (29) and Caldes d'Estrac (30) within the Maresme *comarca*.

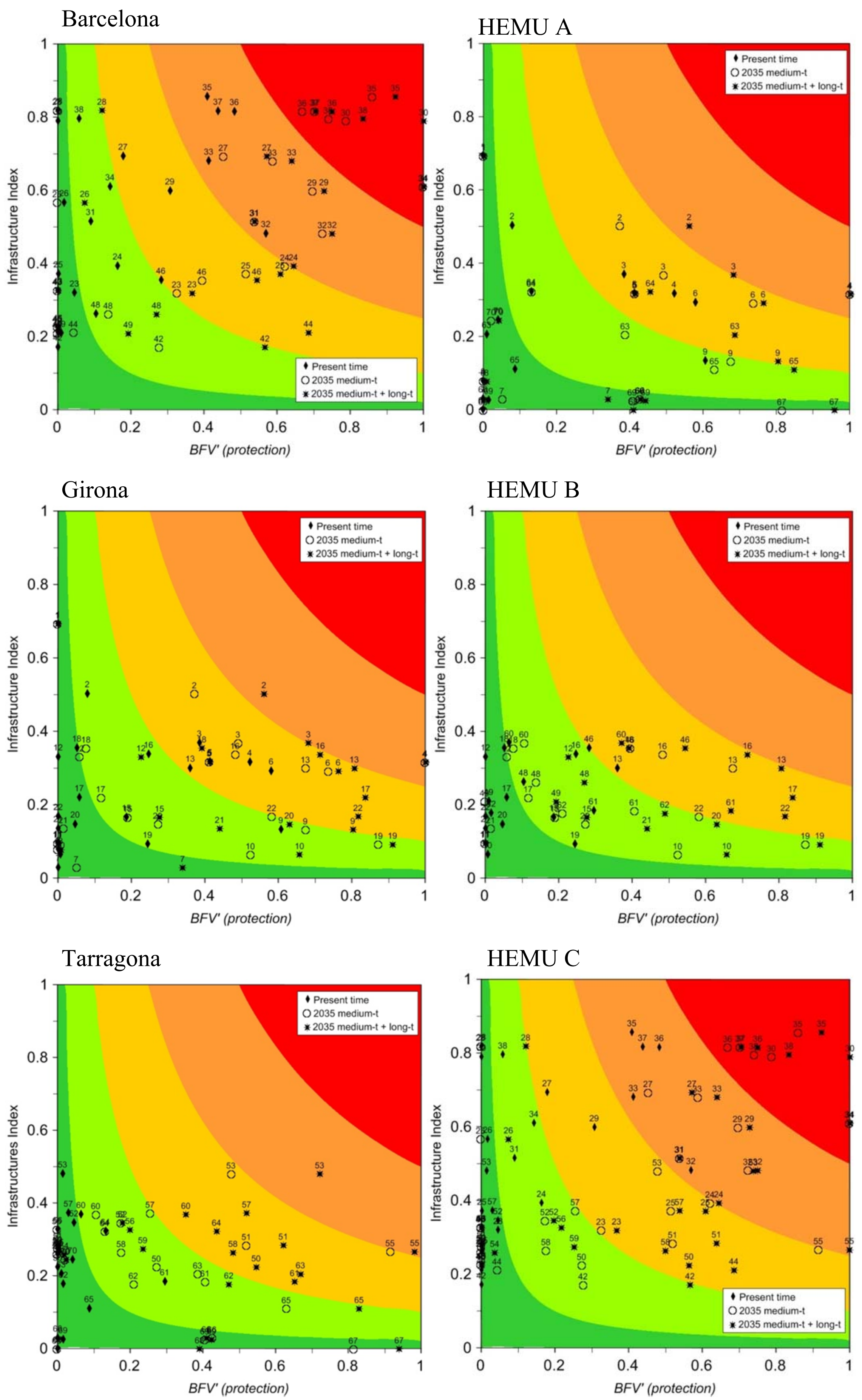


Figure 4.10 Erosion risk for a protection use- Province and HEMU level.

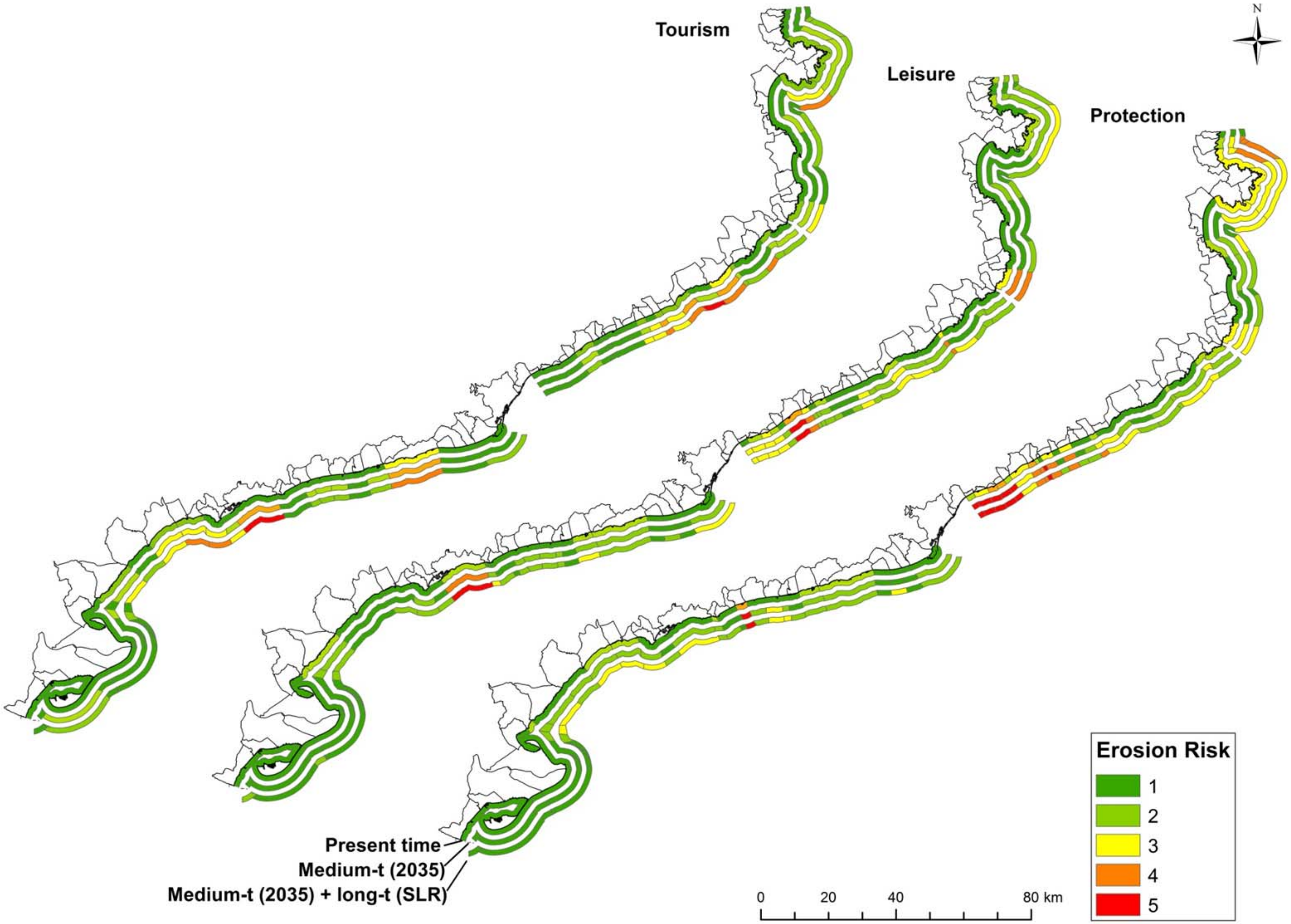


Figure 4.11 Erosion risk for the Catalan coast considering recreation (touristic/leisure use) and protection coastal functions.

Chapter 5
Flood risk analysis*

5.1 Introduction

Floods are considered to be one of the most harmful phenomena, causing 69% of the overall natural catastrophic losses in Europe (CEA 2007; Llasat 2009). In Spain, the Consorcio de Compensacion de Seguros (CCS), a public corporation which provides insurance to cover “extraordinary“ risks, states that 61% of its resources are required to mitigate damages incurred as a result of flood events (Insurance Compensation Consortium 2016). The greatest number of casualties and material damage have occurred in the Spanish Mediterranean (Barnolas and Llasat 2007; Camarasa-Belmonte and Soriano-García 2012). Moreover, in the absence of additional adaptation, the risk from coastal flooding is predicted to rise in the future as a result of two primary factors. First, climate change and rising sea levels are expected to increase the frequency and severity of flood events (EEA 2013b) and second, the number of potentially exposed receptors (infrastructure, socio-economic assets, population) is increasing in floodplains and/or near the sea (e.g. Hallegatte et al. 2013).

Flood risk can be defined as the product of the probability of flooding and the associated negative consequences or damages (UNISDR 2009). In order to reduce the negative consequences of flooding, it is necessary to consider the implications of the hazard and the exposure values potentially affected. Traditionally, flood risk in coastal areas has been managed with the use of physical structures to protect against floods (e.g. Saurí-Pujol et al. 2001). However, it is recognized that absolute protection is both unachievable and unsustainable due to the high costs and inherent uncertainties involved (Schanze 2006). As a result, there has been a shift in environmental policy in the European Union from emphasis on flood protection to flood risk management. The European Floods Directive 2007/60/EC (EC 2007) urges flood risk analysis and flood

* Edited version of A multi-component flood risk assessment in the Maresme coast (NW Mediterranean) by Ballesteros C, Jiménez JA and Viavattene C (2017) accepted (in review) to the journal Natural Hazards.

risk management at the community level, based on local circumstances and the specific types of flooding (river floods, flash floods, urban floods, and flooding from the sea in coastal areas) which may be present.

To correctly define coastal management policies for successful flood risk management, given the spatial and temporal nature of flood risk, broad-scale integrated assessments are essential (Dawson et al. 2009; de Moel et al. 2015). Thus, in order to manage the coastal zone at a regional scale, a holistic approach is required where, in addition to the factors determining flood risk (hazards and consequences), the various flood processes acting at different temporal scales should be considered.

In Mediterranean coastal regions, floods can be present as a result of forcings from multiple origins acting at different timescales. Hence, flooding from a marine origin (related to changing sea levels), can be the result of a marine storm associated with a short-term scale. Regarding flooding from the same origin, but associated with a long-term scale, the effect of climate change can cause a permanent inundation due to SLR. Finally, regarding flooding of a terrestrial origin and caused by short-term convective rainfall at the mouth of stream systems, floods in the Mediterranean coast can be present in the form of flash floods.

In order to manage coastal flood risk and to develop measures for effective and long-term disaster risk reduction, it is therefore necessary to know not only the magnitude of each of the different flood components (flash flood, marine storm, SLR) and their associated consequences, but also their relative importance in relation to one another. This input is essential when analyses at a regional scale are taken into account, as it allows coastal managers to identify and detect the most critical areas at risk as a result of the different flood components. This analysis then enables a more detailed assessment to be undertaken and for resources to be focused in these specific locations.

Although established approaches exist to carry out a comprehensive analysis and assessment of flood risk for each individual flood component, few studies address all components combined together (Kappes et al. 2012). Doing so presents particular challenges due to the difficulty of analysing multiple components (processes) acting at different spatial and temporal scales. In order to tackle this problem, different methodologies have been developed using indicators (e.g. Gornitz 1990; McLaughlin et al. 2002; Birkmann 2007). Through the use of indicators, it is possible to integrate risk components with homogenous units and to integrate multiple-flood hazards into one flood risk assessment. One advantage of this approach is that it allows an evaluation of all components and their associated risks using methods that do not require extensive data or a high degree of model accuracy.

Here, a methodology framed within the Source-Pathway-Receptor-Consequence (SPRC) model is presented in order to determine the potential flood risk as a result of different flood components. The methodology uses representative indicators that are suitable for comparing flood risk between different locations and also between flood types.

Within this context, a framework to analyse coastal flood risk as a result of multiple components (flash flood, marine flooding, SLR) at the regional scale is introduced. The practical objective is to identify the most sensitive areas to flooding and to verify the most relevant flood component in terms of magnitude and potential for damage. With this information, coastal managers can prioritize their efforts in areas where risk management is needed the most.

5.2 Methodology

In the present application of the SPRC, coastal flood risk is presented as the result of different forcings (sources) that cause flood processes at different spatial and temporal scales (pathways) with an associated impact for the exposure values and consequences (Figure 5.1). Three main flood processes are here considered as: flash floods, marine floods, and inundation by SLR. Flash floods and marine floods are characterised as episodic events associated with hydro-meteorological, acute and ephemeral phenomena (the inundation is transient) that are expressed in probabilistic terms. In contrast, SLR is characterised as a long-term process which causes a permanent inundation of the affected surface. In this case, the forcing is characterised as the evolution over time of sea level for different scenarios.

To characterise the receptor (the coast) and the associated flood consequences, a number of socio-economic coastal values are considered. Hence, the consequences are the resulting value of the integration of the following five components: land use, social vulnerability, transport system, utilities, and business setting.

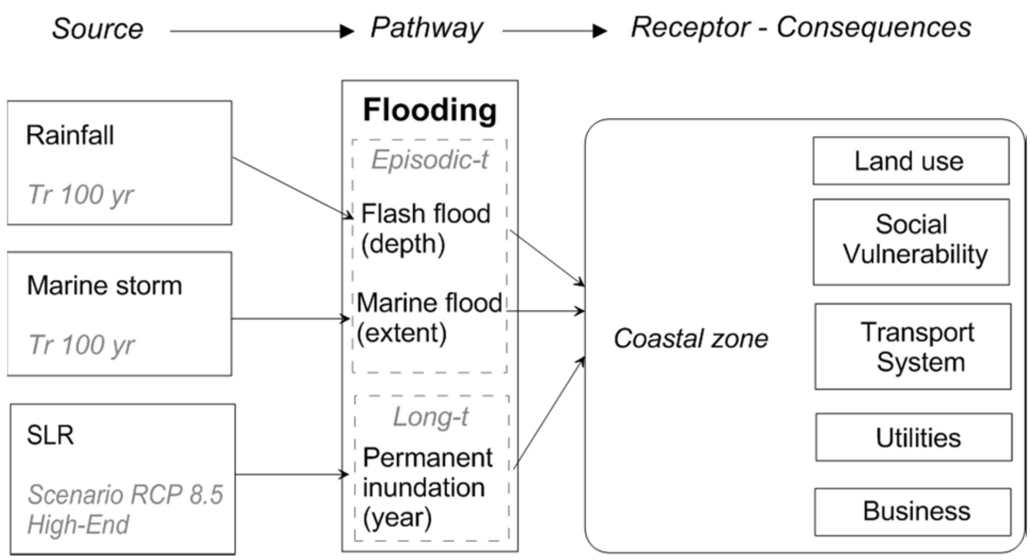


Figure 5.1 SPRC model for multi-component flood risk analysis.

5.2.1 Flood risk assessment

In order to assess the flood risk associated with each component, an approach has been adopted in which the different flood components have been evaluated in terms of their hazards and exposure values by means of representative indicators. As the main objective is to identify the most sensitive areas along the coast as well as the contribution of each component, the selected indicators have been classified and standardized in homogenous units. To this end, a hazard intensity scale from 1 to 5 is considered where, 1 represents the least harmful level and 5 the most harmful (see Table 5.1). This classification has been made considering the implications for potential damage given the characteristics of the different processes and the affected area.

For the exposure values, the same scale was adopted where 1 represents the lowest level of exposure and 5 the highest (see Table 5.2). This consideration will allow the integration of the various risk components (hazard and consequences) and the multiple flood hazards into one flood risk assessment. It should be noted that this approach assumes that all values at exposure will be affected by the considered flood hazards without taking into account their physical vulnerability. As such, it should be noted that this risk assessment will represent a type of worst-case scenario.

Finally, both components are integrated, defining an absolute flood risk R_{abs} as;

$$\mathrm{R}_{abs} = \sum_{j}^{n} (HI_j * E_j)^{1/2} * S_j \qquad (5.1)$$

where *HI* represents the hazard intensity indicator, *E* the indicator to measure the exposure values, *S* the affected area, and *j* each of the *n* areas in which the coastal area is divided for the assessment. The principal objective of most coastal indices is the classification and partition of the coastline into units that exhibit similar attributes or characteristics (Cooper and McLaughlin 1998). Hence, with the aim of spatially comparing the risk at the regional scale, a flood risk value is obtained for each component at the municipality level. This value allows for the identification of the most susceptible flooding areas at the management level (assuming that the municipality level is the lowest level of management for decision makers).

Furthermore, an average risk value for each municipality was obtained in order to characterise, in unitary terms, their relative importance along the coast i.e. the risk has been assessed without considering the flooding area. This will be expressed on a scale from 1 to 5. The average risk, R_{aver} is defined as,

$$\mathrm{R}_{aver} = \frac{\sum_{j}^{n} (HI_j * E_j)^{1/2} * S_j}{\sum_{j}^{n} S_j} \qquad (5.2)$$

5.2.2 Flood hazard assessment

Hazard assessment can be defined as the process which enables an understanding of the characteristics, nature, and magnitude of the considered threat. In the simplest case, a flood hazard can be characterised as a land surface covered by water. However, as was previously presented, the different flood hazards that were considered differ widely in their characteristics, in relation to their physical processes and temporal and spatial scales. Thus, the flooded area associated with episodic components (storms) is temporarily flooded, being a quasi-instantaneous process (the duration of the event), whilst in the case of the long-term component, the flooded surface is permanently flooded, being characterised by a very slow and continuous process.

In this study, for flood components associated with a probability of occurrence, a return period (*Tr*) of 100 yr was selected, following the indications of EU Flood Directive (EU 2007), also being considered as representative for medium-probability events.

In the following sections, the assessment procedure carried out for each component is presented.

Flash flood

Flash floods are defined as extreme flood events associated with short, high-intensity rainfalls, mainly of convective origin, that occur locally (Marchi et al. 2010). Extreme events, being greater in magnitude and with a strong seasonality, occur in Mediterranean regions (Gaume et al. 2009; Llasat et al. 2010; Camarasa-Belmonte and Soriano-García 2012). It is in the coastal areas where these phenomena pose a considerable risk due to the high vulnerability of urban development and an increase in population and tourism during the summer season (Llasat et al. 2010; Camarasa-Belmonte et al. 2011).

To carry out a flash flood assessment, a two-step approach has been developed. The first step is an analysis of the most susceptible sub-basins affected. Once identified, the second step involves a detailed hazard assessment.

To identify the most susceptible sub-basins, a modified version of the Flash Flood Potential Index (FFPI) developed by Smith (2003) has been used. This index combines different physiographic characteristics, which have a strong influence on the hydrologic response of the catchments, and therefore, the potential for flash flooding. The index includes information about soil texture (*S*) important in determining water holding and infiltration characteristics, terrain slope (*M*) on account of water speed and concentration of runoff , vegetation (*V*) that affects soil moisture and hydrologic flow, and land use (*L*) that can play a significant role in water infiltration, concentration and runoff behaviour (see Appendix A).

Here, a modified version has been obtained by adding a new factor with information about climatology of extreme precipitation using annual maximum daily rainfall statistics (*R*) to account for the potential influence of local climatology (Jiménez et al. 2015). Therefore, not only is a territory sensitive to flash flooding due to physiographic factors, but also because it is subjected to a given rainfall regime that may induce such a hazard. The final modified FFPI' index is calculated as follow:

$$FFPI' = \frac{M + L + S + V + \boldsymbol{R}}{5} \tag{5.3}$$

To combine these factors, the associated raster data has been ranked at the same scale from 1 to 10 (see Appendix A), considering the hydrologic response as a criteria, as established by Ceru (2012). This index is calculated using raster data, so that the territory is completely divided into cells, each with the combined information previously mentioned. In order to identify the highly-susceptible sub-basins, this information is integrated by assessing an averaged value of each cell at sub-basins level (Figure 5.2). The resulting values are classified into five categories, which allow for the identification of the most susceptible areas to the effects of flash flooding.

Once susceptible flash flooding areas are identified, a second and more detailed hazard assessment is carried out. To do so, a standard fluvial flood analysis was conducted. Thus, for a given return period (Tr =100 yr), the flooded area and the flood depth are assessed. In this sense, flood depth is considered a good variable in flood assessment because it is relatively straightforward to link this to direct damages using depth-damage curves.

For the study area, the Catalan Water Agency (ACA) provides information regarding flood depth associated with three return periods, in accordance with the European Floods Directive (2007/60/EC) recommendations. This data has been obtained by means of a hydrological analysis using the HEC-HMS model, and a hydraulic analysis made using the Guad2D model with a detailed, digital, elevation model (Generalitat de Catalunya 2015).

As mentioned, the flood depth variable can be used to estimate a damage value through the use of depth-damage curves. To establish the hazard intensity scale in five categories, curves proposed by Velasco et al. (2015) have been used which were obtained for the city of Barcelona. From a practical viewpoint, each flooded area, with a given depth interval, is assigned a corresponding hazard intensity value (see Table 5.1).

Marine flood

This component assesses a temporary coastal flood under the influence of marine storms. In this case, the forcing is the temporary increase in mean sea level induced by low atmospheric pressure and onshore winds during the storm resulting in both wave run-up and overtopping. The methodology used here has been developed within the RISC-KIT project (see Ferreira et al. 2016; Viavattene et al. 2017).

The hazard intensity along the coast has been evaluated by estimating the water level extreme climate and the extension of the area to be inundated. This has been calculated for a total of 376 sectors of 1 km in length along the coast for long beaches and in the case of smaller beaches the sectors have been define by their total length. From each sector the most representative beach profile has been defined. The run-up, *Ru*, as the main water levels contributor in the study area (Mendoza and Jiménez 2008) has been calculated using the Stockdon et al. (2006) model in beaches and the Pullen et al. (2007) model when the coastline is formed by breakwater. Resultant *Ru* time series calculated for each profile have then been fitted by means of a General Pareto Distribution (GPD), obtaining a probability distribution for representative beach slopes of the study area.

Given the characteristics of the beach profiles typified by the monotonous increase in elevation landwards, and in order to calculate the extension of the area to be inundated, a bathtub approach has been applied, assuming that those areas hydraulically connected to the sea and below a certain height will be flooded (Poulter and Halpin 2008; Gallien et al. 2011).

Subsequently, flooded areas have been classified on a hazard intensity scale based on the reach of the flood extension, considering the characteristics of the beaches in the study area (see Table 5.1).

Inundation by Sea Level Rise

This component assesses coastal flooding due to an increase of the sea level in the long term, generally associated with climate change. In contrast to other flood hazards in which the area affected by flooding returns to pre-event conditions following a recovery time, this hazard, due to SLR, is characterised as a permanent inundation, resulting in an irreversible land loss as a consequence of the sea advancing. Therefore, the criteria to define hazard intensity have been established based on time. Thus, it is considered that those areas submerged by water for the longest duration will be the most damaged, whereas those submerged by water during a shorter duration, will incur less damage. With this assumption, those areas affected first (more time submerged) might not have time (or they will have a shorter time) for adaptation, so damages may be greater, whilst the areas which require more time to be covered by water (less time submerged) will have time to adapt to the changing territory and therefore, future damages could be smaller.

To define the corresponding hazard intensity, a continuous rank is established every 20 years from the present time (2020) to the future (2100). Thus, the flooding area affected first (2020) is assigned a value of five, and so on (see Table 5.1). In this case, as the variable considered is time, flood levels will change as different scenarios are considered. In this case, RCP 8.5 and the High-End scenario with a rise of 1.75 m have been selected.

To calculate the inundated area for the different scenarios, a bathtub approach has been adopted, assuming that those areas hydraulically connected to the sea and under a certain height will be flooded (Poulter and Halpin 2008; Oltra 2010; Gallien et al. 2011).

Table 5.1 Flood hazard intensity.

Flash flood	Marine flood	Inundation by SLR	Hazard intensity
Flood depth (m)	Flood extent (m)	Year when the area will be flooded (yr)	
<0.15	≤50 % beach width	>2100	0
0.15-0.3	≤100 % beach width	2080-2100	1
0.3-0.5	≤beach width +20 m	2060-2080	2
0.5-1.0	≤beach width +40 m	2040-2060	3
1.0-2.0	≤beach width +60 m	2020-2040	4
>2.0	>beach width + 60 m	2020	5

5.2.3 Consequences

In the assessment of the consequences, flood damages are usually divided between those caused by direct contact with the receptor, and indirect damages trigged in secondary effects, principally with a relationship to the disruption of physical and economic linkages. At the same time, the methods for calculating damages vary depending on whether the damages are tangible (i.e. can be assigned a monetary value), or intangible, which are not traded in a market (Messner et al. 2007; Green et al. 2011). As the type of receptor varies (properties, people, ecosystems, etc.) the unit of measurement changes, and therefore, many evaluation methods for assessing the consequences exist.

As previously mentioned, within the framework of this work, it is assumed that the consequences can be represented by a set of socio-economic indicators. Following the characterisation of the study area, and bearing in mind the potential direct and indirect consequences of coastal floods, these indicators are represented by the following categories: land use (e_{LU}), the social vulnerability of the population (e_{SFV}), transport systems (e_{Ts}), utilities (e_{Ut}) and business settings (e_{Bs}). These indicators are evaluated and classified in homogenous units (Table 5.2), and then combined in a unique exposure value (e_T), using a linear aggregation method, as shown below (Viavattene et al. 2015):

$$e_T = [(e_{LU} * e_{SFV} * e_{Ts} * e_{Ut} * e_{Bs})]^{1/5} \qquad (5.4)$$

To calculate this aggregate value, the exposure values have been characterised in a different way for each flood component.

In the case of flash flooding and inundation by SLR, as the spatial extent of the flood is known, those exposure indicators which are determined by their spatial distribution in the territory such as land use (e_{LU}), transport system (e_{Ts}) and utilities (e_{Ut}) have been evaluated within the flooded area. To this end, since the hazard intensity of these two flood components are also spatially represented in the territory, information on the hazard and the exposure indicators (both in vector format) are jointly intersected providing information on the hazard for each land use within the flooded area. Remaining indicators such as social and population vulnerability (e_{SFV}) and business settings (e_{Bs}) are calculated on account of statistic data which is provided in Catalonia at the municipal level, this being the minimum scale for statistical data.

To evaluate exposure values for marine floods, a buffer area of 100 m along the coast is considered. Since there is not a map with information of the flooded area, the buffer is considered the maximum expected extent of the flood landwards of the beach. This buffer area is selected given the characteristics of this process along the Catalan coast (also applicable to most of the Mediterranean coast), so it should be adapted depending on the area to be analysed. In areas where marine flooding can extend in large, low-lying areas, such as a typical main flood in the North Sea (see e.g. McRobie et al. 2005; Dawson et al. 2009), this can be substituted by the area of the flood extension.

In what follows, the methodology carried out to evaluate and classify each indicator aforementioned is presented.

Land use (e_{LU})

The land use exposure indicator measures the different types of land in the flood area. To assess it by means of the land cover map of Catalonia (Ibàñez and Burriel 2010), which provides detailed information in vector format, land uses have been reclassified into 10 classes, covering the most representative uses for the study area (see Table 5.2). For each class, a value from 1 to 5 has been assigned, depending on their relative importance. In this sense, the criteria to establish the values will be dependent on the orientation of the analysis and the coastal management purposes. In this study, an anthropocentric perspective has been adopted, and thus, higher values were assigned to those land uses where flood damages affecting economic activities are reported (see Table 5.2). This indicator does not consider the physical vulnerability of the different land uses but reflects the exposed area and the associated importance value for each land use.

Population and social vulnerability (e_{SFV})

In order to measure intangible impacts to the flood-affected population, a Social Flood Vulnerability Index (SFVI) has been applied. This index represents the relative vulnerability of various communities to long-term health impacts and financial recovery from a flood event (Viavattene et al. 2015). As there are no previous studies for the area to inform how the population may cope with flood events, characteristics and variables suggested by Tapsell et al. (2002) have been considered. The variables selected, listed below, accurately represent the socio-economic characteristics of the study area. Among the social variables, the long-term sick (*a*), single parents (*b*) and the elderly (*c*) were taken into account. Financial-deprivation variables are represented by unemployment (*d*), overcrowding of households (*f*), non-car ownership (*g*) and non-home ownership (*h*) (see Appendix B). To create the social flood vulnerability index, each variable has to be standardised following different transformation methods (see Appendix B) to produce the minimum skewness kurtosis within their distributions. As Tapsell et al. (2002) indicate the aggregation method adopted gives more importance to the social variables than to the financial-deprivation variables. Eq.5.5 presents the aggregation method used.

$$e_{SFV} = a + b + c + ((d+f+g+h)*0.25) \tag{5.5}$$

An important consideration when applying the SFVI is the level of data aggregation. For the Catalan coast (with the exception of Barcelona), due to the small municipality dimensions in terms of settlement and built-up areas, and the fact that this is a regional study, the most recent and appropriate data (IDESCAT 2016) is at the municipality level. This can be considered the minimum scale for obtaining SFVI values. However, if data is available at smaller scales (e.g. census level), it should be implemented at this level as the extension of the flood plain is often narrow and short.

When the social vulnerability indicator (e_{SFV}) value is evaluated for each municipality, this is reclassified into a scale from 1 to 5. In this case, *natural breaks* has been considered an adequate method to identify groups with similar values, whilst maximizing the differences between classes (see Table 5.2).

Transport system (e_{Ts})

Another key element when assessing the consequences of flood events is the transport system. To obtain a representative indicator of the direct impact of flood events on this infrastructure, two criteria have been considered due to the different characteristics of each flooding hazard. The first criteria considers the total linear metres of railways and motorway within the flood area (flash flood and SLR-induced inundation). This is then ranked into five classes, taking into account that damages will be greater when an increased length of transport system has become exposed. The second criteria considers the presence or absence of different transport systems within the buffer area (marine flood). In this case, a ranking has been made, taking into account their relative importance to the overall system and the probable systemic impacts resulting from the disruption (see Table 5.2).

Utilities (e_{Ut})

This component assesses the presence of any critical infrastructures providing essential services which floods can affect, interrupt, or cease with serious consequences for the community, both inside and outside the affected area. The presence of critical infrastructure in the flood area has been identified with information provided in the land use map. Once identified, these utilities have been classified on a scale from 1 to 5 according to their relative importance in terms of the level of population served (see Table 5.2).

Business settings (e_{Bs})

To assess the impact of coastal floods on business activity, two indices were selected. For marine processes (such as marine floods and inundation by SLR) on the coastal fringe, tourism is the most important economic sector. To obtain a representative value of this activity, a tourist index developed by La Caixa (2013) has been used (see section 4.2.3). Damages caused by flash floods can be found inland where other businesses may be located. As considered previously, an industrial index developed by La Caixa (2013) has also been used as it offers a useful assessment of flash flood consequences to business activity. This index is based on tax revenues corresponding to industrial activities, and reflects the relative weight of industry in each municipality with respect to all of Spain. Both indices have been ranked into five categories by applying an *equal intervals* method (see Table 5.2).

Table 5.2. Exposure indicators ranking.

Exposure indicators		Consequences				
		1 Inexistent or very low	**2 Low**	**3 Moderate**	**4 High**	**5 Very high**
Land use (e_{LU})	Anthropogenic perspective	-Barren -Riparian buffer/Wetland (1.5) -Grassland (1.5)	-Forest -Urban green	-Beach and dune -Cropland	-Campsite -Industrial	-Urban
Transport system (e_{Ts}) *Metres of railway and highway affected* (Flash flood/SLR)		<250	250-500	500-1,000	1,000-2,000	>2,000
Presence (Marine flood)		No significant utilities networks	Local road	Motorway	Coastal railway	Motorway and coastal railway
Utilities (e_{Ut})		No significant utilities networks/assets	Mainly local and small utilities networks/assets	Presence of utilities networks/assets with local/regional importance	High-densely and multiple utilities networks/assets of local importance or regional importance	High-densely and multiple utilities networks/assets of national or international importance
Business (e_{Bs}) *Tourist Index* (Marine flood/ SLR)		<45	45-89	89-133	133-177	>177
Industrial Index (Flash flood) ***method: equal interval**		<78	78-154	154-231	231-307	>307
Population and social (e_{SFV}) *Social Flood Vulnerability Index* ***method: natural breaks interval**		≤-4.4	-4.4 -(-1.8)	-1.8-(-0.2)	-0.2-1.8	>1.8

5.3 Results

5.3.1 Introduction

In this section, the results obtained from flood risk analysis are presented. Here, the flood component results are presented differently from erosion since the consequences are different for each flood component. Thus, each flood component is individually presented with the obtained results from the hazard, consequences and risk. Obtained marine and flash flooding results presented here are associated to a return period of 100 yr. Moreover, results obtained from all the flood components (flash flood, marine flood and inundation by SLR) have only been presented at the Catalan scale, without considering the other scales of analysis (province and HEMU level). This is because the levels of risk associated with the remaining scales do not imply significant risk variability along the coast due to the fact that only two variables are able to produce differences (Business settings (e_{Bs}) and SFVI (e_{SFV})).

5.3.2 Flash flood

Figure 5.2 shows the FFPI’ along the Catalan coast, integrated at the sub-basin level. These results indicate that for the same region there are differences in the level of susceptibility to the effects of flash flooding. This is mainly due to geomorphologic characteristics such as the slope and the type of soil as well as the spatial variations in rainfall. These results permit an identification of the most potentially hazardous areas in terms of flash flooding in Catalonia.

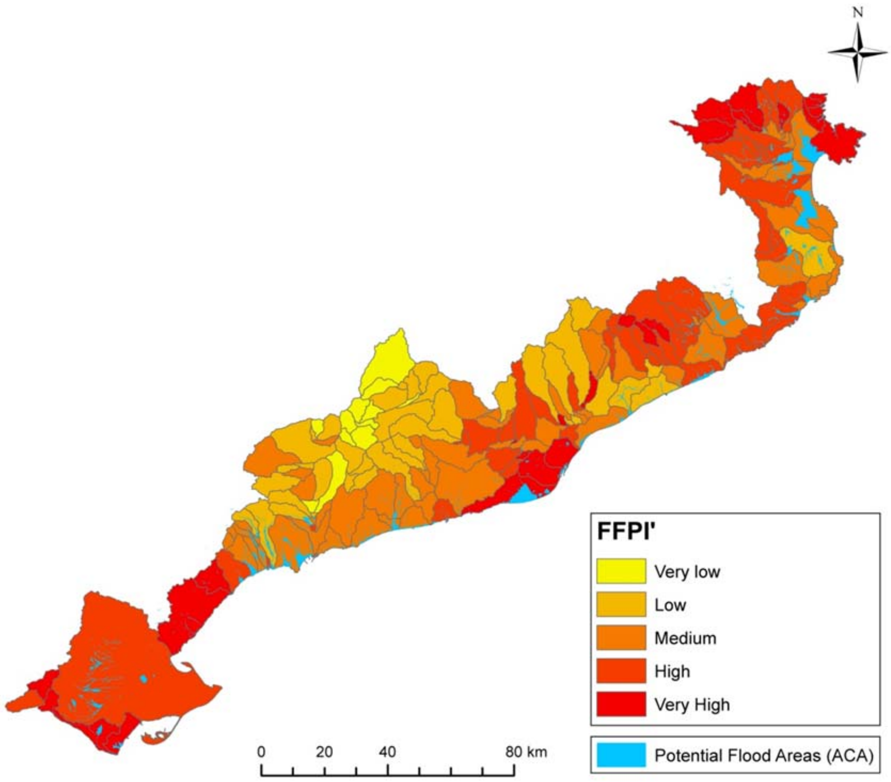


Figure 5.2 Flash Flood Potential Index (FFPI') for sub-basins along the Catalan coast.

Figure 5.2 shows the potential flooding areas identified by the Catalan Water Agency (Generalitat de Catalunya 2015) in order to implement the EU Floods Directive (Directive 2007/60/EC) (EC 2007). These areas were identified by combining geomorphological studies based on visual analyses (topography and morphology), flooding studies, aerial photographs and field visits. This information suggests that there is a strong correlation between the largest flood areas and medium and high FFPI' levels, which allows for a validation of this index as a first approach in identifying areas prone to flash floods. However, one exception has been identified in the Ebro delta, as this area corresponds with a plain surface not affected by flash flooding. In this case, rainfall and vegetation could be the factors in generating higher values.

In the second step, those sub-basins likely to be affected by flash flooding with medium and high FFPI' levels were chosen to undertake a detailed flash flood assessment. To this end, flood data of the sub-basins prone to flash flooding was obtained from the Catalan Water Agency (Generalitat de Catalunya 2015) which uses hydrologic and hydraulic studies to determine the flood area and variables such as flood-depth or flood-velocity associated with three return periods. In this case, the flood-depth information for a return period of 100 yr has been used. However, the

Catalan Water Agency only provides this information for the Maresme region where the presence of dry streams usually causes flash flooding. Further information available from the Catalan Water Agency along the coast corresponds with permanent rivers, which is not of interest for the present assessment. Thus, the second step of the flash flooding analysis has only been carried out in the Maresme. However, if data were available, the proposed methodology could be applied in any sub-basins prone to flash flooding. In Figure 5.3 the flash flooding extension area and hazard classification, following flood damage curves proposed by Velasco et al. (2015), are presented. As an example, three areas are highlighted to show more detailed information on the flood extension area and the different hazard intensity levels. If areas are classified in terms of the average hazard intensity (flood depth values) the most hazardous area is located in Sant Pol de Mar (27). The second most hazardous area is located between Cabrera de Mar (34) and Mataró (33) with the highest values in Mataró. When the hazard is evaluated in absolute terms, i.e. taking into account the total affected area, the most hazardous are Santa Susanna (24) and Pineda de Mar (25).

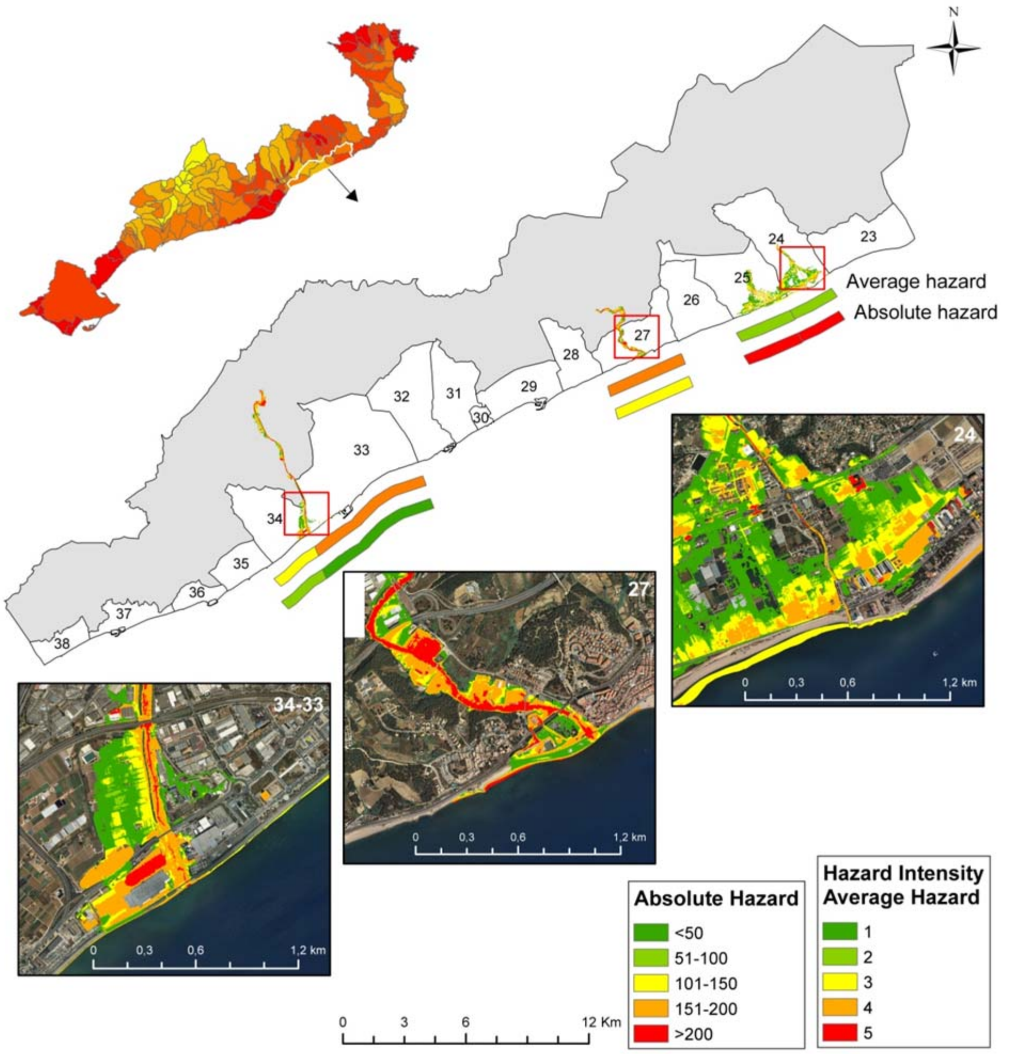


Figure 5.3 Flash flooding areas and hazard intensity classification for the municipalities more prone to flash flooding in the Maresme coast.

Obtained exposure indicators for the areas are representative of medium values (Figure 5.4) with Mataró (33) showing the highest values. This is due to the existence of a different number of assets with high relevance at local and regional level being affected (e.g. railway, road, factories and a water treatment plant) as well as the high values of social and population vulnerability to floods (see Figure 5.8).

Figure 5.4 also shows total risk values at municipality level after combining hazard and exposure values. Hence, risk values are presented considering the risk in unitary terms (average risk) and the total area affected (absolute risk). The municipalities of Mataró (33) and Sant Pol de Mar (27) are the ones which present higher average risk values whereas, Santa Susanna (24) and Pineda de Mar (25) show the highest absolute risk.

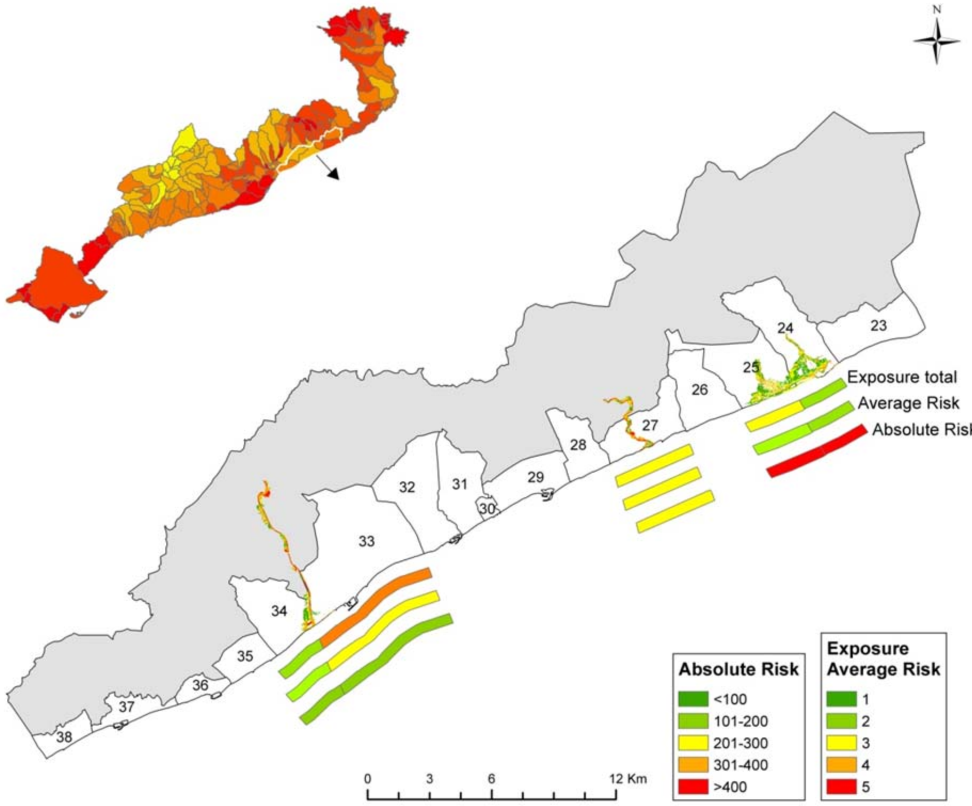


Figure 5.4 Flash flood total exposure (e_T), average and absolute risk for the municipalities more prone to flash flooding in the Maresme coast.

5.3.3 Marine flood

As described in the methodology (section 5.2.2), the analysis of marine flooding has been undertaken in basic units given by sectors of 1 km in length along sedimentary coastlines and at beach length in the cases of shorter stretches or pocket beaches. To illustrate obtained results at this smallest scale, Figure 5.5 shows the marine flooding hazard for 46 sectors along the Maresme coast. Results indicate that this region, in general, is characterised with low marine flood hazard levels, although there are exceptions in a few sectors, where the hazard intensity is high due to the combination of both large run-up values and low topographic levels. Therefore, these sectors represent the highest susceptible areas to be affected by marine storm-induced flooding. However, since the goal of this study is to undertake a comparative analysis along the entire territory, results for each sector have been integrated at the municipality level.

Figure 5.5 Marine flooding hazard in sectors of 1km along the Maresme coast.

Figure 5.6 shows the marine flooding hazard integrated at municipality level for the Catalan coast. It should be noted that in order to integrate sectors at municipal level only the extension of the municipality coastline where computations have been done (essentially the sedimentary coast) are considered. Thus, in Figure 5.6 it can be observed that most of the municipalities are subjected to medium and high marine flooding hazard values even though that in some cases, the hazard has been assessed in a small fraction of the municipality coastline.

Within the Girona province, municipalities such as Cadaquès (5) Castelló d'Empùries (7), Sant Pere del Pescador (8), Torroella del Montgrí (10), Palamòs (15) and Blanes (22) present the highest values. Sant Andreu de Llavaneres (32), Cabrera de Mar (34), Viladecans (43) and Gavà (44) within Barcelona province, are the municipalities presenting the highest hazard values.

Whereas in Tarragona province the highest hazard values are presented in the municipalities of Creixell (54), Torredembarra (55), Altafulla (56), and Sant Jaume d'Enveja (67) and Amposta (68) with the final two being mainly controlled by the geomorphologic characteristic of the beaches, typified by very low profile elevation.

Nevertheless, it should be noted that due to the short length (1 km) of the sectors of analysis and marine flooding scope, when integrating at municipal level, sectors with high marine hazard values can be hidden at such a level. In any case, results obtained at basic km-sectors can enable an identification of these if needed.

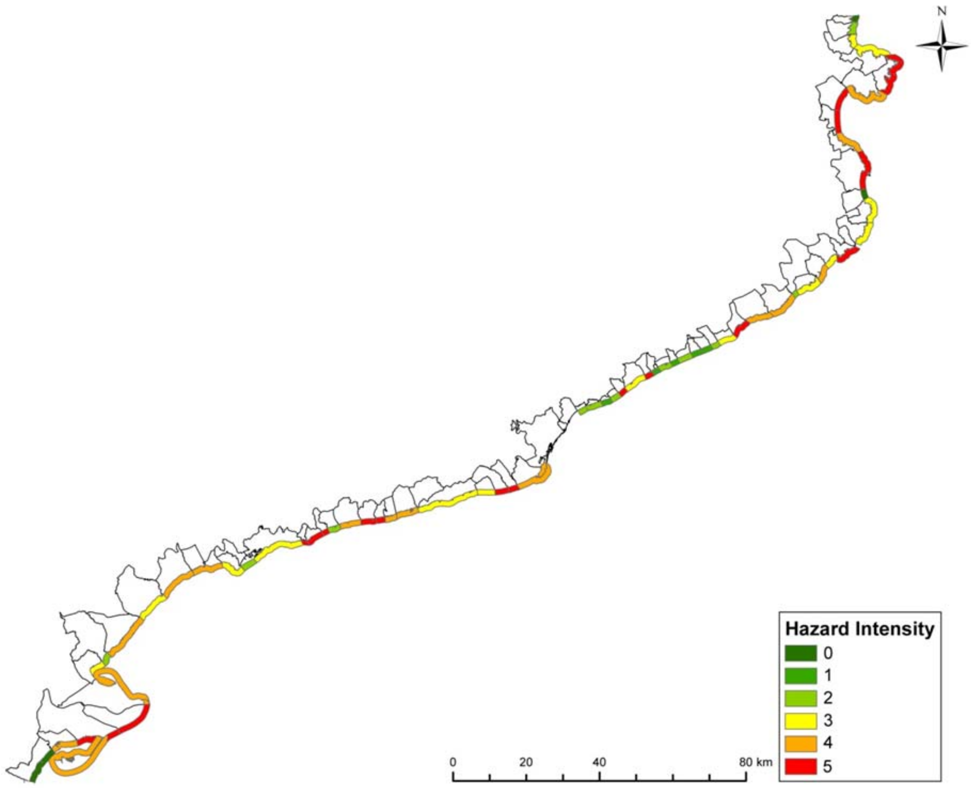


Figure 5.6 Marine flooding hazard average for the coastal municipalities.

Figure 5.7 shows three of the consequences indicators (land use (e_{LU}), transport system (e_{Ts}) and utilities (e_{Ut})) which have been calculated within the flooding area that in the case of marine flooding is taken as a buffer area of 100 metres along the coast. Firstly, they have been calculated for each 1km-sector and then integrated to represent the total value at municipality level. The land use indicator (e_{LU}) shows a distribution in which the highest values are in those municipalities with an important presence of urban beaches. This reflects the orientation of the analysis, in which major importance is given to socio-economic developments rather than natural ecosystems. However, in order to assess the consequences to different categories, the weights assigned can be customized to reflect the objective of the analysis. The transport system indicator (e_{Ts}) generally highlights low and medium values, with the exception of the Maresme region where higher values are presented. This reflects the elevated number of infrastructures in this area. Regarding the utilities indicator (e_{Ut}), no important potentially impacted elements have been identified.

As occurred for the hazard assessment, in the case of municipalities with a small section being composed of beaches, the municipality-integrated value is controlled only by this part. An example of this is the high value of infrastructures in Roses (6) (Figure 5.7).

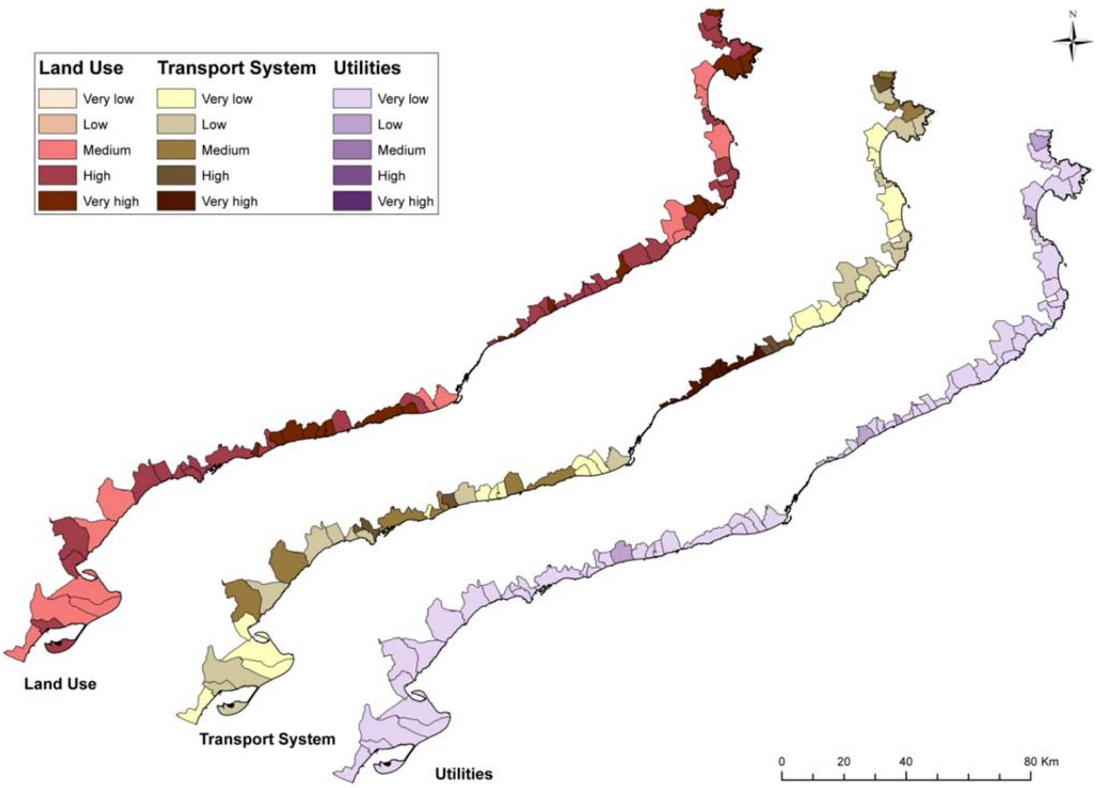


Figure 5.7 Land use (e_{LU}), Transport system (e_{Ts}) and Utilities (e_{Ut}) exposure indicators (municipality average for sedimentary coasts) for marine flooding.

The two remaining indicators that are directly obtained at municipality level, the business setting (e_{Bs}) using a tourist index, and the SFVI (e_{SFV}) can vary depending on the scale of analysis i.e. province, HEMU and regional (Figure 4.5 and Figure 5.8) for the three spatial scales of analysis. As there is no a spatial variation in the assessment of these indicators, but rather an analysis of statistical data at municipal scale, these indicators are common for the three flood components analysed.

The SFVI indicates the areas where the population is more likely to be severely affected by floods, in terms of health and financial recovery. Results for Catalonia show high SFVI values in the municipalities of Palamòs (15), Blanes (22), el Perelló (64), Sant Jaume d'Enveja (67) and Sant Carles de la Ràpita (69). For the other scales (HEMU and province), these municipalities also indicate high SFVI values. Focusing on the HEMU level A, the municipalities which present higher values are situated in the southern part, in the Baix Ebre and Montsià *comarcas* whereas in contrast, Alt Empordà in the northern part presents relatively low values. HEMU level B shows the highest values situated in the municipalities of Palamòs (15), Blanes (22) and Cubelles (49), whereas for level C higher values are found in the Maresme *comarca.* At province level the major values are presented mainly in Tarragona in the municipalities situated in the Baix Ebre and Montsià *comarcas*.

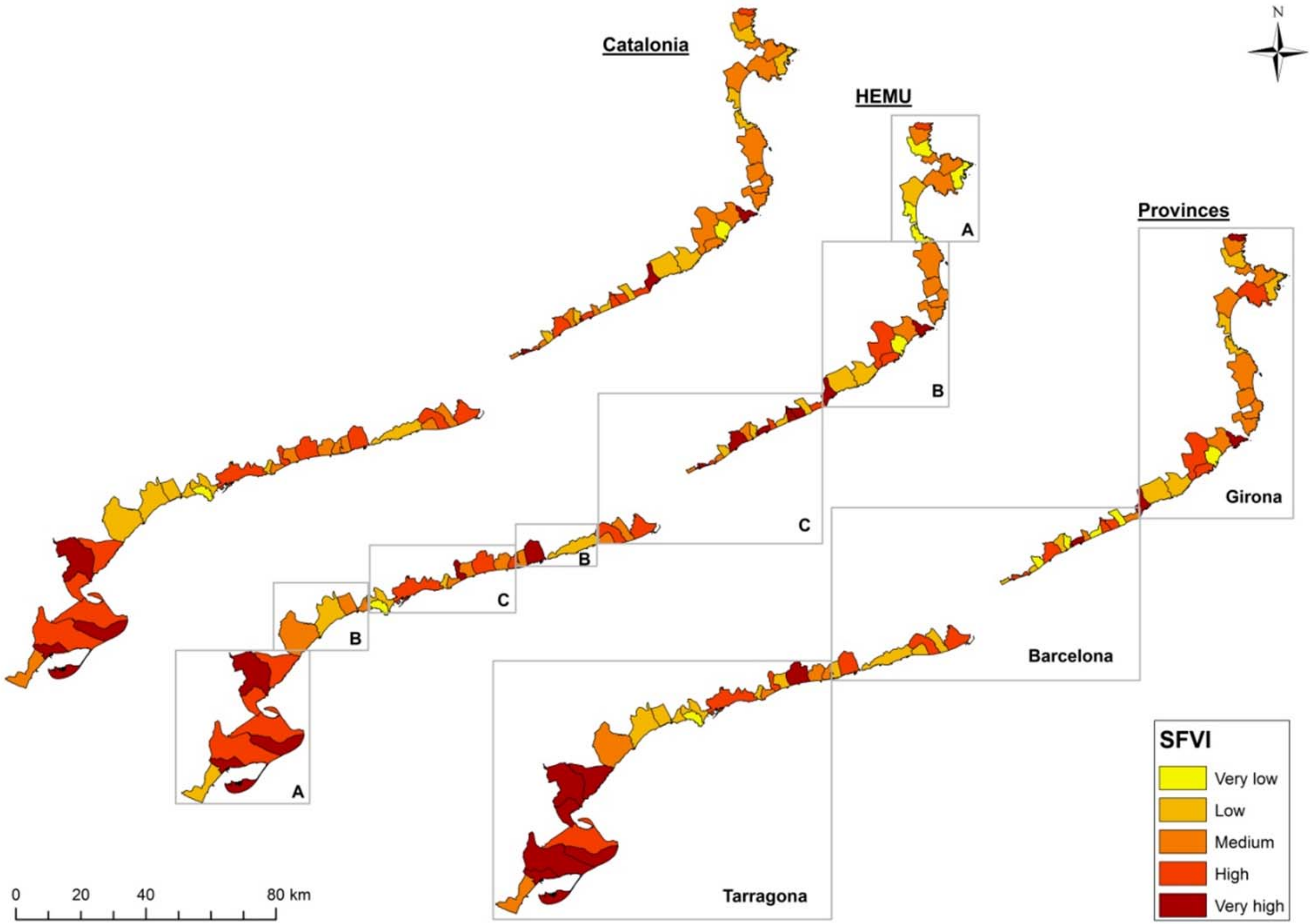


Figure 5.8 Social Flood Vulnerability Index (SFVI) for the three scales of analysis.

The five socio-economic indicators are integrated (Eq.5.5) to obtain the total exposure indicator which is shown in Figure 5.9. Although there are differences along the coast when exposure indicators are evaluated individually, when they are integrated together in a unique value relatively low and medium exposure values for all the municipalities are observed. Major exposure indices are situated in Barcelona, and more specifically in the Maresme *comarca.*

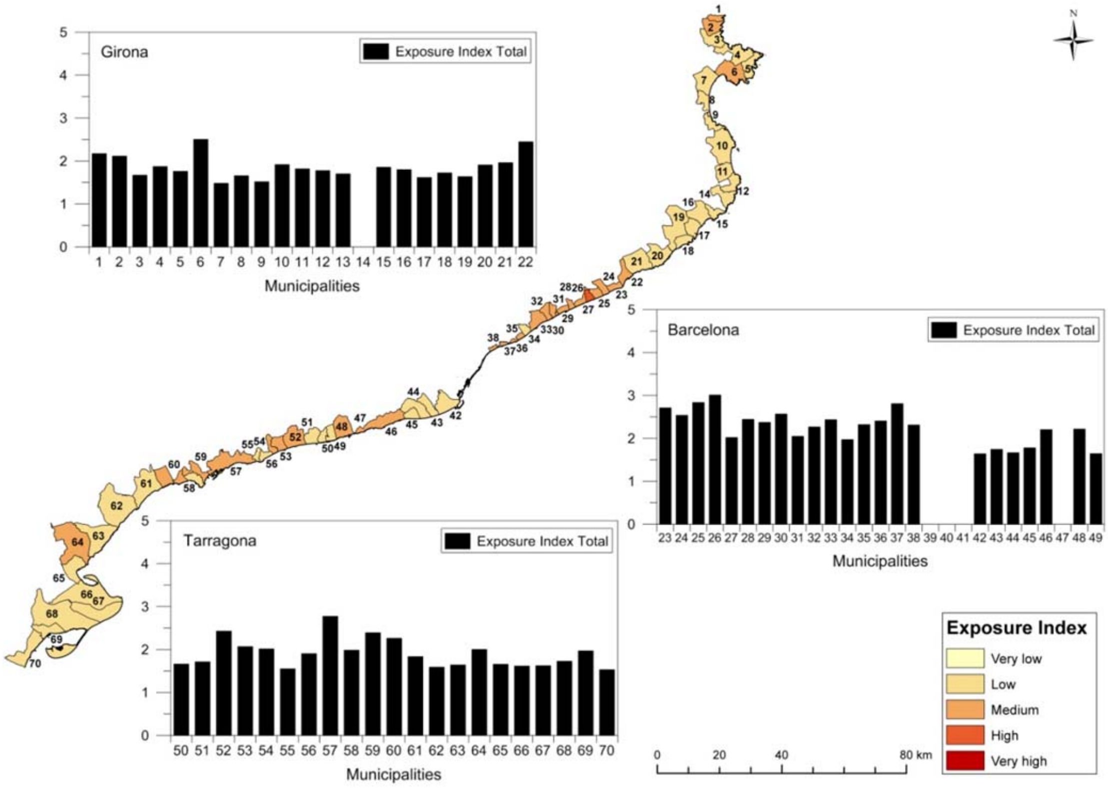


Figure 5.9 Marine flooding total exposure (e_T).

The total risk from marine flooding along the Catalan coast is presented in Figure 5.10. The results obtained for the combination of hazard and exposure values reflect, in general, medium risk from marine flooding at municipality level. However, municipalities such as Torroella de Montgrí (10), Palamòs (15), Blanes (22), St. Andreu de Llavaneres (32), Cabrera de Mar (34) and Creixell (54) indicate high values of risk for this hazard.

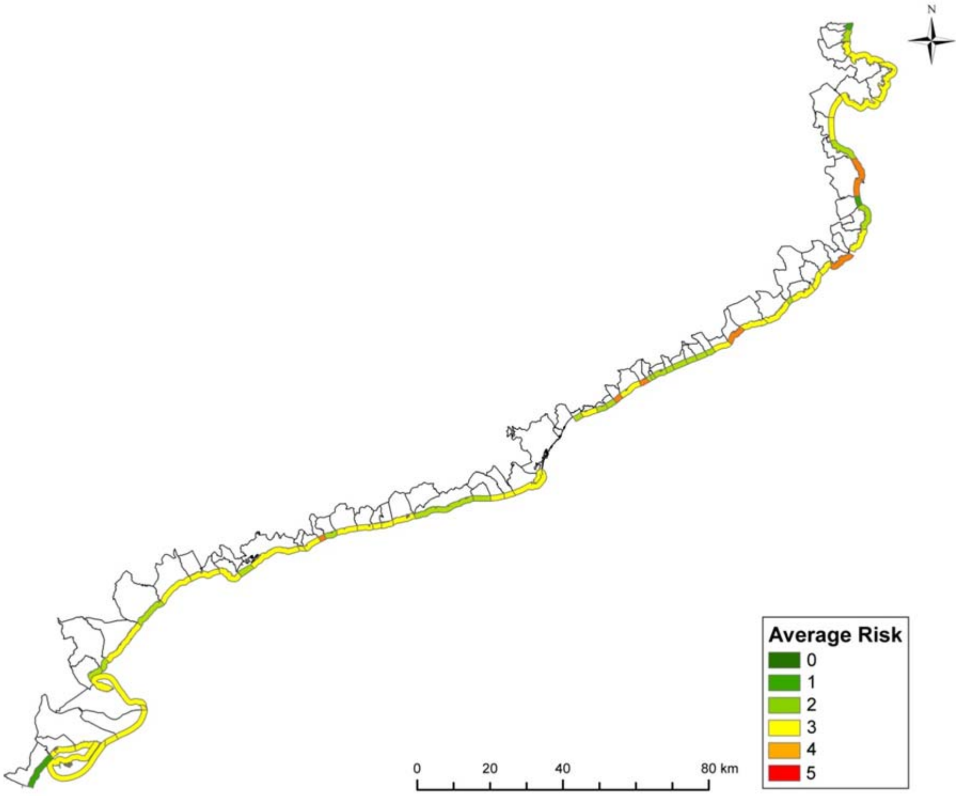


Figure 5.10 Marine flooding risk.

5.3.4 Inundation by Sea Level Rise

Figure 5.11 presents inundation associated with SLR considering two scenarios, RCP 8.5 and High-End. In both cases, and for the spatial scale presented here, the most significantly inundated area is located in the Ebro delta. When considering the High-End scenario, the inundation area for the Ebro delta and Gulf of Roses further increase, and a new inundation area can also be observed in the Llobregat delta. The largest increase in risk areas from scenario RCP 8.5 to High-End occurs for the highest part of the territory. These require a longer time to be inundated and, as a consequence, new areas are essentially of low risk.

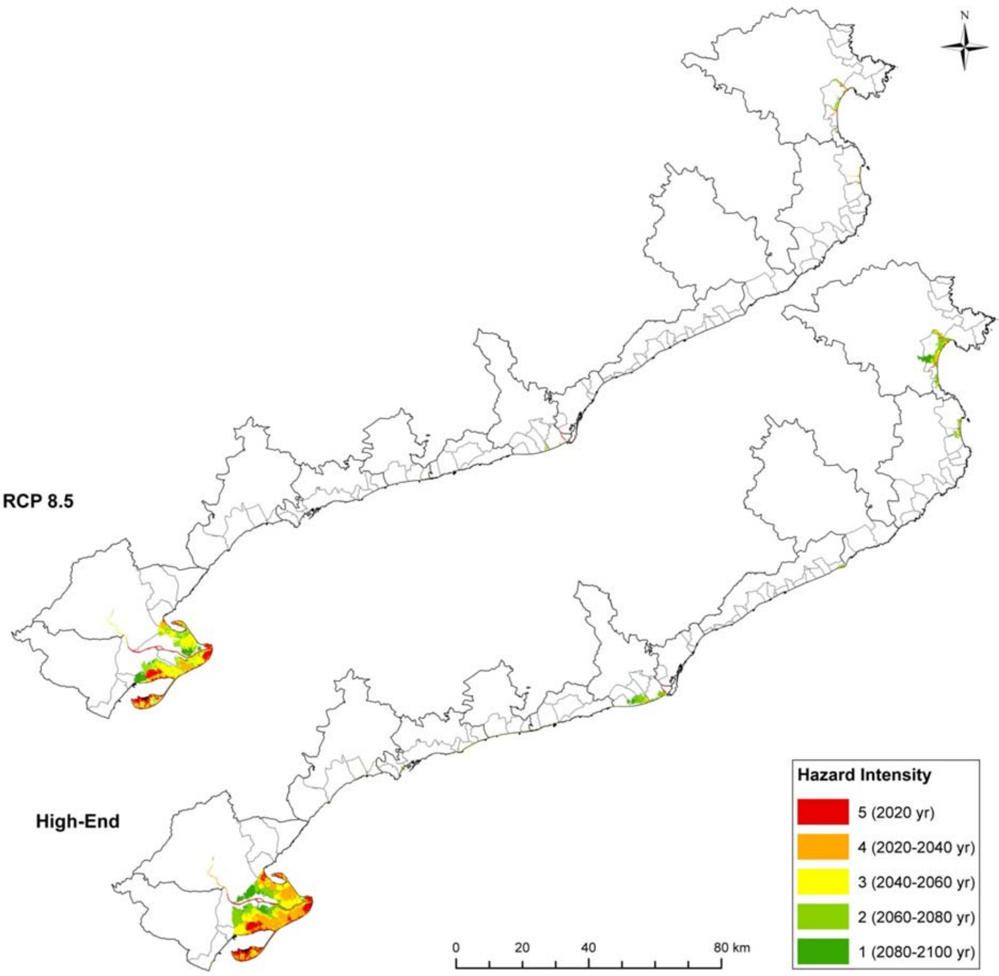


Figure 5.11 Inundation by SLR and hazard intensity classification.

As an example for the rest of the coast Figure 5.12 shows the inundated area and corresponding hazard intensity along the Maresme coast under the High-End scenario. As can be observed, the extension of inundation is very small and can only really be appreciated in the north of the region where the low-lying area of the Tordera delta (Malgrat de Mar municipality (16)) is located. With the exception of the Tordera delta, these results indicate the relatively low importance of SLR, in term of inundation, due to the small surface of flood-prone areas which are only restricted to beaches. This highlights the geomorphologic characteristics of the coastline, which can be typified as having moderately steep profile slopes (with the exception being the low-lying area of the Tordera delta).

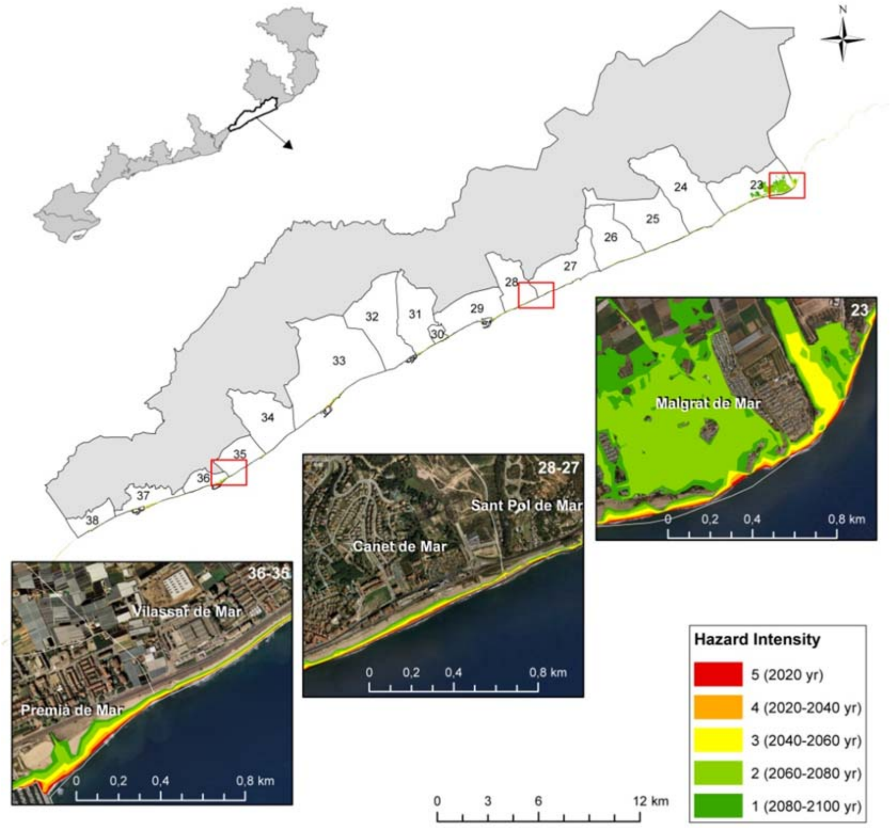


Figure 5.12 SLR inundation (High-End Scenario) and hazard intensity classification in the Maresme coast.

Figure 5.13 show the obtained results in Figure 5.11 integrated at municipality level for the Catalan coast. It should be noted that, when considering the average hazard, the hazard level does not always increase when the High-End scenario is taken into account. This is due to the value representing the hazard in unitary terms and does not take into consideration the total area affected. Moreover, the relative area inundated over time (hazard intensity criteria) varies depending on the scenario analysed.

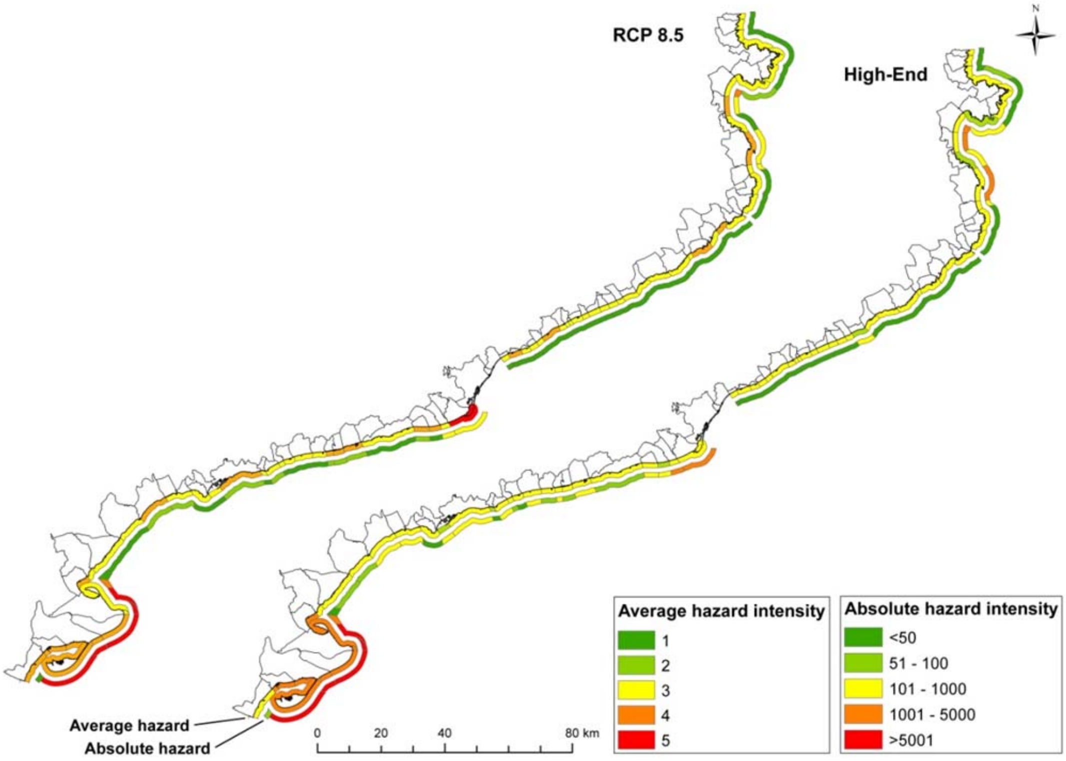


Figure 5.13 SLR hazard intensity for RCP 8.5 and High-End scenarios (average inshore buffer/absolute offshore buffer).

The exposure indicators to SLR considering a High-End scenario are presented in Figure 5.14. In this case, these have been evaluated within the extension of the flooded area. Results for the land use indicator (e_{LU}) show a distribution where higher values are shown in municipalities with an intensively urbanised coastal fringe. With respect to the transport system indicator (e_{Ts}), higher values are found in areas where the extension of the inundation is substantial, thus impacting increased lengths of this form of infrastructure. As a result, higher values are observed in deltas, particularly the Ebro delta and other municipalities such as Tarragona (57) and Sant Pere Pescador (8). Finally, the utilities indicator (e_{Ut}) identifies the municipalities with important critical infrastructure, which in some cases are, again, directly related to low-lying areas and the extension of the inundation such as in the Ebro delta or the Llobregat delta. In the Llobregat delta the values include the presence of Barcelona airport. Another municipality in which important utilities are exposed to SLR (High-End) is Valdellòs i l'Hospitalet de l'Infant (62) as part of the area classified as a nuclear power plant is inundated under this scenario.

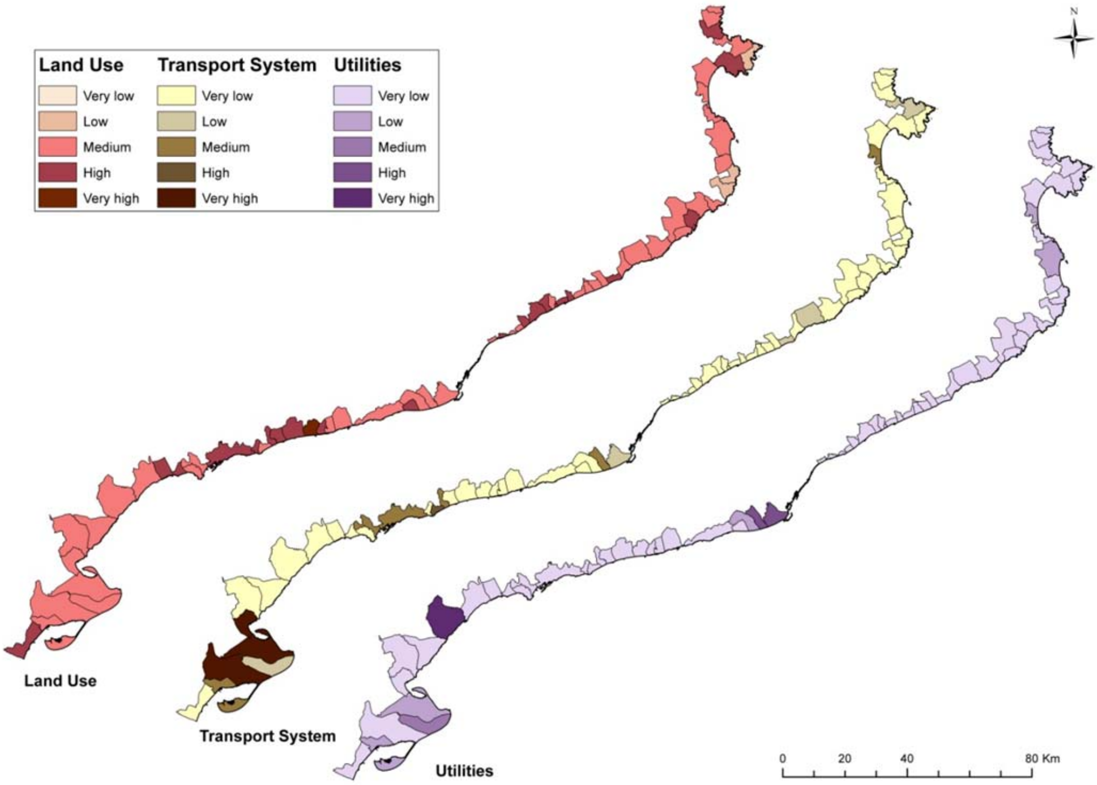


Figure 5.14 Land use (e_{LU}), Transport system (e_{Ts}) and Utilities (e_{Ut}) exposure indicators (municipality average for sedimentary coasts) considering SLR High-End scenario.

Finally, a total exposure value represented by the integration of the aforementioned indicators and the business settings (e_{Bs}) and SFVI (e_{SFV}) indicators is obtained for the SLR component considering both scenarios (RCP 8.5 and High-End).

The total exposure (e_T) for the High-End scenario is presented in Figure 5.15. The results indicate generally low values at exposure. However, the main differences are found in the municipalities where the extension of the inundation is more severe such as those including low-lying areas, which at the Catalan coast contain substantial human activity and important socio-economic receptors.

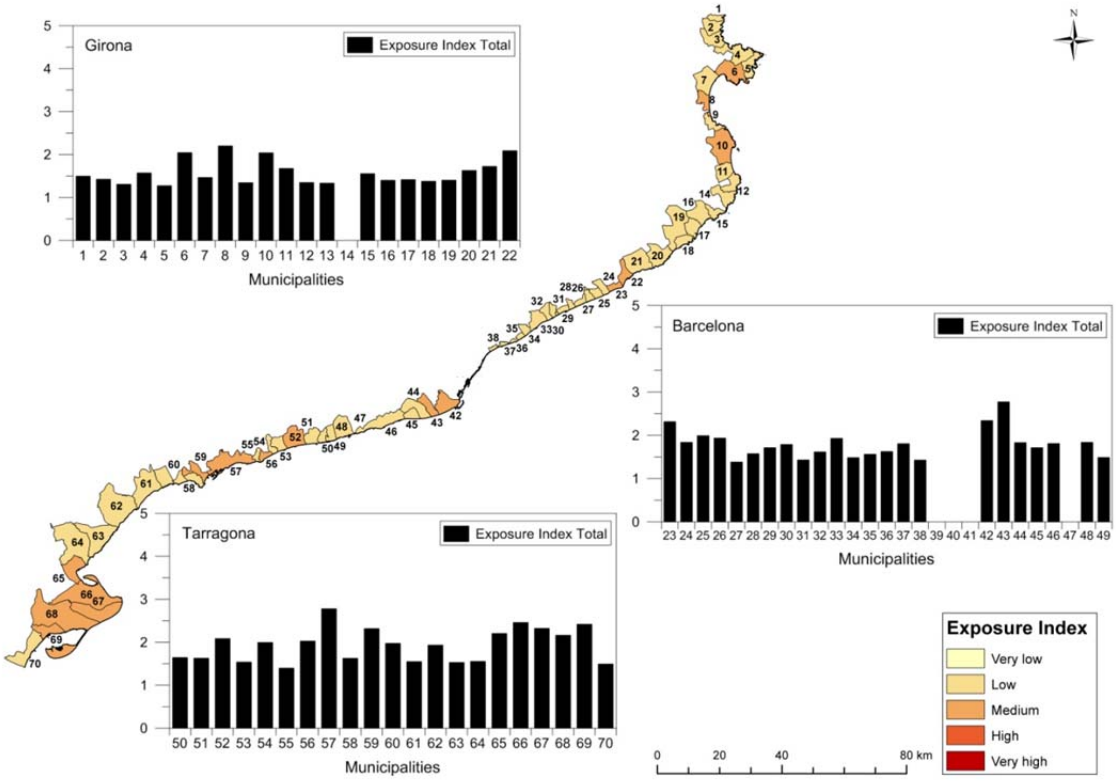


Figure 5.15 SLR (High-End scenario) average total exposure (e_T).

The risk associated with SLR for the two scenarios considered is presented in Figure 5.16. In general the average risk to SLR considering both scenarios is medium and low for all the municipalities. Focusing on the absolute risk, it can be clearly observed that the highest risk value is in the Ebro delta. However, although for the rest of the coast the risk is low and medium, there is a general distribution in which the municipalities situated south of Barcelona present medium values and north of Barcelona low values of risk, with an exception being low-lying areas of the Gulf of Roses and Baix Empordà *comarca*. This pattern is likely to reflect topographic characteristics of the coastal profiles along the coast.

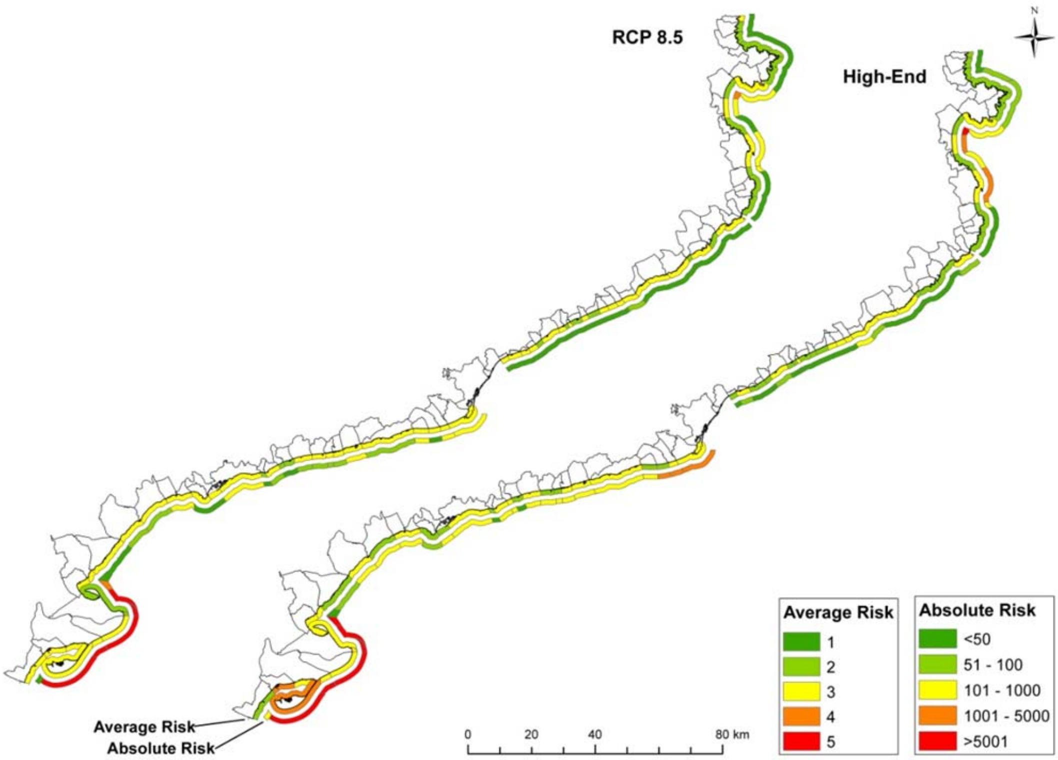


Figure 5.16 SLR inundation risk for RCP 8.5 and High-End scenarios (average inshore buffer/absolute offshore buffer).

5.3.5 Integrated food risk

Figure 5.17, Figure 5.18 and Figure 5.19 show the risk distribution associated with the three flood components along the Catalan coast (with the flash flood component only presented for the Maresme *comarca*). As the analysis has been classified in a common scale for all of the flood components, this permits an integrated representation of flooding risk along the coast. The results indicate that when the absolute flood risk is considered the SLR for both scenarios is the most relevant component in low-lying areas such as the Gulf of Roses, Llobregat delta and Ebro delta. The latter highlights an order of magnitude considerably superior to the other low-lying areas. This highlights that the major contributor to determining the risk is the flooded extension area. Thus, the marine flooding risk does not appear to be important since the maximum expected extension of the flood area considered is a buffer of 100 m for each municipality. In spite of the high absolute risk values for the SLR component, the importance of the flash flood component can be observed in the Maresme *comarca* for the municipalities of Pineda de Mar (25) and Santa Susanna (24). In order to express the risk at municipality level in unitary terms (without considering the total flooded area) the average risk shows that marine flooding represents, generally, the most important component. This stresses that although the characteristic effects of this component can be observed in a short period of time (episodic-term component) its scope given a return period (100 yr) and as a result the consequences, can involve potential risk values higher than SLR. Therefore, due to the relatively small scope of the inundation area (with the exception of the low-lying area) and the resultant consequences, the SLR component generally represents lower risk values. Moreover, another consideration to be made is that the risk calculated for SLR is cumulative, i.e. considering the accumulated impact in a long time period (2100). However the risk associated to storms is for one event. To properly compare them, the risk associated with the impact of multiple events in a similar period should also be cumulated. In this sense, average risk may be a more “fair” way of comparison. Along the coast, it can be stressed that the municipalities of Palamòs (15), Blanes (22), Sant Andreu de Llavaneres (32) Cabrera de Mar (34) and Creixell (54) are the areas where risk from marine flooding is considerably higher compared to the other components.

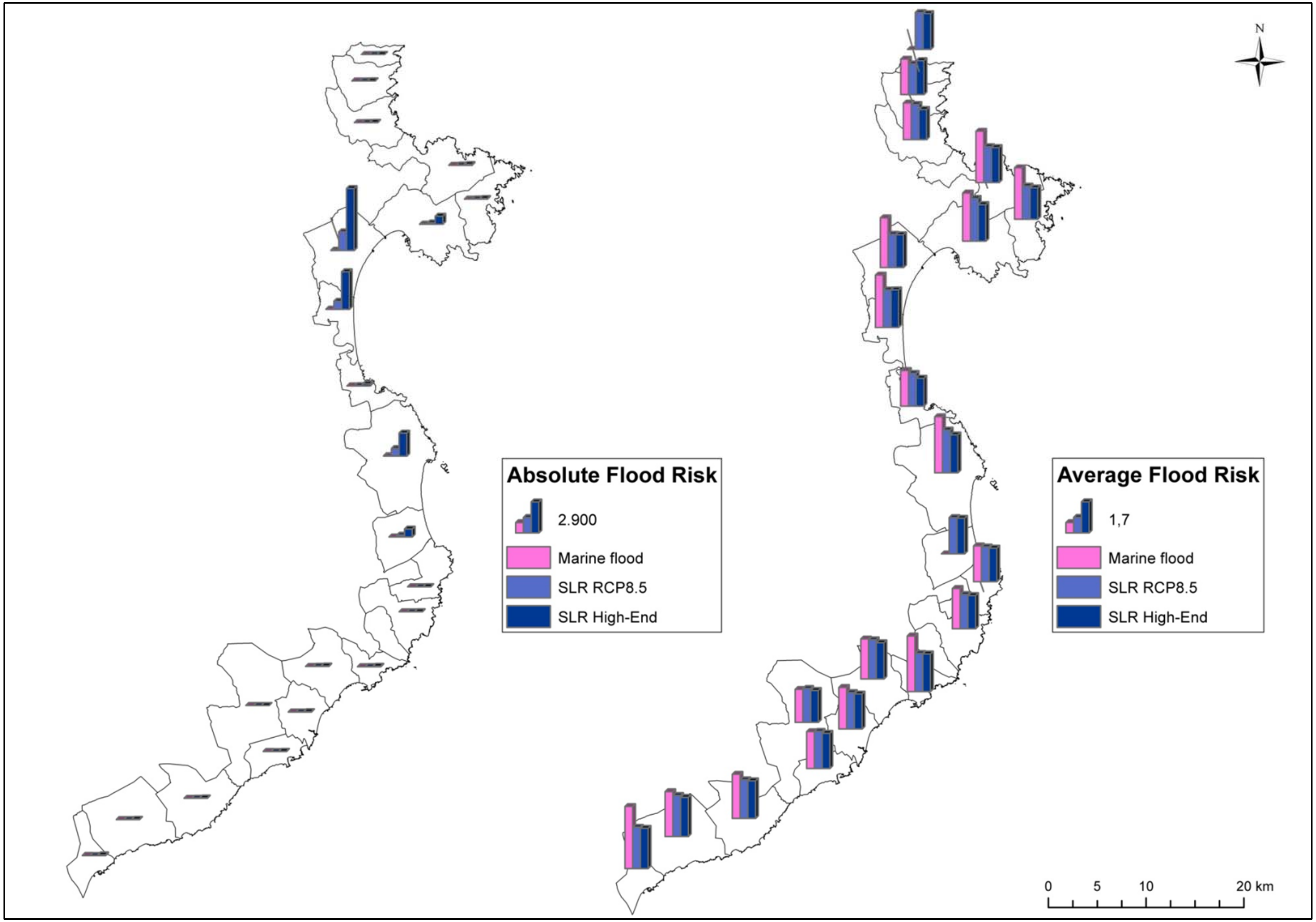


Figure 5.17 Absolute and average flood risk for marine and SLR components (Girona province).

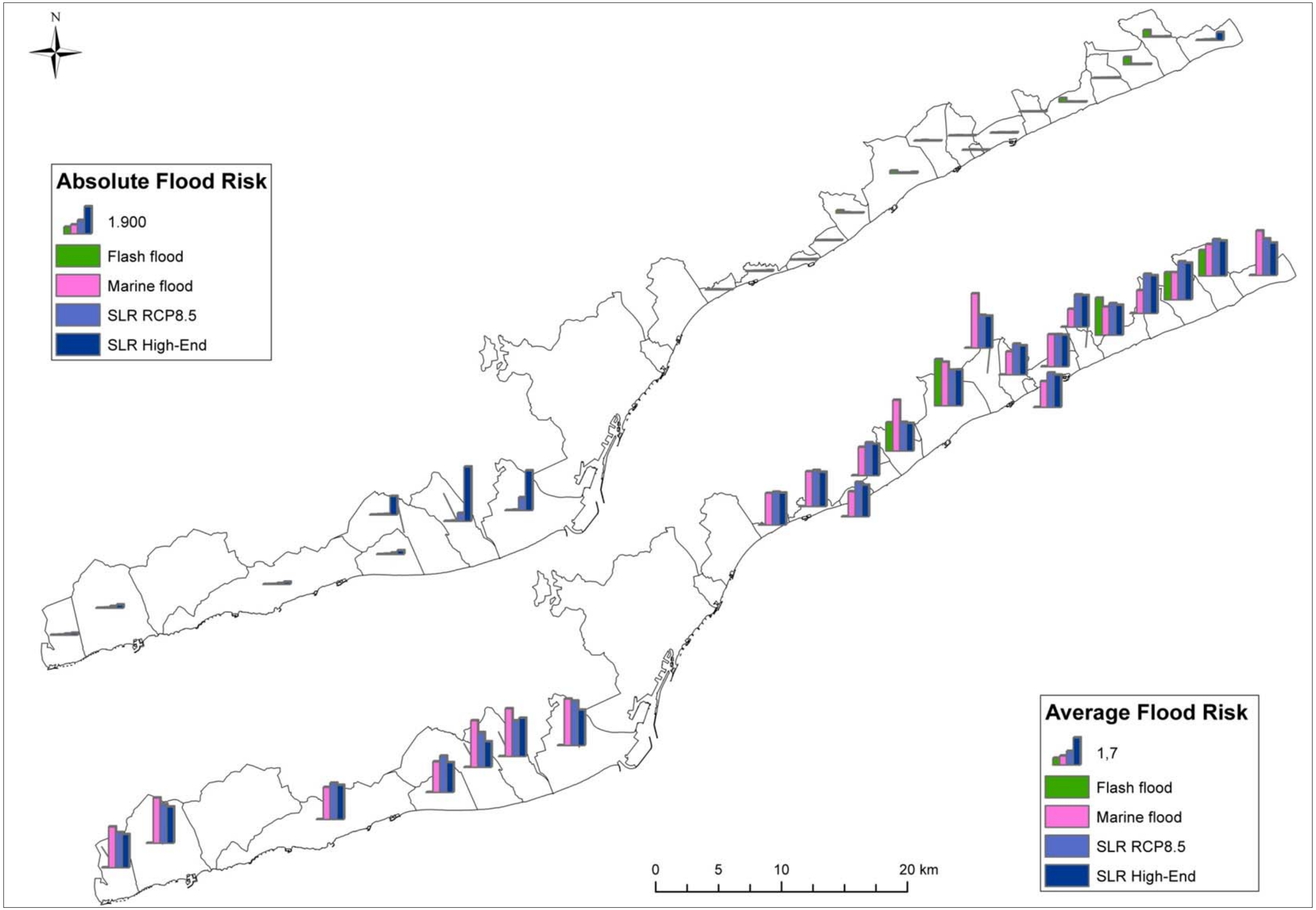


Figure 5.18 Absolute and average flood risk for marine and SLR components (Barcelona province).

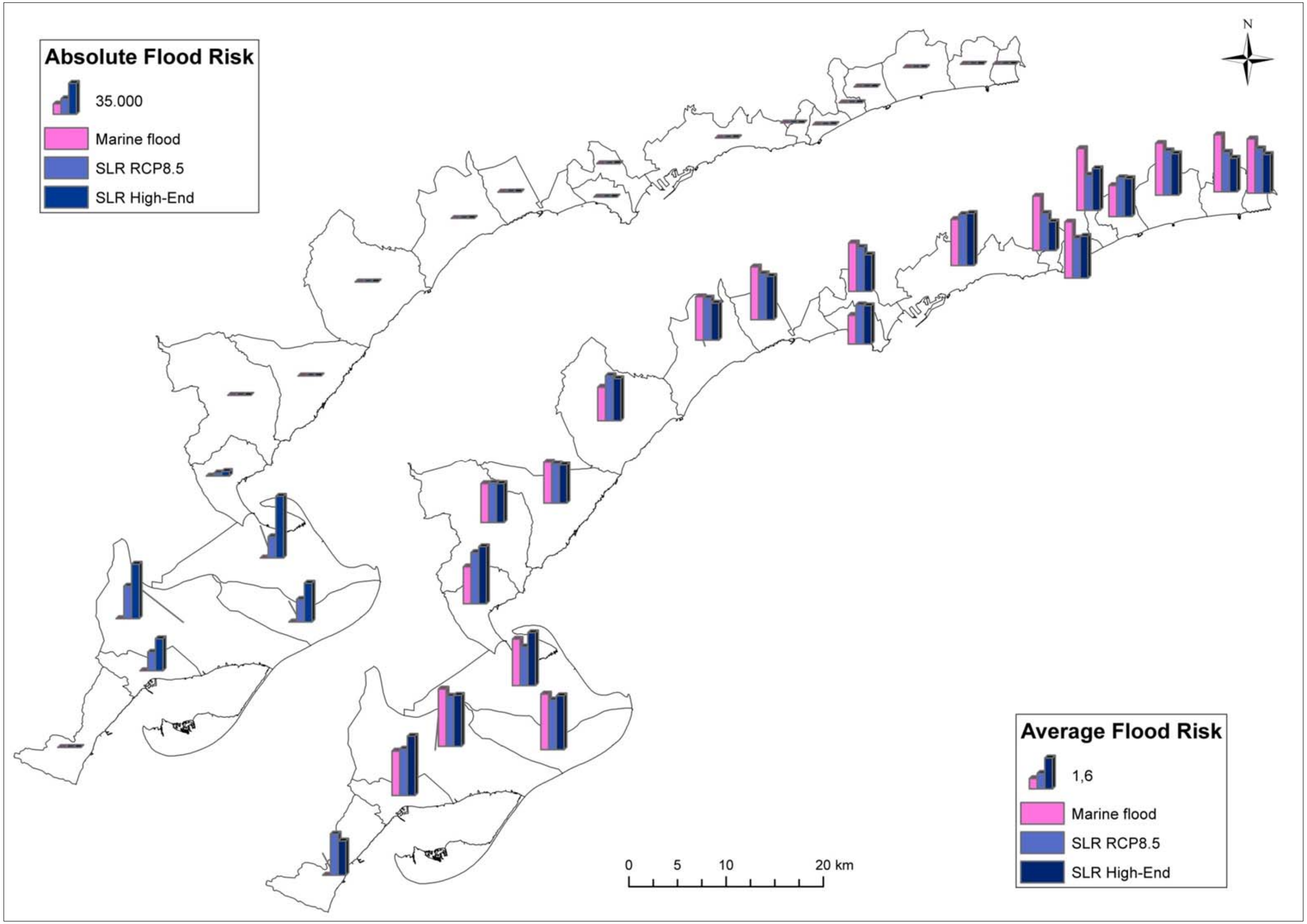


Figure 5.19 Absolute and average flood risk for marine and SLR components (Tarragona province).

Chapter 6
Discussion. Integrating risks along the Catalan coast

6.1 Methodological aspects

Coastal areas are subjected to the effects of multiple hazards (Kron 2013). However, here only coastal erosion and flooding have been analysed as they are considered to be the most relevant for the Catalan coast and induce the highest degree of damage (Jiménez et al. 2012).

In this work, these two hazards have been assessed separately since although induced by the same forcings, they produce different impacts and consequences and, moreover, the way to mitigate them is different. For this reason, it is important to identify sensitive coastal stretches for each hazard to allow coastal decision makers to properly undertake mitigation actions.

Any hazard can be decomposed into various components in relation to different processes and their associated timescales. This disaggregation should be done in advance in accordance with the target of analysis. Therefore, whether or not a particular component must be included will depend on the stated objectives of the analysis. In this work, each hazard was analysed focussing on the most expected and the likely impacts.

For erosion, the focus has been set considering the consequences to recreation and protection. Since recreation is a seasonal activity taking place during the summer, and, for mid-latitudes, storms are unlikely to happen during this season, erosion components affecting recreational use are limited to the medium and long-term components. If the objective of the analysis is to assess the potential impact of out-of-season storms, the episodic component could also be added. However, for the protection function, all the erosion components are included because the storm-induced (episodic) component is the main contributor to protection needs and, the mid- and long-term components determine the future evolution of such needs.

When considering the flood hazard, flash floods, marine floods and inundation by SLR have been considered the most relevant flood components (processes) acting at different time and spatial scales in Mediterranean coastal environments.

The spatial scale and method of aggregation have been selected from the management perspective. Each hazard and associated risk is assessed at a given basic scale of analysis (which depends on the hazard) and, later, is integrated up to the management scale which is determined by the administrative characteristics of the study area. Thus, for erosion, the minimum scale corresponds to mid-term shoreline evolution which is computed in sectors every 100 m whereas the largest is associated to the SLR-induced erosion which is calculated for very long coastal regions (10-100s km). For flooding, the minimum scale corresponds to marine flooding which has been analysed for 1 km long sectors. For this hazard, the SLR component is calculated nearly in a continuous manner since the coast is inundated taking into account local topography. Despite this, all components have been integrated at the municipality scale. This is due to the fact that the municipal scale is the lowest management unit in Spain. However, since the information is provided at different levels, the integration can be done at any scale. It should be stressed that in municipalities with short stretches of sedimentary coastline, the total municipality risk value presented only corresponds with the sedimentary parts of the coastline (e.g. Cap de Creus). Moreover, with the focus on the identification of “negative” situations (stretches at greater risk), a risk-orientated method of aggregation has been proposed for erosion, in which higher importance has been given to eroding stretches than to accretive sections to avoid masking the existence of sensitive areas by simple averaging.

With respect to time integration, erosion analysis has been assessed for current conditions plus a minimum time for projection. The proper transfer of useful information to decision makers must permit action to be taken in order to prevent/mitigate expected damages. This requires time, and territorial planning takes in the order of a few decades. It is recommend, therefore, to make projections at 10-20 years in order to properly include erosion risk within management plans.

To characterise the socio-economic consequences of the hazards, quantifiable, comparable and robust indicators have been selected, to assess the potential values affected in each case (erosion and flooding). It should be noted that this approach is primarily useful for identifying critical location while comparing sites.

In the case of erosion, two indicators have been selected for recreation: a tourist index and a leisure index. The first evaluates coastal tourism, this being one of the most important economic activities, and the second evaluates the service provided by beaches for leisure. These indicators allow an analysis of the effects on resources, not only for foreign tourists, but also for the local population. Although the assessment has been undertaken assuming tourist use and population to be steady during the period of analysis, the method can easily deal with future projections by assessing and implementing available socio-economic indicators.

For protection evaluations, the selected indicator for assessing the consequences represents the main infrastructures that would be affected if the protection function of the coast fails. In this sense, the decision on which assets to consider in the analysis will depend on which need protecting. The assets were selected within a buffer area of 100 m, taking into account the maximum and the more likely reach of coastal hazards induced by the beach narrowing process. Therefore depending on the site, the buffer should be adjusted accordingly.

For flooding, five indicators have been selected to properly reflect the potential direct and indirect consequences of flooding hazards. These indicators reflect the presence of receptors in the flood zone, from infrastructure to socio-economic activities. Within these five indicators, the land use indicator has been weighted taking into account an analysis from an anthropogenic perspective which can be adjusted to different the objective of the analysis. The social and population vulnerability indicator is represented by the SFVI, which determines the vulnerability level of the population using social and financial-deprivation variables (see Appendix B). This index allows a quantitative assessment of the intangible damages to floods, a parameter commonly overlooked in the assessment of consequences. The variables comprising this index are considered appropriate for the study area, although they were originally derived for UK conditions and have also been used in the Maresme coast in the framework of the RISC-KIT project (e.g. Jiménez et al. 2017). However, they can be adapted to other territorial and social characteristics, such as seasonal behaviour of the populations in coastal areas. The total exposure index obtained by the integration of the five indicators is produced using a linear aggregation method, which can also be modified by assigning different weights to give more, or less, importance to specific aspects (e.g. social vulnerability or businesses).

The selected indicators are robust for the site (frequently used and well-calculated). However, they can be adapted and/or substituted by any other indicator reflecting similar values, as long as they are acceptable to decision-makers. Indicators such as tourism, leisure and SFVI indices have been normalized (scaled from 0 to 1) within three scales of analysis (Catalonia, province and HEMU level) which in the case of erosion has permitted the differentiation of risk levels according to different management scales. It should be stressed that beyond damages, this analysis considers consequences as exposure values i.e. it is the maximum potential damage, since vulnerability associated with physical fragility is not considered.

In the case of erosion, a risk matrix has been used as a means to reflect hazards and consequences independently while incorporating new components in their assessment over time. The qualitative level of risk, ranked within the risk matrix between the two factors has been fixed according to the safety level required to prevent erosion risk and to prioritize actions in carrying out proper risk management activities.

When comparing flood components, it should be noted that the risk calculated for SLR is cumulative, i.e. considering the accumulated impact in a long time period (2100). However, the risk associated to storms is for one event. To properly compare them, the risk associated with the impact of multiple events in a similar period should be also cumulated. In this sense, average risk should be a more “fair” way of comparison.

6.2 Erosion and flooding risks at the Catalan coast

The assessment undertaken in this work only concentrates on the most sensitive part of the coast, about 219 km of sedimentary coast, of the more than 600 km of Catalan coast. This does not mean that the rest of the coast is not subjected to risk, but since this is expected to be smaller, the focus has been limited to beaches.

Figure 6.1 and Figure 6.2 show, in an aggregated manner, the main results for erosion and flooding risks (displayed in parallel) associated to a given timescale and process.

Figure 6.1 shows the spatial distribution of erosion and flooding risk associated to the episodic scale, i.e. the storm-induced risk. This is illustrated here for the return period (*Tr*) of 100 years and will change if another *Tr* is considered. This is an important consideration as the classification will change depending on the safety requirements of the specific location. If erosion risk is considered, most of the Catalan coast is relatively safe, with most of the exceptions being along the Maresme coast.

It should be stressed that these values give an overall view of the municipality as a whole and this does not preclude that in a given point of the coast there will be a sensitive stretch (which can be identified in 1 km sectors). The information provided here is indicating the whole municipality coastline sensitivity. Moreover, it has to be considered that represented values integrate hazards and consequences and, in some cases, although the coast would be severely eroded, damages could be low due to the unimportance of existing assets.

Despite the fact that at the present time, storm-induced erosion (episodic-term component) can be considered low in Catalonia, with the exception of the Maresme coast, when the mid- and long-term components are included in the analysis, new at-risk areas appear along the coast and levels of risk in the Maresme coast considerably increase (see Figure 6.3). This indicates the progressive sensitivity of the coast due to background erosion (mid-term) and SLR (long-term) components.

Flood risk associated with the episodic-term components corresponds with marine and flash flooding, however, the flash flooding component is not presented in Figure 6.1 to avoid an overestimation of the risk level in the Maresme *comarca* (the unique region of analysis). Along the Catalan coast, the risk associated with marine flooding can be classified as having medium risk values. Nevertheless, the Maresme coast again shows some higher values and other sectors along the coast also emerge as potentially at-risk. In this sense, these results permit to characterise the Catalan coast as more sensitive to storm-induce flood risk than to erosion risk. Moreover, taking into account both results, the Maresme region emerges as one for the most at-risk areas to storms in Catalonia.

Figure 6.2 shows the erosion and flooding risk long-term components. In this case erosion in the long-term is presented for a tourist use of the beaches. This function does not consider the episodic-term component, but only the mid-term component projected at 2035, plus the effect of the long-term component at such time. The latter has been measured in a decadal scale (2035), which is considered a suitable scale to take into account the long-term component while providing timely information for coastal management decisions.

Erosion results show that in order for beaches to provide a recreational function, most of the current municipalities with a tourism focus will be at-risk by 2035 (i.e. tourism conurbation areas of Salou (59) and Lloret the Mar(21)). Moreover, when considering the leisure use of beaches, new municipalities along the coast providing such recreational uses primarily for the local population emerge at-risk by 2035.

Results obtained considering the long-term flooding component, SLR by 2100 (Figure 6.2), show that the Catalan coast generally has a very low sensitivity to the effects of SLR given the topographic characteristic (i.e. steep beach slopes). However, it is only in the low-lying areas along the coast (Gulf of Roses, Llobregat delta and Ebro delta) where the effects of SLR will induce high risk, highlighting the sensitivity of the Ebro delta, not only by 2100 but also in the medium-term (2035) (see Figure 5.11).

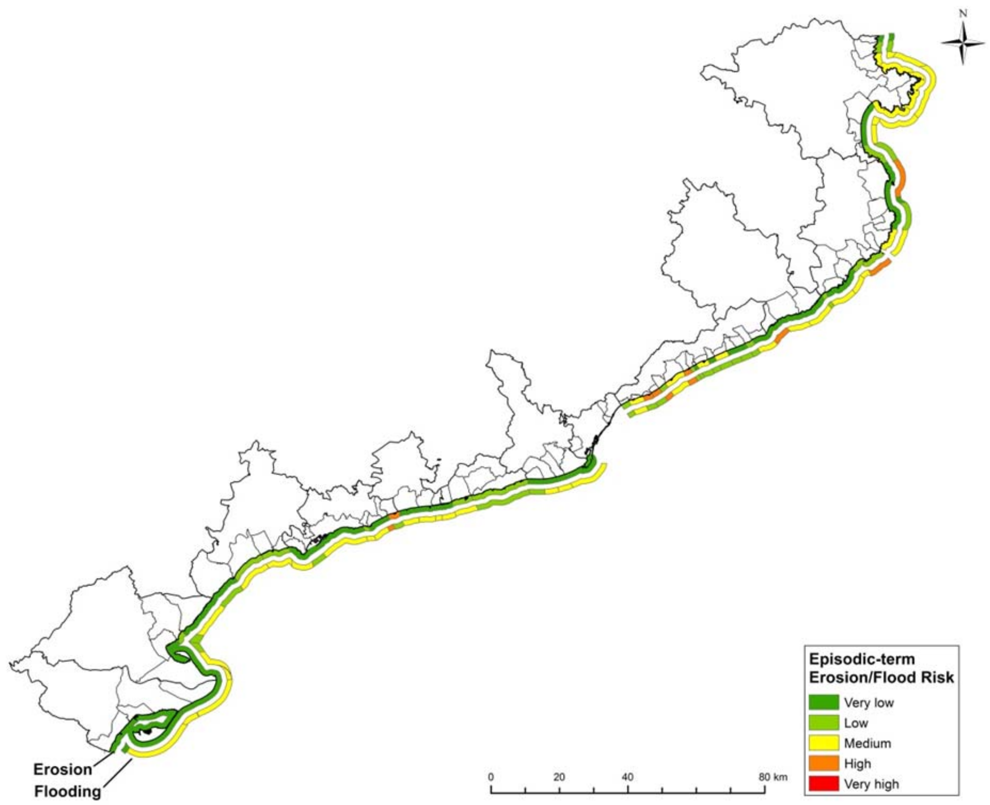


Figure 6.1 Episodic-term erosion (protection) and flood risks (marine flood component) for the Catalan coast.

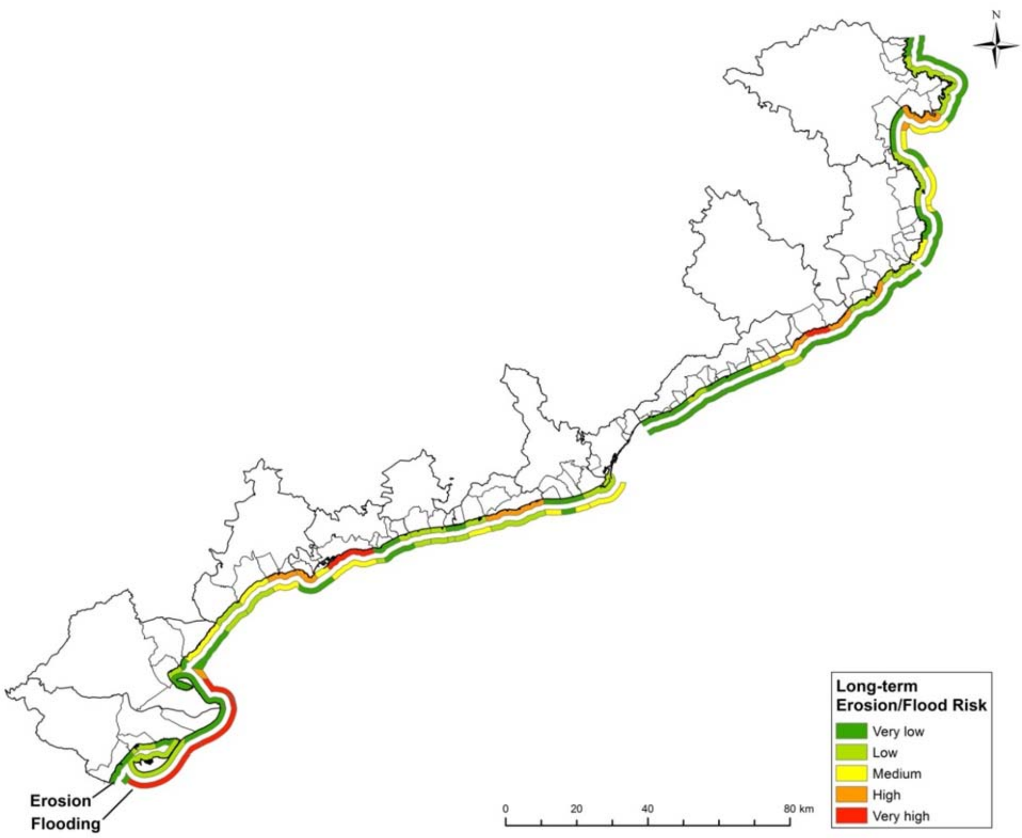


Figure 6.2 Long-term erosion (touristic use by 2035 + SLR RCP 8.5) and flood risks (SLR RCP 8.5) for the Catalan coast.

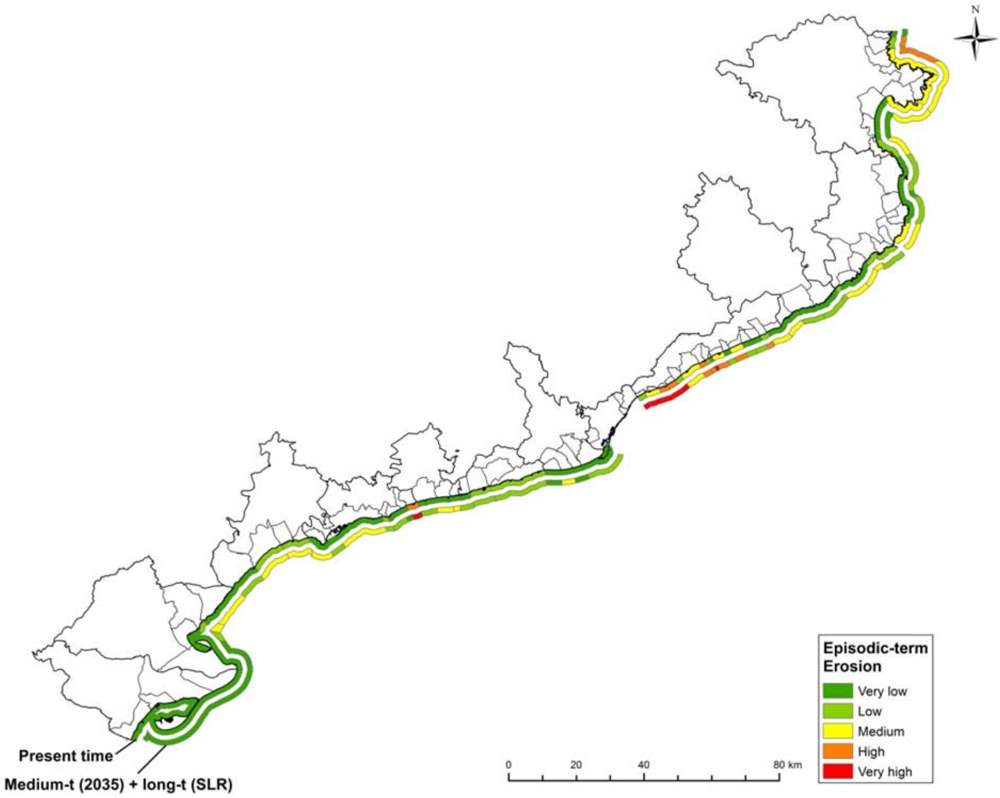


Figure 6.3 Episodic-term erosion at present and projected by 2035 (medium-t by 2035 + SLR RCP 8.5).

The results obtained for the Maresme *comarca* were integrated with an analysis of public perception in order to identify, in this territory, any gaps and misunderstanding in public awareness which could then be included in risk communication campaigns. Thus, it is observed that "objective" results obtained here reflect a high correlation with stakeholder perceptions for the area ("subjective"). As Roca et al. (2015) suggest, stakeholders clearly perceive episodic coastal processes, such as marine storms and flash flooding, as the intensity and frequency of these hazards is regularly reflected in their induced impacts on coastal assets. Thus, Figure 6.4 shows the results obtained for these perceived impacts, where the railway and roads as well as the loss of beach for a protection function, are the items most valued.

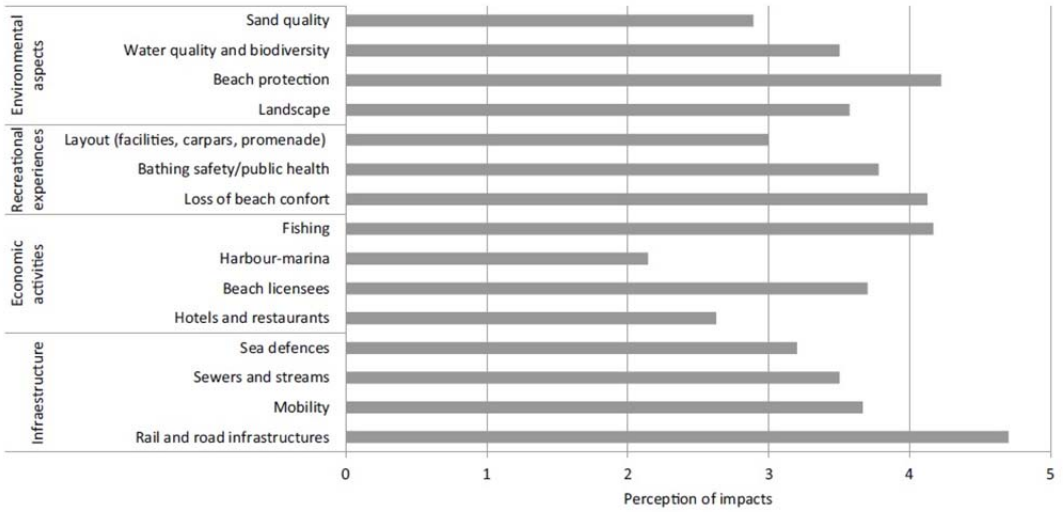


Figure 6.4 Perceived impacts in the Maresme (Roca et al. 2015).

In contrast, long-term processes in this region are not perceived as a major issue as stakeholder concerns are associated with short-time scales. This is presented in Figure 6.5 where "objective" results are combined with perceived information ("subjective") obtained from surveys conducted in the area. These results show that in the northern part of the Maresme (i.e. Alt Maresme), where the SLR is more relevant due to the presence of the low-lying area of the Tordera delta, stakeholders do not perceive this component as a risk (Ballesteros et al. 2016).

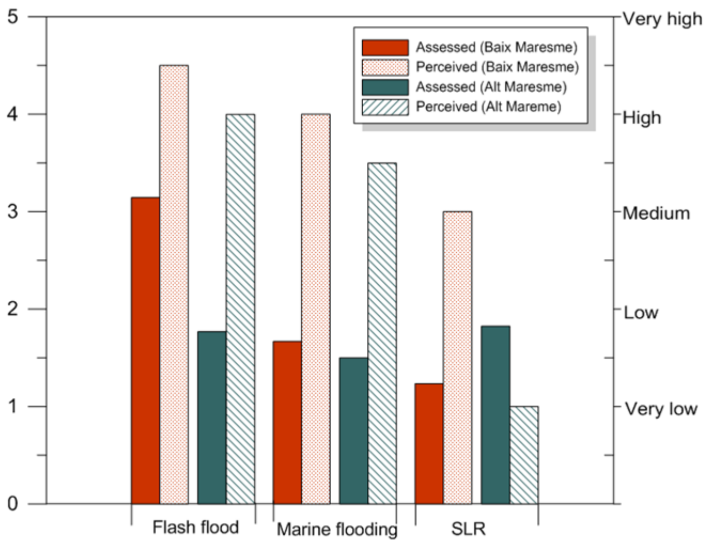


Figure 6.5 Flooding objective and perceived risk in the Maresme *comarca.*

Chapter 7
Summary and Conclusions

7.1 Erosion and flooding risk methodology

In this work, a methodology to assess coastal erosion and flooding risks at different timescales and at a regional scale has been developed. This has been framed within the SPRC model, in which the pathway has been adapted to represent each hazard by considering the different related processes acting at different timescales.

Erosion and flooding hazards have been considered individually, and are evaluated independently. In the case of erosion, this has enabled the consideration of the most important components for each coastal function in the assessment of the consequences and to evaluate the expected time evolution of the risk. For flooding, marine and flash floods (storm-induced floods) are characterised as episodic-term components, and inundation-induced by SLR as a long-term component.

The consequences of erosion and flooding have been determined separately taking into account the most relevant impacts, from the management standpoint, potentially induced by each process, i.e. recreation and protection. Thus, in order to assess erosion consequences, a *beach functional vulnerability* (*BFV*), defined as the lack of capacity of the beach to cope with erosion to properly provide a given function, has been employed. Since the main objective of the analysis is to provide useful information to inform management decisions at a regional scale, results are integrated at the minimum administrative/management unit, which, in the case of Spain, is the municipality. The considered coastal function has been evaluated in socio-economic terms to assess the potential consequences for each municipality. The results are combined within the risk matrix, which is independently obtained for each management (function) target. This permits a comparison, in a consistent form, of the considered risk among different management units (municipalities).

Flooding consequences are calculated by measuring values at exposure within the flood prone area. This is achieved using an indicator that encompasses five categories representing most representative values at the study site (land use, population and social vulnerability, transport system, utilities and business setting). The total affected area, at municipality scale, is presented both as the absolute risk (considering the total affected area) and the average risk (where the risk is considered in unitary terms).

By considering multiple coastal processes, beach functions and socio-economic values, it is possible to manage erosion and flooding to accomplish more specific goals in a more efficient and sustainable manner. This permits an identification of the most sensitive areas along the coast, which are the main contributors to the quantified risk, and thus, to properly design risk reduction measures.

As the methodology considers a joint analysis of the implications of components acting at different timescales, this will help to delineate medium and long-term risk management strategies as a prerequisite for long-term coastal planning.

7.2 Erosion and flooding risk at the Catalan coast

The proposed methodology has been applied to 219 km of beaches along the Catalan coast, where the large variability in the physical characteristics and socio-economic developments has permitted the identification of a differentiated risk distribution.

By considering two coastal functions (i.e. recreation and protection) in the assessment of erosion risk, the different sensitivity levels of the beaches along the Catalan coast, in providing such functions, can be observed. From a recreational standpoint, the analysis also demonstrates the need to include specific indicators for tourism and leisure. These indicators reflect strong regional differences in tourism development, while the social recreational use of beaches is almost as important along the entire territory.

At a regional scale (Catalonia), results reflect the current adequate status of the beaches to properly provide a recreational use. However, despite these good conditions, future projections to 2035, considering background erosion (medium-term component) and SLR-induced erosion (long-term component), indicate that an elevated number of municipalities along the Catalan coast will present high risk levels to support a recreational function in the medium-term. Thus, most of the current municipalities with a tourism focus (i.e. tourism conurbation areas of Salou (59) and Lloret the Mar (21)) will unable to support such uses by 2035. When considering the leisure use of beaches, primarily for the local population, new municipalities along the coast which provide such recreational uses emerge at-risk by 2035. In this case, the surrounding municipalities of Barcelona (i.e southern Maresme *comarca* municipalities) and Tarragona are highlighted as the most sensitive areas.

The protection function provided by beaches along the Catalan coast, shows a generally low level of risk, with the exception being the Maresme *comarca.* In this region, results demonstrate that at the present time beaches barely provide the required level of protection since most of the stretches are eroded despite supporting various forms of infrastructure. Moreover, this situation worsens when future conditions are taken into account (mid and long-term components) where additional municipalities along the Catalan coast emerge with medium risk levels, and beaches in the Maresme no longer provide a protection function.

These results stress the importance of considering the long-term component (SLR-induced erosion) within a timeframe (2035) which permits mitigation measures to be undertaken. For both coastal functions, the Maresme *comarca* represents the most sensitive area. Furthermore, the results show that by 2035 recreation along the Catalan coast will be the most at-risk function due to erosion.

The consideration of various flood hazards shows that the episodic components, marine and flash flooding, are the most relevant along the Catalan coast. However, the main difference is that storm-induced marine flooding acts along the entire coast (with different magnitudes) whereas flash floods take place in a localised part of the territory. In this sense, the whole Catalan coast presents a generally medium risk value to storm-induced marine flooding, with scattered municipalities in the northern part (e.g. Torroella de Montgrí (10), Palamòs (15), and Blanes (22)) and the Maresme *comarca* presenting high risk values. The latter can, again, be considered one of the most sensitive areas to the effects of episodic-term flood components, both of marine origin and flash flood.

The comparison of erosion and flooding risk associated with storm-induced components (episodic-term) shows that the Catalan coast is more sensitive to the effects of marine flooding than to erosion.

At the mid-term (2035) the only significantly affected area by SLR is the Ebro delta. When the analysis is undertaken at 2100, the total floodplain in low-lying coastal systems (i.e. Ebro delta, Llobregat delta and Gulf of Roses) is affected by a permanent inundation due to SLR. This will have serious implications for agriculture, ecosystems and tourism within these areas.

7.3 Future developments

The research presented in this thesis is a comprehensive assessment of different coastal erosion and flooding processes and their consequences at regional scale. However, there are inevitably ways in which this study could be refined or improved with further work. Some of the most pertinent of these suggestions are as follows:

- The consideration of actual direct and indirect damages in monetary terms (€) to evaluate the consequences. This would help to undertake cost-benefit analyses for coastal erosion and flood risks and to inform the allocation of the budget for general management policies.
- To incorporate new natural and human-induced hazards (e.g. pollution) in the assessment.
- To assess the understanding of risk (at different timescales) for the whole Catalan coast in order to analyse and compare the calculated and perceived levels of risk. This information could be included in coastal management policies and awareness raising campaigns.
- Improvements in the data collected by others would increase the robustness of the analysis. In particular, flash flood maps for a given return period with depth and velocity information for the more prone sub-basins would improve the regional assessment.

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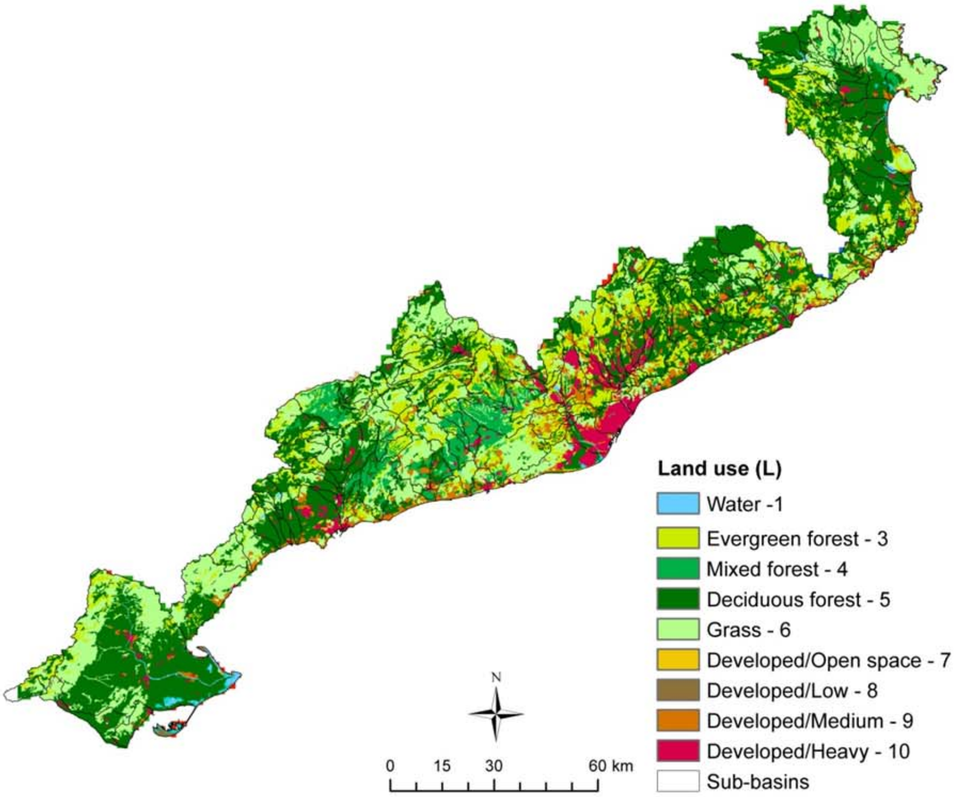
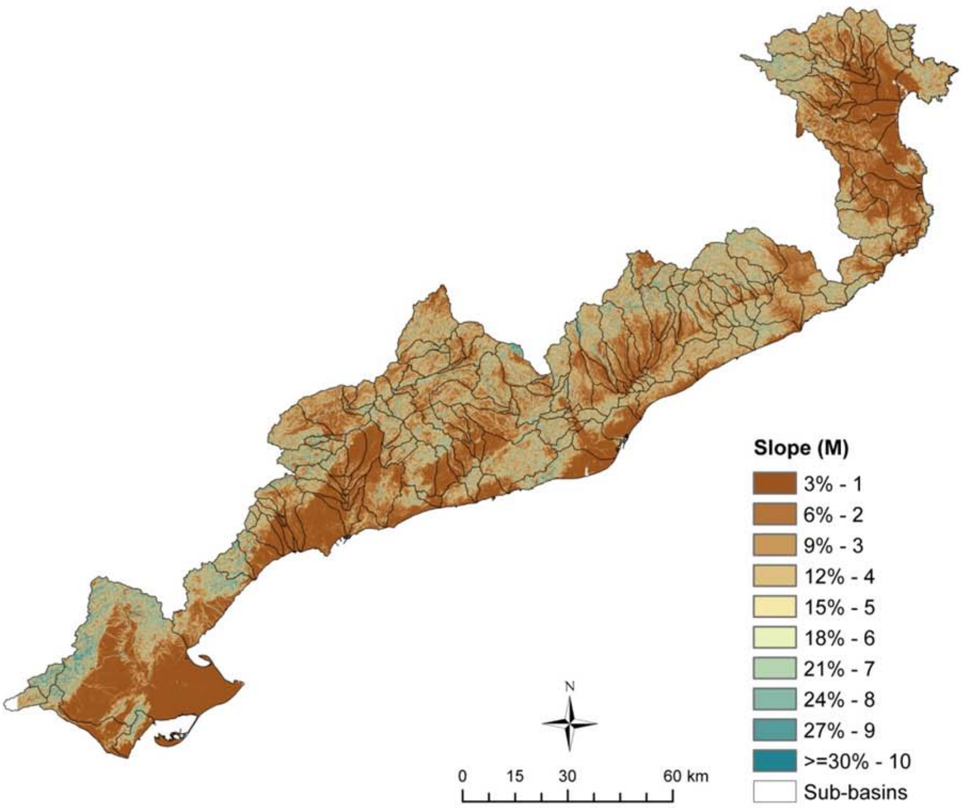
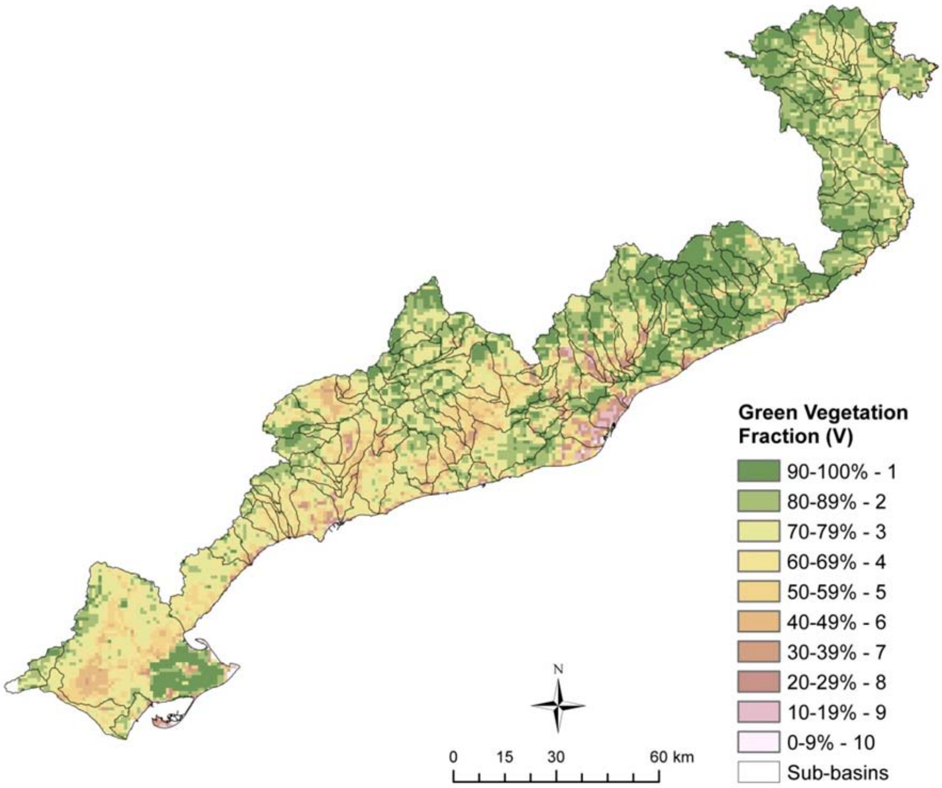
Appendix A

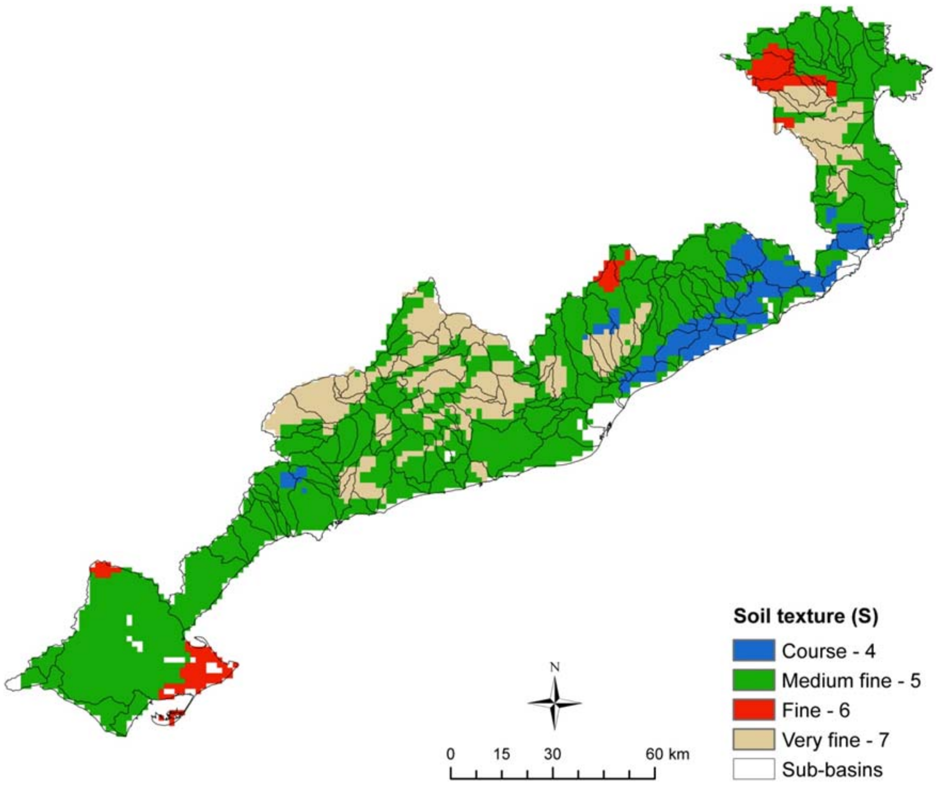
FFPI’ variables

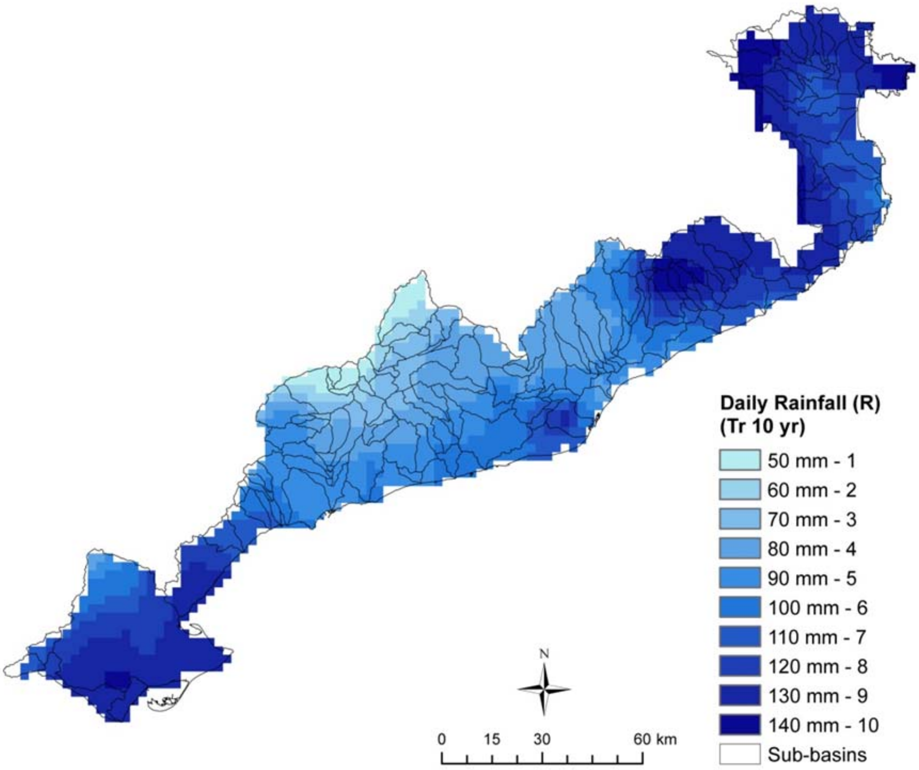
Set of variables used and ranking for the FFPI'






Green Vegetation Fraction (V)
90-100% - 1
80-89% - 2
70-79% - 3
60-69% - 4
50-59% - 5
40-49% - 6
30-39% - 7
20-29% - 8
10-19% - 9
0-9% - 10
Sub-basins
N
0 15 30 60 km


Soil texture (S)
Course - 4
Medium fine - 5
Fine - 6
Very fine - 7
Sub-basins
N
0 15 30 60 km


Daily Rainfall (R)
(Tr 10 yr)
50 mm - 1
60 mm - 2
70 mm - 3
80 mm - 4
90 mm - 5
100 mm - 6
110 mm - 7
120 mm - 8
130 mm - 9
140 mm - 10
Sub-basins
N
0 15 30 60 km

Appendix B

SFVI

Justification of the variables used in the Social Flood Vulnerability Index (SFVI) from Tapsell et al. (2002) and the corresponding data for Catalonia.

Variable	Rationale	IDESCAT DATA (Statistical Institute of Catalonia) www.idescat.cat
Elderly	Elderly people was chosen because epideminiological research has shown that after this age there is a sharp increase in the indicence and severity of arthritis (and other conditions) and this illness is sensitive to the damp, cold environmental conditions that would follow a flood event.	• Población por grupos de edad De 65 a 84 años+De 85 años y más. [(c) elderly]
Lone parents	Previous FHRC (Flood Hazard Research Centre) research has shown that lone parents are badly affected by floods because they tend to have less income and must cope singlehandedly with both children and the impact of the flood with all the stress and trauma that this can bring.	• Hogares. Por tipo de núcleo / Padre o madre con hijos. [(b) single parents]
Pre-existing health problems	Research by FHRC has shown that post-flood morbidity (and mortality) is significantly higher when the flood victims suffer from pre-existing health problems.	• Personas reconocidas legalmente con discapacidad [(a) long-term sick]
Financial deprivation	The financially deprived are less likely to have home-contents insurance and would therefore have more difficulty in replacing households' items damaged by a flood event (and it would take longer)	• Viviendas familiares principales. Por régimen de tenencia/De alquiler. [(h) non-home ownership] • Hogares. Por dimension/ Cuatro personas y más. [(f) overcrowding] • Paro registrado/población activa. [(d) unemployment] • Índice de motorización. [(g) non-car ownership]

Transformation methods applied in the compilation of the SFVI:

indicator	transformation method
lone parents	long natural (x+1)
aged 63+	long natural (x+1)
long-term sick	square root
non-homeowners	square root
unemployed	long natural (x+1)
non-car owners	square root
overcrowding	long natural (x+1)

Appendix C

Scientific contributions

Publications

Ballesteros C, Jiménez JA, Viavattene C (2016) Evaluación del riesgo de inundación a múltiples componentes en la costa del Maresme *Revista Iberoamericana del Agua* (in press)

Ballesteros C, Jiménez JA, Valdemoro HI, Bosom E (2017) Erosion risk analysis in the Maresme coast (NW Mediterranean, Spain) *Nat Hazards* (accepted, in review).

Ballesteros C, Jiménez JA, Viavattene C (2017) A multi-component flood risk assessment in the Maresme coast (NW Mediterranean) *Nat Hazards* (accepted, in review).

Jiménez JA, **Ballesteros C**, Sanuy M, Valdemoro HI. (2017) Storm-induced risks along the coast northwards of Barcelona (NW Mediterranean). *Coastal Eng* (accepted, in review).

Jiménez JA, **Ballesteros C**, Sanuy M, Nicholls R (2017) Impacts of sea-level rise-induced inundation on the Catalan coast (NW Mediterranean). *Reg Environ Change* (in preparation).

Conference participation

Ballesteros C, Roca E, Jiménez JA, Villares M (2016) Assessing the coastal risk landscape in the Maresme region. *ECSA56, Coastal systems in transition. From a "natural" to an "anthropogenically-modified" state*, Bremen (Germany).

Ballesteros C, Jiménez JA, Viavattene C (2015) Evaluación socio-económica del impacto de las inundaciones en la costa del Maresme. *XIII Jornadas Españolas de Ing. de Costas y Puertos,* Avilés (Spain).

Jiménez JA, **Ballesteros C**, Valdemoro HI, Bosom E (2015) Erosion risk assessment along the Catalan coast at decadal scale. *Coastal Sediments*, San Diego (USA).

Ballesteros C, Jiménez JA, Valdemoro HI, Bosom E (2014) The risk landscape in the Maresme coast (Catalonia, NW Mediterranean). *3rd Int. Symposium on ICZM.* Antalya (Turkey).

Valdemoro HI, **Ballesteros C**, Bosom E, Jiménez JA, Sanchez-Arcilla A (2014) Impact assessment of high-end SLR scenarios on the recreational and protection functions provided by beaches along the Catalan coast (NW Mediterranean). *3rd Int. Symposium on ICZM.* Antalya (Turkey).

Roca E, **Ballesteros C**, Villares M, Jiménez JA (2014) Perceptions on coastal risk landscape: From hazard measurements to communication campaigns. *3rd Int. Symposium on ICZM,* Antalya (Turkey).

Ballesteros C, Jiménez JA, Villares M, Garola A, Roca E (2013) El Paisaje del Riesgo Costero en el Litoral Catalán *XII Jornadas Españolas de Ingeniería de Costas y Puertos*, Cartagena (Spain).

Contributions to scientific reports

Sanuy M, **Ballesteros C**, Jiménez JA (2016) *Tordera Delta CRAF Phase 2*. RISC-KIT – Deliverable 5.2.

Jiménez JA, **Ballesteros C** (2016). *CRAF Phase 1: Identification of Hotspots in the Catalan coast*. RISC-KIT - Deliverable 5.1.

Jiménez JA, Valdemoro HI, **Ballesteros C**, Bosom E, Sánchez-Arcilla A (2015) *High-end scenario impact assessments under BaU adaptation conditions. The Catalan coast*. RISES – Deliverable 3.1.

Participation in research projects

PaiRisC-M, “El Paisaje del Riesgo Costero en el Mediterráneo. Aplicación al litoral catalán”. CTM2011-29808

PaiRisClima, “El Paisaje del Riesgo Costero en el litoral catalán. La influencia del cambio climático” CGL2014-55387-R

RISC-KIT, “Resilience- Increasing Strategies for Coasts-toolKit”. EU Grant No. 603458

RISES-AM, “Responses to climate change: Innovative Strategies for high End Scenarios-Adaptation and Mitigation” EU Grant No. 603396

Workshops

RISC-KIT Consortium Meeting (Faro, Portugal)

Period: 20th - 22th April, 2016

Objective: Meeting to discuss project progress and a workshop on applying the CRAF tool. Attended by the RISC-KIT International Expert Board.

RISC-KIT Workshop (Delft, Netherlands)

Period: 27th - 30th June, 2016

Objective: Information session on data gathering and applying the INDRA model (INtegrated DisRuption Assessment model) at the case study site.

I Jornada de joves investigadors en riscos costaners: sinèrgies entre grups d'investigació UPC-UB / I Conference of young researchers on coastal risks: synergies between research groups UPC-UB (Barcelona, Spain)

Period: 20th January, 2017

Objective: Cross disciplinary networking meeting between young researchers from UPC and University of Barcelona on coastal risks.

International research placement

Flood Hazard Research Centre (FHRC), Middlesex University (London, UK)

Period: 10th September - 12th December, 2014

Host researcher: Dr. Christophe Viavattene, Senior Research Fellow

Objective: To expand my knowledge from coastal risk to fluvial flood risk management, cost benefit analyses and the social and health impacts of flood events. Also built the Spanish social vulnerability index for use in the EU RISC-KIT project.