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The Tordera Delta, a hotspot to storm impacts in the coast northwards of Barcelona (NW Mediterranean)

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ABSTRACT

The Catalan coast, as most of the developed Mediterranean coastal zone, can be characterized as a high-risk area to the impact of storms due to the large concentration of values together with the dominance of eroding shorelines. In consequence, any long-term coastal management scheme must include a risk analysis to permit decision makers to better allocate resources. This can be done in a nested approach in which hotspots are first identified along the coast at a regional scale and secondly, they are further analysed to produce dedicated risk reduction strategies. In this work, we apply the methodology developed within the RISC-KIT project for identifying and analysing coastal hotspots in the Catalan coast as a test for applying it to Mediterranean conditions. Obtained results show that this methodology is very efficient in identifying hotspots of storm-induced flooding and erosion at a regional scale. The adoption of the response approach resulted in the direct assessment of the hazards' probability distributions, which allowed for the selection of the severity of the hotspots to be identified. When a given coastal stretch behaves as a hotspot for both hazards, it is identified as a very highly-sensitive area to storm impacts. In the study area, the Tordera Delta possesses this condition of very high "hotspotness." This has been demonstrated by the large and frequent damages suffered by the site during the past decades. The paper analyses different aspects related to the risk management of this area, including stakeholder actions.

1. Introduction

Two of the most important natural hazards causing significant damages in costal systems worldwide are storm-induced erosion and flooding (Kron, 2013). The progressive concentration of urban settlements in coastal zones has increased the exposed values and this, together with the nearly worldwide erosive trend of our coastlines (Bird, 2000; European Commission, 2004), has led to an increase in the associated risks, even under a steady-storm climate e.g., (Zhang et al., 2000; Jiménez et al., 2012a). Moreover, it is expected that under a climate change scenario, these risks will increase in the near future (Hallegatte et al., 2013; Wong et al., 2014). This current situation and the plausible perspective of worsening conditions stress the need for including risk management as a regular chapter in any exercise of long-term coastal planning. In this sense, the Protocol for Integrated Coastal Zone Management in the Mediterranean (PAP/RAC, 2007) dedicates a specific chapter to natural hazards where parties (countries) are advised to undertake vulnerability and hazard assessments to address the effects of natural disasters in coastal zones. To this end, there is an increasing number of existing practical approaches ranging from vulnerability to risk assessments e.g., (Ferreira, 2004; Bosom and Jiménez, 2011; Villatoro et al., 2014; Cirella et al., 2014; Rangel-Buitrago and Anfuso, 2015). In this line, recently in the framework of the RISC-KIT research project, a set of tools and approaches have been developed to support storm-induced risk management in coastal areas (van Dongeren et al., 2017).

When this risk management process is going to be implemented for very large spatial scales, one of the first steps to be done is the identification of hotspots. In simple terms, a *coastal hotspot* can be defined as a coastal stretch that is more sensitive to a given hazard (and within the context of this work, an associated risk) than surrounding areas. This is a screening process that allows for the delimitation of sensitive stretches along the coast to storm impacts, where a further and -more refined risk assessment analysis will be implemented at a later time.

Within this context, the main aim of this paper is twofold: (i) to identify hotspots to the impact of storms along the coast northwards of Barcelona (NW Mediterranean) by applying the methodology developed within the RISC-KIT project (Viavattene et al., 2017); and (ii) to analyze the importance of storm-induced risks in the most highly-sensitive hotspot of the area, namely, the Tordera Delta.

The structure of the remainder of this paper is as follows: (i) the second section describes the study area and the data used; (ii) the third section presents the identification of hotspots at the regional scale along the Maresme coast; (iii) the fourth section analyses in detail risk assessment and management at the hotspot scale in the Tordera Delta; and

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finally, (iv) the summary and general conclusions of this work are presented in the last (fifth) section.

2. Study area and data

2.1. Study area

Maresme is the coastal region of Catalonia (Spain, NW Mediterranean), extending from the city of Barcelona to the south to the Tordera river to the north (Fig. 1). It is composed by about 45 km of straight, coarse, sandy beaches that, originally was an uninterrupted coast. Today it is segmented into five coastal cells due to the presence of five marinas. The combination of relatively high net longshore sediment transport rates directed toward the SW, and the presence of these barriers has induced a typical alternating shoreline evolution pattern, with upcoast accreting beaches and downcoast eroding ones.

From an administrative standpoint, the coastal fringe extends along 16 municipalities, which are the most densely-populated areas of the region (IDESCAT, 2014). The region can be divided into two different areas in terms of socio-economic and territorial dynamics. Southern municipalities are strongly influenced by the presence of the city of Barcelona, which has a large, residential development, while the northern ones have largely based their economies on tourism. This area supports an important transport link composed of a coastal railway and a national road. The coastal railway is located very close to the shoreline, and in many sections is only separated from the sea by a revetment protecting the infrastructure against direct wave impact. The large urban and infrastructure development in the coastal fringe makes this region particularly vulnerable to extreme marine events, having experienced significant damage during the past decades (Jiménez et al., 2012a).

The northern end of the study area is formed by the Tordera Delta coast (Fig. 1). This is a highly dynamic zone, currently in retreat due to the net result of the littoral drift and the decrease of the Tordera River sediment supplies. As a result of this, beaches surrounding the river mouth, traditionally stable or accreting ones, are being significantly eroded during the last 20 years, with a measured shoreline retreat of about 120 m at the point of maximum erosion (Jiménez et al., 2011, 2016). The hinterland of this area is composed by the deltaic plain, which is occupied in its outer part by different campsites which are solely protected from wave action by existing beaches, with the exception of a few spots where small revetments exist.

2.2. Data

The topography of the study area has been characterized by using a 2 m × 2 m Digital Elevation Model obtained from Lidar flights performed between 2008 and 2011 by the Cartographic and Geologic Institute of Catalonia. Sediment sizes along the coast have been obtained from data supplied by (CIIRC, 2010).

Wave and water level data have been obtained from the extended SIMAR dataset obtained by Puertos del Estado (Spanish Ministry of Public Works) for the Spanish coast. This dataset originally consisted of a 44-year (1958–2001) time series of wave and water level data obtained within the Hipocas project (Guedes-Soares et al., 2002; Ratsimandresy et al., 2008), which has been extended until 2016. Waves were generated by using the third-generation wave model WAM forced by wind fields, whereas sea level data were obtained by means of the baroclinic HAMSOM model. This database has been widely used (Bosom and Jiménez, 2011; Gomis et al., 2008; Alvarez-Ellacuria et al., 2009; Casas-Prat and Sierra, 2010) and has been extensively validated in the Mediterranean (Ratsimandresy et al., 2008; Sotillo et al., 2005; Musić and Nicković, 2008). Although some extreme events are underestimated, we have used the time series without further calibration. A similar approach was also used by (Casas-Prat and Sierra, 2010) in analysing storminess along the Catalan coast.

To characterize existing land uses in the coastal zone we have used the last version of the land-use map of Catalonia developed by CREAF for the Government of Catalonia (Ibàñez and Burriel, 2010). Socio-economic

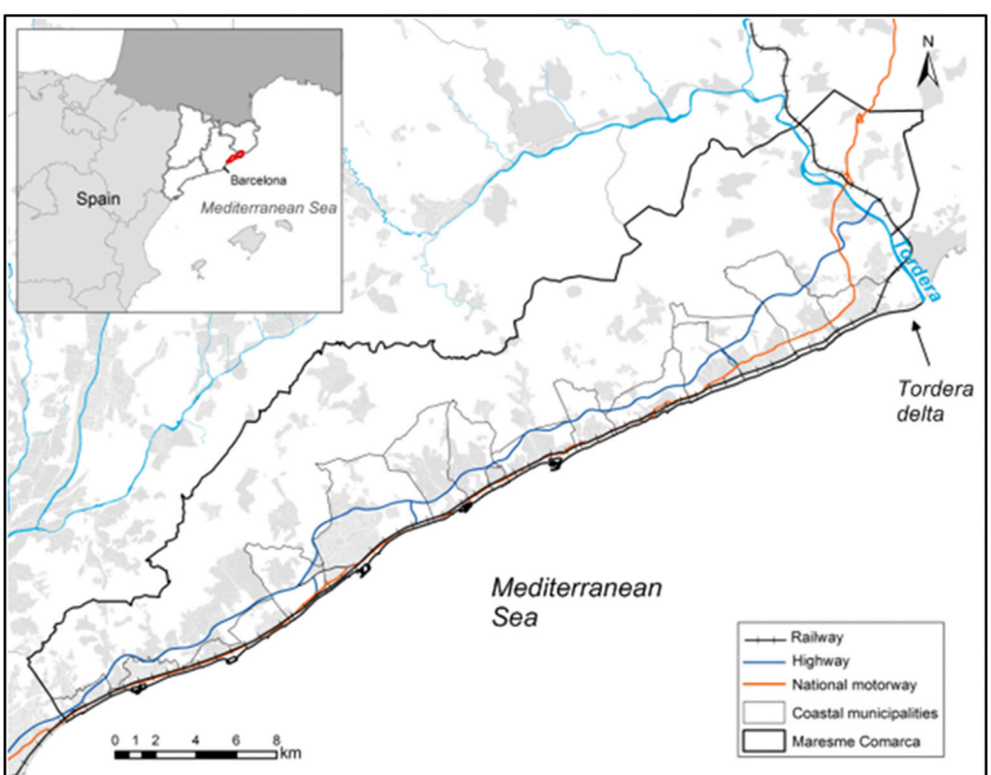

Fig. 1. Study area.

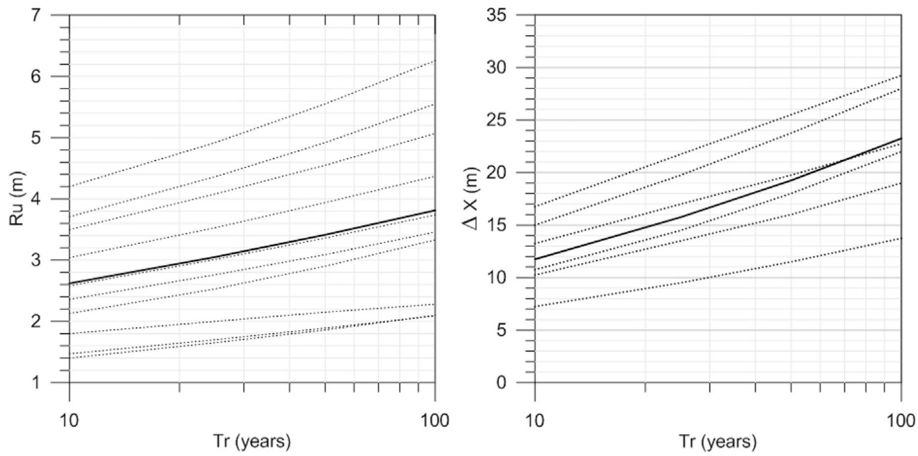

Fig. 2. Extreme *Ru* (flooding) and *ΔX* (erosion) climates along the Maresme coast. Dashed lines correspond to regimes for computed for representative profiles along the coast and the solid line is the regional-averaged climate.

data have been obtained from the official information provided by the Statistical Institute of Catalonia (IDESCAT, 2014).

3. Regional assessment of hotspots

The first step in the analysis consisted of the identification of coastal hotspots to the impact of extreme events in the area. It essentially consists of assessing storm-induced risks, in terms of flooding and erosion hazards associated to a given probability of occurrence and their potential consequencesalong the coast to identify sectors with higher risks than surrounding areas. This is done by evaluating a risk index along the coast, *CI*, which is composed by a hazard, i_h, and, an exposure $i_{\exp}$ indicator and it is given by

$$CI_{hazard} = \left(i_h{}^*i_{exp}\right)^{1/2}$$

To this end, the area was segmented in 46 sectors of one km length along the coast, each one being defined in terms of a representative beach profile which has been selected by taking the most sensitive one to analysed hazards. Hazards are characterized in each sector by using the response approach, which requires computing hazard time series from initial forcing data to directly obtain hazard–probability distributions (see Fig. 2 in (Viavattene et al., 2017)).

The magnitude of the flooding hazard was assessed by estimating the water level extreme climate along the coast and the extension of the area to be flooded. Storm surges in the area are relatively small (maximum recorded values up to 0.5 m) and thus, wave-induced runup, *Ru*, becomes the main contributor to water levels during storms (Mendoza and Jiménez, 2008), and they were calculated by applying the Stockdon et al. (2006). model in each sector along the coast. In the southern part of the study area, there are some stretches where the beach is fully eroded and the coastline is formed by a riprap revetment. In these areas, *Ru* has been calculated using the EuroTop model (Pullen et al., 2007). Resulting *Ru* time series calculated for each beach profile (defined in terms of its slope) were fitted by means of a General Pareto Distribution (GPD). Obtained *Ru* probability distributions for representative beach slopes of the study area are shown in Fig. 2, together with the representative regional regime, which has been obtained by averaging *Ru* climates obtained in each one km section.

The extension of the area to be potentially flooded along the coast was calculated using the bathtub approach. Due to the characteristics of the study area, with beach profiles characterized by a monotonous increasing elevation in the landward direction, this approach is a good representation of the maximum area to be (temporarily) potentially affected by inundation. The point where the storm-water level intersects the beach was individually calculated for each profile, taking into account the corresponding water level for selected return periods, *Tr,* and the local beach topography. Computed values were converted to a flooding hazard scale, which was derived by taking into account the local characteristics of the process. These values range from zero (potentially flooded area restricted to the beach) to five (a large area at the hinterland will be affected) (Viavattene et al., 2017).

The magnitude of storm-induced erosion hazard was assessed by estimating the eroded volume from the inner part of the beach and the corresponding shoreline retreat during the impact of the storm in each sector along the coast. This was done by applying the parametric erosion model proposed by (Mendoza and Jiménez, 2006) which predicts the storm-induced beach profile erosion as a function of storm (wave height, wave period and storm duration) and profile (slope and sediment grain size) characteristics. Since storms need to be defined in order to compute the associated erosion during each event, a threshold criteria given by $Hs = 2.5$ m and minimum duration of 6 h was used. This threshold was selected based on previous works on the storm climate in the area (Mendoza and Jiménez, 2008; Mendoza et al., 2011) and adapted to the objective of this work. These authors used a threshold of 2 m and 6 h, which has been increased to just retain the most significant storms per year (about 3 storms per year) which will be the most hazardous for the coast.

Similarly than for flooding, in order to compute the extreme beach erosion climate, and resulting eroded-volume, time series calculated for each sector were fitted by means of a GPD. Fig. 2 shows the calculated shoreline retreat values associated with different return periods for representative beach profiles of the study area.

Once the probability distributions of storm-induced hazards assessed along the coast, the next step is to derive the value of corresponding hazard indicators, i_h. This is done by selecting the hazard magnitude associated to the target probability of the analysis and, ranging them from 0 to 5 according to the scale showed in Table 1.

Table 1
Hazard scales for erosion and flooding along the Maresme coast as a function of the remaining beach width (*W*) after storm impact and extension of the flooding respectively. ΔX_{10} corresponds to the storm reach associated to a return period of 10 years.

i_h	Hazard	
	Erosion	Flooding
	Beach width after erosion (m)	Flooding extension (m)
5	beach fully eroded	> beach width + 60 m
4	$W \le \Delta X_{10}$	≤ beach width + 60 m
3	$\Delta X_{10} < W \le 2\ \Delta X_{10}$	≤ beach width + 40 m
2	$\Delta X_{10} < W \le 3\ \Delta X_{10}$	≤ beach width + 20 m
1	$\Delta X_{10} < W \le 4\ \Delta X_{10}$	≤100% beach width
0	$\Delta X_{10} < W \le 5\ \Delta X_{10}$	≤50% beach width

Table 2
Scale used to assign values to each component of the exposure indicator.

Exposure indicators	Consequences				
	1 Inexistent or very low	2 Low	3 Moderate	4 High	5 Very high
Land use (i_{exp-LU})	Barren Riparian buffer/wetland (1.5) Grassland (1.5)	Forest Urban green	Beach and dune Cropland	Campsite Industrial	Urban
Transport system **(i_{exp-TS})** *Presence of*	No significant	Local road	National road	Coastal railway	National road + coastal railway
Utilities **(i_{exp-UT})** *Presence of*	No significant	Mainly local and small	Moderate of local/ regional importance	High dense/multiple utilities of local/regional importance	High dense/multiple utilities of national/international importance
Business **(i_{exp-BS})** *Tourist Index*	<45	45–89	89–133	133–177	>177
Population and social (i_{exp-SV}) *Social Vulnerability Index*	≤ −4.4	]-4.4; −1.8]	]-1.8; −0.2]	]-0.2; 1.8]	>1,8

In order to assess the "consequences" component of the risk, exposed values susceptible to the effects of storm-induced hazards were characterized, following the methodology outlined in (Viavattene et al., 2017). To do this, an exposure indicator (i_{exp}) which integrates five types of receptors was used: land use (i_{exp-LU}); population (i_{exp-SV}); transport systems (i_{exp-TS}); critical infrastructures (i_{exp-UT}); and business settings (i_{exp-BS}). It is given by

$$i_{exp} = \left(i_{exp-LU} * i_{exp-SV} * i_{exp-TS} * i_{exp-UT} * \ i_{exp-BS}\right)^{1/5}$$

i_{exp-LU} measures the importance of the different types of land uses susceptible to be affected. i_{exp-SV} indicates the intangible impacts to the affected population in terms of their socio-economic characteristics by adapting the Social Vulnerability Index (SVI) suggested by (Tapsell et al., 2002). i_{exp-TS} and i_{exp-UT} indicate the existence and importance of a transport network and critical infrastructures respectively. i_{exp-BS} measures the potential impact on business. Since, tourism is the most representative coastal economic sector involved, we have used the tourist index developed by la Caixa bank (Caixa, 2013). This indicator measures the relative importance of the tourist sector at municipal level based on the tax rate (Business Activities Tax), and it takes into account local characteristics of tourism establishments (category, number of rooms and annual occupancy). Exposure indicator is calculated and ranked from 1 to 5 following the scale shown in Table 2 for each sector along the coast. The exposure will vary depending on the hazard extent, which will depend on the hazard type (flooding or erosion), which is calculated independently. In the case of flooding, it is computed for a 100 m-wide buffer landwards from the beach, whereas for the case of erosion, it is computed considering only a 25 m buffer behind the beach.

Fig. 3 shows the computed values for each component of the exposure indicator, as well as for i_{exp}, for flooding along the Maresme coast. With these values, this coastal stretch can be classified as having medium values at exposure, with a more or less homogeneous distribution along the coast with the exception of transport and business. The southern part

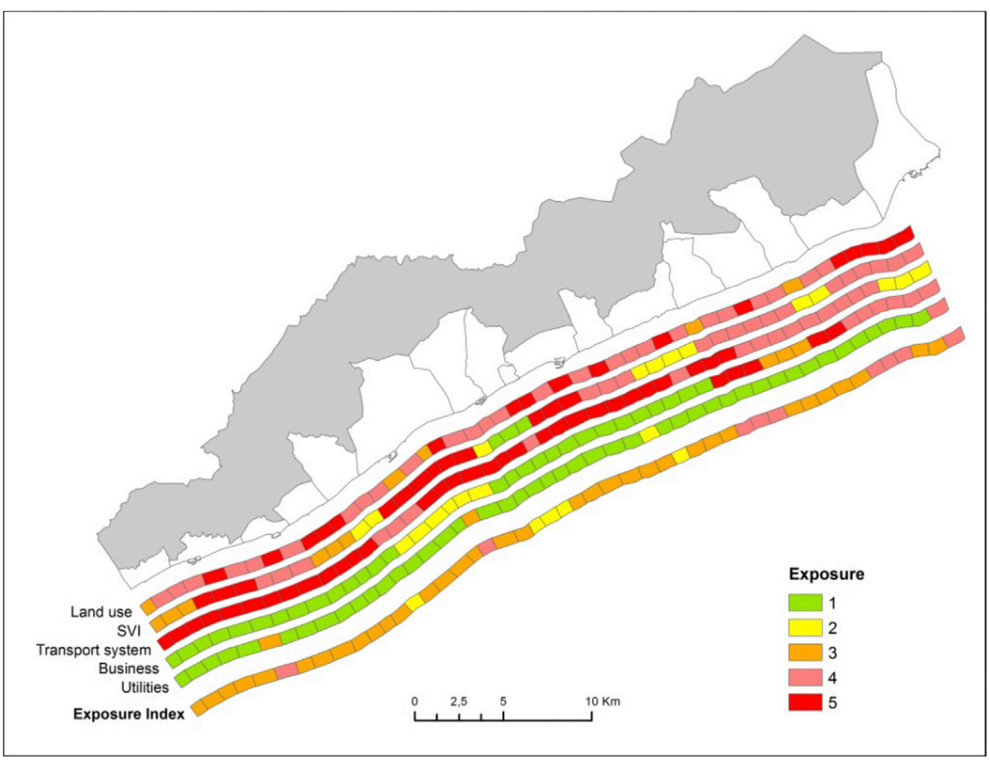

Fig. 3. Exposure indicator and contributing components along the Maresme coast for flooding risk analysis.

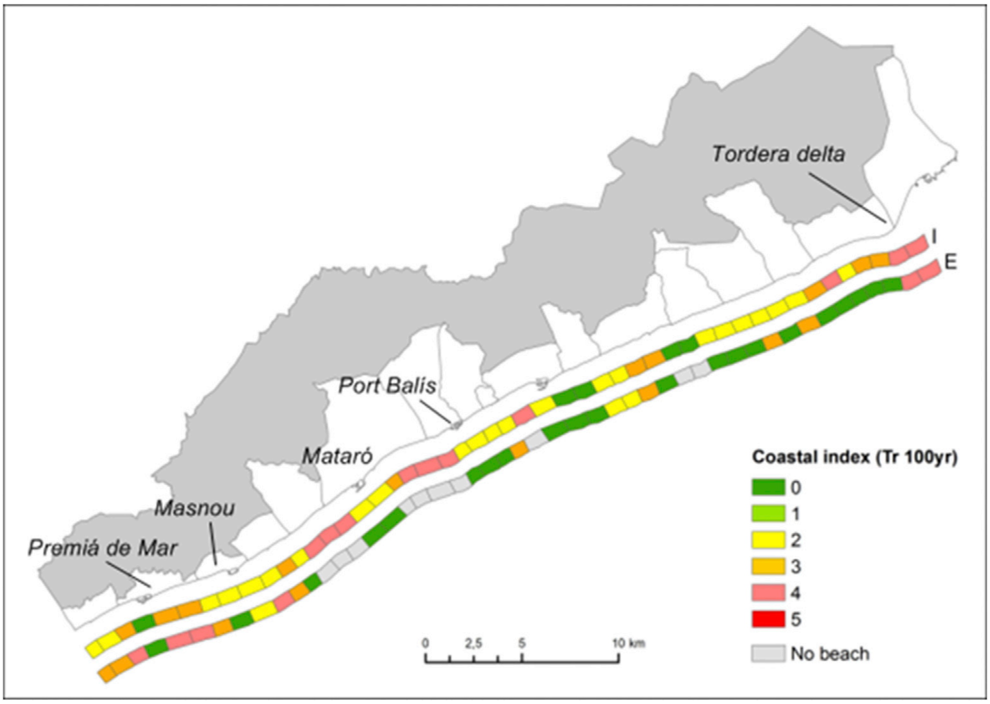

Fig. 4. Coastal flooding (I) and erosion (E) indexes associated to a probability of occurrence given by Tr = 100 years along the Maresme coast.

has important transport elements subjected to exposure and low-business importance (tourism), whereas the northern part has high-business values and few transport elements subjected to exposure.

As mentioned before, hazard and exposure indicators are integrated into a Coastal Index for each analysed hazard.

This index can be calculated associated with any probability of occurrence since hazards have been characterized in probabilistic terms (Fig. 2). The selection of the probability to be used to find hotspots is a choice of the decision-maker and depends on the safety level to be used in the analysis. As an example, here we use the probability of occurrence given by a Tr of 100 years, which is the value used in the EU Flood directive as representative for medium probability events (EC, 2007). Fig. 4 shows the spatial distribution of flooding and erosion coastal risk indexes obtained for a T_r of 100 years along the Maresme coast.

With respect to flooding, the area can be classified as a low-medium risk due to the relatively short extension of inundation reaches, with the exception of two areas. The first exception is the Tordera Delta, at the north, which is composed of relatively narrow and steep beaches protecting a low-lying area. In terms of values at exposure, beaches in this area are used for recreational purposes, being important in economic terms (local scale), supporting various campsites, which are the basis for local tourism. This area has been experiencing systematic storm-induced

Fig. 5. Affectation of the coastal railway along the Maresme coast during the impact of a storm on March 2003.

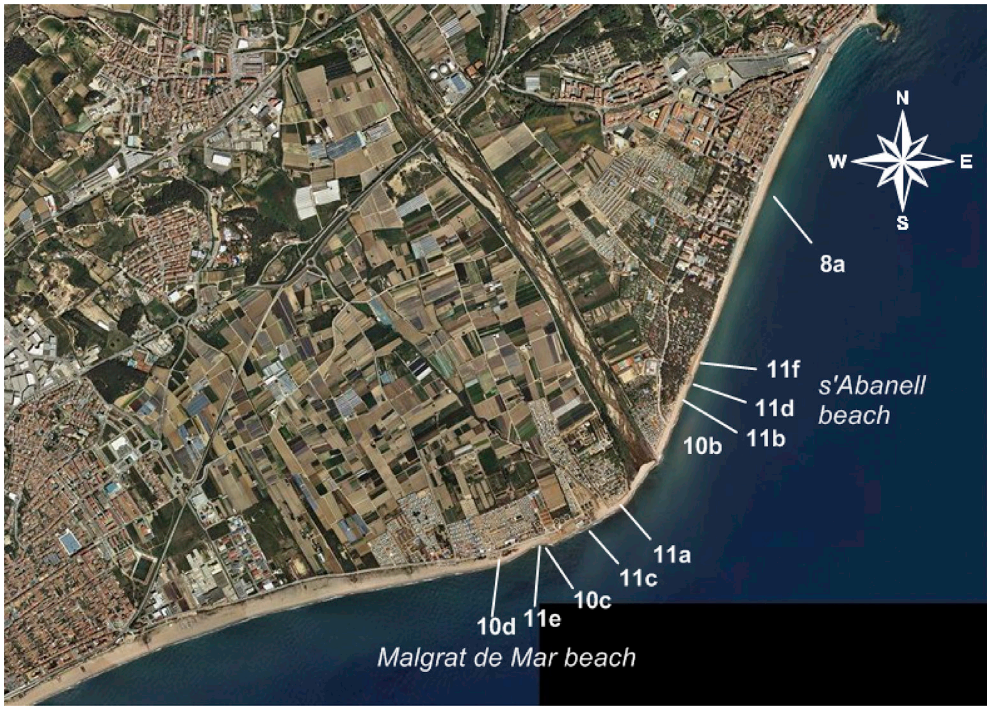

Fig. 6. The Tordera delta coast. Numbers refer to locations of photos in Fig. 10 and 11.

problems since the end of 90's, which have been aggravated in recent years due to the significant deltaic front retreat and the consequent increase in the level of exposure of the hinterland (Jiménez et al., 2011, 2016). The second exception represented by two spots to the south, which are located downcoast to the Balis and Mataró harbours, where the beach has been fully eroded in such a way that currently, the coastal fringe is composed by a riprap revetment protecting the coastal railway from wave action. During the impact of moderate and extreme storms, wave-induced runup can exceed the height of the revetment, producing overtopping and, as a consequence, affecting the railway traffic. This has been observed several times during the last decades along this coastal stretch (see Fig. 5).

With respect to erosion, the obtained coastal risk index reflects the spatial distribution of hazard intensities but is modulated by the spatial distribution of values at exposures, and specifically, by the level of protection of the hinterland (the coastal railway and the revetment protecting it). In comparison with flooding, the area presents lower risk values due to both lower hazard intensities and values at exposure. In general, the area can be classified as low to medium risk with the exception of two spots: one to the north, which coincides with the one

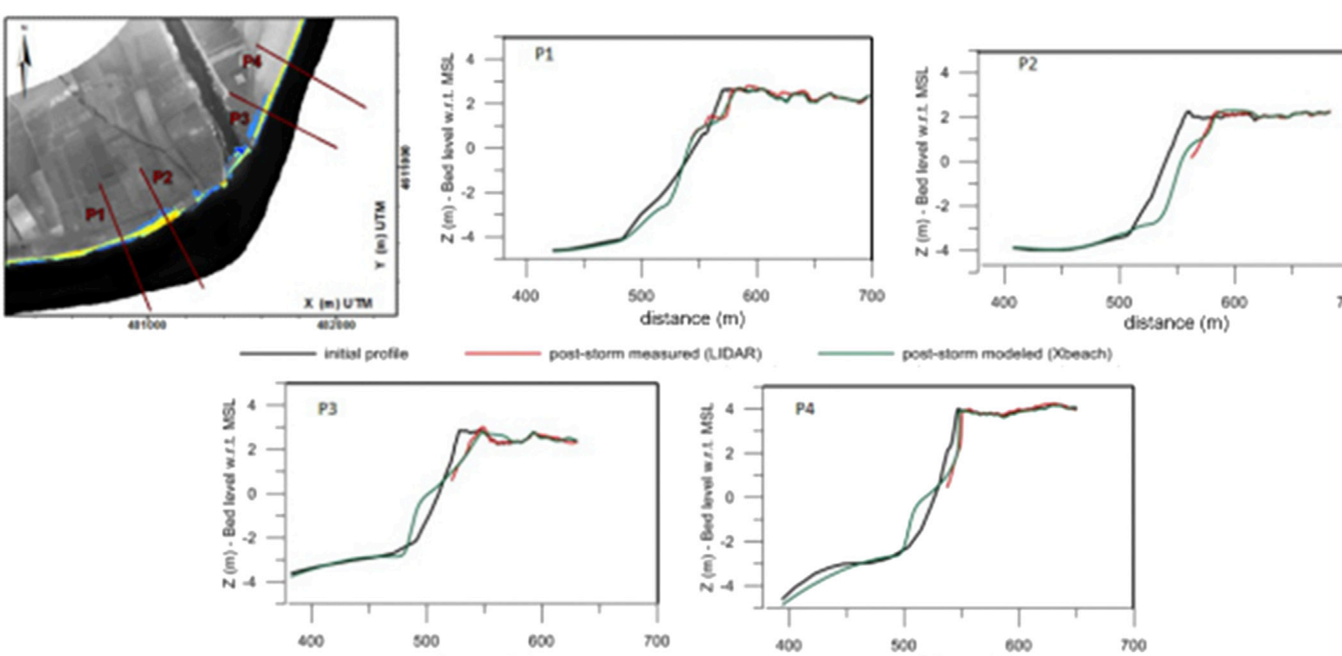

Fig. 7. Calibration of the XBeach model in the Tordera delta for the 26th December 2008 storm. Insets show measured (only the subaerial part) *vs* modelled beach profile changes at both sides of the river mouth.

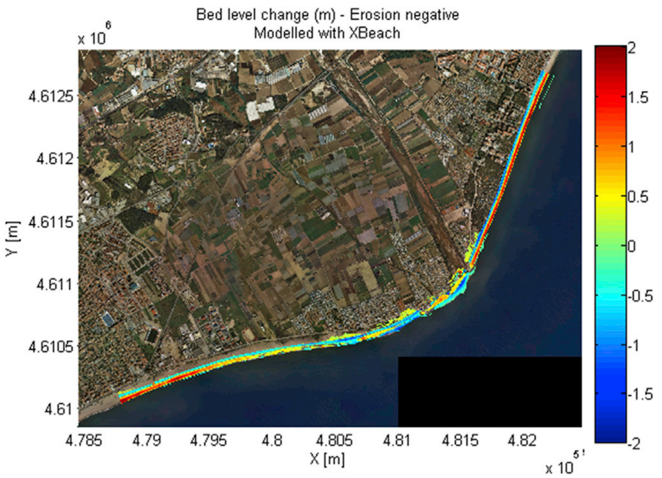

Fig. 8. XBeach simulation of beach changes in the Tordera delta due to the impact of an extreme storm ($Tr \sim 100$ years) that took place in December 2008.

previously identified in the inundation analysis, namely, the Tordera Delta beaches; and one to the south, located between the Premia de Mar and Masnou municipalities. Although beaches upcoast existing marinas are wide, the rest of the coast presents relatively narrow beaches, which can be fully and instantaneously eroded by the impact of storms. It has to be mentioned that the southern hotspot identified in the inundation analysis has not been identified for erosion because the coast was composed of a revetment where no erosion is possible.

4. Storm-induced risks at the Tordera Delta coast

Among all the identified sensitive areas along the Maresme coast, the Tordera Delta is one of the most significant hotspots for both storm-induced hazards, flooding, and erosion. This is a simple cuspate deltaic sandy shoreline where the northern part is composed by a straight beach (s'Abanell) with an orientation of 20° with respect to the East whereas the southern part is orientated from 55° to 70° with respect to the East (Fig. 6). The combination of this configuration and location determines the coastline to be directly exposed to the action of the most energetic storm waves in the area (E-NE storms) as well as to those coming from secondary directions (S) (see details on storms characteristics in the study area in (Mendoza et al., 2011).

To analyze in detail the sensitivity of this hotspot, we have used the XBeach model (Roelvink et al., 2009) to simulate storm-induced erosion and flooding hazards. First, the model was calibrated using Lidar measurements of the beach before and after the impact of an extreme storm ($Tr \sim 100$ years), the St. Esteve storm, on the 26th December 2008 (Jiménez et al., 2012b; Sánchez-Vidal et al., 2012; Plana Casado, 2013). Pre-storm and post-storm Lidar data were acquired on 16th October 2008 and 17th January 2009 respectively by the Institut Cartogràfic de Catalunya and they have an average vertical error of 8 cm (see also (Durán et al., 2016)). To select model parameters during the calibration we used the Brier Skill Score (*BSS*) to assess the model skill by comparing it to the real post-storm LIDAR measurements of the emerged profile. Final calibrated model resulted in a *BSS* score of 0.651 which according to (Sutherland et al., 2004) can be considered as a very good morphodynamic model performance. Fig. 7 shows some simulated vs measured beach profiles at both sides of the river mouth obtained during the calibration process.

After that, the model was used to simulate storm-induced hazards for a set of storms covering the full range of potential storm conditions in the area in terms of wave height, direction, and storm duration. This permitted the assessment of the expected magnitude of storm-induced hazards for any condition, and thus, to assess their possible implications in terms of damages induced in the hinterland.

It is out of the scope of this paper to present the details of the performed numerical analysis. However, to illustrate obtained results, Fig. 8 shows the simulation of the morphodynamic response of the area to the impact of the previously-mentioned extreme storm of December 2008. This was an ENE storm reaching a *Hs* of about 4.7 m just in front the Tordera Delta (Jiménez et al., 2012b). As it can be seen in Fig. 8, the response of the area was different at both sides of the river. The northern beach was directly exposed to wave action, and it suffers a generalized typical storm-induced erosion with significant sediment volumes eroded from the emerged beach and deposited in the submerged beach due to cross-shore transport. The volume of sediment eroded from this northern beach was estimated to be about 88,000 m^3 with a beach-averaged erosion of 37 m^3/m reaching a maximum of about 100 m^3/m (Jiménez et al., 2014). The area closest to the river mouth, due to its lower elevation, was also overwashed during the storm, resulting in some onshore sediment deposition, a fact that was also well reproduced in the model (see Fig. 8). These volume changes resulted in a beach-averaged shoreline retreat of 11 m, with a maximum value of about 25 m (Jiménez et al., 2014).

On the other hand, due to its orientation, the southern beach was partially sheltered from wave action during the storm. This, together the presence of a submerged longshore bar running parallel to the beach from the river mouth to the south, resulted in a different behaviour. Thus, for the southern beach, the storm-induced erosion was smaller, with a

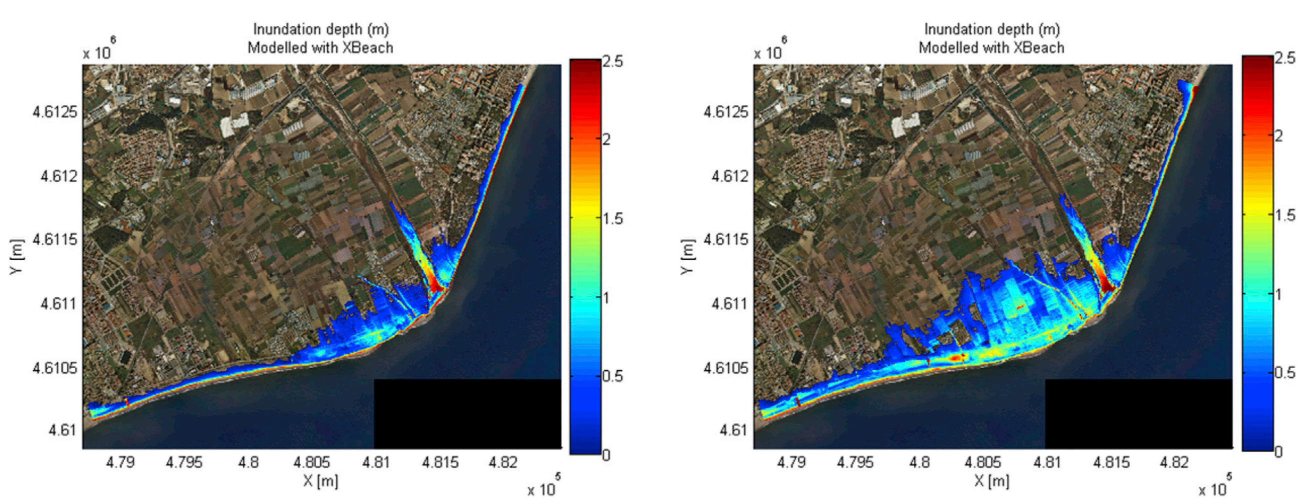

Fig. 9. Simulation of coastal flooding in the Tordera delta using XBeach under the impact of an extreme storm ($T_R > 100$ years) coming from E (left) and S (right) directions.

beach-averaged erosion of about 17 m^3/m and maximum shoreline retreats of about 10 m. However, due to its lower elevation, this beach suffered a larger overwash, with sediment accumulations in the back of the beach up to 10 m^3/m (Jiménez et al., 2014). This spatial variation in the response to storm impacts was well reproduced by the model (Fig. 8).

This spatial variation in hazard magnitude at both sides of the river mouth is also detected in storm-induced flooding. As an example of the analysed potential variations, Fig. 9 shows XBeach simulations of storm-induced flooding under the impact of an extreme storm ($Tr > 100$ years) with different directions (E and S). As can be seen, whereas the flood-prone area northwards of the river mouth has a similar extension for both storms, the affected area in the southern beach is very sensitive to incident wave direction. Under the impact of an E storm, the extension of the flood prone area, although large, is smaller than under the S storm, due to the orientation of the coastline. Under the impact of an S storm, the potential extension of the flood prone area significantly increases, because on the one hand, waves impact nearly perpendicular to the coast and, on the other hand, the existing submerged longshore bar is not very efficient in protecting the area.

These results stress the sensitivity of the southern part of the delta to wave direction during storms. However, it has to be considered that wave heights during S storms are usually smaller than during E storms (Mendoza et al., 2011). In spite of this, this analysis permits the identification of potential changes in storm-induced flood risk under a scenario of wave climate variations see, e.g., (Casas-Prat and Sierra, 2013).

The hinterland of this area has been occupied by campsites for over 40 years, which were originally protected from wave action by relatively wide beaches (from 60 m to 100 m, depending on the location). However, as was previously mentioned, beaches along the deltaic front on both sides of the river have been retreating during the last 20 years (Jiménez et al., 2011, 2016). This has resulted in an increasing exposure of values in the hinterland to storm impacts, which has become an alarming situation due to the current high frequency of damages (Jiménez et al., 2011, 2012a). Moreover, due to the decrease in protection provided by beaches, these situations are beginning to occur under the impact of relatively moderate storms, which reinforce their "hotspotness" to storm-induced hazards. Fig. 10 shows an example of damages experienced by the area due to storm impacts during the last decade, which include beach promenade collapses at the north, campsite infrastructures damages at both sides of the river, as well as flooding of various campsites with associated damages in their installations.

Until now, disaster reduction measures have seldomly been implemented in the area by the responsible Administrations and, when done, they have been met with limited success. As an example, a 180,000 m^3 nourishment was done by the Catalan Water Agency in the northern beach to protect a pumping station of a desalination plant that was directly exposed to wave action (Fig. 10b) due to a massive shoreline retreat. However, the lifetime of the works was only 1.5 months, since they were fully eroded after the impact of a moderate storm (Jiménez et al., 2011). Under this situation of increasing damages and the perception of being abandoned by the Administration, local private stakeholders have taken action under their own initiative to cope (or to try to) with coastal disasters (Fig. 11). It should be stressed that these actions are illegal, and they have usually been undertaken without any integrated perspective, in such a way that, some of the implemented measures have affected adjacent neighbours by inducing new problems. The clearest example of these new induced problems is observed downcoast of a revetment that was built to locally protect a building at Les Nacions campsite (point 11 c in Fig. 6). Once the beach in front of the revetment was fully eroded, the revetment started to affect littoral dynamics and produced the typical flanking effect downcoast accelerating erosion in front of the neighbouring campsite.

In order to test the performance of different risk management strategies, we analysed the behaviour of the system by simulating the same set of storms used to characterize current conditions by including different measures in the southern beach (Malgrat de Mar). The first one was designed to reduce the magnitude of the hazard by increasing the protection provided by the beach. This was done by means of moderate beach nourishment to only increase the beach width 40 m along 600 m of the coastline and, by building a +4 m-high artificial dune at the back of the beach. Obtained results showed that the protection strategy was effective in reducing storm-induced risks, although it behaves as a very ephemeral measure due to erosion of the fill during the impact of the storm. This implies that after each storm season, the beach has to be renourished in order to maintain its protective capacity against storms. The

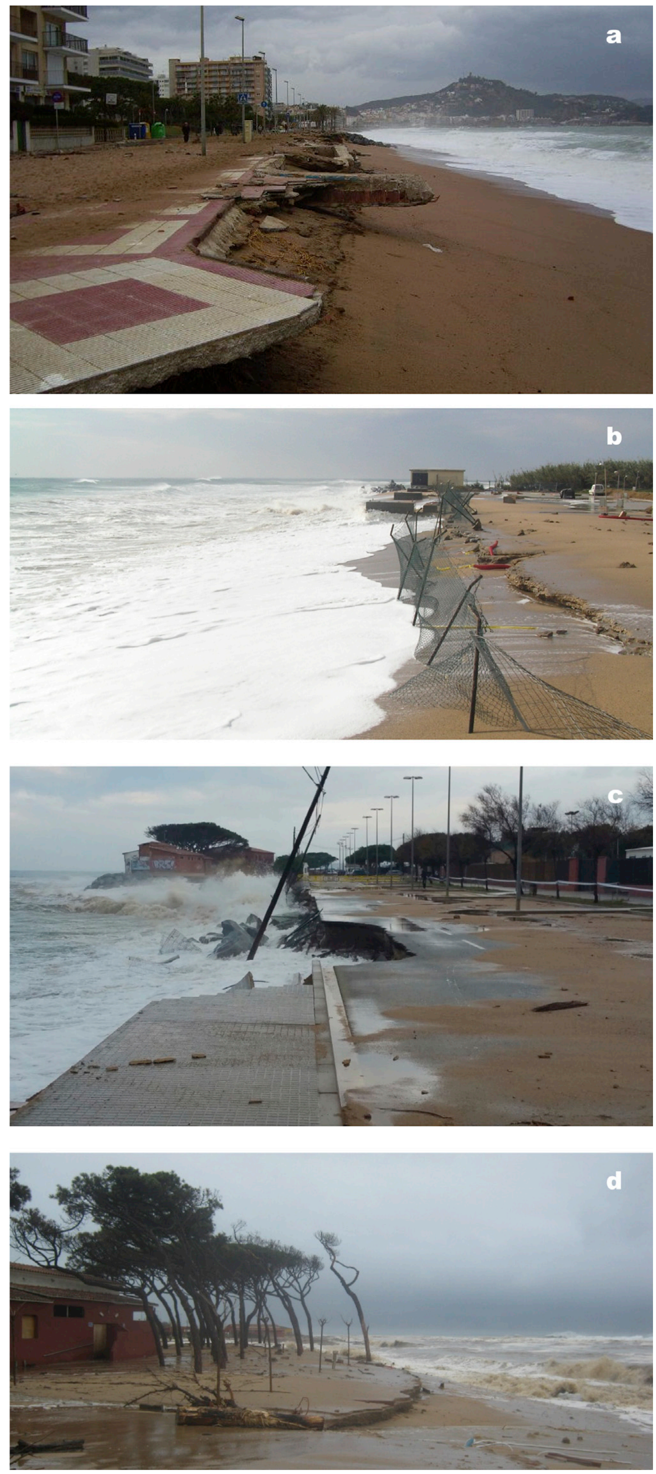

Fig. 10. Example of damages induced in Tordera delta beaches during the impact of different storm events in the last decade (see locations in Fig. 6).

Fig. 11. "Self-protection" measures against erosion and inundation implemented by campsite owners in the Tordera delta beaches (see locations in Fig. 6). Left figures correspond to Malgrat de Mar beach (southwards of the river mouth) and right figures correspond to s'Abanell beach (northwards of the river mouth). Top: temporary artificial dunes/dikes to avoid flooding during storms in winter season; middle: revetments to protect exposed camping installations; bottom: sand bags to locally maintain the beach.

effectiveness of this strategy was also tested in the field by analysing the behaviour of a 114,000 m^3 nourishment done to increase the width of a southern beach (Malgrat de Mar) in July 2015. The hinterland remained protected during the impact of two moderate storms ($Hs = 3.5$ m) in October 2015, although the fill was fully eroded (Jiménez et al., 2016). It has to be mentioned that most of the sediment eroded during the impact of dominant E storms are removed from the site and alongshore transported towards the south. The most efficient conditions to promote local beach recovery correspond to the action of S waves which bring sediment to the area, which are the least frequent ones.

The second strategy consists of reducing the damages by managed realignment, which implies the redefinition of the public domain limit and the removal of all values at exposure between the new limit and the shoreline. To this end, we tested the effects of imposing three different setbacks: 25 m, 50 m, and 75 m. As expected, this strategy was also effective in reducing risks, with larger reductions for larger retreats (see (Sano et al., 2011) for discussion on setbacks and coastal erosion). As in the previous case, if additional action is not taken, this will also be an ephemeral strategy due to the existing background erosion, although at a longer timescale.

Finally, we consulted risk management strategies in the area with local stakeholders in a Multi-Criteria Analysis as described in (Barquet and Cumiskey, 2017). Strategies were scored taking into account three different criteria, i.e. feasibility, acceptability and sustainability, where corresponding weights were agreed by stakeholders (3/8, 1/8 and 4/8 respectively). Obtained results showed that the most valued strategy was the one based on beach nourishment and the artificial dune. This was essentially due to the fact that, in addition to solving the problem, it permits the maintenance of the economic activity (campsites) as they are at present and, also provides a beach for sustaining coastal tourism. With respect to its ephemeral behaviour, stakeholders consider that eroded volumes will positively contribute to the sediment budget of the neighbouring area, acting as a sediment input. Of course, the acceptance of this strategy is assuming that re-nourishment is granted when necessary.

On the other hand, setback redefinition was very negatively considered, with rejection increasing the greater the retreat was. Private stakeholders argue that they have already retreated to accommodate to background erosion, and that under this strategy, they bear the brunt of the costs. Moreover, they state that if no further action is taken, new retreats will be required in the near future. In summary, from the perspective of the private stakeholder, this is not a solution. In any case, the selection of any risk management strategy must be integrated in a general beach management framework, such as the ecosystem-based one proposed by (Sardá et al., 2015).

5. Summary and conclusions

In this paper we have tested the methodology developed within the RISC-KIT project for identifying and analysing coastal hotspots to the impact of storms in the Catalan coast. Analysed conditions can be considered as characteristic of the Mediterranean coastline where the influence of waves usually dominates over surges, and where the erosion hazard is, at least, as important as flooding.

Obtained results show that, at a regional scale (several tens of km), the employed methodology has been very efficient in separately identifying hotspots to storm-induced flooding and erosion. The use of the response approach resulted in the direct assessment of the hazards' probability distributions, which permitted the selection of the severity of the hotspots to be identified. This selection will be made by decision-makers as a function of the safety level of the analysis and, in this work, we have used the probability of occurrence associated with Tr = 100 years.

The obtained spatial distribution of hazards shows that, although they are related, they are not necessarily coincident. This is due to the different dependence of hazards' magnitude on storm variables and, on the different variables determining the resilient capacity of the coast, i.e., beach width and height. In spite of this, there are few locations behaving as hotspots simultaneously for both hazards, and when present, they become very highly sensitive stretches to storm impacts. In the study area, this condition of very high “hotspotness” is the Tordera Delta.

The spatial distribution of risks along the coast will depend on the hazard distribution but modulated by their potential consequences. In this sense, the adopted approach in which these consequences are hypothesised by means of indicating values at exposure, implies to assume a kind of worst-case scenario, i.e., potential damage does not depend on values' vulnerability. In areas as the analysed one, where many of the exposed values present a more or less homogeneous distribution along the coast, local variations can determine a significant relative increase in the assessed risk. This is important because it will permit an improved discrimination of sensitive coastal stretches. In the study area, existing values at exposure in the identified Tordera Delta hotspot, have been significantly affected during the past decades, with most of the damages affecting campsite installations (tourist use).

When the analysis is done at the hotspot scale (few kms), the adopted approach in which storm-induced processes are simulated in detail for the full range of storm conditions permit the testing of the associated risk under any risk reduction strategy. In our case, this small-scale approach has been used to test the efficiency of two typical strategies based on protection and retreat. In both cases, they efficiently cope with storm-induced damages, but both are temporary solutions. This is due to the medium-term coastal behaviour in the area, where existing erosion rates determine a continuous shoreline retreat. Thus, any beach nourishment-based solution needs to consider an adequate re-nourishment scheme to compensate such erosion. Otherwise, the capacity to protect the hinterland will progressively decrease until its total disappearance in a relative short period. Similarly, to design a long lasting retreat-based solution, the setback definition must consider not only the storm-induced erosion but the background shoreline retreat to avoid the need of further retreat in a relatively short period. The absence or the non-application of a storm-induced risk analysis (from identification, quantification, and proposal of solutions) in the study area has led to non-regulated operations by private stakeholders to protect their assets. Of course, they have not solved existing problems and, even worse, they have been aggravated in some locations. These experiences highlight the need to include these types of risk management frameworks in coastal planning, as well as to promote a participatory process that involves the affected stakeholders.

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