Vulnerability of Catalan (NW Mediterranean) ports to wave overtopping due to different scenarios of sea level rise

Joan Pau Sierra[1,2], Ignacio Casanovas[1], César Mösso[1,2], Marc Mestres[1,2] & Agustín Sánchez-Arcilla[1,2]

[1]Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya BarcelonaTech, Jordi Girona 1-3, Mòdul D1, Campus Nord, 08034 Barcelona, Catalonia, Spain.

[2]Centre Internacional d'Investigació dels Recursos Costaners (CIIRC), Jordi Girona 1-3, Mòdul D1, Campus Nord, 08034 Barcelona, Catalonia, Spain.

Corresponding author:
Email: joan.pau.sierra@upc.edu
Tel: +34 934016467
Fax: +34 934011861

Abstract

The overtopping of port breakwaters may affect the assets located at the breakwater lee side. If adaptation measures are not taken, the sea level rise will increase the overtopping discharges putting those assets at significant risk. This study compares, at a regional scale, overtopping discharges over port breakwaters for three storm conditions (return periods of 1, 5 and 50 years) under present climate as well as for three scenarios of sea level rise based on recent projections. The results indicate that, for the worst storm and sea level rise conditions, the overtopping discharge would not be negligible (larger than 1 l/s/m) in 35 ports (84%), in contrast with only 18 ports (42%) being affected under present conditions. In addition, in 28 ports (65%) the overtopping would be at least one order of magnitude larger than for present conditions. In the case of large storms, in 2 ports the overtopping discharge exceeds 200 l/s/m (the discharge that can initiate breakwater damage) under present conditions, while in the worst scenario of sea level rise the number of ports exceeding this value would be 7. On the other hand, the vulnerability of each port for which overtopping flow is greater than an acceptable discharge flux is assessed, and regional maps of vulnerability are plotted. For the worst storm conditions, 23% of the Catalan ports have risks associated with overtopping under present climate conditions. This percentage would increase to 47% in the worst sea level rise scenario.

Keywords

Port, sea level rise, harbour, overtopping, vulnerability

Introduction

In coastal areas, one of the best-known consequences of global warming is the rising of the sea level (SLR). The study of SLR impacts has focused on its effects on beaches (e.g. Revell et al. 2011; Sánchez-Arcilla et al. 2011; Torresan et al. 2012; Monioudi et al. 2015), coastal defence structures (Chini and Stansby 2012; Isobe 2013; Lee et al. 2013; Burcharth et al. 2014), coastal ecosystems

(Reynolds et al. 2012; Kane et al. 2015) or flooding of urban areas (e.g. Hallegatte et al. 2011; Paudel et al. 2015), but few studies have addressed its impacts on harbours.

Since seaports are located on the coast or in estuaries, they are susceptible of being affected by SLR or wave storms. A higher mean sea level will cause ships to sit higher in the water, possibly resulting in less efficient port operations. In addition, SLR will increase the water depth around and inside the harbour, modifying wave propagation patterns that can in turn produce other impacts on ports affecting processes like agitation (oscillations within the port), siltation or structure stability (Sierra and Casas-Prat 2014). The impacts may be either positive or negative, i.e. they can improve or worsen port operability. Besides these potential impacts ports are not yet considering them on their own operations (Becker et al. 2012) and the physical effects of climate change on ports have received little attention. Only some studies have analyzed the impact of changes in wave patterns due to climate change on port agitation (Casas-Prat and Sierra 2010, 2012; Sierra et al. 2015) or the effects of climate change on port breakwater stability (Takagi et al. 2011; Mase et al. 2013; Suh et al. 2013).

Nevertheless, one of the greatest impacts of climate change in general, and SLR in particular on seaports is related to wave overtopping (Sierra and Casas-Prat 2014). SLR reduces the port breakwater's freeboard, easing the passing of waves over such structures, increasing overtopping discharges and potentially endangering assets (boats, goods, warehouses…) located at the breakwater lee side.

The aim of this paper is to make a first estimate of the effects that SLR produced by climate change can induce on the overtopping of port breakwaters, focusing on the harbours located on the Catalan Coast. The analysis of these impacts is made in a simple way, trying to quantify in a rough manner (i.e. to obtain orders of magnitude) the expected overtopping discharges under different SLR scenarios and comparing them with present conditions. The objective is to perform a study at regional scale, identifying those ports susceptible of having overtopping problems in the future due to SLR. Moreover, the effect of potential changes in wave patterns (whose expected magnitude is limited as shown in Casas-Prat and Sierra, 2013) is not taken into account, although their combination with SLR could modify impacts on port breakwater overtopping, being these impacts either positive (reducing overtopping discharge) or negative (enhancing discharges).

Study area

The Catalan coast, which is about 700 km long, is located in the Northwestern Mediterranean from latitude 40°45′ N to 42°25′ N and from longitude 0°45′E to 3°15′ E. This area is a microtidal environment, with predominantly semidiurnal mixed tides and tidal ranges of about 20 cm.

The Mediterranean Sea region has unique characteristics, being a transitional area with a large environmental gradient between the northern side (humid and colder) and the southern one (arid and warmer). This sea is a great heat reservoir and moisture source for land areas serving as the source of energy for most of the cyclone activity generated in this region. Recent studies state that 69% of the wind storms in this area have their origin in cyclones generated in this sea, with the remaining 31% being originated in the North Atlantic or Northern Europe (Nissen et al. 2010).

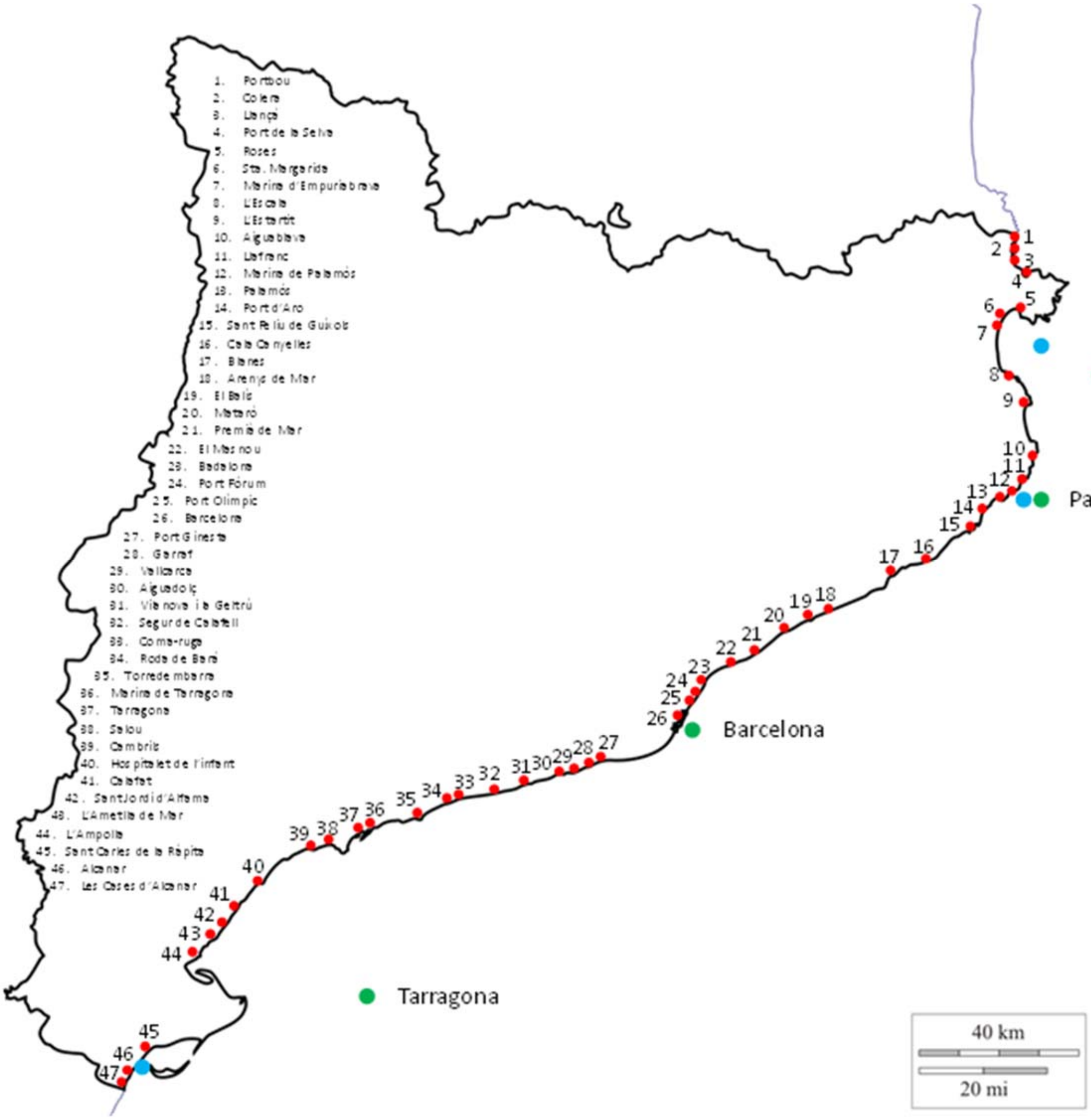


Fig. 1. Location of the Catalan ports (red points), the buoys (green points) and forecasting points (in blue)

The environmental properties of the NW Mediterranean are highly conditioned by its complexity (orography, bathymetry, veering winds…) and semi-enclosed character, which lead to a large seasonal variability (Campins et al. 2011) and determine the spatial distribution of winds and, therefore, wave fields. In summer, short-lived and weak cyclones can be observed (Lionello et al. 2006), mainly caused by thermal and orographic effects. On the other hand, winter storms are well developed, featuring long, deep and mobile low pressure centres (Bolaños et al. 2007). Spring and autumn are transitional seasons between these two extremes (Lionello et al. 2002). In terms of intensity, the wind climate is characterized by low to medium average winds, with some extreme synoptic events occurring (Sánchez-Arcilla et al. 2008).

All these climate conditions have a direct influence on the generation of waves and, thus, on the study of overtopping. The complex spatial and time variability of wind fields results in waves also affected by short fetches, shadow effects caused by the Balearic Islands for waves coming from S and SE, and by the complex bathymetry with deep canyons close to the coast (Casas-Prat and Sierra 2013). The directional distribution of waves along the coast shows a predominance of NW and N wave conditions at the southern and northern sections of the area, whereas the central part is dominated by E and S wave conditions. The largest waves come from the E or E-NE, where the longest fetches and stronger winds coincide (Sánchez-Arcilla et al. 2008).

Along the Catalan Coast there are 47 seaports, 2 of which are large commercial harbours (Barcelona and Tarragona), 3 are small commercial (with facilities for leisure and fishing boats), 2 are industrial, 18 are mixed (fishing and leisure) and 22 are marinas. The location of all ports is shown in Figure 1. In the last years, 10 out of the 47 ports have reported overtopping problems. In this paper, 43 of them (91%) are studied, while the remaining 4 (Portbou, L'Escala, Badalona and Marina Tarragona) could not be analyzed due to the unavailability of information, in particular detailed port breakwater sections.

Material and methods

The first step to study the wave overtopping related to climate change is to select plausible scenarios of SLR. The latest projections from the AR5 of IPCC (Church et al. 2013) suggest that mean sea levels for the period 2081-2100 will be between 0.26 and 0.82 m higher than the average for the period 1986-2005, with a maximum value of 0.98 m by 2100 with respect to this last period, corresponding to scenario RCP8.5. These ranges are derived from CMIP5 climate projections in combination with process-based models and literature assessment of glacier and ice sheet contributions. Other recent studies suggest much higher mean SLRs (up to 1.86 m) for 2100 (Jevrejeva et al. 2012; Mori et al. 2013).

Taking this into account, three other scenarios of SLR have been considered, besides present conditions, to study port overtopping: one corresponding to a middle SLR (given by scenario RCP4.5), another to an extreme scenario (RCP8.5) and the last to a high-end scenario representative of very extreme SLR, physically feasible although with a very low probability of occurrence (less than 5% by 2100, Jevrejeva et al. 2014). With respect to this, several authors (e.g. Hinkel et al. 2015) consider that, from a coastal risk management viewpoint, it is better to use the upper tail end rather than the central distribution, because there is a probability between 0% and 33% of SLR lying outside the range projected by IPCC scenarios (Church et al. 2013).

For the RCP4.5 scenario the central value of SLR in 2100 (0.53 m) has been chosen, while for the RCP8.5 scenario the upper band of SLR in 2100 (0.98 m) has been selected, to include the most unfavourable conditions in the analysis. In addition, AR5 projections indicate that SLR in the Mediterranean Sea will be slightly lower than the SLR global average (up to a 10%). Based on these considerations and assuming a SLR decrease of 10% with respect to the global averages, the scenarios considered in this study are:

- Scenario 0: Base level (present conditions, 1985-2005)
- Scenario 1: RCP4.5 (Base level + 0.47 m)

- Scenario 2: RCP 8.5 (Base level + 0.88 m)
- Scenario 3: High-end scenario (HES, Base level + 1.80 m)

Table 1. Assignation of buoy data to each port considering their proximity and tolerable overtopping mean discharge per unit width (l/s/m) and their particular conditions.

Buoy	Port	Discharge (l/s/m)
BEGUR	Colera	10
	Llança	10
	Port de la Selva	10
	Santa Margarida	200
	Empuriabrava	200
	L'Estartit	10
	Aiguablava	10
PALAMOS	Lafranc	10
	Marina Palamos	10
	Palamos	10
	Port d'Aro	200
	Sant Feliu	10
	Cala Canyelles	10
	Blanes	10
BARCELONA	Arenys de Mar	1
	El Balis	10
	Mataro	10
	Premia de Mar	200
	El Masnou	10
	Port Forum	200
	Port Olimpic	10
	Barcelona	0.4
	Port Ginesta	10
	Garraf	10
	Vallcarca	10
	Aiguadolç	10
	Vilanova i la G.	0.4
TARRAGONA	Segur de Calafell	10
	Coma-Ruga	1
	Roda de Bara	10
	Torredembarra	10
	Tarragona	0.4
	Salou	10
	Cambrils	1
	Hospitalet Infant	10
	Calafat	10
	S. Jordi Alfama	200
	L'Ametlla de Mar	10
	L'Ampolla	10
	Alcanar	10
	Cases d'Alcanar	10
Wind	Roses	10
Wind	S. Carles Ràpita	0.4

Although future changes in global sea level are uncertain, homogeneous values of SLR along the whole Catalan Coast have been assumed due to the lack of updated projections for local variations. Moreover, two ports (Barcelona and Sant Carles de la Ràpita) are located in two of the three deltas existing on this coast, where compaction-related subsidence may be significant (Gámez et al. 2005). The subsidence rate is 1.75 mm/yr at the Ebro Delta (Somoza et al. 1998) and 5 mm/yr at the Llobregat Delta (Pros Llavador et al. 2013). Taking into account these rates and the time interval between 2015 and 2100, subsidence values of 15 cm for Sant Carles de la Ràpita port (located in the Ebro Delta) and 42.5 cm for Barcelona Port (in the Llobregat Delta) are obtained. In both ports, the subsidence values are added to the SLR to obtain the relative sea level rise in the three future scenarios.

Table 2. Significant wave heights given by the buoys for the three return periods considered and all the directions affecting the ports.

Buoy	Direction	Hs (m)		
		Tr = 1 year	Tr = 5 years	Tr = 50 years
BEGUR	N	5.02	5.87	6.94
	NNE	4.57	5.35	6.31
	NE	5.38	6.29	7.43
	ENE	5.64	6.59	7.79
	E	3.57	4.18	4.94
	ESE	3.67	4.28	5.06
	SE	2.34	2.74	3.24
	SSE	2.49	2.91	3.44
PALAMOS	NE	3.19	4.22	5.80
	ENE	4.14	5.48	7.53
	E	3.03	4.01	5.51
	ESE	2.22	2.94	4.04
	SE	1.90	2.51	3.45
	SSE	1.89	2.50	3.44
	S	1.86	2.46	3.38
	SSW	1.97	2.61	3.59
BARCELONA	NE	1.35	1.69	2.17
	ENE	2.90	3.64	2.78
	E	3.46	4.35	5.57
	ESE	2.45	3.09	3.96
	SE	1.63	2.05	2.62
	SSE	1.50	1.89	2.42
	S	1.66	2.09	2.68
	SSW	2.37	2.98	3.82
	SW	1.79	2.26	2.90
TARRAGONA	ENE	3.85	4.61	5.59
	E	2.93	3.51	4.26
	ESE	2.34	2.80	3.40
	SE	1.68	2.01	2.44
	SSE	1.67	1.99	2.42
	S	2.36	2.82	3.42
	SSW	3.10	3.70	4.50
	SW	2.82	3.38	4.10

Detailed wave data in the Catalan coast are also needed. Since wave projections based on AR5 (Church et al. 2013) are still not available, and considering that the aim of the paper is to study only the effect of SLR and not the combined effect of SLR and changes in wave patterns, the same wave climate has been assumed for present and future conditions. This wave climate has been obtained from buoys located offshore of the Catalan Coast, because instrumental data are those providing the highest quality information. The data set was obtained from the Spanish Harbour Authority (Puertos del Estado) and includes the buoys of Palamos, Begur, Barcelona and Tarragona (PPEE 2012, 2013a, 2013b, 2013c), whose location is shown in Figure 1. As opposed to the latter three buoys, which record directional wave data, the Palamos buoy is scalar; thus, the extreme wave climate obtained from this buoy has been completed with the directional information extracted from the closest forecasting data point (shown in Figure 1). A possible alternative to using recorded data is the use of wave hindcast series that are available in this area (e.g. Ratsimandresy et al. 2008; Liberti et al. 2013; Martínez-Asensio et al. 2013; Mentaschi et al. 2015).

For the study of overtopping, the different Catalan ports have been gathered into four different groups considering their proximity to the four buoys, with each port assigned to the closest one (See Table 1). Using the data provided by each of these buoys (in reference to extreme climate conditions), wave conditions at deep water have been obtained for different return periods T_R (1, 5 and 50 years) and for all the directions affecting each port. These return periods have been selected because they represent three different levels of storminess: events that occur on average once a year and represent relatively frequent storms (1 year), storm events that are relatively intense for the area of study (5 years) and exceptional storm events (50 years). Wave data have been grouped considering sixteen directional sectors. In Table 2 the wave data used in this study are shown.

Subsequently, the deep water wave conditions have been propagated from the buoys to each port using linear theory in order to obtain wave parameters at the port breakwater location. The lack of detailed bathymetries in the areas between the harbours and the buoys prevented the use of more accurate tools (e.g., numerical models) to propagate the waves shoreward.

Applying the linear wave theory is particularly critical when there are diffraction effects (due to the presence of geographical accidents). In most of the cases studied here the wave propagation is performed in open coasts, so there is no diffraction due to the presence of obstacles. Two ports (S. Carles de la Rápita and Roses) are situated within a bay and only receive the attack of diffracted waves or waves generated by local wind within the bays (due to the reduced fetch). As explained below, in these two ports the waves are computed directly from wind and fetch and they are not propagated, obviating thus the potential diffraction effects. Moreover, the scope of the paper (the analysis of several ports within a regional scope) is to analyze the difference between present and future conditions based on three scenarios of SLR, so the use of linear theory does not introduce any bias in the results for comparative purposes and gives enough accuracy for an analysis at a regional scale.

The average orientation of the isobaths and the water depth at the breakwater were taken into account to compute the shoaling and the refraction coefficients required to propagate the waves using linear theory. The average bottom slope has also been used to verify if wave breaking occurs before waves arrive to the breakwater. If wave breaking takes place, the wave height considered is that of the greatest wave that can reach the breakwater. For evaluating the breaking wave height H_b, the equation proposed by Goda (2007) is used:

$$H_b = 0.1 L_0 \left\{ 1 - \exp\left[-1.5 \frac{\pi h}{L_0} \left(1 + 11 \tan^{4/3} \theta \right) \right] \right\} \tag{1}$$

where L_0 is the deep water wave length, h the water depth and $\tan\theta$ is the slope of the sea bottom.

In a number of cases, the port is parallel to the isobaths, so that the water depth along the breakwater is constant and it is used for computing the wave propagation and for verifying if the wave breaks. In other cases, the water depth at the breakwater varies within a certain range; wave propagation is then computed for each direction and for all the depth range at 1 m intervals. As an example, if the breakwater is located at water depths between 6 and 9 m, the wave propagation and the overtopping are computed for 6, 7, 8 and 9 m depths, taking the greatest discharge as the value for this particular port and direction.

It is worth mentioning that SLR has been taken into account for both freeboard reduction and variation of water depth. This latter point is very important because, in this coast, many breakwaters of small ports and marinas are located at depths of 5-8 m. Therefore a SLR of 0.88 m or 1.8 m represents an important change in % of their depth. This entails significant changes in wave propagation conditions and therefore of wave height at the structure toe.

In the list in Table 1, two ports are not assigned to any buoy: Roses and Sant Carles de la Ràpita. They have to be analyzed differently since they are both located in bays and are not affected by open sea conditions due to their unique geographical location. In these two ports, wind extreme climate has been obtained using 3-hourly series (1958 to 2001) of forecasted wind data (see Figure 1). Once the extreme probability function has been determined at each port, wind velocities corresponding to the same return periods (1, 5 and 50 years) have been derived. With these velocities and considering the maximum fetches existing in each bay (15 km at Roses and 12.5 km at Sant Carles de la Ràpita), the wave parameters at both ports have been computed using the expressions given in CEM (2002) as a function of fetch and wind velocity.

Once the wave conditions (for the different return periods) are known at each port, the next step is to assess the corresponding overtopping discharge. Due to the large number of ports analyzed, detailed studies carried out with numerical models for each individual port have not been possible. For this reason the analysis in this paper is done using the equations of the Empirical Methods proposed by the European Overtopping Manual (Pullen et al. 2007). For rubble mound structures the equation is:

$$\frac{q}{\sqrt{g H_s^3}} = 0.2 \exp\left(-2.3 \frac{R_C}{\xi H_s \gamma_f \gamma_\beta} \right) \tag{2}$$

where q is the overtopping discharge, H_s the significant wave height, R_C the structure freeboard, γ_f is a correction factor for permeability and roughness and whose value (between 0.43 and 1.0) depends on the type of blocks (rocks, cubes, tetrapods…) and the number of layers of the breakwater, γ_β is a correction factor for oblique wave incidence and ξ is the breaker parameter. γ_β is computed as:

$$\gamma_\beta = 1 - 0.0063|\beta| \tag{3}$$

where β is the angle (in degrees) between the waves and the structure (0º for perpendicular wave incidence), while ξ is calculated as:

$$\xi = \frac{\tan\alpha}{\sqrt{\dfrac{2\pi H_s}{gT_m^2}}} \tag{4}$$

where α is the slope of the structure and T_m the mean wave period.

Some rubble mound breakwaters have berms for dissipating energy and in this case a reduction coefficient C_r is applied to the computed discharge:

$$C_r = 3.06\exp\left(-1.5\frac{G_C}{H_s}\right) \tag{5}$$

where G_C is the berm width.

In the case of vertical walls, before computing the overtopping discharge, the wave regime (impulsive or non-impulsive) has to be defined. An impulsiveness parameter h_* is defined in Pullen et al. (2007):

$$h_* = 1.35\frac{h_s}{H_s}\frac{2\pi h_s}{gT_m^2} \tag{6}$$

where h_s is the water depth at the toe of the structure. When a berm is present at the toe of the wall, a modified impulsiveness parameter d_* is obtained:

$$d_* = 1.35\frac{d}{H_s}\frac{2\pi h_s}{gT_m^2} \tag{7}$$

where d is the water depth above the berm of the structure. Non-impulsive conditions are given when h_* (or d_*) > 0.3, and impulsive ones when h_* (or d_*) < 0.2. If the value of these parameters is between 0.2 and 0.3, the overtopping must be estimated for both regimes and the higher value is assumed.

The equation for overtopping under non-impulsive conditions is:

$$\frac{q}{\sqrt{gH_s^3}} = 0.04\exp\left(-1.8\frac{R_C}{H_s}\right) \tag{8}$$

When non-impulsive conditions prevail, this equation is also used for the calculation of overtopping in composite vertical walls. For vertical walls under impulsive conditions, the following equation is applied:

$$\frac{q}{h_*^2\sqrt{gh_s^3}} = 2.8\times10^{-4}\left(h_*\frac{R_C}{H_s}\right)^{-3.1} \tag{9}$$

This equation is modified in the case of composite vertical walls:

$$\frac{q}{d_*^2\sqrt{gh_s^3}} = 7.8\times10^{-4}\left(d_*\frac{R_C}{H_s}\right)^{-2.6} \tag{10}$$

Information about the breakwater geometrical features was gathered for 43 of the 47 ports existing along the Catalan Coast. With these features, the most suitable equation to compute the overtopping discharge q for each structure was selected from the presented set.

Another important point to be considered for each port to assess its vulnerability to overtopping is the amount of water allowed to pass over the structure. The definition of a tolerable overtopping limit is still an open question due to the high irregularity of this phenomenon and the difficulty in quantifying these flows. Nowadays, many factors must be considered when defining the security of coastal structures and ports. It is obvious that the limit of overtopping in the design of the structure depends on the safety level and the considered risk, always assuming that the highest probability for overtopping occurs under the highest sea level conditions. Guidance on tolerable overtopping discharges was derived from the analysis of overtopping perceived by port engineers to be safe. As a result of further investigations, a series of acceptable levels of overtopping has been collected in the Eurotop Manual (Pullen et al. 2007). These are the acceptable overtopping levels considered in this work, determining the tolerable discharge for each port according to its particular conditions and the activities and assets located at the lee side of the port breakwater (Table 1). To define these values it has been assumed that no activities and no pedestrians are allowed in the exposed areas during storms. The limit of 200 l/s/m is assigned to ports in which there is nothing behind the breakwater, and corresponds to the flow that could damage the structure. The limit of 10 l/s/m is defined when there are small boats berthed at the lee side of the breakwater, while 1 l/s/m is imposed when there are buildings on the dock behind the breakwater; if goods or other equipment are there, this limit is reduced to 0.4 l/s/m.

The employed methodology has limitations that are related to the uncertainty of future projections of SLR and waves as well as to the use of empirical methods to estimate overtopping rates. Further uncertainty is introduced by approximate methods for translating wave height and direction from deep water to the studied domain. As it was mentioned before we used linear theory instead of detailed modelling due to the lack of accurate bathymetries offshore from the harbours. Nevertheless, as most of these uncertainties are unbiased, the results can be considered coherent and with enough accuracy considering that the aim of the paper is to carry out a study at regional scale to illustrate the challenges that Catalan ports will have to face in the near future.

Results and discussion

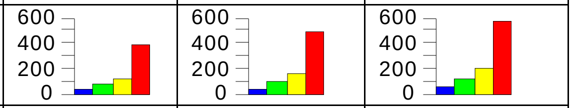
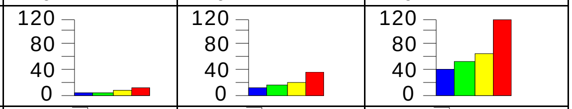
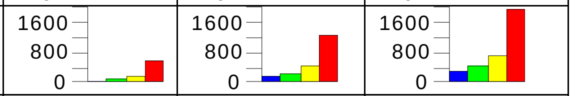
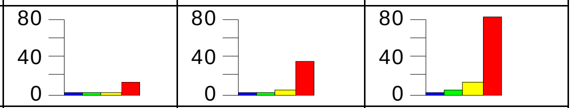
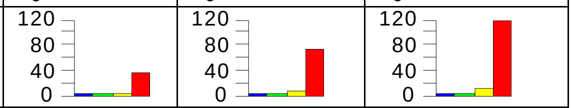
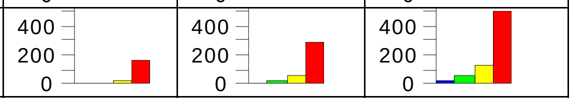
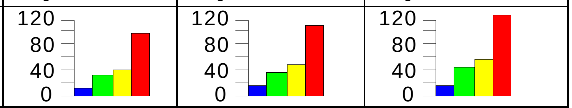
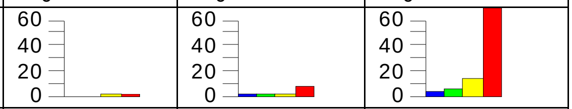
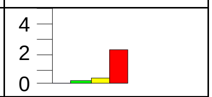
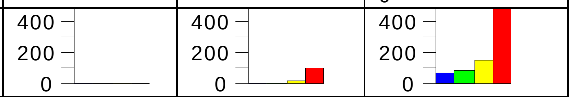
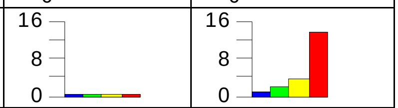
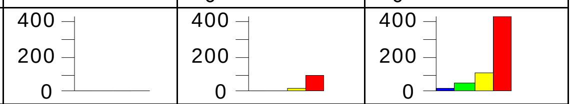
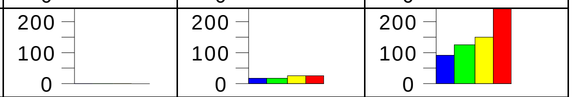
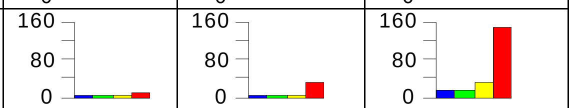
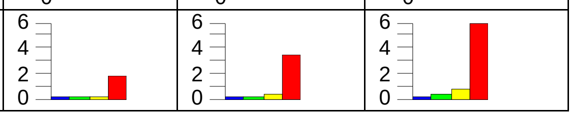
Some of the figures corresponding to the obtained results are presented in a file of Supplementary Material. The computed overtopping discharges have been plotted in Figure 2 for the 3 mentioned return periods (1, 5 and 50 years respectively) and the 4 scenarios studied. In this figure, several ports with large overtopping flows are observed for scenario 0 (present sea level conditions). For frequent storms (T_R = 1 year) three ports have already overtopping discharges exceeding the tolerable levels. Two of these ports (Colera and Port de la Selva) have reported overtopping problems (DPTOP, 2007), while the third (Aiguablava) must remain closed in winter due to the problems generated by storms, including overtopping. If more intense storms are considered (T_R = 5 years), the tolerable overtopping discharge value is exceeded in two other ports (Blanes and Port Olímpic). Both ports have also reported overtopping problems (DPTOP, 2007). If very strong storms are assumed, a total of 10 ports show overtopping flows exceeding the tolerable limit, seven of which (the 5 aforementioned plus Llança and Port Fòrum) have previously reported overtopping problems (DPTOP, 2007). Therefore, in spite of the aforementioned limitations and uncertainties associated to it, the presented methodology works qualitatively well, since it computes excessive overtopping discharges under the present conditions for most of the ports that actually report having overtopping problems.

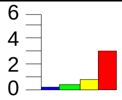
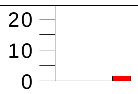
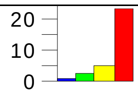
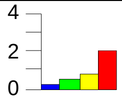
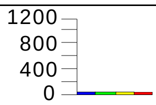
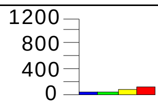
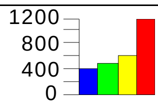
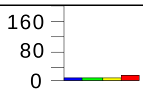
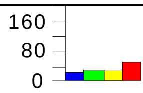
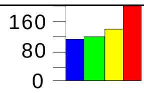
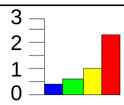
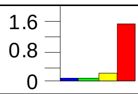
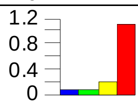
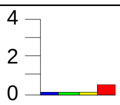
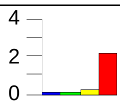
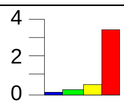
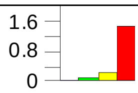
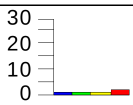
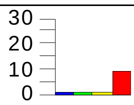
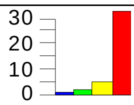
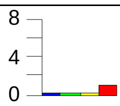
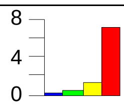
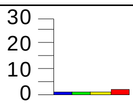
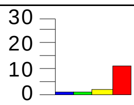
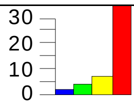
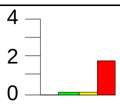
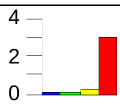
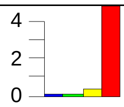
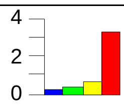
For frequent storms (T_R = 1 year), in the present situation 35 ports (81%) have negligible (< 1 l/s/m) overtopping flows. With a SLR of 47 cm (scenario 1) this number remains unchanged although most ports significantly increase those flows, which in some cases are doubled (Colera and L'Estartit) or even tripled (Aiguablava). A SLR of 88 cm (scenario 2) reduces to 33 (77%) the number of ports with these negligible flows. In this scenario, the rate of increase of the overtopping with respect to scenario 1 is lower than between scenarios 1 and 0 and only 2 ports double the discharges (L'Estartit and Sant Jordi d'Alfama). The high-end scenario 3 reduces to 25 (58%) the number of ports with negligible flows and entails, in 14 cases, increases of the overtopping discharge larger than one order of magnitude with respect to the present situation. For this scenario, the computed overtopping flow in two ports (Colera and Port de la Selva) exceeds 200 l/s/m, that is, the discharge that can start to damage the breakwater. This illustrates the huge impact of scenario 3 on the overtopping process.

For more intense storms (T_R = 5 years), the number of ports with negligible overtopping flows at present (scenario 0) is 32 (74%), which is reduced to 29 (67%) for scenario 1 and 28 (65%) for scenario 2, showing again that changes between scenario 2 and 1 are lower than between scenario 1 and 0. In the case of scenario 3, only 18 ports (42%) have overtopping discharges lower than 1 l/s/m. In 20 ports, the overtopping flow in this scenario 3 is at least one order of magnitude larger than for present conditions. For this type of storms, in one port (Port de la Selva) the value of 200 l/s/m (indicative of potential structural damage) is exceeded in scenario 1 and 2. In scenario 3 this happens in 2 additional ports (Colera and L'Estartit).

In the case of exceptional storms (T_R = 50 years), 25 ports (58%) have presently overtopping flows lower than 1 l/s/m. This amount is reduced to 23 (53%) for scenario 1, 20 (46%) for scenario 2 and 7 (16%) for scenario 3. Therefore, large storms would generate some overtopping discharge in almost all the ports of the Catalan Coast in case of scenario 3. In 28 ports the overtopping estimated for this scenario 3 would be at least one order of magnitude larger than for present conditions.

For this type of storm, in present conditions, 2 ports have overtopping flows greater than 200 l/m/s; both ports also exceed this threshold in scenarios 1 and 2. This shows that, for these large storms and these two scenarios, the overtopping discharge is mainly caused by the high waves rather than the SLR when this is lower than 1 m. In the case of scenario 3, the number of ports that could be damaged by overtopping discharges is 7 (16%), indicating that high-end SLR would significantly increase the volume of water passing over the breakwaters of ports in the Catalan Coast.

Port	Tr = 1 year	Tr = 5 years	Tr = 50 years
Colera			
Llança			
Port de la Selva			
Roses			
Sta. Margarida			
Marina d'Empuriabrava			
L'Estartit			
Aiguablava			
Llafranc			
Marina de Palamós			
Palamós			
Port d'Aro			
Sant Feliu de Guíxols			
Cala Canyelles			
Blanes			
Arenys de Mar			
El Balís			

Mataró			
Premià de Mar			
El Masnou			
Port Fòrum			
Port Olímpic			
Barcelona			
Port Ginesta			
Garraf			
Vallcarca			
Aiguadolç			
Vilanova i la Geltrú			
Segur de Calafell			
Coma-ruga			
Roda de Barà			
Torredembarra			
Tarragona			
Salou			
Cambrils			
Hospitalet de l'Infant			

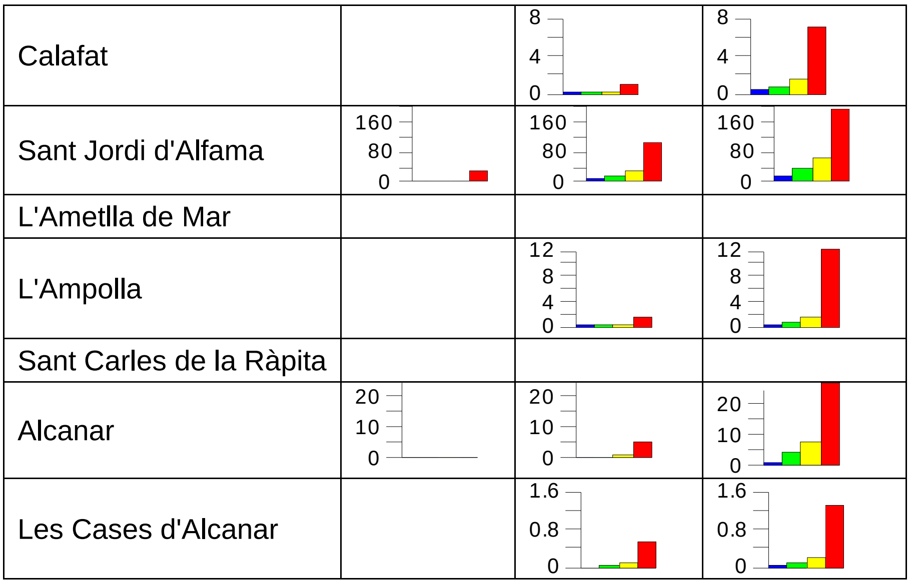


Fig. 2. Overtopping discharges (vertical axis in l/s/m) for the 4 scenarios and the three return periods considered. Blue: scenario 0 (SLR = 0 m), green: scenario 1 (SLR = 0.47 m), yellow: scenario 2 (SLR = 0.88 m), red: scenario 3 (SLR = 1.80 m). The empty boxes indicate that the overtopping discharge is null or negligible (q < 0.4 l/s/m) for the 4 scenarios.

To estimate the vulnerability of Catalan ports to overtopping a qualitative scale of vulnerability with five levels is defined, based on the expected damages caused by a flow q greater than the tolerable discharge q_t. This scale is the following:

- Very low vulnerability, when $q_t < q \leq 1.2\ q_t$. In this case it is assumed that although the tolerable discharge is exceeded, there is no damage.
- Low vulnerability, when $1.2q_t < q \leq 2\ q_t$. The level of damage is negligible.
- Medium vulnerability, when $2q_t < q \leq 5\ q_t$. Within this range damage is appreciable.
- High vulnerability, when $5q_t < q \leq 10\ q_t$. The level of damage is significative.
- Very high vulnerability, when $q > 10\ q_t$. Damage to the port is very large.

Figure 3 shows vulnerability maps corresponding to storms with T_R of 1 and 50 years and for scenarios 0 and 3. The remaining scenarios and the results for a T_R of 5 years are included in the Supplementary Material (Figures SM1 to SM4). It is evident that, for the three return periods, the SLR scenarios increase the number of vulnerable ports or the level of vulnerability, as it could be expected. Table 3 summarizes for each scenario and return period the total number of vulnerable ports and the number of ports with a high or very high level of vulnerability.

For frequent storms (T_R = 1 year) the number of vulnerable ports is low in the present conditions and scenarios 1 and 2. For scenario 3 there is a noticeable increase of the total number of vulnerable ports (19%) and those with a high or very high level of vulnerability (12%).

For more intense storms (T_R = 5 years) the number of ports with high or very high vulnerability to overtopping is very similar to that of frequent storms. However the total number of vulnerable ports is significantly greater for all the scenarios, reaching 26% in the case of scenario 3.

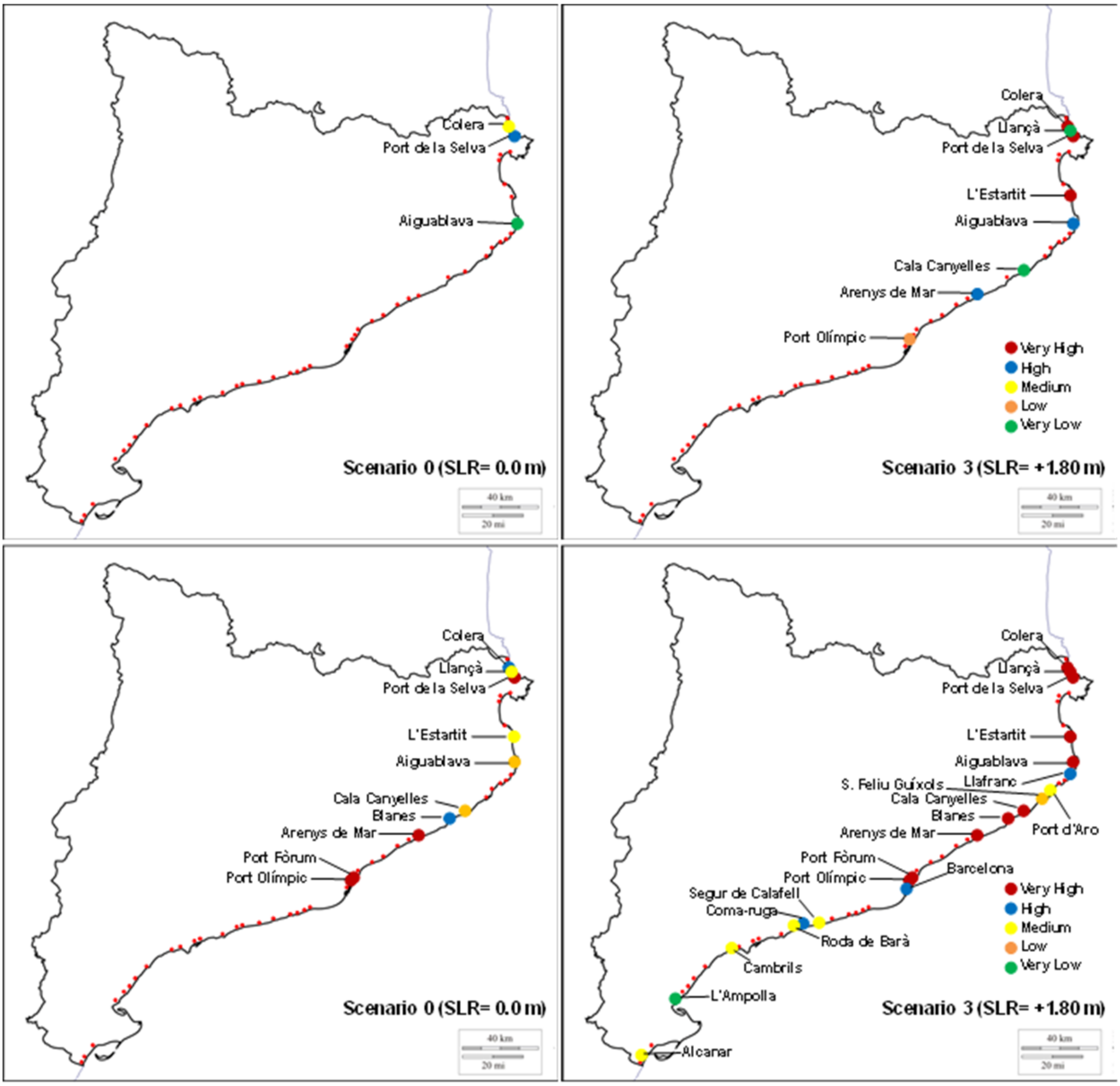


Fig. 3. Upper panels: Overtopping vulnerability maps for a return period of 1 year (Left: scenario 0. Right: scenario 3). Lower panels: Overtopping vulnerability maps for a return period of 50 years (Left: scenario 0. Right: scenario 3).

Finally, for exceptional storms (T_R = 50 years), the number of ports with high or very high vulnerability increases with the SLR, reaching 13 (30%) for scenario 3. The total vulnerable ports also increase with SLR, but between scenarios 2 and 3 there is a huge variation and the number of ports affected by overtopping is 20 (47%).

Table 3. Number of ports vulnerable to overtopping (Total), and number of them with a high or very high level of vulnerability (HV)

Return Period	SCENARIO 0		SCENARIO 1		SCENARIO 2		SCENARIO 3	
	HV	Total	HV	Total	HV	Total	HV	Total
1 year	1	3	2	4	2	4	5	8
5 years	1	5	2	8	3	9	5	11
50 years	6	10	9	11	10	13	13	20

Table 3. Number of ports vulnerable to overtopping (Total), and number of them with a high or very high level of vulnerability (HV)

Observing the vulnerability maps (Figures 3 and SM1 to SM4) it is clear that the ports with overtopping problems both at present or in the future for all the scenarios considered are concentrated in the northern half of the Catalan Coast, while those located at the south only show vulnerability to overtopping under the worst scenario, and even then only a few ports become affected. This is due to the larger values of H_s given by the two northernmost buoys as compared to the two buoys further south, because the overtopping discharge is proportional to $H_s^{3/2}$. Another remarkable feature of the vulnerability patterns for all the storm levels is that differences between scenarios 1 and 2 are minimal.

.

Summary and conclusions

The main objective of this paper is to analyse how SLR due to climate change can affect port overtopping, focusing on 43 harbours (from the 47 existing in this region) located on the Catalan Coast (NW Mediterranean). Four are not studied due to lack of data (in particular, detailed breakwater sections). The potential variation of wave climate (wave height and directions) has not been considered, but recent studies suggest that these changes will be of limited magnitude (Casas-Prat and Sierra 2013).

The study considers the present situation and three scenarios of SLR, two of them based on AR5 projections. The third corresponds to a high-end scenario, which is physically feasible although with a low probability of occurrence. Present data from 4 buoys located along the coast are taken into account for the study and only the effect of SLR is considered (including subsidence where it is relevant), i.e. the same wave climate is assumed for all the scenarios. The overtopping discharges are computed using empirical expressions from the Eurotop Manual (Pullen et al. 2007). From the comparison of present and future discharges for each scenario, the variation of overtopping flow can be estimated, which serves to assess the potential changes due to SLR.

Besides the different scenarios considered, the study is performed for three levels of storminess corresponding to frequent (T_R = 1 year), more intense (T_R = 5 years) and exceptional (T_R = 50 years) storms. In addition, a qualitative vulnerability index is defined as a function of the excess of overtopping flow computed versus the tolerable discharge, which in turn depends on the type of activity performed at the lee side of the breakwater.

The employed methodology has limitations that include the uncertainty of future projections of SLR and waves, the use of empirical methods to estimate overtopping rates and the use of linear theory for translating wave height and direction from deep water to the studied structures. The use of linear theory instead of detailed modelling is due to the lack of accurate bathymetries offshore from the harbours and the large number of ports studied, which also prevents the use of sophisticated numerical models to assess the overtopping discharge. Nevertheless, as most of these uncertainties are unbiased, the results can be considered coherent and with enough accuracy for the aim of the paper, which is to perform a study at a regional scale. The suitability of the followed approach is illustrated by the results obtained for the present situation, since most of the ports that have actually reported overtopping problems show excessive overtopping discharges when applying this methodology.

Under present conditions 5 ports have overtopping problems for strong storms (T_R = 5 years) and 10 in the case of exceptional storms (T_R = 50 years), which corresponds with the observed situation. Considering the different scenarios, it is obvious that SLR increases the vulnerability of Catalan ports to overtopping. However, differences between scenario 1 and 2 are small in number of ports affected, although obviously the overtopping discharge increases rather significantly. The high-end scenario 3 greatly increases the overtopping flows and increases by a factor of 2 or larger (depending on the return period) the number of vulnerable ports with respect to the present situation. For medium intensity storms, 13 (30%) ports are vulnerable, and for exceptional storms the number of vulnerable ports rises to 20 (47%). In this scenario the number of port breakwaters that could be damaged by overtopping discharges is 7 (16%).

Another conclusion of this work is that the ports with overtopping problems for all the scenarios considered are concentrated in the northern half of the Catalan Coast, due to the higher waves recorded by the buoys located there.

In summary, the most probable scenarios of SLR (scenarios 1 and 2, based on AR5 projections) would increase overtopping discharges in most of the Catalan ports and the number of vulnerable ports would grow in several units, in particular for medium intensity storms affecting the port operability and potentially leading to serious management problems. In the case of the unlikely scenario 3, the situation would worsen significantly.

The results of this study could be extended to other regions with similar climate, ports and morphology. The port community needs therefore to be aware of this potential problem that increases port risks and can lead to huge adaptation costs. The future exposure of ports to SLR emphasizes the need of considering climate change into long-term port management and planning. However, further studies are needed in this regard, trying to reduce the uncertainty, for example, by using more accurate numerical models.

Acknowledgements

The work described in this publication was funded by the European Union's Seventh Framework Programme through the grant to the budget of the Collaborative Project RISES-AM-, Contract FP7-ENV-2013-two-stage-603396. The support of the Secretaria d'Universitats i Recerca del Dpt. d'Economia i Coneixement de la Generalitat de Catalunya (Ref 2014SGR1253) is also acknowledged.

Finally, the authors are grateful to the Organismo Público Puertos del Estado (Spanish Ports and Harbors Authority) for providing wave data.

References

Becker A, Inoue S, Fisher N, Schwegler B (2012) Climate change impact on international seaports: knowledge, perceptions, and planning efforts among port administrators. Clim Change 110:5-29. doi: 10.1007/s10584-011-0043-7

Bolaños R, Sanchez-Arcilla A, Cateura J (2007) Evaluation of two atmospheric models for wind–wave modelling in the NW Mediterranean. J Marine Syst 65:336-353. doi:10.1016/j.jmarsys.2005.09.014

Burcharth HF, Andersen TL, Lara JL (2014) Upgrade of coastal defence structures against increased loadings caused by climate change: A first methodological approach. Coast Eng 87:112-121. doi: 10.1016/j.coastaleng.2013.12.006

Campins J, Genovés A, Picornell MA, Jansà A (2011) Climatology of Mediterranean cyclones using the ERA-40 dataset. Int J Climatol 31:1596-1614. doi: 10.1002/joc.2183

Casas-Prat M, Sierra JP (2010) Trend analysis of wave storminess: wave direction and its impact on harbour agitation. Nat Hazard Earth Syst Sci 10:2327–2340. doi:10.5194/nhess-10-2327-2010

Casas-Prat M, Sierra JP (2012) Trend analysis of wave direction and associated impacts on the Catalan coast. Clim Change 115:667–691. doi: 10.1007/s10584-012-0466-9

Casas-Prat M, Sierra JP (2013) Projected future wave climate in the NW Mediterranean Sea. J Geophys Res Oceans 118:3548-3568. doi:10.1002/jgrc.20233

CEM (2002) Meteorology and wave climate. In Coastal Engineering Manual, Part II Chaper 2, US Army Corps of Engineers

Chini N, Stansby PK (2012) Extreme values of coastal wave overtopping accounting for climate change and sea level rise. Coast Eng 65:27-37. doi:10.1016/j.coastaleng.2012.02.009

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS (2013) Sea level change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working Group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York NY, USA

DPTOP (2007) Pla de Ports de Catalunya. Departament de Política Territorial i Obres Públiques, Generalitat de Catalunya

Gámez D, Simó JA, Vázquez-Suñé E., Salvany JM, Carrera J (2005) Variaciones de las tasas de sedimentación en el complejo detrítico superior del Delta del Llobregat (Barcelona): su relación con causas eustáticas, climáticas y antrópicas. Geogaceta 38:175-178

Goda Y (2007) How much do we know about wave breaking in the nearshore waters. Proc. of Asian and Pacific Coasts 2007, pp. 65-86.

Hallegatte S, Ranger N, Mestre O, Dumas P, Corfee-Morlot J, Herweijer C, Wood RM (2011) Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. Clim Change 104:113-137. doi: 10.1007/s10584-010-9978-3

Hinkel J, Jaeger C, Nicholls RJ, Lowe J, Renn O, Peijun S (2015) Sea-level risk scenarios and coastal risk management. Nat Clim Change 5:188-190

Isobe M (2013) Impact of global warming on coastal structures in shallow water. Ocean Eng 71:51-57. doi: 10.1016/j.oceaneng.2012.12.032

Jevrejeva S, Grinsted A, Moore JC (2014). Upper limit for sea level projections by 2100. Environ Res Lett 9, doi:10.1088/1748-9326/9/10/104008

Jevrejeva S, Moore JC, Grinsted A (2012) Sea level projections to AD2500 with a new generation of climate change scenarios. Glob Planet Change 80–81:14–20. doi:10.1016/j.gloplacha.2011.09.006

Kane HH, Fletcher CH, Frazer LN, Barbee MM (2015) Critical elevation levels for flooding due to sea-level rise in Hawaii. Reg Environ Change. doi: 10.1007/s10113-014-0725-6

Lee C-E, Kim S-W, Park D-H, Suh K-D (2013) Risk assessment of wave run-up height and armor stability of inclined coastal structures subject to long-term sea level rise. Ocean Eng 71:130-136. doi: 10.1016/j.oceaneng.2012.12.035

Liberti L, Carillo A, Sannino G (2013) Wave energy resource assessment in the Mediterranean, the Italian Perspective. Renew Energy 50:938-949. doi: 10.1016/j.renene.2012.08.023

Lionello P, Dalan F, Dalan F, Elvini E (2002) Cyclones in the Mediterranean region: The present and the doubled CO2 climate scenarios. Clim Res 22:147-159

Lionello P, Malanotte-Rizzoli P, Boscolo R (2006) Mediterranean Climate Variability, Elsevier, Amsterdam

Martínez-Asensio A, Marcos M, Jordà G, Gomis D (2013) Calibration of a new wind-wave hindcast in the Western Mediterranean. J Marine Syst 121-122:1-10. doi: 10.1016/j.jmarsys.2013.04.006

Mase H, Tsujio D, Yasuda T, Mori N (2013) Stability analysis of composite breakwater with wave-dissipating blocks considering increase in sea levels, surges and waves due to climate change. Ocean Eng 71:58-65. doi: 10.1016/j.oceaneng.2012.12.037

Mentaschi L, Bessio G, Cassola F, Mazzino A (2015) Performance evaluation of Wavewatch III in the Mediterranean Sea. Ocean Model 90:82-94. doi: 10.1016/j.ocemod.2015.04.003

Monioudi IN, Karditsa A, Chatzipavlis A, Alexandrakis G, Andreadis OP, Velegrakis AF, Poulos SE, Ghionis G, Petrakis S, Sifnioti D, Hasiotis T, Lipakis M, Kampanis N, Karambas T, Marinos E (2015) Assessment of vulnerability of the eastern Cretan beaches (Greece) to sea level rise. Reg Environ Change. doi: 10.1007/s10113-014-0730-9

Mori N, Shimura T, Yasuda T, Mase H (2013) Multi-model climate projections of ocean surface variables under different climate scenarios—future change of waves, sea level and wind. Ocean Eng 71:122-129. doi: 10.1016/j.oceaneng.2013.02.016

Nissen KM, Leckebusch GC, Pinto JG, Renggli D, Ulbrich S, Ulbrich U (2010) Cyclones causing wind storms in the Mediterranean: characteristics, trends and links to large-scale patterns. Nat Hazard Earth Syst Sci 10:1379–1391. doi:10.5194/nhess-10-1379-2010

Paudel Y, Botzen WJW, Aerts JCJH (2015) Influence of climate change and socio-economic development on catastrophe insurance: a case study of flood risk scenarios in the Netherlands. Reg Environ Change. doi: 10.1007/s10113-014-0736-3

PPEE (2012) Extremos máximos de oleaje (altura significante). Boya de Palamos. Banco Oceanográfico de Puertos del Estado, Madrid

PPEE (2013a) Extremos máximos de oleaje (altura significante). Boya de Begur. Banco Oceanográfico de Puertos del Estado, Madrid

PPEE (2013b) Extremos máximos de oleaje (altura significante). Boya de Barcelona. Banco Oceanográfico de Puertos del Estado, Madrid

PPEE (2013c) Extremos máximos de oleaje (altura significante). Boya de Tarragona. Banco Oceanográfico de Puertos del Estado, Madrid

Pros Llavador F, Gonzalez López S, Martínez-Benjamín JJ (2013) Control de asentamiento de los diques Este y Sur del Puerto de Barcelona mediante datos InSAR. Proc. XV Congreso de la Asociación Española de Teledetección, Torrejón de Ardoz (Madrid) 4p

Pullen T, Allsop NWH, Bruce T, Kortenhaus A, Scüttrumpf H, van der Meer JW (2007) EurOtop wave overtopping of sea defences and related structures—assessment manual. Kuratorium für Forschung in Küsteningenieurwesen, Heide, Germany
Ratsimandresy AW, Sotillo MG, Carretero Albiach JC, Álvarez Fanjul E, Hajji H (2008) A 44-year high-resolution ocean and atmospheric hindcast for the Mediterranean Basin developed within the HIPOCAS Project. Coast Eng 55:827-842. doi: 10.1016/j.coastaleng.2008.02.025
Revell DL, Battalio R, Spear B, Ruggiero P, Vandever J (2011) A methodology for predicting future coastal hazards due to sea level rise on the California Coast. Clim Change 109:251–276. doi 10.1007/s10584-011-0315-2
Reynolds MH, Berkowits P, Coutrot KN, Krause CM (eds) (2012) Predicting sea-level rise vulnerability of terrestrial habit and wildlife of the Northwestern Hawaiian Islands. U.S. Geological Survey Open-File Report 2012-1182
Sánchez-Arcilla A, González-Marco D, Bolaños R (2008) A review of wave climate and prediction along the Spanish Mediterranean coast. Nat Hazard Earth Syst Sci 8: 1217–1228. doi:10.5194/nhess-8-1217-2008
Sánchez-Arcilla A, Mösso C, Sierra JP, Mestres M, Harzallah A, Senouci M, El Raey M (2011) Climate drivers of potential hazards in Mediterranean coasts. Reg Environ Change 11:617–636. doi: 10.1007/s10113-010-0193-6
Sierra JP, Casas-Prat M (2014) Analysis of potential impacts on coastal areas due to changes in wave conditions. Clim Change 124:861-876. doi 10.1007/s10584-014-1120-5
Sierra JP, Casas-Prat M, Virgili M, Mösso C, Sánchez-Arcilla A (2015) Impacts on wave-driven harbour agitation due to climate change in Catalan ports. Nat Hazards Earth Syst Sci 15:1695-1709. doi:10.5194/nhess-15-1695-2015
Somoza L, Barnolas A, Arasa A, Maestro A, Rees JG, Fernández-Molina FJ (1998) Architectural stacking patterns of the Ebro delta controlled by Holocene high-frequency eustatic fluctuations, delta-lobe switching and subsidence processes. Sediment Geol 117:11-32
Suh K-D, Kim S-W, Kim S, Cheon S (2013) Effects of climate change on stability of caisson breakwaters in different water depths. Ocean Eng 71:103-112. doi: 10.1016/j.oceaneng.2013.02.017
Takagi H, Kashihara H, Esteban M, Shibayama T (2011) Assessment of future stability of breakwaters under climate change. Coast Eng J 53:21-39. doi: 10.1142/S0578563411002264
Torresan S, Critto A, Rizzi J, Marcomini A (2012) Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. Nat Hazards Earth Syst Sci 12:2347–2368. doi:10.5194/nhess-12-2347-2012

Supplementary material

This Supplementary material file includes four additional figures. The results shown in these figures are discussed in the paper.

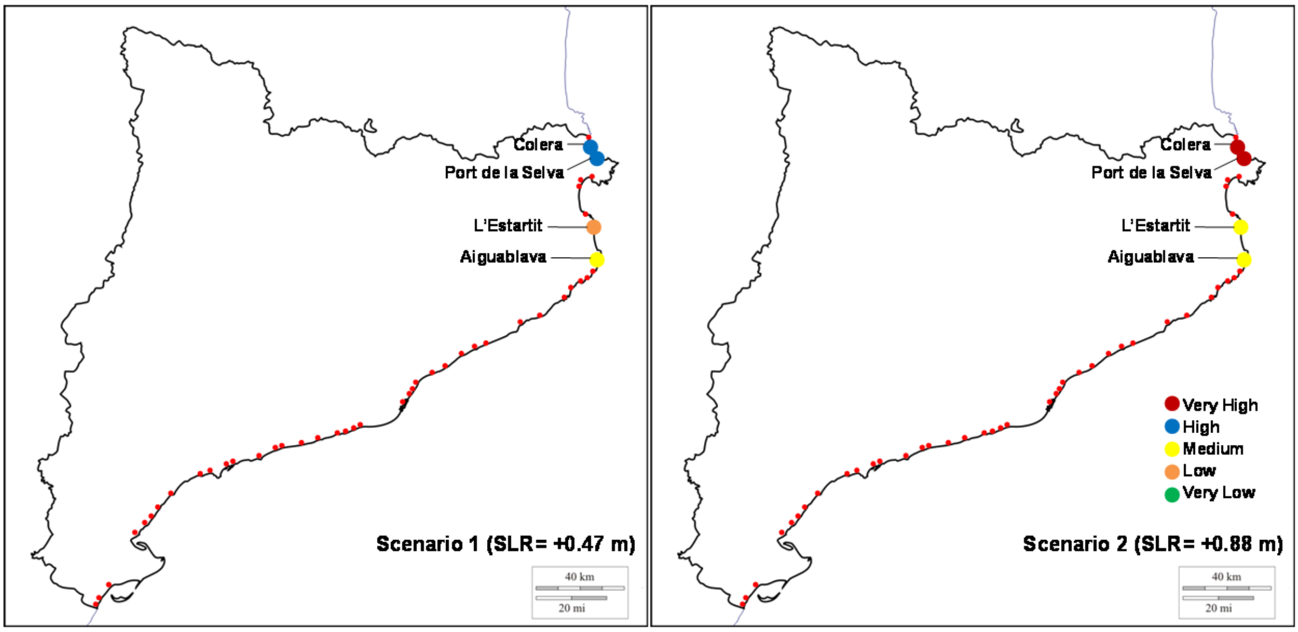


Fig. SM1. Overtopping vulnerability maps for scenarios 1 and 2 and for a return period of 1 year.

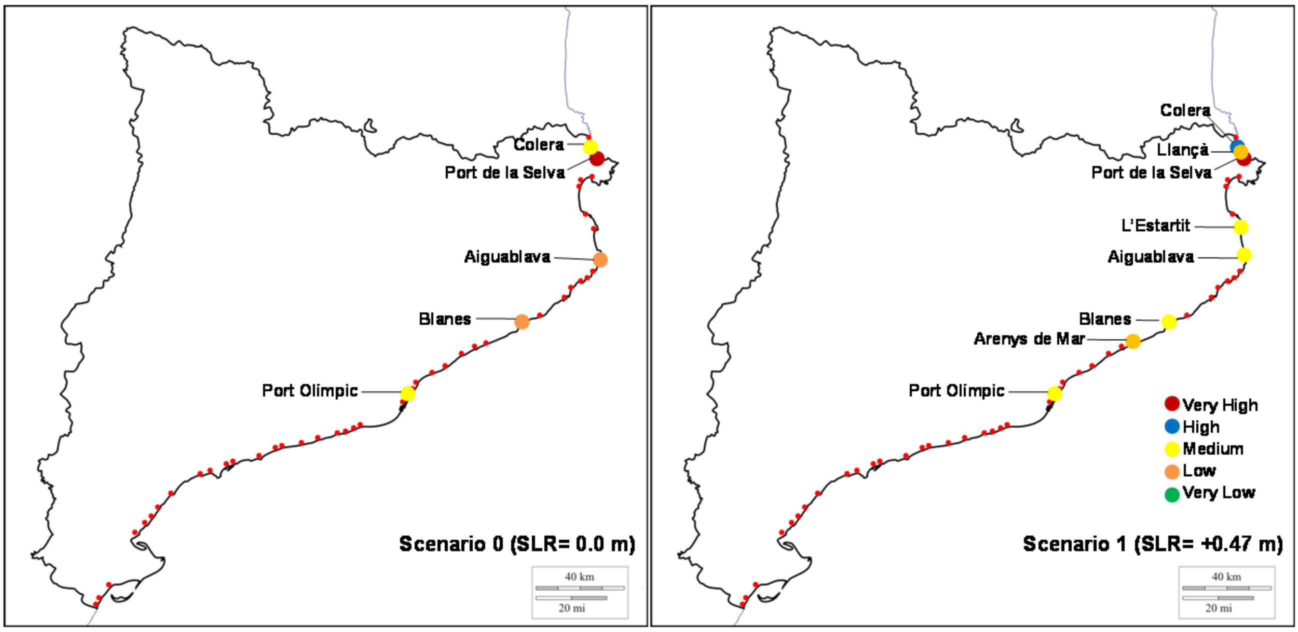


Fig. SM2. Overtopping vulnerability maps for scenarios 0 and 1 and for a return period of 5 years.

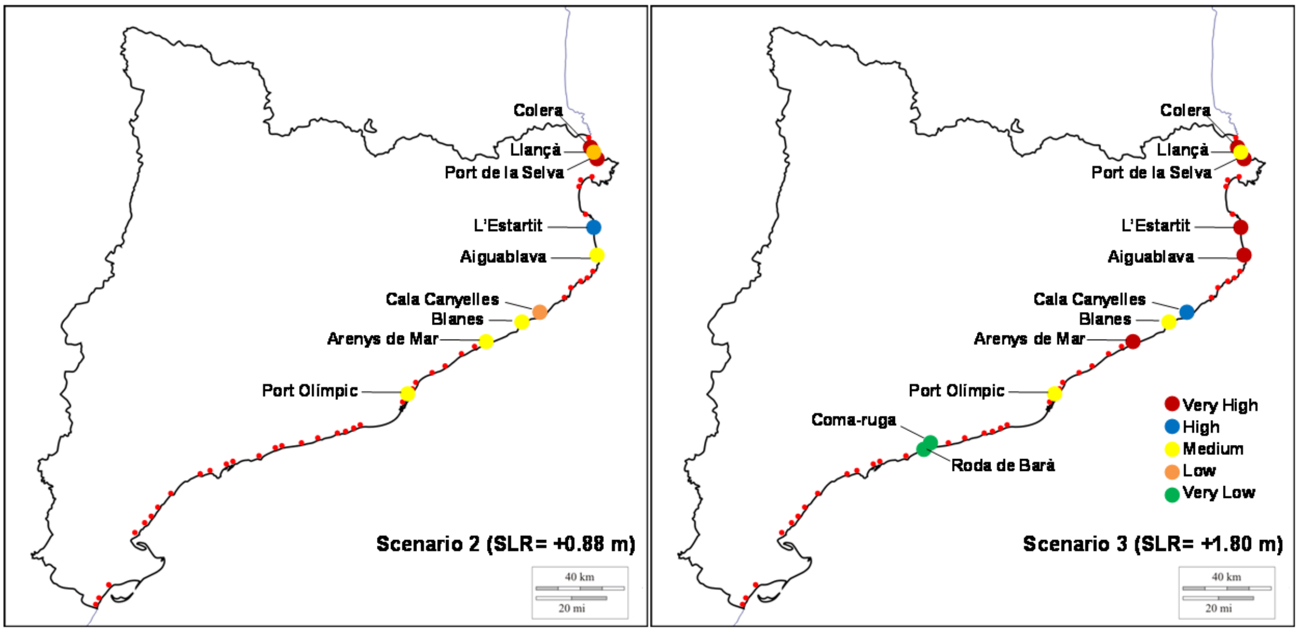


Fig. SM3. Overtopping vulnerability maps for scenarios 2 and 3 and for a return period of 5 years.

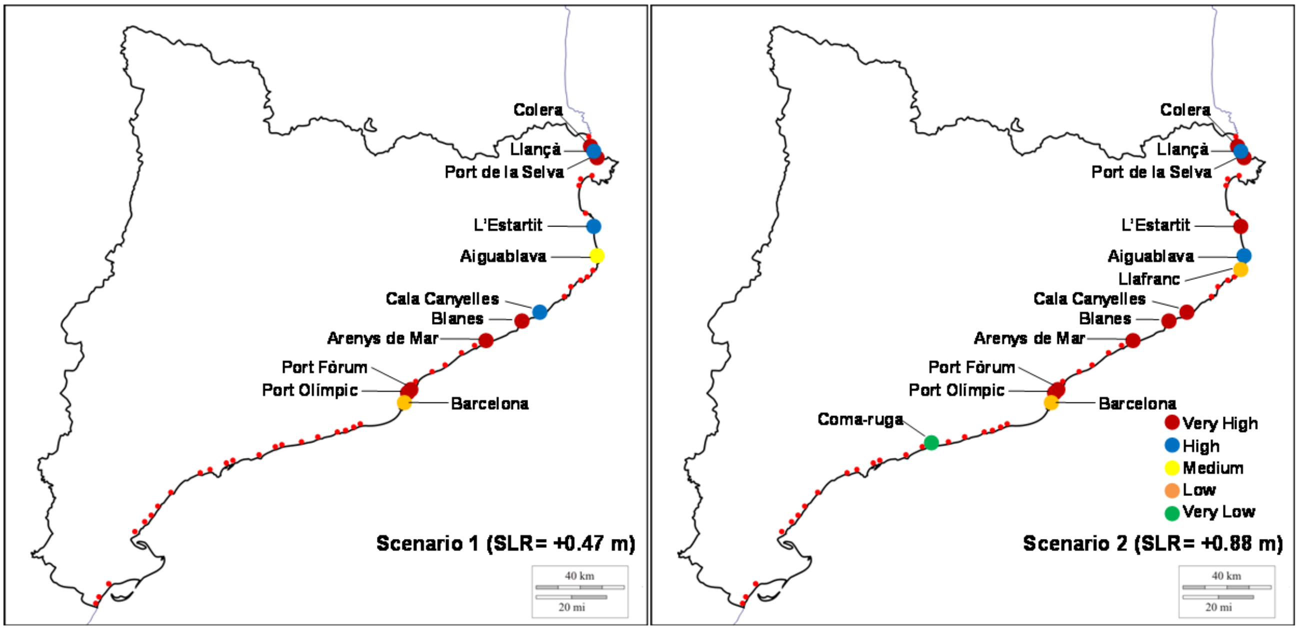


Fig. SM4. Overtopping vulnerability maps for scenarios 1 and 2 and for a return period of 50 years.