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COASTAL PROTECTION

Coastal defence techniques and climate change: a review

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Abstract
Coastal areas are characterized by a high level of risk because of its intrinsic vulnerability to the sea action and the high number of socio-economic activities as well as of marine habitats. Traditional methodologies for the design of coastal defences cannot be applied straightforward in the presence of the effects of climate change because of the need to take into account the non-stationarity of natural processes. A novel approach based on an integrated coastal zone management is required to counteract the main consequences of global warming effects in coastal areas (i.e. sea level rise and the increase in frequency and magnitude of extreme events). In particular, besides institutional measures and preparedness and prevention actions, also structural intervention should be implemented. First of all, the upgrade of existing coastal defence structures should be considered, where this strategy is technically and economically feasible. In addition, it is suggested the realisation of Nature-Based Solutions, which consist on using natural processes to create a resilient system. Finally, the integration of traditional and innovative techniques for the design of coastal defences to realise resilient or, even better, antifragile systems is the most preferable approach. Indeed, perfect knowledge of future conditions is not needed for the design of antifragile systems, since this kind of structures are able to improve themselves when hit by unexpected events.

Keywords Global warming · Coastal risk · Structure upgrade · Nature-Based Solution · Antifragility

1 Introduction

Coastal zones are highly populated and, consequently, a huge number of economic activities linked to the presence of harbours, industries and communication infrastructures are located there. Indeed, 41% of the European population live in areas close to the sea (European Environment Agency 2015).

In addition, it is important to point out the countless marine ecosystems which live in coastal zones being composed of many kinds of unique species.

The economic, social and environmental relevance of coastal areas, together with the fragility of coastal natural processes, leads to the need to carry out studies to acquire all the necessary information to protect such regions against coastal risk.

In general, coastal risk is defined as the probability that a certain phenomenon, of natural or anthropogenic origin, exceeds a fixed threshold, causing loss of human lives, properties and productive capacity. It follows that a potential hazardous event becomes a risk only when it directly interacts with an exposed good. Considering such a definition, the reason of the high level of risk of coastal areas is clearly a consequence of the intrinsic vulnerability to the sea actions as coastal flooding, erosion and the exposure of numerous socio-economic activities and marine habitats.

As regards coastal flooding, there are many Italian examples of territories affected by this stress, such as the lagoon of Venice (Favaretto et al. 2019) or the South-East of Sicily (Iuppa et al. 2019). For instance, Fig. 1 shows the recent coastal flood of the 29th October 2018 in Venice (northern

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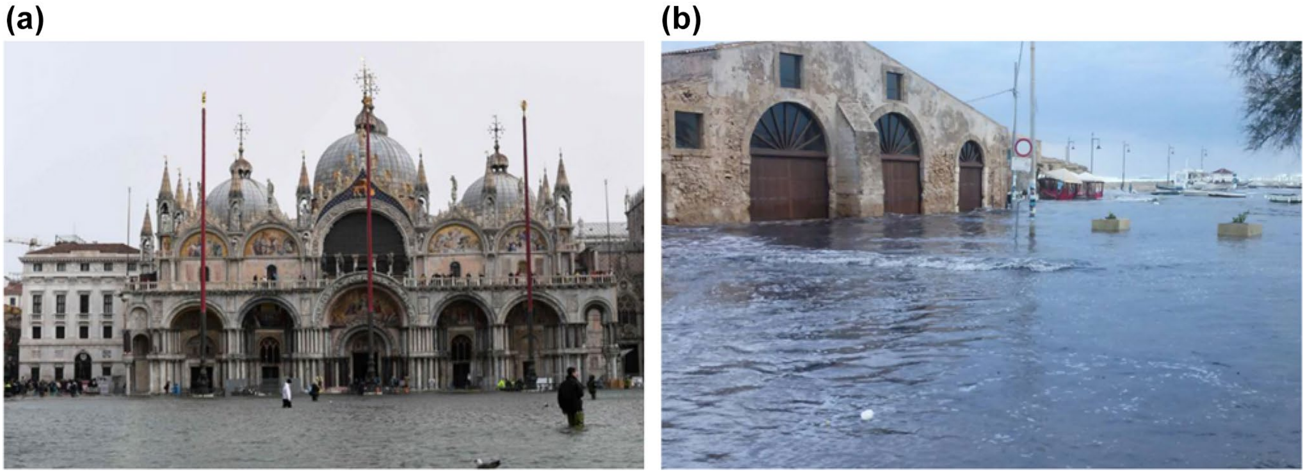

Fig. 1 Coastal flooding in: **a** Venice (Italy), 29th October 2018; **b** Marzamemi (Syracuse, Italy) 28th September 2018

Italy) and the event of the 28th September 2018 in Marzamemi (Southern Italy).

The risk related to coastal flooding is enhanced by the effects of climate change, which intensify the non-stationary component in natural processes and produce an increase of intensity and frequency of extreme events (Arns et al. 2017; Chini et al. 2010; Vousdoukas et al. 2016, 2018). In addition to this, coastal erosion phenomena involve the destruction of the first line of defence of coastal regions during storms, which directly hit buildings, roads, railways and other infrastructures (Fig. 2b, c).

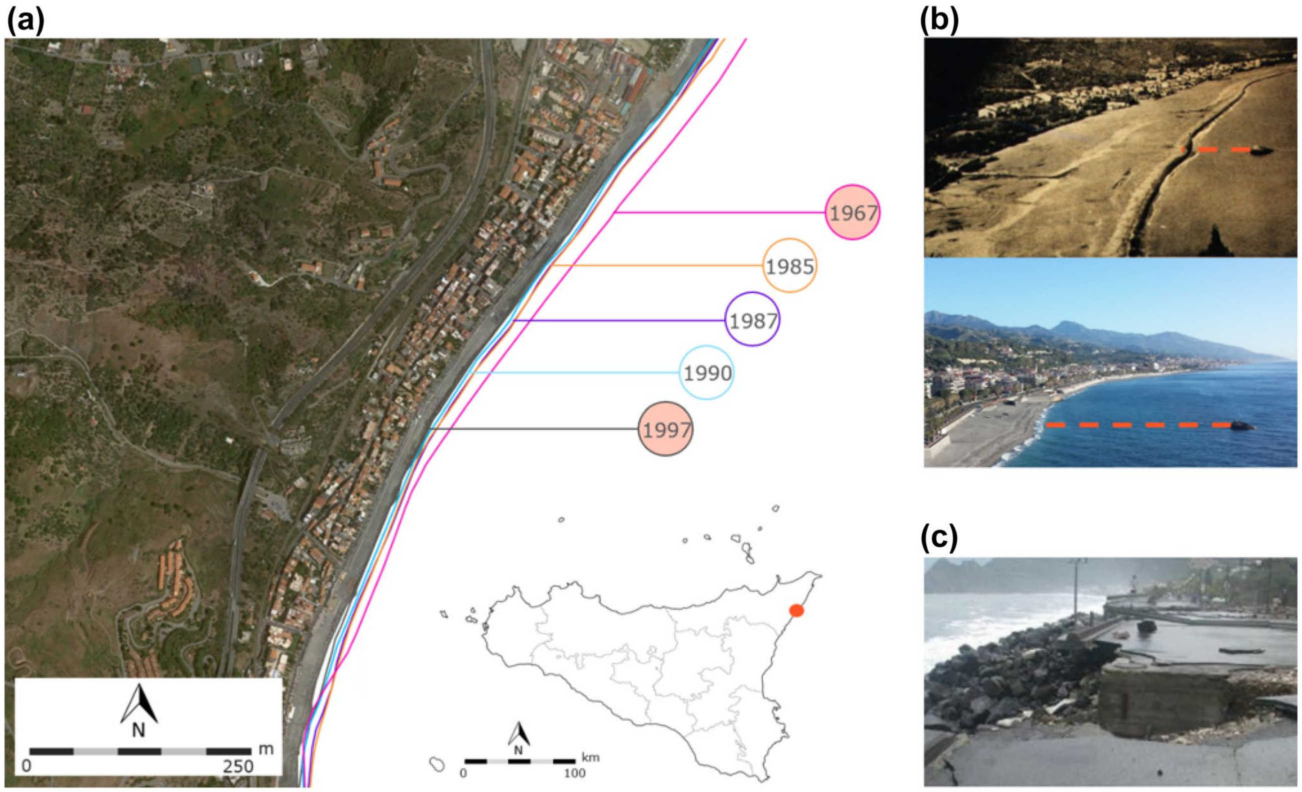

Fig. 2 Sant'Alessio Siculo (Messina, Sicily, Italy): **a** shoreline evolution between 1967 and 1997 (data courtesy of SIGMA INGEGNERIA s.r.l); **b** example of the effects of coastal erosion between the years 1900 and 2017; **c** destructive effect of a storm surge occurred in 2003 in the absence of the first line of defence (i.e. the beach)

Coastal erosion is the result of human activities and natural environment changes unbalancing the effects of the coastal dynamic action (i.e. waves, currents, wind) and causing the long-term loss of sediments in the coastal zone, resulting in coastline retreat and beach erosion (van Rijn 2011). The anthropogenic activities that have impacts on coastal erosion are essentially linked to urbanization and consequent land use changes in coastal areas, water resource projects, sand mining and navigation and shore-protective works (Magoon et al. 2001). As regards urbanization in coastal areas, the construction of buildings, streets, railways and in general paved zones prevents land surface erosion during storms and causes the decrease of the quantity of sediments that can reach the beach and thus restore it positively contributing to the sediment balance of the stretch of coast. In addition to this, waterways layout structures produce the weakening of the rivers erosive processes and the entrapment of huge amounts of sediments. In particular, interventions such as river bottom and bank revetments prevent erosion of the river sediments to stabilise the riverbed. Instead, dams constructed for energy generation, irrigation or potable water supply stop the run of the river sediments towards the beach acting as barriers. It is worth to point out that these entrapped sediments may be contaminated and thus a complex procedure must be followed to employ them for beach artificial nourishments. Moreover, erosion downstream of the dam is weakened or even avoided, because of the reduction of the peak stream flow velocities. The mining of sand from beaches, offshore areas, dunes and rivers and streams, mainly for building material procurement, is another human activity that directly impacts the beach sediment balance. In recent years, the awareness of the need to stop this dangerous practice has led to the definition of several regulations all over the world. For instance, as regards beach sand mining, the Italian Court of Cassation has recently issued a sentence according to which the removal of sand from beaches is considered grand theft (sent. n. 11158/2019). Finally, the construction of harbours and coastal defence structures can generate imbalance to the sediment movement along the beaches. Indeed, harbour elements act as obstacles to the long-shore sediment transport. Regarding rigid coastal defence structures, they can harden the beach, impeding its natural restoration. Furthermore, even if the stretch of coast of interest benefits from the rigid defence structure, near beaches can be damaged by the resulting change in long-shore sediment transport.

Considering the effects of erosive phenomena, they produce damage not only, as showed, by enhancing flooding phenomena, but also to marine ecosystems as well as economic activities, especially those linked to tourism. For this reason, the Italian coastlines are very vulnerable. An investigation carried out by Regione Lazio, Eurobuilding S.r.l., and Nomisma in 2005 provided an estimate of the economic value of the beach of about 1200 €/m^2, considering revenues due to seaside activities. For instance, the Italian coastal town of Sant’Alessio Siculo (Fig. 2a) lost about 95,000 m^2 of beach in the period 1967–1997, with a potential consequent economic loss of about 114,000,000 €. A study carried out by the Italian Ministry of Environment, Land and Sea Protection (in Italian Ministero dell’Ambiente e della Tutela del Territorio e del Mare) in 2017 showed an upward trend of the mean annual retreat of Italian beach (see Table 1). An exception to this trend is the region Emilia-Romagna, which testifies that an appropriate management of coastal zones can effectively reduce erosive phenomena.

Numerous coastal defence structures have been constructed all over the world to act as mitigation measures against flooding and erosion risk. However, as already mentioned, past coastal defence interventions have often been planned not considering the negative effects that such measures could produce on the stretches of coast near to the zone of interest and neglecting the hardening of the latter. Furthermore, the design approach traditionally used seems not to be appropriate in the presence of the effects of climate change; therefore, new strategies are required.

The present work presents a short description of the traditional methodology applied for the design of coastal defences, stressing its inappropriateness in the presence of the effects of global warming. Then, a brief analysis of global warming effects on coast is presented. Subsequently, a novel approach based on an integrated coastal zone management is proposed, focusing on upgrading existing coastal defence structures, implementing resilient measures and, if possible, antifragile coastal systems.

Table 1 Coastal erosion in different Italian regions. Shoreline variation between 1960 and 2012—data elaborated from Italian Ministry of Environment and Land and Sea Protection. Update (March 2017)

Annual mean shoreline retreat in terms of length of coast stretches (km/year)	Veneto	Sicilia	Toscana	Puglia	Calabria	Emilia-Romagna
1960–1994	2.0	9.8	2.3	3.0	8.6	2.0
1994–2012	2.5	10.9	3.6	3.7	12.7	1.1

2 Coastal defences: traditional design method

To counteract the erosion of the beaches and to protect coastal areas from marine flooding, two types of defence structures were traditionally built: passive and active defences. Passive coastal defences ensure a simple protection of the coastal zone. Interventions of coastal protection that fall under this category are coastal revetments. On the other hand, active coastal defences not only attenuate the energy of incident wave motion, but also produce a local advancement of the shoreline. Emerged or submerged breakwaters and groins are typical examples of active structures (Fig. 3). Beach nourishments are usually considered as soft active interventions, since the short-term effect of adding large quantities of sand or sediment to beaches is the advancement of the shoreline. However, the erosive process is not significantly reduced, thus the increase of the beach width is only temporary. To limit the periodic maintenance interventions of an artificial beach nourishment and the loss of sediments, the deposits of materials can be combined with containment works, both adherent and detached, both parallel and orthogonal to the shoreline to protect beach nourishments, such as submerged reef and groins.

In the past, coastal defence was usually planned not considering the physiography of the study area and the relationship with near stretches of coast. This approach mainly led to the construction of hard coastal defence structures, which modified the natural long-shore sediment transport at the expense of the near shores, which lost their natural capability to restore themselves. Furthermore, the study area itself was often damaged by such hard intervention that eliminated the possibility of natural advancement of the beach.

As regards the design approach, all the coastal defences described above are usually designed following a traditional methodology based on the statistical analysis of historical met-ocean data, i.e. direct measures of wave height and period, speed and direction of currents and winds at the interest site. In particular, a Probability Distribution Function (PDF) is best-fitted to each historical timeseries of met-ocean data, under the hypothesis of stationarity of the natural processes. The intrinsic assumption here is that what happened in the past will occur in the future, following a probabilistic law expressed by the PDF of the considered physical quantity. Once the good adaptation of the PDFs to the timeseries is verified, it is possible to determine the design conditions for a specific return period, corresponding to the frequency of occurrence of an event of fixed magnitude. It is clear that the traditional methodological approach for coastal defences design relies on the availability of historical series of high-quality met-ocean data from a monitoring network in operation for a long period at the site of interest. Up to 2014, the Italian National Sea Wave Measurement Network (RON) has represented one of the Italian most advanced system for the monitoring of the directional

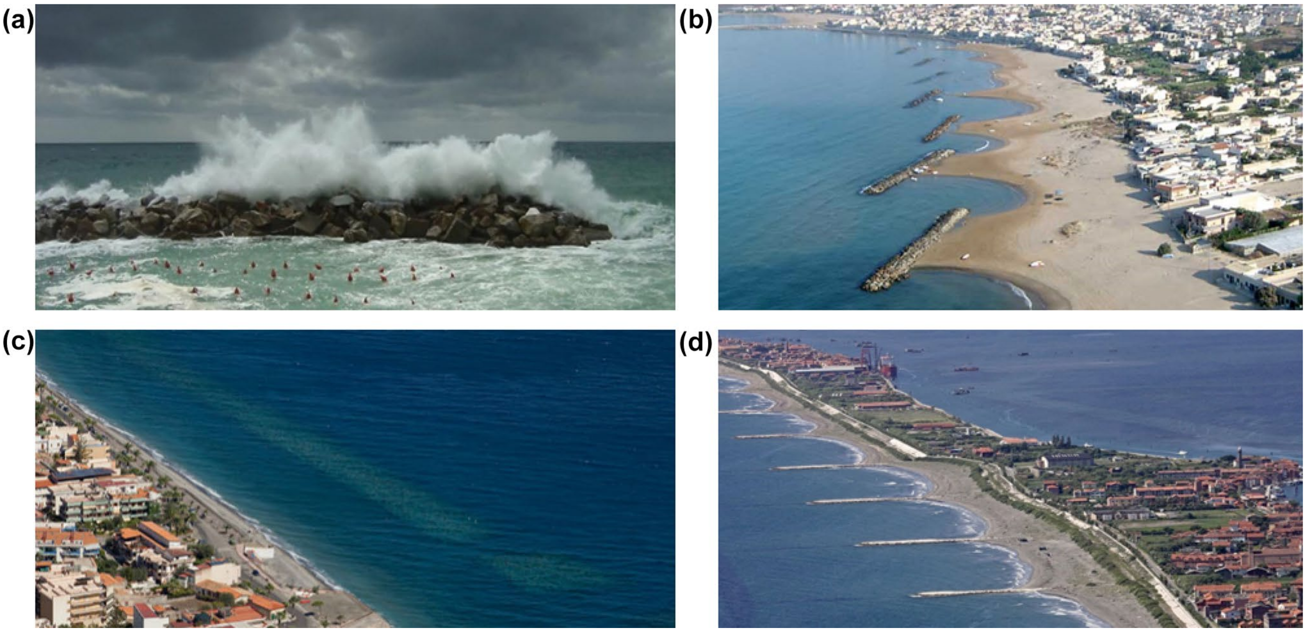

Fig. 3 Examples of coastal active defences in Italy: **a** emerged breakwater in Riomaggiore, Liguria (www.fondalicampania.com); **b** emerged breakwaters in Scicli (RG), Sicily (www.strettoweb.com); **c** submerged breakwater in Sant'Alessio Siculo (ME), Sicily (sikilynews.it); **d** coastal groins in Venice, Veneto (www.mosevenezia.eu)

wave motion. However, due to the high management costs, it has been disinvested and now wave monitoring is performed only by some of the Italian Regions without following a national standard.

The lack of data clearly undermines the validity of the traditional design method for coastal defences. Furthermore, the effects of climate change cause the impossibility to apply the principle of stationary and thus the traditional approach itself (Gersonius et al. 2013; Mudersbach and Jensen 2010).

3 Effect of climate change on coastal areas

A statistically important modification of the mean state of the climate or its variability, which last for an extended period, is defined climate change. The variation in climate patterns may be caused not only by natural processes, but also by anthropogenic activities that transform the composition or the atmosphere or the land use (IPCC 2014).

The first direct effect of global warming is the shifting of weather patterns, with consequent unpredictability of precipitation and increase of the frequency and/or the magnitude of extreme weather events, such as heavy downpours (Simmons et al. 2010), floods, heat waves (Christidis et al. 2011; Duffy and Tebaldi 2012), drought (Sheffield et al. 2012), hurricanes and changes in other storms (Bender et al. 2010; Lin et al. 2012; Marsooli et al. 2019). As regards the open sea and the coastal zone, climate change appears through a number of impacts. For instance, the absorption of some of anthropic excess emissions acted by the ocean causes its acidification, which poses a serious threat to underwater life (Hoegh-Guldberg et al. 2017; Sunday et al. 2017). Moreover, the global warming generates the rise of the mean sea level, due to melting ice and thermal ocean expansion (Church et al. 2013), increased storm surge events (Chini and Stansby 2012; Chini et al. 2010; Hemer et al. 2013; Lowe and Gregory 2005; Vousdoukas et al. 2016), changes of the frequency and the direction of extreme wind and wave events (González-Alemán et al. 2019), etc. As a consequence, extreme wave run-up and overtopping of coastal structures could rise, thus causing the increase of wave penetration into harbours and more intense beach erosion (Nicholls et al. 2007; Sanchez-Arcilla et al. 2016).

To facilitate future assessment of climate change and its effects, the intergovernmental panel on climate change (IPCC) request the scientific communities to develop a set of scenarios as a basis for long-term and near-term modelling experiments (IPCC 2007). The research community answered with the definition of four different scenarios containing greenhouse gas emission, concentration and land use trajectories consistent with the current-scenario literature, allowing subsequent analysis by both climate models (CMs) and Integrated Assessment Models (IAMs). These four scenarios, referred to as “representative concentration pathways” (RCPs) and whose main features are described in Table 2, together span the range of year 2100 radiative forcing values from 2.6 to 8.5 W/m^2 (van Vuuren et al. 2011), being the radiative forcing a direct measure of the change the Earth’s energy balance due to natural and anthropogenic processes. RCP2.6 and RCP8.5 are respectively the best and the worst scenario, since the first one represents a condition characterised by very low greenhouse gas emissions, while the latter corresponds to the pathway with the highest air pollutants concetrations and no mitigation policy. In particular, the cumulative total anthropogenic CO$_2$ emissions from 1870 are expected to reach 3000 GtCO$_2$ for RCP2.6 and 7600 GtCO$_2$ for RCP8.5 in 2100 (IPCC, 2014). As regards the change in mean temperature, a rise of ~ 1.8 °C for RCP2.6 and ~ 4.7 °C for RCP8.5 with respect to the period 1861-1880 is forecast for the year 2100 (IPCC, 2014).

As already mentioned, one of the most significant consequences of the increase of the global mean temperature is sea level rise. Church et al. (2013) found that it is almost certain that global sea level will continue to rise during the 21st century and beyond. In particular, with respect to the year 2000, it is expected an increase of ~ 45 cm for RCP2.6 and of ~ 75 cm for RCP8.5 of mean global sea level, taking into account the uncertainties of these projections. While the main contributing factors to global sea level are thermal expansion of the ocean and melting of the ice sheets, ice caps and glaciers, on a local scale changes in salinity, atmospheric pressure, ocean circulations and land movements may lead to different patterns and magnitudes of sea

Table 2 Characterization of representative concentration pathways (data from van Vuuren et al. 2011)

	RCP2.6	RCP4.5	RCP6	RCP8.5
Radiative forcing pathway	Peak and decline	Stabilisation without overshoot	Stabilisation without overshoot	Rising
Maximum radiative forcing by 2100 (W/m^2)	~ 2.6	~ 4.5	~ 6.0	~ 8.5
Maximum CO$_2$ eq concentration by 2100 (ppm)	~ 490	~ 650	~ 850	~ 1370
Greenhouse gas emission baseline	Very low	Very low	Medium	High baseline
Mitigation policy	None	Medium–low	High	None

level rise than the global average. For this reason, coastal management needs local scenarios elaborated from global sea level rise but taking into account all relevant processes for a given spatial scale (Vellinga et al. 2011). Furthermore, the global models do not resolve the coastal shallow regions because of their coarse horizontal and vertical resolutions (Malanotte-Rizzoli 2018). For instance, the Mediterranean Sea, which is a mid-latitude, semi-enclosed and deep sea, is characterised by a peculiar dynamic regime governed by the Strait of Gibraltar and then a regional model is needed. Galassi and Spada (2014) developed a regional model for sea level analysis in the Mediterranean Sea. Using published estimates for terrestrial ice melt and ocean response components (e.g. ocean circulation contributions and thermosteric and halosteric effects resulting from regional, high-resolution coupled models) of future sea level change and glacial isostatic adjustment modelling, it was found that the minimum and maximum spatially averaged projected sea level rise by 2040–2050 in the Mediterranean Sea will be, respectively, 9.8 cm and 25.6 cm.

However, the sea level rise is not the only effect of global warming which interests coastal areas. For instance, Vousdoukas et al. (2018) found a projected intensification in frequency of occurrence of extreme sea levels, which are determined by the combination of mean sea level rise and water levels driven by tides, waves, and storm surges. The reduction of the return period of extreme sea levels will likely exceed the design condition of existing coastal defence structures and hence a higher coastal risk is expected. Vousdoukas et al. (2018) show also that upgrading existing coastal protection would imply increasing elevations by an average of at least 25 cm by 2050 and by more than 50 cm by 2100. In addition, local required increments can be in the order of 1–2 m. Therefore, considerable economic, environmental, and societal costs must be borne in order to implement interventions of adaptation to climate change along the ~ 620,000 km of global coastline. Furthermore, Arns et al. (2017) underlined that coastal regions bounded by shallow continental shelf areas are sensitive to several common non-linear feedbacks induced by sea level rise, which can influence wave heights, tide characteristics and surge magnitudes. In particular, simulations suggest that wave height and wave run-up (influenced by the predicted decrease in wave breaking away from the coast) are much more sensitive to sea level rise than tides or surge. The change in design height of a coastal defence can be more than doubled relative to sea level rise alone if these non-linearities are considered in risk assessments. Likewise, Isobe (2013) noticed that the crown height of coastal defence structures should be raised not only because of sea level rise but also because of the increase in wave run-up height and overtopping.

Another consequence of climate change, which strongly affects coastal zones, is the rise of intensity and frequency of occurrence of extreme weather events which were rare or non-existing in the past, such as hurricanes and Medicanes (i.e. Mediterranean hurricane). On 27th–28th September 2018, the so-called Medicane Zorbas took place in the Ionian Sea (Fig. 4a). Zorbas was one of the greatest ever recorded hurricanes in the Mediterranean Sea, classified of category between I and II. It was characterised by wind speed larger than 140 km/h and caused offshore wave heights bigger than 6 m. Even though Zorbas did not follow the track towards Sicilian coasts as predicted by numerical models, turning toward Greece (Fig. 4b), it produced substantial damages to many ports and towns in the provinces of Catania, Syracuse and Ragusa (Eastern Sicily), highlighting the inadequacy of existing coastal defence structures.

In summary, the projected sea level rise and possible changes in the frequency and intensity of storm surges as well as non-linear effects are expected to cause significant ecological damage, economic loss and other societal problems for low-lying coastal areas across Europe, unless additional adaptation measures are implemented (European Environment Agency 2016).

4 Coastal defences: an innovative approach

4.1 Mitigation measures

Three kinds of protection measures to mitigate the risk of coastal flooding and erosion are usually identified: institutional measures, preparedness and prevention actions and structural interventions.

Institutional measures include the managed realignment (i.e. relocating existing anthropic activities and identifying a more landward line of defence) and the limitation of economic and social development in those areas that a previous risk assessment has defined as high-risk zones (Turner et al. 2007; Williams et al. 2018). Furthermore, policymakers should promote insurance policies against coastal risk and encourage the construction of systems capable of going back to their initial state after being damaged by an extreme event, i.e. resilient systems (Hallegatte 2009).

Preparedness and prevention actions consist, for example, of upgrading the existing monitoring networks of coastal risks and developing new ones, where needed. It is essential to support the progress of prediction models and corresponding warning systems to reduce the potential impact on people of extreme events. Moreover, educational programmes addressed both to stakeholders and ordinary citizens, should be promoted to make people aware of the extent of coastal risk and its consequences (Keim 2008). The Civil Protection plays an important role not only in the preparation of these awareness campaigns, but also in the coordination of

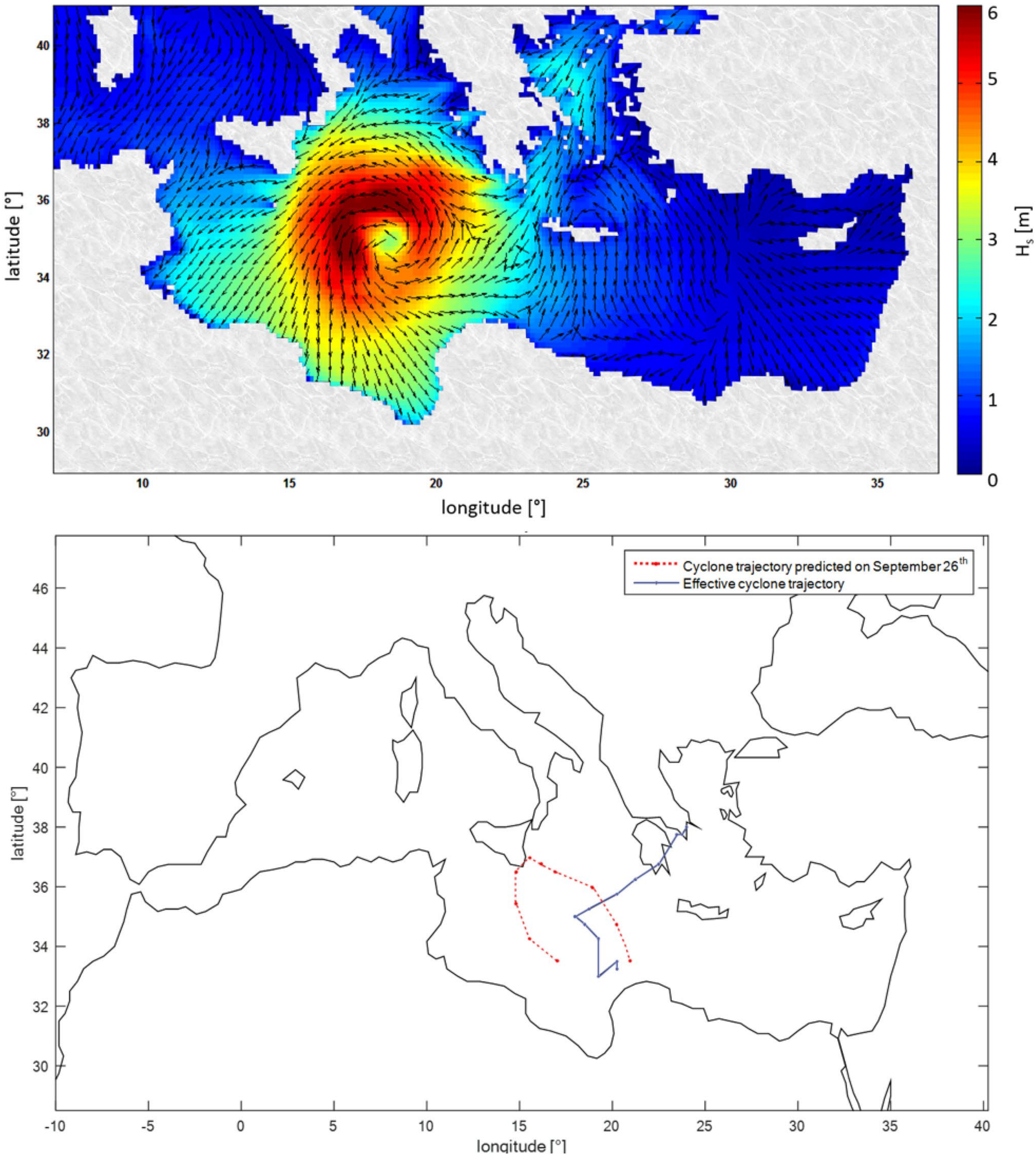

Fig. 4 Medicane Zorbas: **a** significant wave height H_s (m) predicted by ECMWF (European Centre for Medium-range Weather Forecasts) on the 28th of September 2018, 12:00; **b** cyclone trajectory predicted on the 26th of September 2018 and effective cyclone trajectory

resources and actions useful for ensuring prompt assistance in case of emergency (Groven et al. 2012).

Finally, structural interventions can be divided into three types: upgrade of existing coastal defences; use of Nature-Based Solutions within the scope of creating sustainable and resilient systems; integration of traditional and innovative techniques for the design of coastal defences to realise resilient or, even better, antifragile systems.

4.2 Upgrade of existent coastal defences

As discussed in Sect. 3, the study of the impacts of climate change on coastal areas suggests the necessity of upgrading existing coastal defence structures, such as by raising crown height and increasing the weight of armour blocks. Figure 5 shows three examples of possible upgrading of a rubble-mound breakwater (adapted from Burcharth et al. 2014). The first concept (Fig. 5a) consists in the realisation of an extra layer on the armour slope and crest to increase the stability of the structure and to reduce wave run-up and overtopping discharges. However, in the presence of specific environmental restrictions, the rise of the height of the structure could be non-acceptable and other kinds of upgrading solution could be required. For instance, an extra armour layer flatter than the existing one (Fig. 5b) or a berm can be built, obtaining a greater stability of the armour units and a reduction of run-up level and overtopping compared to the original design. Finally, a submerged reef located in front of the existing structure (Fig. 5c) can be a suitable option to reduce the wave impact on the latter, producing improvement both in the structural and hydraulic response of the breakwater.

Isobe (2013) roughly estimated the total costs for improving coastal structures within the port areas in Japan, founding that they might be beyond the reasonable technical limits. For this reason, a strategy for adapting coastal defence structures to the effects of climate change has to be developed.

Starting from the guidelines provided by Burcharth et al. (2014), a procedure for adaptation of existing coastal defence structures is proposed here (Fig. 6). First of all, a survey of the existing structure is needed to evaluate its rate of deterioration and conduct a preliminary selection of the most appropriate concepts for upgrading. The apriori design of the adaptation options requires the definition of the service lifetime of the upgraded structure, the identification of possible environmental restrictions at the considered site and the selection of the structural and hydraulic performance criteria to be taken into account. As regards the design conditions, the definition of future climate scenarios over the service lifetime of the structure allows the estimate of future mean sea level (MSL), offshore significant wave height (H_s), peak wave period (T_p) and wave direction (D) at the site of interest for every return period considered. Then, the characteristics of the wave motion in the nearshore zone and the morphological changes of the coast can be calculated through the application of specific numerical models, always referring to all the return periods selected. Once the future values of the wave parameters and of MSL

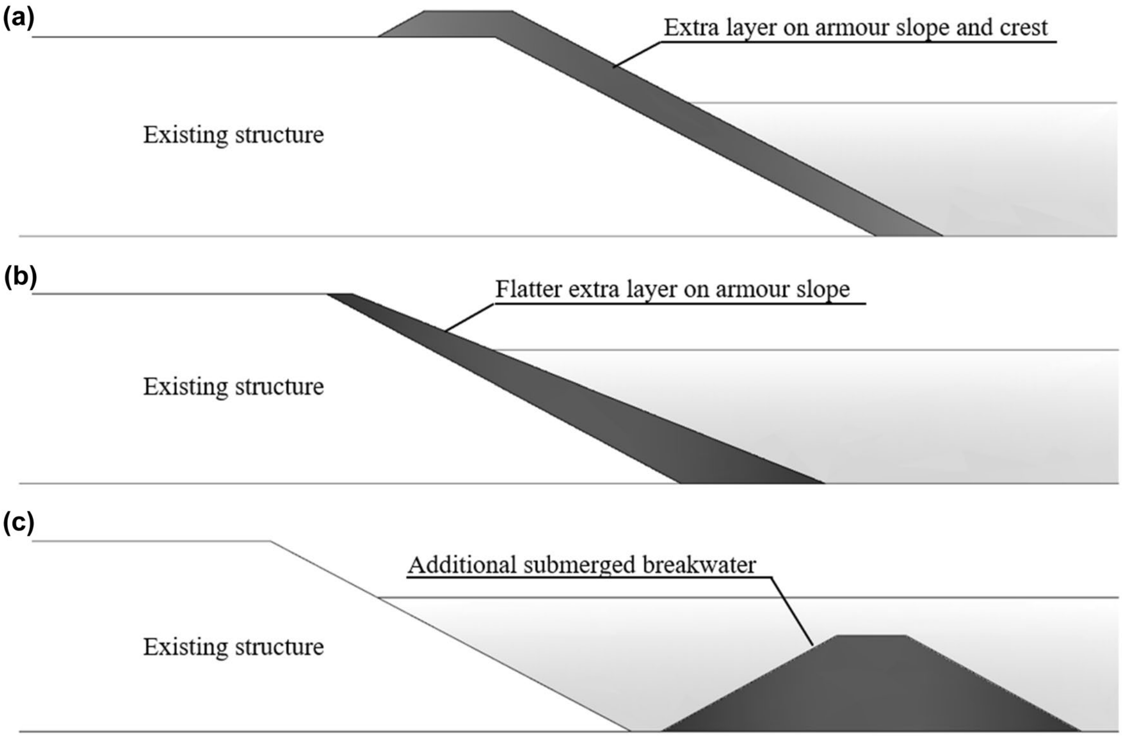

Fig. 5 Examples of concepts for upgrading rubble-mound breakwaters (adapted from Burcharth et al. 2014): **a** extra armour layer to increase height and stability of the existing structure; **b** extra flatter armour layer to limit the impact of the wave motion and increase the structure stability; **c** additional submerged breakwater to limit the impact of the wave motion on the existing structure

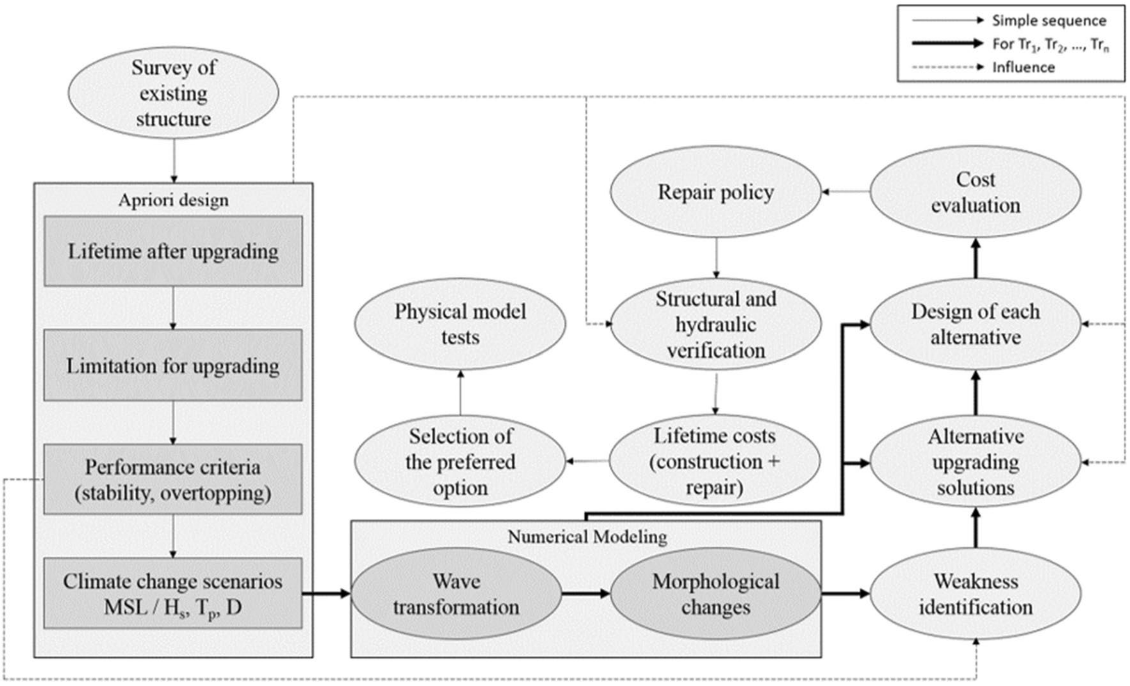

Fig. 6 Proposed procedure for adaptation of existing coastal defence structures to climate changes

in front of the structure are known for each return period, the identification of weakness in the structural and hydraulic response of the existing structure is possible. At this point, all necessary information to choose the best upgrading options for the analysed structure are available. Based on the results of the various steps of the apriori design, each selected alternative can be designed for the return periods considered (using formulae, neural network and numerical models) and then the cost of every option can be evaluated. The comparison between the different designed solutions in terms of economic cost enables the definition of a repair policy. Therefore, the structural and hydraulic performances of the selected upgraded structures can be verified following the criteria defined during the apriori design and the lifetime costs, which include construction and repair ones. Finally, the most suitable solution for the upgrading of the coastal defence structure can be identified and its design can be optimised by means of physical modelling. Actually, structure response formulae for many of the upgrading interventions do not exist and hence the performance of physical model tests is the only way to investigate the real behaviour of this kind of structures.

4.3 Creation of resilient systems

As stressed, in the past, coastal defence has been usually performed by means of the construction of rigid structures, such as breakwaters, groins and revetments. However, this approach frequently produced an increase of coastal erosion along some stretches of the coast and the hardening of the latter, because of the lack of an overall view of the beach system during the planning and designing of coastal defences. The concept of coastal resilience is the inherent ability of the coast to accommodate changes induced by sea level rise, extreme events and occasional human impacts, whilst maintaining the functions fulfilled by the coastal system in the longer term.

To restore or simply reinforce the coastal resilience, a good strategy is to use Nature-Based Solutions (NBSs), which consist in the reconstruction and preservation of coastal habitat (Bridges et al. 2015; European Commission and Union 2015). An impressive example of NBS is the Sand Motor (de Schipper et al. 2016; Stive et al. 2013; van Slobbe et al. 2013), which is a pilot project developed in the Netherlands presenting an innovative approach to coastal protection. The idea behind this project consists in using Nature to provide protection from the action of the wave motion and to create a temporary area for nature and recreational activities (Fig. 7a). Wind, waves and currents spread the artificial sand bank (18.7 million m^3 of sand, total cost about 70 milion €) in the form of a peninsula, which was created on the coastline between Ter Heijde and The Hague in 2011. To determine whether the objectives of the project have been achieved and make knowledge development possible, a monitoring and evaluation plan

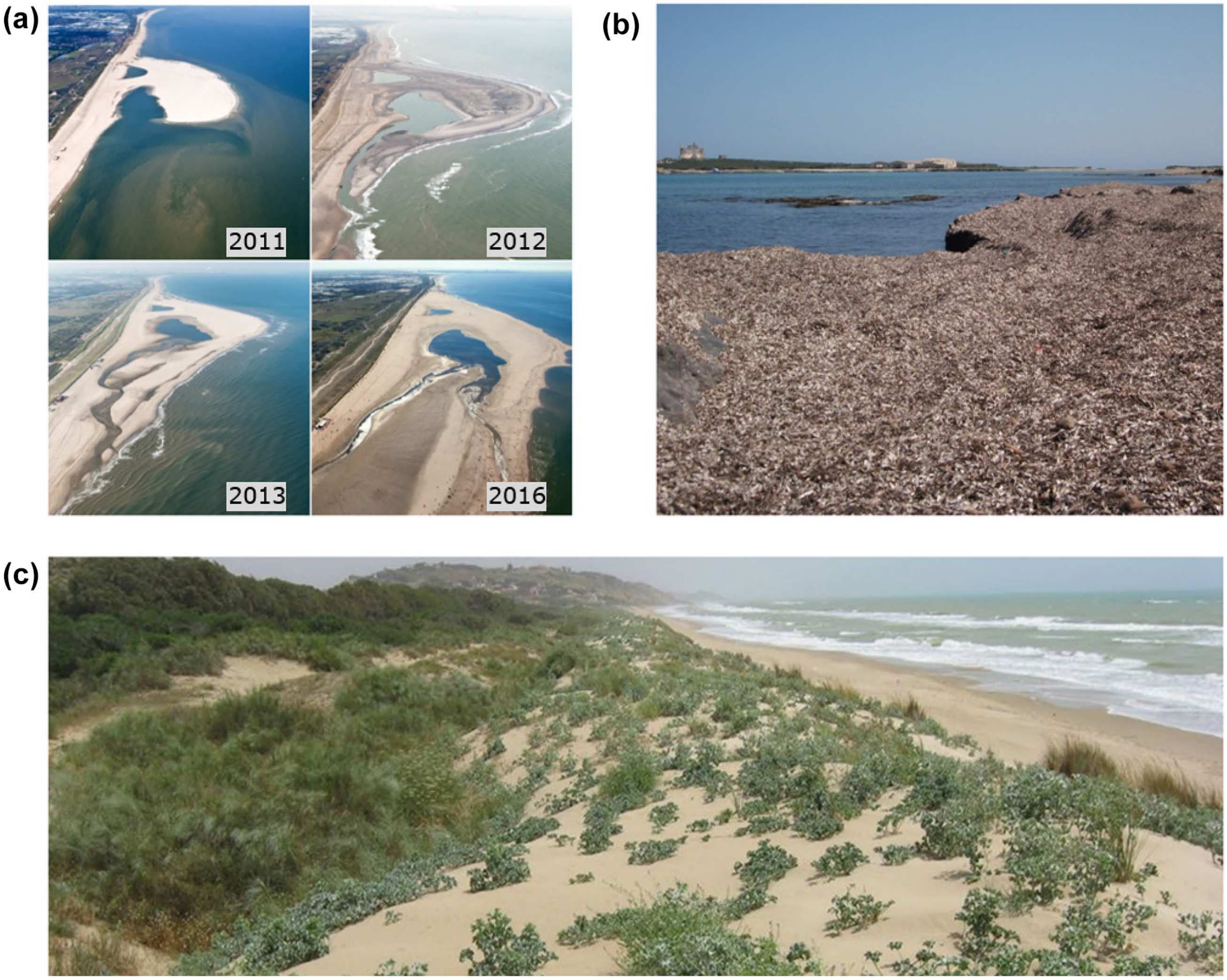

Fig. 7 Examples of Nature Based Solutions: **a** an overview of the changing Sand Motor from year 2011 to 2016 (Rijkswaterstaat 2016); **b** drifts of *Posidonia oceanica* (L.) Delile on the beach of Castelvetrano (TP), Sicily (trapani.gds.it); **c** restored dune vegetation on the beach of Gela (CL) Sicily (Tomaselli et al. 2014)

Table 3 The development of the Sand Motor between 2011 and 2016 in brief (Rijkswaterstaat 2016)

Length along the beach	Extended from 2.37 km to approximately 5.5 km
Farthest distance into the sea	Extended from 1 km to 650 m into the sea. Storms have removed sand on the seaward side, creating ‘cliffs’
Highest point	The highest point was 7 m high and was 50 cm lower
Size of lagoon	Approximately 300,000 m^3 of sand has been deposited in the lagoon, more than half as a result of drifting
Depth of lagoon	The deepest part of the lagoon is more than 4 m deep
Length and depth of gully	The gully has lengthened from 1.2 km to 2.7 km
Surface area of dune lake	Approximately 100,000 m^3 of sand has drifted into the dune lake, particularly on the western side. The lake is now smaller as a result. The depth remains approximately 2 m

was drafted. Table 3 summarises the development of the Sand Motor between 2011 and 2016.

Another example of NBS is the restoration of original dune vegetation, whose task is to contribute to construction, stabilisation and geomorphologic evolution of the dune system (Fig. 7c). It is important to preserve the dune system because it represents not only a natural reservoir for beach nourishment, but also the principal defence line from seawater intrusion during coastal storms. At present, the main cause of disturbance of the dune system is of anthropic origin. For instance, the Project Life Leopoldia (Tomaselli et al. 2016) entailed the restoration of dune vegetation in short stretches of the coast located in the South-East of Sicily (physiographical coastal unit 8, Punta Braccetto-Licata) to reinforce its resilience (Tomaselli et al. 2014).

A NBS for the protection of beaches from erosion is the use of algae and marine plant debris as revetment. Guillén et al. (2014) suggested some guidelines for the management of algae and marine plant debris under the Project Life Seamatter (Latorre Mollá 2015), where they noticed that actually, especially on the Mediterranean coast, algae and marine plant debris are usually removed from beaches mainly for aesthetic reasons. However, this debris seems to play an important role in protecting beaches from erosion and its removal can negatively affect not only the morphology of the beach, but also the functioning of coastal ecosystems due to the permanent loss of the nutrients and sediments that are accidentally eliminated when algae are removed (Guillén et al. 2014). Furthermore, the removal, transport and landfill of algae and marine plant debris have no negligible costs. Therefore, it is evident the environmental and economic advantage of leaving these debris on the beach. For instance, in the Mediterranean, the plant debris is mainly made up of *Posidonia oceanica* (L.) Delile (Fig. 7b), a superior endemic plant.

Nevertheless, the use of NBSs is not the only strategy to improve coastal resilience. Recently, the tendency to integration of traditional and innovative techniques for coastal defence structures design to create a resilient system has encouraged the development of several projects. The Staten Island Living Breakwaters Project (SCAPE/Landscape Architecture PLLC et al. 2013) is one of the selected proposals within the framework of a competition to respond to Superstorm Sandy's devastation in the NorthEast region of the United States held in June 2013. The combination of erosion prevention, wave energy attenuation and improvement of ecosystems and social resilience is presented as the selected approach to promote risk reduction. In particular, the project will be implemented along the Tottenville shoreline, in the South Shore of Staten Island, whose community suffered severe damage caused by storm events and erosion, with serious consequences for the oyster farming industry-based economy. In particular, a combination of structural interventions, environment restoration and educational programmes is planned. As regards the coastal defence structures, approximately 980 m of near-shore emerged or partially submerged breakwaters will be built. These structures will be rubble-mound breakwaters, with a stone core and an armour layer to counteract the wave motion impact. However, different from the traditional rubble-mound breakwaters, special armour units designed to promote biological activity and recruitment of marine species will be employed. Furthermore, the living breakwaters present rocky protrusions on the seaside, separated by narrow spaces that will locally modify the wave motion and provide the appropriate habitat for species reproduction. In addition to the construction of breakwaters, where an increase in the distance between the shore and the buildings is needed, beach nourishment will be realised. Activities for oyster restoration will be performed to raise the oyster farming industry-based economy of the city. Finally, a Water Hub (i.e. a floating vessel) will be constructed, where educational, monitoring, and stewardship activities could take place.

Therefore, the living breakwaters, which are designed not only to reduce risk, but also to provide habitat enhancements, represent the perfect example of integration between tradition and innovation in coastal defence. Although the Staten Island Living Breakwaters Project is based on the concept of resilience, actually it seems to aim at a higher purpose, which is the realisation of an antifragile system.

4.4 Creation of antifragile systems

The concept of antifragility questions the traditional approach for coastal defence, whose aim is the creation of an optimised system to operate only in specific conditions, without taking into account the uncertainties linked to the effect of climate change. A fragile structure is designed to withstand stresses until a fixed threshold is exceeded, so it could fail at any moment losing its functionality or being totally devastated. Taleb (2012) describes fragility through a mythological equivalence, comparing a fragile system to the courtier Damocles, who is usually depicted as enjoying a magnificent feast with a sword hanging over his head by means of a single horsehair, ready to hit him at any moment. Instead, a resilient system that struck by a certain external force cannot be destroyed, since it returns to its initial state once the latter stops to act. According to Taleb (2012), the symbol of resilience is the Phoenix, a mythological bird that is able to be reborn from its own ashes every time it is murdered. Finally, antifragility is the characteristic of a system that becomes even stronger after the occurrence of a damaging event, like the monster Hydra, whose number of heads rise every time one of them is cut off (Taleb 2012). Therefore, antifragility extends the concept of resilience, providing a mechanism by which the system restores itself continuously taking advantage of unexpected extreme events. This kind of process is typical of the human body's response to physical training (Babovic et al. 2018), of living organisms who adapt themselves to the changing environmental condition and of technologies, institutions, social practices and systems which last for a long time benefiting from failures (Blečić and Cecchini 2017). Also the City, considered as the general form of human settlement, is intrinsically antifragile, since it continuously has adapted itself to changing conditions through the history, acquiring new features that have allowed it to exist despite of the adverse events by which it was hit (Blečić and Cecchini 2017).

Considering the cities as individuals, many urbanist and planners think that an antifragile planning is the way to create cities capable of adapting themselves to the unpredictable future, ensuring their continued existence through time. For instance, Blečić and Cecchini (2017) listed seven factors which make urban planning responsible of fragilize the city: (1) plans based on accurate predictions of the future, coming from models highly sensitive to small variations of its parameters and then fragile; (2) excess of centralisation; (3) efficiency and optimisation, which strongly reduce the possibility of adaptation to unpredictable future scenarios; (4) specialisation, which reduces the inclination to adaptation of the system; (5) excessive simplification of the complex behaviour of the system; (6) lack of consensus; (7) inequality and inequity. Furthermore, the realisation of an antifragile city cannot be obtained from a large project, which is based on uncertain predictions of the future scenarios and thus hardly adaptable to changing conditions. Instead, large projects composed by a multitude of small and medium interventions (modular, distributed and reversible) and a coherent flexible long-term coordination plan is the preferred way to design an antifragile system. The concept described above can be extended to fields strongly connected to urban planning, such as transport organization, water resource employment, mitigation of hydraulic risks of different nature (urban flooding, coastal flooding and erosion).

Regarding design of coastal defence, the traditional methodology based on future predictions has to be overcome, since the design of an antifragile system does not need the perfect knowledge of future conditions. In Italy, there is an example of potential antifragile system of coastal defence: the integrated solutions that the Italian Government promoted to reduce the impact of flooding in the Venice lagoon.

The Venice lagoon (Fig. 8a) is one of the most important areas in Italy because of its historical and cultural heritage and because it is home to one of the widest and most important lagoon ecosystems in both Europe and the entire Mediterranean basin (Fletcher and Spencer 2005). It is located in the northern part of the Adriatic Sea and it is characterized by a surface area of around 550 km^2, a length of about 52 km and a width ranging between 8 km and 14 km. The lagoon's surface area is composed by 8% of land, including Venice itself and many smaller islands, and by 92% of dredged channels, mud flats and salt marshes. The connection between the Venice lagoon and the Adriatic Sea is obtained by means of three inlets (width between 500 and 1000 m and depth in the range from 6 to 20 m), from North to South: Lido, Malamocco and Chioggia. Situated at the end of a largely enclosed sea, the lagoon is characterized by high variations in water levels. Such variations may be the result of several concurring mechanisms: (1) the astronomical tide, which ranges between + 50 and − 50 cm; (2) the storm surge, whose considerable magnitude is due to the shallow water of the northern part of the Adriatic Sea and the effect of the Scirocco and Bora winds; (3) the wave set-up; (4) the surge induced within the lagoon by wind directly blowing over it. Furthermore, both land subsidence and the eustatism contribute to increase the flooding risk in the Venice lagoon. The subsidence, which is the sinking of the land due to natural and anthropogenic causes, is primarily induced by the drawing of groundwater that in the past has been intense, especially in the industrial area of Marghera. The eustatism is the sea level rise due to climate change. Over the last 100 years, the relative sea level in Venice rose of about 23–26 cm. The contribution from mean sea level rise is 11 cm, whereas the remaining 12–15 cm results from vertical land movement: 3–4 cm from natural subsidence and 9–11 cm from the anthropogenic one (Gatto and Carbognin 1981).

The effects of the phenomena described above, whose intensity is increased by climate change influence on mean sea level, wave motion and storm surge, can be summarised as follows: (1) Acqua Alta (i.e. high waters); (2) damage produced by storm surges; (3) coastal erosion; (4) water pollution. Following the flood of 4 November 1966 (Trincardi et al. 2016), during which the flood level reached 194 cm MZPS (i.e. the water level is referred to the Mareographic Reference of Punta della Salute), the Italian Government promoted a series of activities to reduce the severity of these hydraulic-environmental problems. In particular, various interventions were realised: 56 km of new and protected beaches; 12 km of restored and naturalised dunes; 11 km of reinforced piers; 16 km^2 of rebuilt and naturalised marshes; 30 km of protected marshes; 12 recovered small islands. Furthermore, mobile barriers were planned for the three lagoon inlets. These mobile barriers are known as the experimental electromechanical module (MoSE) and they are designed to protect Venice and the lagoon from floods of up to 3.0 m MZPS. The mobile barriers in the lagoon inlets are being constructed by the Italian Ministry of Infrastructure and Transport (Provveditorato Interregionale per le Opere Pubbliche per il Veneto, Trentino Alto Adige e Friuli Venezia Giulia). The construction of the barriers began in 2003 and the total number of gates is 78: 21 at the barrier of North Lido, 20 at the barrier of South Lido, 19 at the barrier of Malamocco inlet, and 18 at the barrier of Chioggia inlet. The current barrier closure criteria are based on the classification of weather events in five class with respect to numerically predicted meteorological quantities such as water level, wind velocity, wind direction, rainfall and so on. Therefore, for each of the five classes of events identified, a closing water level is fixed. To reduce the interference between the MoSE system and the maritime traffic in the Venice lagoon, during the flooding events characterized by a non-extreme water

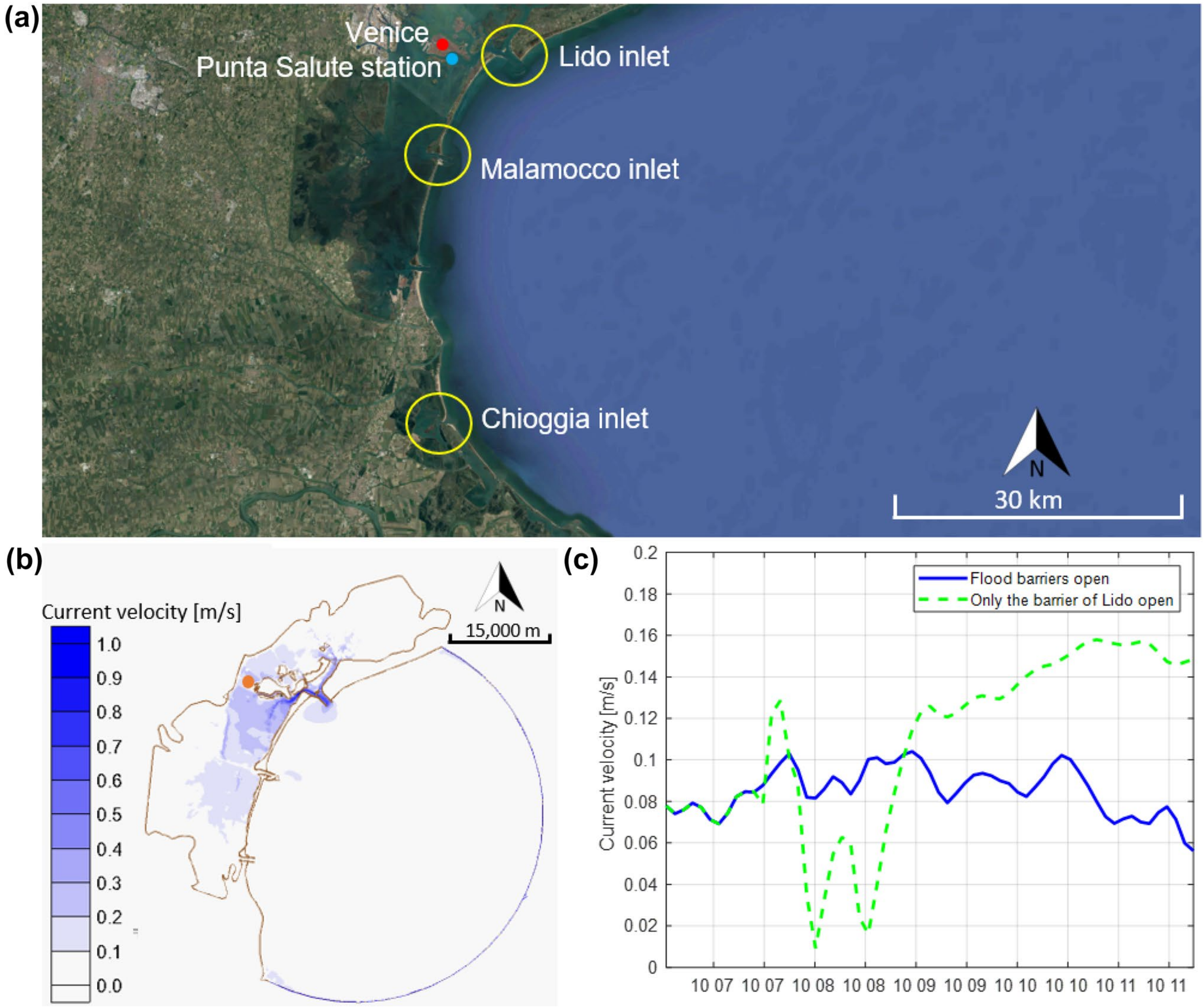

Fig. 8 **a** Localization of the three inlets of the Venice lagoon and of the Punta Salute station; **b** example of application of the ADCIRC model for the evaluation of the maximum current velocity in each node of the computational domain with only Lido barrier open for the event of the 10th August 2010; **c** example of the beneficial effect of partial closure of barriers on a point of the lagoon characterized by a very high residence time (indicated in **b**), for the event of the 10th August 2010 with only the barrier of Lido open

level, one of the three inlets can be left open to ensure the transit of vessels. Cavallaro et al. (2017) presented the findings of a numerical investigation in which the partial use of the MoSE is simulated by means of the model advanced circulation (ADCIRC), which is a numerical model for the evaluation of sea level and current velocities from the solution of time-dependent, free-surface circulation and transport problems in two and three dimensions. Starting from such a study, it is possible to demonstrate that a partial closure of the gates can be used to force an unusual water circulation within the lagoon during summertime. Indeed, the low water exchange typical of the summer season causes accumulation of pollutants and eutrophication, with the consequent oxygen concentration reduction. Therefore, conditions of hypoxia and anoxia develop within the lagoon, producing the death of fish and algae. The existence of MoSE, which is due especially to the necessity to protect Venice from flooding, gives the possibility to improve the lagoon water circulation, solving several environmental problems as can be seen in Fig. 8b, c, where the beneficial effects of forced circulation are shown for a point of the lagoon characterized by a very high residence time.

Therefore, it is possible to state that the overall integrated solutions adopted to reduce the impact of flooding in Venice lagoon can potentially generate an antifragile system. Indeed, the weakness of this region stimulated the creation of the prerequisite for the upgrade of the actual conditions, by means of the restoration of natural ecosystems that had been destroyed by past events and the possibility to enhance the lagoon water circulation. Even the Staten Island Living Breakwaters Project (see Sect. 4.3) paves the way for the development of an antifragile system, since the occurrence of a disastrous event (i.e. Superstorm Sandy) encouraged the application of solutions that will improve the actual condition of the region.

5 Conclusions

Coastal zones are subject to high erosion and flooding risk, due to both the high population density and a large number of habitats, which determine a large exposure, and the fragility of these areas, which produce a considerable hazard.

The traditional design of coastal defence structures requires the availability of a large amount of historical met-ocean data, which are analysed by means of a statistical approach, under the hypothesis of stationarity of the natural processes. The aim of this methodology is the determination of the design conditions for a specific return period. However, the lack of data, at least in Italy, and the impossibility to apply the principle of stationary in the presence of climate change undermines the validity of the traditional method for coastal defence. Global warming produces an increase of sea level as well as an intensification of extreme events, both in terms of severity and frequency, and thus imposes the necessity of an innovative approach for coastal defence design in unsteady climatic conditions. In particular, erosion and flooding risk needs to be mitigated by means of the combination of institutional measures, preparedness and prevention actions and structural interventions. As regards structural interventions, there are three possible strategies: upgrade of existing coastal defences; use of Nature-Based Solutions within the scope of creating resilient systems; integration of traditional and innovative techniques for the design of coastal defences to realise antifragile systems.

The upgrade of existing coastal defence structure such as rubble-mound breakwaters mainly consists of raising crown height or increasing the weight of armour blocks, considering the effects of climate change on external forcing and possible environmental restrictions. However, as part of an integrated coastal zone management, the simple upgrade of existing coastal defence structures to withstand the effects of climate change needs to be integrated with the realisation of resilient intervention and above all with the search for solutions which make the system antifragile. To restore or simply reinforce the capability of the coast to adapt itself to the changing conditions due to the effects of global warming though maintaining the functions fulfilled by the coastal system in the longer term, a good strategy is to use Nature-Based Solutions, such as mega beach nourishments based on the transport capacity of winds, waves and currents, dune vegetation reconstruction, living shoreline and employment of algae and plants debris as coastal protection. The integration of traditional and innovative techniques for coastal defence structures design also can contribute to the creation of resilient systems (e.g. Staten Island Living Breakwaters Project). Furthermore, the combination of integrated solutions for the reduction of coastal risk can lead to the development of an antifragile system, which is able to improve its condition after an extreme event has occurred. The defence system realised to protect the Venice lagoon from coastal flooding represents a positive example of how the weakness of a region can lead to the upgrade of the actual conditions, by means of the recovery of natural ecosystems that had been previously destroyed and the possibility to enhance the lagoon water circulation.

Given the impossibility of accurately predicting future climate scenarios, antifragility appears to be a suitable approach for coastal defence in the presence of climate change, since perfect knowledge of future conditions is not required. However, several studies that involve experts having different backgrounds are still needed to implement this new approach in terms of design criteria.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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