Journal of Coastal Research	34	3	687–703	Coconut Creek, Florida	May 2018

REVIEW ARTICLES

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Climate Change, Adaptation Measures, and Integrated Coastal Zone Management: The New Protection Paradigm for the Portuguese Coastal Zone

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ABSTRACT

Antunes do Carmo, J.S., 2018. Climate change, adaptation measures, and integrated coastal zone management: The new protection paradigm for the Portuguese coastal zone. *Journal of Coastal Research,* 34(3), 687–703. Coconut Creek (Florida), ISSN 0749-0208.

The efforts made to reduce the causes and mitigate the effects of global climate change continue to be critical in coastal areas. Many adaptation strategies implemented in coastal areas remain inadequate or ineffective. Using primarily events and interventions carried out along the Portuguese Atlantic coast, this work aims to show the paradigm shift that has occurred in Portugal since the last century (the 1990s) within the scope of the National Coastal Zone Management Strategy, taking into account the new guidelines for the implementation of coastal defence works. In this context, this paper also aims to assist coastal communities in carrying out operational coastal management by presenting and discussing management tools and primary options that should be considered in any adaptation programme that is to be implemented. Both nonstructural and structural measures are considered. Action plans, warning systems, emergency plans, and evacuation plans belong to the first category. Education and training are also considered, because they play a key role in the sustainability of coastal areas, especially in the coming generations. Structural measures are adaptation options that are designed to increase the safety of people and reduce risks. They are discussed and grouped into categories that include accommodation, protection, and retreat. Recent cases of successful accommodation and protection measures implemented along the Portuguese coast are also presented and discussed.

ADDITIONAL INDEX WORDS: *Storms, multifunctional options, management tools, public participation.*

INTRODUCTION

The coastal zone, which represents an interface space between ocean and land areas, is highly dynamic and simultaneously sensitive. This sensitivity has been affected by strong urban and industrial pressures, rise of traffic flows, and increases in recreational uses, leading to the deterioration of natural habitats and to a growing instability of the inhabited areas (Martins *et al*., 2002).

Therefore, vulnerabilities and risks in coastal areas have been increasing, particularly since the middle of the last century, and a more marked increase is anticipated after the middle of the current century. It is also clear that human action has been the primary cause of the current imbalances, both directly (through local actions) and indirectly (through contributions to global warming and climate change). Adjustments in natural and human systems are thus necessary to respond to present-day or expected climate changes and their effects.

DOI: 10.2112/JCOASTRES-D-16-00165.1 received 27 August 2016; accepted in revision 6 June 2017; corrected proofs received 24 July 2017; published pre-print online 10 October 2017.
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As has been widely reported in the literature, the interactions amongst three entities, land, humans, and ocean, have manifested in positive and negative ways in different contexts. Many studies have shown that the more human activities try to change, dominate, or even replace natural ecosystems, the more environmental vulnerability increases; as a result, both the occurrence and the scale of extreme events will be exacerbated (Bullimore, 2014; Linton and Warner, 2003). In the future, the growth and increased concentration of populations in cities, as well as the ageing of populations, will contribute to further increases in the vulnerability of cities to climate change (EEA, 2012).

To a large extent, the direct and indirect consequences of human activities in coastal areas must be considered carefully to maintain a sustainable balance. Therefore, the need to regulate human activities and reduce risks to achieve sustainable development is of paramount importance. Although there is some perception of imbalances and vulnerabilities, there is not yet real awareness of the negative effects of human-induced activities on such fundamental environments for the survival of humanity in the mid- and long term.

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The European Coastal Zones

The use of coastal land for agriculture, building ports and harbours, development of industrial infrastructure, tourist activities, and urbanisation are amongst a range of human activities affecting Europe's coasts. The scale of development is reflected by an estimated 200 million people of the total European population of 680 million living within 50 km of coastal waters (Doody, 2002). The placement of buildings and other structures and the location of low-lying agricultural land have produced a reliance on artificial defences to prevent erosion and/or incursions by the sea.

Because of seasonal factors and for reasons that have to do with tourism, the populations of communities in some coastal zones increase by a factor of two or even three during some periods of the year. This is the case for several coastal regions in southern European countries. Frequently, these communities rely on groundwater for their water supplies. In such circumstances, an increase in the pumping of water can have a marked effect on the position of the saltwater–freshwater interface. Lowering the freshwater head encourages the incursion of saltwater, which can rapidly render the supply undrinkable. The removal or lowering of coastal dunes has a similar effect, as is the case for the reduction of the dunes' width. Dunes both act as recharge zones and support elevated water tables (Carter, 1988).

The combined effects of land reclamation and its associated flood defences, as well as protecting mobile habitats from erosion, have resulted in many kilometres of sea banks, seawalls, and groyne fields (Doody *et al*., 2004). The natural erosion of cliffs threatens individual buildings, towns, and villages, which are often protected by massive concrete seawalls and revetments as a result. The reduction in longshore drift by the erection of these structures can lead to increases in erosion elsewhere, because the beaches are deprived of sediment. As long as sea level continues to rise in response to global warming, increasing the height and resilience of hard coastal defences will not ensure the protection of urban areas and territory for many years. As experience has proven, hard constructions have positive effects only over short periods and limited areas.

In addition, such technical interventions performed in coastal zones tend to be expensive, in terms of both investment and monitoring costs (Costa and Coelho, 2013; Hudson, Keating, and Pettit, 2015; Maia, Bernardes, and Alves, 2015; Roebeling, Coelho, and Reis, 2011), particularly when performed with a single goal (protection, for example). Using a cost–benefit analysis of the coastal defences in two cases, Maia, Bernardes, and Alves (2015) conclude that the costs associated with the presence of such structures substantially reduce the benefits.

It is therefore crucial to discuss forms of social and economic intervention that are acceptable to stakeholders and local communities more clearly and in greater depth. However, coastal managers and policymakers should make effective and timely decisions on the use of appropriate adaptation measures for the immediate and longer term. In other words, decisions should be made on the measures to be implemented with the objective of providing benefits immediately. These measures should also be effective enough to face future challenges.

Keeping all these problems in mind, an ideal approach to the planning and management of coastal zones must include the production of well-integrated action plans and emergency plans, in addition to monitoring systems and implementation of emergency alert systems. A traditional methodology developed by the Intergovernmental Panel on Climate Change (IPCC, 1992), commonly known as the common methodology, can be used for this purpose (Sterr, Klein, and Reese, 2003; Vellinga and Klein, 1993). This methodology is based on seven successive steps and considers potential impacts on populations, economies, and ecological and social assets.

In this planning process, public participation is crucial. This is a learning process that should involve discussions amongst a multitude of actors: public institutions (local, regional, and national), coastal managers, scientists (engineers, geologists, biologists, economists, and sociologists), nongovernmental organisations, investors, stakeholders, and coastal communities.

Past Guidelines for Protecting the Portuguese Coast

The Portuguese Atlantic coast is an energetic environment. Waves often reach significant heights of 2 to 3 m. Significant heights of 9 m or more are achieved during storms, and such conditions can persist for up to 5 days (Rosa-Santos *et al*., 2009). Examples include the storms Rafael, Hercules, Stephanie, and Joaquin, which occurred in October 2012, January 2014, February 2014, and September 2015, respectively (León and Soares, 2015; NOAA, 2017).

This scenario is aggravated by the serious problems that result from the increasing urban occupation of these areas, which has resulted in considerable degradation of many natural protection systems. Simultaneously, activities and interventions of anthropogenic origin (such as the construction of dams, sand extractions in rivers, and dredging operations in ports) have contributed to major disturbances in these systems, notably through significant reductions in the sediment they receive.

The policy adopted in Portugal until the 1990s, which provided a measure of coastal protection, relied almost exclusively on the construction of hard engineering structures and largely employed groyne fields. At that time, hard protection structures were in widespread use in shorelines experiencing erosion without beach nourishment schemes. As pointed out in Taborda, Magalhães, and Ângelo (2005), this strategy was not because of the lower cost of these structures, whether in terms of their construction or in terms of monitoring, because cost–benefit analysis practises have only been adopted relatively recently in this field.

Until the 1990s, coastal defence works in Portugal were generally of the hard engineering type (design and construction), and the concerns were physical. As in many other countries at that time, the decision maker hired an engineer to analyse the coastal issue, produce a design, and supervise its implementation (Kamphuis, 2005). That is, no environmental concerns were considered, no environmental impact studies were carried out, the degree of information and communication was limited, and the scientists involved were almost exclusively engineers. Moreover, engineering works were often implemented to address emergency situations; therefore, no

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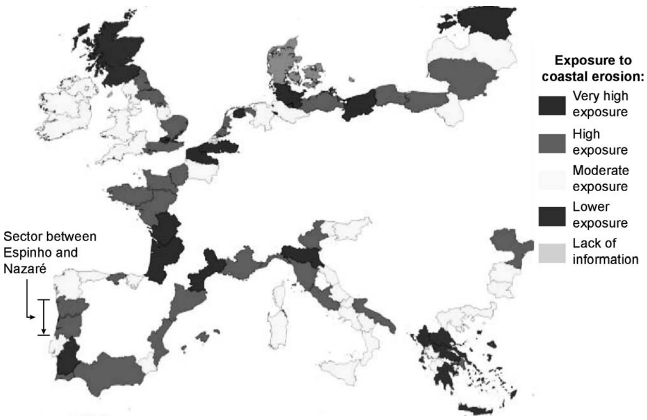

Figure 1. Exposure of European regions to coastal erosion (the coastal regions shown in colour belong to different countries of the European Union with maritime borders). It is shown that most European coastal zones experience moderate to high vulnerability (adapted from Doody *et al.*, 2004). (For interpretation of the reference to colour in this figure, see the web version of this article.)

planning studies or analyses of alternative solutions were carried out.

In parallel with the mandatory compliance with European Union guidelines, this trend began to change in the 1990s, and some alternative solutions have been tested successfully. These solutions are detailed later in 'New Protection Paradigm for the Portuguese Coast.'

After demonstrating several events along the Portuguese coast that require global adjustment actions, this work aims to systematise possible structural and nonstructural management tools for decision making in the context of current integrated coastal zone management practises. Having detailed these concepts, the work proceeds with a brief reference to successful practises carried out in different parts of the world and considered relevant to the Portuguese context. Finally, examples of adaptation measures successfully implemented along the Portuguese coast are discussed.

THE ATLANTIC COAST OF PORTUGAL

The European shorelines are quite threatened (see Figure 1, which is adapted from EUROSION; Doody *et al.*, 2004), largely because of anthropogenic activity. Climate change will aggravate coastal erosion further; rising sea levels, increased storminess, changes in prevailing wind directions, and higher waves will place Europe's coast under additional pressure. A map presented in Greiving *et al.* (2013) shows that the physical assets in Europe that are most sensitive to extreme weather events like flash floods and coastal storm surges are mainly concentrated along the coastline. In addition, according to the ESPON Programme (Greiving *et al.*, 2013), the populations that are sensitive to river flooding, coastal flooding, flash floods, and heat are mainly concentrated in Southern European agglomerations and along the coastline. Consequently, most European coastal areas are in a situation in which they have some degree of vulnerability, whether existing or potential.

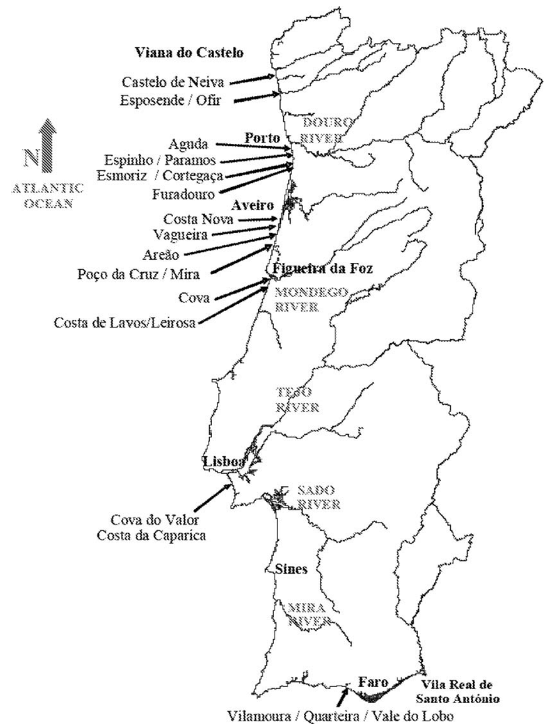

Figure 2. Locations of the most important hard protection defences (mainly groynes and sea-walls) built up to the 1990s in the western Portuguese coastal zone (shown on the left side of Figure 1) (adapted from Rosa-Santos *et al.*, 2009).

Portugal is a southern European country with an extensive Atlantic coastline (Figure 1). The extremely energetic climate of the Atlantic thus affects the west coast of Portugal, making it particularly vulnerable. The sector of this coastal area that is most affected by erosion phenomena is shown in Figure 1 by dashes with an arrow in the lower left portion of this figure. This stretch is located between Espinho and Nazaré and extends along the shoreline for approximately 160 km. According to the ESPON Programme (Greiving *et al.*, 2013), this is a region where climate change is expected to have moderate to severe environmental impacts. The ESPON Programme has also stressed that this region has low potential for adaptation and mitigation. Several urban areas located in this region are artificially protected by groynes and seawalls. Figure 2 shows the most important hard protection works (mainly groynes and seawalls) built in the years before the 1990s to protect the most important waterfront areas. The sector from Porto to approximately 20 km south of Figueira da Foz (Rosa-Santos *et al.*, 2009) is particularly notable.

The great vulnerability of the residential areas of Esmoriz, Cortegaça, and Furadouro, which lie within this coastal zone (Figure 2), has been particularly pronounced since the middle of the last century. The first hard protection works built along this stretch of coastline date back to the 1940s and were reinforced with the construction of new groynes and seawalls in the 1980s and 1990s. Because the solution was put into practise

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Figure 3. NW coast of Portugal. The urban fronts of Esmoriz and Cortegaça, in the southern part of Porto, are stabilised artificially, are deprived of sediment, and thus do not permit bathing (courtesy of Lopes, 2010).

at that time, today these urban centres can only be maintained at the expense of hard engineering works (Figure 3).

Also, the low-lying areas located to the south of those urban centres and composed of unconsolidated sediment (including sands), and especially forest areas without natural protections, such as dunes, are being eroded. The rate of coastal retreat is a few tens of metres per year (Figure 4).

Other urban centres located in this sector are protected by beaches and sand dunes with obvious weaknesses; some of these beaches and dunes are even experiencing conditions of imminent risk (Figures 5 and 6).

A large intervention carried out on the beach and in the dune system of Furadouro during the second half of the last decade allowed the recovery of the urban front and the rehabilitation of the dunes and the beach. This issue is further detailed in 'New Protection Paradigm for the Portuguese Coast.'

The Mira beach sector represents a more worrying situation, because only a few reinforcements of the most vulnerable areas of the frontal dune have been carried out in recent years. These reinforcements were only implemented as a result of storm damage, such as the storms that occurred in 2010 and 2014.

The situation of great vulnerability noted in 2003 (Figure 6) remains today. Rehabilitation of the dune system and reinforcement of the existing groynes are planned. Possible additional protections, such as submerged, detached breakwaters, are also expected. An investment of between € 10 million and € 18 million in this region is expected over the next 10 years, depending on the scenario considered (Costa and Coelho, 2013; Santos *et al.*, 2014).

Many of the previously mentioned weaknesses result from the energetic coastal dynamics that occur along the western Portuguese coast. The coast of Nazaré, at the lower end of the sector shown in Figure 1, is particularly affected by energetic waves. This city is known for the occurrence of 'giant waves'. It is an extremely popular place for surfing, making these waves an additional attraction. These waves reach heights of 30 m or more (Figure 7) and occur because of the existence of the Nazaré canyon, which is the largest submarine canyon in

Figure 4. Cortegaça coast, to the NW of Portugal, which experiences erosion and rates of coastal retreat of some tens of metres per year. This is a low-lying area composed of unconsolidated sediment, such as sand, without natural protection (courtesy of Coelho, 2015).

Europe and one of the largest in the world (Cunha and Gouveia, 2015). The coast of Nazaré does not present a situation of concern in terms of erosion, but the existing beaches are systematically deprived of sand by the deeper zones, forcing the annual artificial nourishment of the beaches.

The weaknesses of the Portuguese coastal sector located between Espinho and Nazaré demonstrate the need for implementation of adaptation measures. The most appropriate measures will differ, depending on the objectives that are to be achieved.

However, most adaptation measures can help in achieving multiple objectives and benefits. Many coastal works, such as multifunctional submerged defences, are designed to produce benefits regardless of the effects of climate change. These measures must provide benefits today by addressing current vulnerabilities, provide benefits in the future by enhancing the

Figure 5. Urban front of Furadouro, Portugal. Until the middle of the last decade, the houses along this urban front were often hit by waves. The beach facilities here were frequently damaged, together with the support infrastructure (courtesy of Lopes, 2003).

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Figure 6. Mira region, Portugal, which is protected by a frontal dune where several cases of failure have occurred with increasing frequency. This is a low-lying region with much urban land situated below sea level during high tide conditions (photo dated January 2003).

ability of ecosystems and communities to cope with current environmental pressures and climate variability, and potentially provide a benefit whether or not the projected climate change becomes a reality.

WHAT IS LIKELY TO OCCUR IN THE FUTURE

Long water-level records (on the order of decades) at various points on the globe reveal no strong evidence for substantial deviation from a linear rate of sea-level increase (Parker, Saleem, and Lawson, 2013). A small decrease in the rate of sea-level increase is even detected in long-term tide gauge data sets. Other publications (Church *et al.*, 2013; Houston and Dean, 2011; Rhein *et al.*, 2013) have argued that the recent increase in sea-level trends represents a long-term change caused by ice melt and the subduction of heat below the upper layers of the ocean. As is well known, both phenomena tend to increase in magnitude over time.

Most coastal regions in Europe have experienced an increase in absolute sea level, as well as in sea level relative to the land, although there is significant regional variation (European Environment Agency [EEA], 2016). The EEA also reported that global mean sea-level increased by 19 cm from 1901 to 2013 at an average rate of 1.7 mm/y.

The literature also demonstrates that a global mean sea-level increase between 0.60 and 1.90 m from 1990 to 2100 would require accelerations of 0.07 to 0.28 mm/y^2 (Houston and Dean, 2011). Published results show relatively large sea-level increases in the western Pacific at Guam, Midway, and Kwajalein contributing to accelerations of 0.2546, 0.1382, and 0.1060 mm/y^2, respectively. Values of this order of magnitude were also obtained by Ezer, Haigh, and Woodworth (2016). Sea-level rises of 2.76 mm/y and accelerations of 0.10 to 0.13 mm/y^2 have been estimated for Dublin, Ireland, from 1938 to 2009.

As noted by the IPCC (2007), an increase in global mean temperature from 1906 to 2005 of 0.74°C has not yet produced

Figure 7. Giant wave reaching the Nazaré headland, Portugal: (A) 2013 and (B) 2016. In this place in January 2013, Garrett McNamara broke his own world record by surfing an estimated 100-foot (30-m) wave (Cunha and Gouveia, 2015; Fletcher, 2016).

acceleration of the global sea level; a significant increase in temperature, as expected, will have consequences at this level. Apparently, however, a study of the processes recorded by long-term tide gauge records is not necessarily a good indicator of future circumstances. Long-term tide gauge records describe a past that has undergone many changes caused by natural and anthropogenic agents. Most of these changes are recent and will express themselves to a greater degree in the near future. In addition, climate change is on the agenda, and its consequences will be felt most strongly after the 2050s.

Additional contributions from sources such as Greenland and Antarctica, amongst others, should not be minimised. It is common knowledge that these ice sheets will contribute to the increase of the global mean sea level. Only growth rates and their spatial distributions remain somewhat unclear. Developing coastal plans based on a scenario for the 21st century with conditions similar to those experienced during the past century would be unwise.

The proof that something is changing is provided by the significant increase in the number of storms in the Atlantic Ocean beginning in the mid-1990s, as reflected by the chart shown in Figure 8. This bar chart shows the number of named storms and hurricanes per year from 1851–2010 (Wikipedia,

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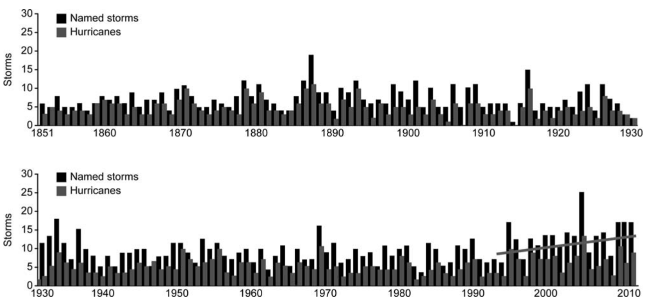

Figure 8. Number of named storms and hurricanes in the Atlantic Ocean per year between 1851 and 2010. A significant increase in the number of storms that occurred beginning in the 1930s and linear growth apparent beginning in the mid-1990s are shown (adapted from Wikipedia, 2016).

2016). A significant increase in the number of storms that occurred from the 1930s and linear growth relevant from the mid-1990s are clearly shown. This significant increase since 1995 has been highlighted by Saunders and Lea (2008).

Evidence that the climate is changing can also be obtained from the evolution of the intensity and size of storms that occurred in the Atlantic before 2015. In general, the intensity of tropical cyclones is assessed in terms of a storm's maximum sustained winds or the lowest barometric pressure at its centre. The 10 most intense hurricanes that occurred in the Atlantic before 2015 in terms of lowest barometric pressure are shown by the U.S. National Hurricane Center (NHC, 2016). Regarding the sizes of storms, the existing records also show a significant increase in recent years. The five largest hurricanes (by gale diameter) ever observed in the Atlantic basin are also shown in NHC (2016).

These findings show that 5/10 (50%) of the most intense hurricanes occurred in the Atlantic in living memory and 4/5 (80%) of hurricanes with a diameter greater than 1295 m occurred in this century, after 2000. Thus, records of the number, intensity, and size of these events show a significant increase in the destructive power of storms. Global climate change will tend to aggravate this trend. Increases in Category 4 and 5 tropical cyclones, hurricanes, and typhoons during the 20th century have been reported (Webster *et al*., 2005).

According to IPCC (2014), the increase in global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 and under representative concentration pathways (RPCs) is likely to be as follows: 0.3 to 1.7°C under RCP2.6, 1.1 to 2.6°C under RCP4.5, 1.4 to 3.1°C under RCP6.0, and 2.6 to 4.8°C under RCP8.5. In addition, in agreement with IPCC (2014), the Arctic region will continue to warm more rapidly than the global mean. Figure 9 shows central estimates and likely ranges for projections of global average temperatures determined by multimodel simulations under RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (IPCC, 2014). All changes are relative to 1986–2005. A 0.5°C increase in sea surface temperature is associated with a 40% increase in hurricane frequency and activity (Saunders and Lea, 2008).

According to IPCC (2013), there are as yet no complete simulations of regional ocean temperature changes near the ice sheets or of ice-sheet responses to realistic climatic forcings.

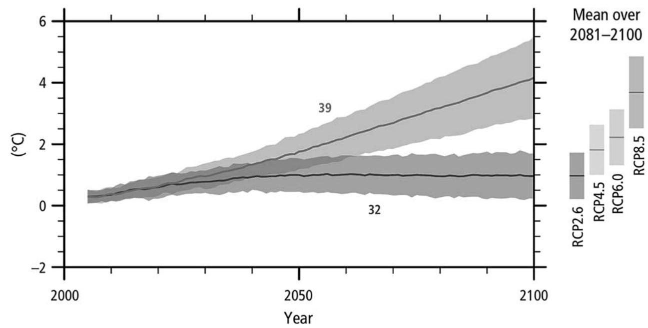

Figure 9. Global average surface temperature changes from 2006 to 2100. Central estimates and likely ranges for projections of global average temperatures determined by multimodel simulations under RPCs are shown (adapted from IPCC, 2014). RCP2.6, RCP4.5, RCP6.0, and RCP8.5 are four greenhouse gas concentration (not emission) trajectories adopted by the IPCC for its Fifth Assessment Report, which was published in 2014 (Moss *et al*., 2008). These scenarios indicate possible radiative forcing values in 2100 relative to preindustrial times (+2.6, +4.5, +6.0, and +8.5 W/m^2).

However, publications to date allow an assessment of the likely range of sea-level rise for the 21st century. Figure 10 shows central estimates and likely ranges for projections of global mean sea-level rise under RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Estimates are relative to 1986–2005.

Rising sea levels pose a serious threat to countries whose coastal areas have high population densities. Figure 10 shows that such effects will be felt with particular intensity in the midterm (within three to five decades). However, sea-level rise is not the only cause of growing vulnerability. Other factors, such as storms, wave climate, and lack of sediments to the coast imply a current need for major adaptation measures. This is the case in Portugal, where two-thirds of the population live less than 50 km from the coastline.

These factors increase the vulnerability of exposed elements and, as a consequence, the risk. The vulnerability changes with the severity and type of hazard (tsunami, wave, storm, flooding, *etc*.) being considered. Vulnerability also depends on the area affected and changes over the duration of a disaster. Excluding the vulnerability of people, direct vulnerability (V) is assessed by comparing the value lost because of damage (loss to the element because of a hazard of a given type and magnitude) with the actual value of the element at risk:

$$\text{Vulnerability}, V = \frac{\text{Losses, or value of damage } (€)}{\text{Value, or construction cost } (€)} \quad (1)$$

A high exposure of people and goods increases the risk exponentially; however, because the number and value of elements at risk (people and property) may change significantly, exposure is also a time-dependent contributor to risk. By definition, risk (R) is the result of three causes that interact with one another: hazard (H), exposure (E), and vulnerability (V); considering the spatial and temporal aspects in assessing risk, they are combined using the following:

$$R_{ahp} = H_{ahp} \times E_{ahp} \times V_{ahp} \quad (2)$$

where, a = the area affected, h = the type of hazard, and p = the

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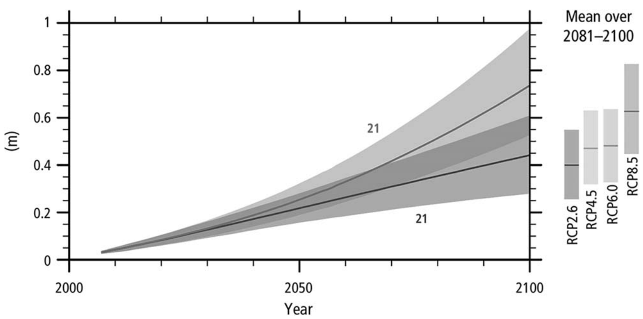

Figure 10. Global mean sea-level rise from 2006 to 2100. Central estimates and likely ranges for projections of global mean sea-level rise under RCPs are shown (adapted from IPCC, 2014).

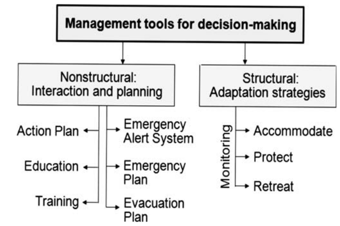

Figure 11. Management tools for decision making in coastal zones. Nonstructural measures occur essentially at the level of education and planning. Structural measures are used to accommodate and protect or to cause people and goods to retreat from potentially dangerous conditions or events.

period with a particular exposure or vulnerability or under the action of a different hazard. Therefore, to effectively reduce risk, it is imperative to reduce the effect of one or more of these causes (H, E, and V), considering time intervals throughout the potential disaster. Risk is often measured as the expected value of an undesirable outcome, and it relates probability and consequences:

$$\text{Risk} = (\text{Probability of the accident to occur}) \times (\text{Expected loss in case of accident}) \qquad (3)$$

The risk can thus be understood as the process of identification, analysis, and either acceptance or mitigation of uncertainty in decision making by coastal managers. This same concept can be applied to residents and stakeholders, who are generally able to accept some degree of uncertainty in terms of their knowledge of the benefits that can result from a given intervention or investment. The degree of acceptance of risk depends on the knowledge that stakeholders and residents have regarding their goals (how, when, and why) and their involvement in the interventions to be conducted.

WHAT CAN BE DONE

All actions to be taken in the coastal zone must be properly planned, bearing in mind the objectives of sustainable development and the conservation and valuation of resources. However, to be successful, they must be understood and well accepted by all stakeholders and local communities. In Portugal, these needs are duly reflected in the document titled National Strategy for Integrated Coastal Zone Management (RCM, 2009), which has recently been approved and is in force as a law. This document establishes principles and defines objectives, such as (1) the conservation and validation of resources, (2) the management of risks, (3) environmental impact studies, (4) the sustainable development of coastal activities, (5) the enhancement of scientific knowledge on coastal ecosystems and landscapes, (6) the enhancement and reinforcement of institutional communities, (7) mechanisms and networks for monitoring and observation, and (8) the promotion of public participation and social awareness (Veloso-Gomes, 2011).

Assessing coastal vulnerability resulting from different actions, such as climate change, sea-level rise, coastal erosion, coastal pollution, and human activities, is on the agenda and is of utmost importance for coastal managers. In the short term, it will be necessary to implement actions to contain the effects of such negative factors. It is therefore urgent to implement adequate and reliable assessment methodologies for decision making by coastal managers. Such decisions should be based on guidelines and management tools prepared in advance, starting with sectoral and local or regional plans of action, which are later integrated in action plans that have a wider scope.

Structural and Nonstructural Management Tools

The management tools that should be prepared and made available for decision making in any action or intervention to be conducted in the coastal zone are of various types and have differing priority levels; these tools are summarised in Figure 11.

Structural adaptation measures are used to accommodate and protect or to cause people and goods to retreat from potentially dangerous conditions or events. These measures can be highly effective when used properly, but they can be overcome by events beyond their design capacity. Some structural measures also transfer the risk of erosion and possible flooding, reducing the risk in one location but increasing the risk in another; such is generally the case with some hard engineering works, particularly groynes and breakwaters (especially if they are detached and emerging; Jha, Bloch, and Lamond, 2012).

A monitoring programme of the conditions before and, when extended in time, after any structural intervention provides data on the effectiveness of the project. Consequently, a monitoring programme should be required for all adaptation projects and factored into the life-cycle cost of every project (Seymour *et al.*, 1996). This issue is addressed in a narrow sense here, following an intervention. However, monitoring is broader and should also be seen as a preventive measure. The complexity of coastal morphodynamic processes makes it advisable to implement comprehensive monitoring programmes to measure sea-level rises, storminess, erosion rates, *etc*. Otherwise, it is not possible to plan efficient adaptation measures.

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Table 1. *Structural adaptation measures used in coastal zones. Depending on the social, environmental, and economic values to be protected and the emergency being considered, either hard or soft solutions will be chosen. Hard solutions are generally more expensive but more effective in the short term, whereas soft solutions are generally less expensive but more effective in the long term (adapted from PRC, 2015).*

Measure	Hard	Soft
Accommodate	Building on pilings; building emergency flood shelters, tidal or floating houses, and houseboats; adaptation of drainage systems	Early warning and evacuation systems, salt-tolerant crops, risk-based hazard insurance
Protect	Seawalls, groynes, breakwaters, dikes, jetties, saltwater intrusion barriers	Sand nourishment, building and rehabilitation of dunes, creation and restoration of wetlands, submerged breakwaters made of geotextile tubes
Retreat	Relocation of threatened buildings	Land use restriction and zoning, buffer zones

Nonstructural measures do not require large investments in monetary terms. These measures do not have a concrete physical form; instead, they require a good understanding of vulnerabilities and risks, as well as adequate warning systems and knowledge of the actions to be taken in emergency situations, and they result in the development of different types of plans (Figure 11). It is clear that education and training will play key roles in the sustainability of coastal zones in the coming generations. The development and implementation of educational programmes are the proper actions. However, such programmes will only be fully effective in the mid- to long term, on the order of a generation.

Effective decision making in the short term comes primarily from the development of a global action plan for protection and enhancement of the coastal zone. This plan should clearly identify the existing vulnerabilities and the potential risks along the coast. It should describe the manner in which the managers of the coastal zone will achieve their goals using detailed action steps that describe how and when decision making should occur. This plan should also include actions to be taken in the short, mid-, and long term, including a schedule of investments.

An action plan is meant to direct the development of policy at the regional or provincial level and to provide guidance for decision making at the local level. Municipalities should be positioned to implement adaptation measures through regulated planning processes and tools, such as municipal plans and coastal zoning.

In addition, for areas experiencing some vulnerability (current or potential), other tools must be developed, amongst which should be an emergency alert system, emergency plan, and evacuation plan. These plans would only be activated at the approach (or occurrence) of an extreme event and imminent risk to people and property.

An emergency alert system is a warning system that requires television and radio broadcasters, cable television systems, wireless cable systems, satellite digital audio radio services, wireline video services, and different service providers to allow communications broadcasts to the local public during an emergency. This system also may be used by regional authorities to deliver important emergency information such as missing children, alerts, and emergency weather information targeted to a specific area. Elements of emergency management planning include determining potential emergency situations and identifying appropriate responses to each situation. An evacuation plan details how to exit a place safely during an emergency. Every resident or visitor should be familiar with several routes by which to leave a place and should know a safe meeting place outside the area.

Adaptation strategies are used to accommodate and protect or cause people and goods to retreat from potentially dangerous conditions or events. Each adaptation strategy includes hard and soft options. Hard engineering options are generally more expensive, at least initially, and are more effective with regard to short-term protection. The soft options last longer, their costs are distributed over time, and they ensure safe conditions and long-term environmental sustainability. Table 1 summarises adaptation measures commonly implemented in coastal zones.

Hard protection was the most common approach to shoreline erosion problems during the past century in Portugal. However, there are many environmental disadvantages to groynes, seawalls, detached breakwaters, and other structures. They can induce down-drift erosion, increase beach reflectivity, or augment sand starvation, eventually causing a chain reaction that results in entire coastlines being fronted by protective structures. Moreover, investment and monitoring costs are high, monitoring is constantly required, and beach aesthetics are lost. Examples include the figures reported by Roebeling, Coelho, and Reis (2011) and updated by Maia, Bernardes, and Alves (2015) for the construction and maintenance of seawalls and groynes, respectively, within a period of 3 to 6 years after construction, which are € 10,125 per metre and € 12,671 per metre for investment costs and € 2282 per metre and € 2534 per metre for maintenance costs. Through a cost–benefit analysis, Maia, Bernardes, and Alves (2015) concluded that the benefits created by the construction of two groynes on the Portuguese coast were negative over the 4-year period between 1998 and 2002. They also made projections extending to 2020 for both cases and concluded that the costs associated with the presence of structures substantially reduce the benefits.

Soft protection techniques, such as beach nourishment and construction of artificial dunes, are attractive to coastal managers because they do not involve the construction of costly structures and the result appears more natural (Carter, 1988). These techniques are also generally considered to be less expensive and more effective over the long term (Basco, 1998; Bijker, 1989; Griggs, 1999; Houston, 1996; Koster and Hillen, 1995). Given that best practises in integrated coastal management require the implementation of good solutions for the present and with sufficient future sustainability, will the beach nourishment process, by itself, be an effective short-term solution?

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In general, soft protection techniques, such as beach nourishment and creation of buffer zones, are management measures that should be considered in any beach rehabilitation and improvement project. Nevertheless, beach nourishment has limitations or disadvantages, because it may have to be repeated regularly, often annually. Therefore, for this strategy to be successful, sand of the necessary quality must be available in quantity and at an affordable cost, which is not always the case. Often, other complementary measures should be implemented. It is not unusual for nourishment projects to be considered failures in which a substantial fraction of the sand is lost in a short period. There are several records of experiments in which a large proportion of the fill disappeared during the first year or during winter (Carter, 1988; Griggs, 1999). It is therefore critical to monitor the fill and the surrounding coastal area to determine whether they are performing as expected or, if not, what can be done to improve the performance of future interventions.

To overcome these problems, mixed solutions involving sand nourishment and complementary measures for sand maintenance, such as groynes and/or longitudinal detached submerged breakwaters made of geotextile material, have been used successfully. A submerged breakwater made of geotextiles can be an interesting and efficient strategy that enhances recreational beach activities, as well as protecting the coastal system (Schreck-Reis, Antunes do Carmo, and Freitas, 2008). Protection of this type can complement natural protection, such as that provided by a beach or dunes, and can be a long-term robust protection at the same time. In most countries with large coastal areas, such geosystems made of geotextile tubes, bags, and containers are increasingly playing a proactive role in coastal engineering protection works as eco-friendly constructions that provide alternatives to traditional engineering solutions.

The creation of buffer zones may also be a good option, particularly in areas that have previously become degraded or that are of little interest for urban development and tourism. However, when economic and social interests of high value are at issue, such solutions may imply significant losses, limiting effective implementation.

Of the adaptation options that have been implemented all over the world, some soft protection examples with recognised success should be highlighted. An innovative pilot project for coastal management implemented in 2011 on the Delfland coast is a reference model (Taal *et al*., 2016). This project consisted of the construction and monitoring of the Sand Motor, which is a peninsula covering 128 hectares. It was intended to contribute to coastal protection over the long term. Three objectives were delineated and assessed: dune growth, the creation of additional natural area and leisure facilities, and knowledge development. Different types of sand nourishment were examined, including the Sand Motor, which represents a meganourishment of approximately 18.7 million m^3 of sand. After 4 years, 95% of the sand used for the Sand Motor was still in the monitoring area, and 80% of that sand was still within the contours of the sand body created in 2011. The coastline is now located seaward of the base coastline. On this basis, the authors concluded that the lifetime of the Sand Motor will exceed 20 years. The authors also concluded that the construction of the Sand Motor has resulted in 'the creation of an additional appealing leisure and nature area on the Delfland coast' (Taal *et al*., 2016, p. 33).

Multifunctional submerged breakwaters built with geotextile sand containers (usually tubes) are relatively new kinds of coastal structures that can serve several purposes. A good example is the Narrowneck artificial reef constructed in 1999–2000 on the Gold Coast of Australia, which was intended to address goals including protection, beach enlargement, and generation of waves for surfing (Jackson *et al*., 2004). This submerged reef was installed with the placement of overlapping geotextile tubes filled with local sand. Periods with some erosion (especially after storms) and accretion were observed. By the end of 2004, the beach to the south (up-drift) of the reef was on the order of 40 m wider than at the commencement of the monitoring programme in 1999. In the lee of the reef, an additional 30 m had been maintained (Jackson *et al*., 2005). The beach was fairly uniform, with a width of approximately 50 to 60 m in May 2009, whereas the monitoring carried out in October 2011 displayed a beach width of approximately 70 m at Narrowneck and increased to 100 m at Surfers Paradise (Jackson *et al*., 2012).

To aid in protecting and enhancing the Young-Jin beach on the eastern coast of Korea, four submerged breakwaters were built using a two-line geotextile tube in each breakwater with diameters of approximately 3.5 m. A single geotextile tube is 50.0 m long and has an effective height of 1.8 m. Based on hydraulic model tests, a two-line geotextile tube with zero water depth above the crest is stable for significant wave heights up to 5.0 m (Oh and Shin, 2006). These submerged breakwaters have proven to be efficient, although a scouring effect caused by breaking waves developed at the geotextile tube situated on the sea side, as well as between the tubes. Two years after this intervention, the beach was enlarged by approximately 2.4 to 7.6 m towards the sea (Oh and Shin, 2006).

Proactive, Participatory, and Accountable Coastal Management

Implementing adaptation measures requires a careful analysis of the objectives to be achieved (protection, bathing, recreation, *etc*.), as well as the risks that can be assumed. According to the framework shown in Table 1, selecting an adaptation measure requires acceptance of the consequences, costs, and risks. In this context, the following issues should be thoroughly discussed by all actors (coastal managers, scientists, stakeholders, residents, *etc*.):

(1) Accommodation and acceptance of risk—Attempt to continue living in vulnerable areas: What is the risk? Is the risk acceptable?
(2) Protection at any cost—Attempt to continue living in high-risk areas: What are the consequences? Is soft protection sufficient? How long can safety be maintained?
(3) Retreat to a safer place—Effort to abandon vulnerable areas: How long will the additional margin of safety last? Are the costs acceptable?

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In general, this is a sequence of steps with increasing degrees of risk and costs. The option that is implemented is always a compromise amongst risk, costs, and environmental protection. Consequently, the first option to be considered should be accommodation, followed by protection, and finally retreat. Accommodation is not necessarily the cheapest option, but it is usually the option with the most favourable cost–benefit analysis. It is assumed that conditions that favour its implementation exist, such as a noncritical situation and available space and sediment.

However, the processes occurring in the coastal zone are dynamic, and the best adaptation response will rarely involve a single, stand-alone measure. To respond to the range of impacts, a combination of measures that work together in a complementary fashion is required, as shown later.

Based on the criteria suggested by Tobey *et al*. (2010b), five key criteria are proposed for deciding upon the adaptation option that best suits the local context. These criteria are technical effectiveness, costs, benefits, implementation, and monitoring. The adaptation measure that is most consistent with the set of answers to the relevant questions for each of the criteria should be implemented, possibly after some form of weighting is used. The relevant questions are as follows:

(1) Technical effectiveness: Will the adaptation option be effective in solving the problems arising from climate change while meeting current development or management goals?
(2) Costs: What is the cost of implementing the adaptation measure? What are the maintenance costs? Are there sufficient financial resources?
(3) Benefits: What types (and magnitudes) of benefits will be generated by the adaptation measure, and who will benefit?
(4) Implementation: How easy is it to design and implement the option in terms of the level of skill required, the information needed, and the scale of implementation?
(5) Monitoring: Are management tools and technical resources available that are adequate to assess the behaviour of the adaptation measure and to adjust responses?

These criteria will have weights that depend on the site and the adaptation measure under discussion. Of note is the great importance of involving residents and all potential stakeholders. For equivalent solutions, this process can be completed with integration of a SWOT analysis (a technique for understanding strengths and weaknesses and identifying opportunities and threats). In this case, the final balance should be the outcome of further analysis of the strengths and weaknesses inherent in these solutions, which necessarily involve cost–benefit analyses that cover other, more specific aspects.

The discussion can be extended so that it considers not only a present isolated measure but also the possible sequence or combination of measures. In selecting the best combination, it helps to look for interdependencies between individual measures and the benefits of those measures for good coastal management (Tobey *et al*., 2010a; USAID, 2009). As with the physical processes, the adaptation process is dynamic; that is, the initial option will change over the years, depending on needs. Figure 12 illustrates possible adaptation measures that might be implemented to address increases in sea level at various stages.

This figure shows that it is recommended to work with natural processes to reduce risks whenever possible while allowing natural coastal change (the lower case). Advancing the existing defence line by constructing new defences seaward (dunes) is the second stage from the bottom. If necessary, a third phase comprises holding the existing defence line by maintaining or changing the standard of protection (third stage from the bottom). Finally, a new line of defence must be identified (fourth stage from the bottom). If there are no housing losses or other significant losses, no intervention in coastal defence is required (the first case shown).

NEW PROTECTION PARADIGM FOR THE PORTUGUESE COAST

Within the framework of the National Strategy for Integrated Coastal Zone Management (RCM, 2009), the current coastal protection policy in Portugal is no longer based on hard protection structures. Most interventions are now dedicated to the maintenance or redesign of existing structures. New structures are only occasionally built to provide support to artificial nourishment projects.

Accordingly, several adaptation options have been tested on the Portuguese coast. The artificial nourishment of beaches and the rehabilitation of the dune systems of Furadouro, Vagueira, and Mira, which lie in the sector between Espinho and Nazaré shown in Figure 1; the Costa da Caparica beach near Lisbon; and the beaches of Vale de Lobo and Pine Cliffs in Algarve are successful examples. Some of these examples are described later. In addition, the rehabilitation and protection of the Leirosa dune system is described as a successful example that can be followed in other dune systems with identical characteristics.

Beach and Urban Front of Furadouro

Following the events recorded in Figure 5, works that included environmental requalification of the beach and reinforcement of the dunes were carried out. These works included artificial nourishment of the beach with sand and rehabilitation of the dune system. As a complement to the artificial sand nourishment operations, the existing support works were reinforced. Specifically, two groynes were installed to contain the sand in the beach, and a seawall was constructed to dissipate the energy of waves and protect the urban front. In addition, the pavement and sidewalks at the beach's edge, the beach supports and the drainage system were improved. The estimated cost of these operations was determined to be € 2 million in 2009.

Artificial sand nourishment operations and adequate monitoring of infrastructure that has already been installed, which have a cost of a few hundred thousand euros per year, have prevented greater losses, in particular those that would have resulted from the storms that struck the Portuguese coast in 2010 and more recently in 2014. Figure 13 shows perspectives

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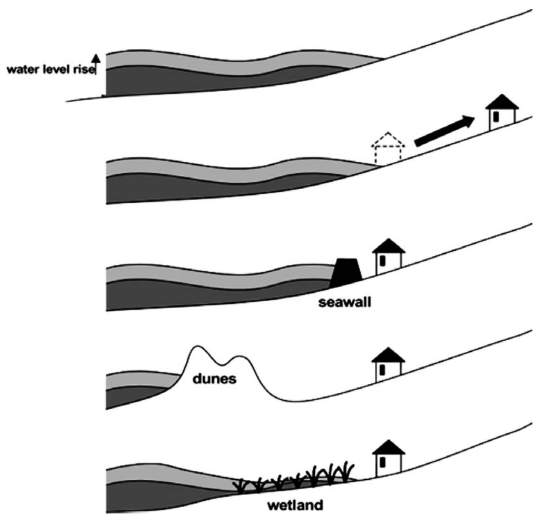

Figure 12. Temporal sequence of adaptation strategies in coastal zones (upwards). It is shown that whenever possible, working with natural processes to reduce risks while allowing natural coastal change is recommended (adapted from Doody *et al*., 2004).

Figure 13. Beach (A) and urban front (B) of Furadouro. Despite the damage to the beach supports and the sand losses that occur every year and are caused by coastal dynamics, regular artificial sand nourishments have allowed the beach to remain wide and pleasant with a favourable cost–benefit ratio.

of the beach and urban front of Furadouro after the artificial sand nourishment and repair of the damages caused by the storms Hercules and Stephanie in winter 2014.

Costa da Caparica Beach

The Costa da Caparica beach is located in the southern part of Portugal near the mouth of the Tagus River. Sand losses from the beach and dune have been taking place for a long time. As a protection measure, a groyne field was built in the middle of the last century. This protection strategy allowed the coastline to remain more or less stable until the late 1990s. However, with urban growth, the pressure on the coast increased considerably at that time, and alternative protection measures became necessary.

A new protection strategy was then approved that consisted of dune and urban seafront rehabilitation and artificial sand nourishment of the beach and dunes with approximately 3 million m^3 of sand (Veloso-Gomes *et al*., 2009). A monitoring programme was implemented, and the sediment balance was carried out regularly. The coastline was also measured. To compensate for sand losses, which were less than 1 million m^3 between 2001 and 2008, other artificial sand nourishments were made. The overall balance of this strategy is clearly positive in terms of economic (investment and monitoring), environmental, leisure, and tourism considerations. The dialogue among authorities, the contractor, local communities, and stakeholders was a key factor in the success of the intervention (Veloso-Gomes *et al*., 2009).

Other artificial sand nourishments have been carried out to replace the few hundred thousand cubic metres per year that are lost from approximately 2 km of beach. In recent years, substantial (about 1 million m^3) artificial sand nourishment was only required in 2014, following the violent storms that struck the Portuguese coast (storms Hercules and Stephanie). Damages were significant that year, costing more than € 5 million, including the costs of the marginal strip and the rehabilitation of the existing hard structures. Figure 14A shows the beach deprived of sand in 2006, and Figure 14B shows the beach and its marginal strip after the works carried out in 2014. The width of the beach has increased relative to the beginning of the artificial sand nourishments, and the coastline remains substantially stable (Figure 14).

Beaches of Vale do Lobo and Pine Cliffs in Algarve

The most common protection strategy on the Algarve coast of Portugal is artificial sand nourishment, which is sometimes supported by hard structures, such as groynes, or soft works, such as tubes made of geotextile material, to retain sand on the beaches. Given that this is a tourist region, the major policy option adopted is clearly to hold the line, and significant public and private investments have been made to achieve this goal.

A successful example of beach nourishment is Vale do Lobo beach, which is located at Quarteira, between Albufeira and Faro, approximately 5 km east of Vilamoura. In the first phase, about 700,000 m^3 of sand were added to the seaward-facing edge of the beach. The sand was obtained from an area located approximately 4 km from the beach and at a depth of about 20 m. The estimated cost of this operation was evaluated at € 3.2 million. Some sand is lost and replenished annually but in significantly smaller amounts.

The Pine Cliffs beach is located between Albufeira and Quarteira, approximately 25 km from Faro. It is another successful example, and its special characteristic is that geotextile tubes have been used to contain the sand on the

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Figure 14. Views of the Costa da Caparica beach deprived of sand in 2006 (A; courtesy of Alveirinho Dias) and the beach and its marginal strip after the last major intervention in 2014 (B). This arrangement has remained substantially constant since 2010, with only some interventions in the support structures and the replacement of small amounts of sand that are lost annually (a few hundred thousand cubic metres per year from approximately 2 km of beach).

beach. These tubes were filled with a small amount of the same sand dredged offshore for beach nourishment. Figure 15 shows the geotextile tubes, which have been properly installed. In this case, some sand is lost and replenished annually but in quantities that are smaller than those that would occur without the complementary protection.

Leirosa Sand Dune System

This dune system is located south of Figueira da Foz, midway along the Portuguese coast (Figure 2). It has long suffered from erosion and was highly degraded at the end of the last century. The recovery of this dune system began in 2000 with artificial reconstruction, followed by the replanting of the foredune with *Ammophila arenaria,* as shown in Figure 16.

A monthly monitoring plan was set up to assess the development of the rehabilitated sand dune. After only a few months, several dune species started to colonise the area,

Figure 15. View of the Pine Cliffs beach after artificial sand nourishment. To reduce the amount of sand lost annually, tubes made of geotextile material filled with sand have been used for sand maintenance on the beach.

meaning that the system was beginning to stabilise. However, in February 2001, during a storm that struck all of central Portugal, especially the coast, the oceanic front of the Leirosa dune system was destroyed.

As a consequence, an alternative solution was implemented in 2005 to stabilise the Leirosa sand dune system. This solution consisted of placing geotextile containers filled with sand. Figure 17 illustrates the technique, which involves placement of the sand containers in layers. Once the sand containers were in place, this protection barrier was covered by a 1.0-m layer of sand, which was planted with dune vegetation (Antunes do Carmo, Schreck-Reis, and Freitas, 2009; Schreck-Reis, Antunes do Carmo, and Freitas, 2005, 2008).

Figure 17 also shows the installation of large geotextile tubes filled with a suspension of sand and water that were placed, during the second stage, at the bottom of the existing structure as protection for its toe.

The good performance of this technique is reflected by the dune front shown in Figure 18. This figure shows stabilisation of the protected extension and dune retreat outside this segment, which is a result of the erosive action of the littoral dynamics.

Although there have been some problems in the application of the geotextile layers, especially in some parts of the three bottom layers, these problems have been solved through the use of geotextile tubes to protect the toe (Antunes do Carmo, Schreck-Reis, and Freitas, 2009). It is believed that the work performed on the Leirosa sand dunes can become an important model to be applied in other dune systems with similar erosion problems.

In any case, given that this environment is of medium energy, a hybrid solution is required to reduce the erosion of the entire dune system, which is approximately 1800 m in length. This solution should include the vegetated dune, the beach, and a submerged breakwater to reduce the wave energy towards the shore. Therefore, constructing a submerged artificial reef has been proposed, thereby avoiding the waves' breaking on the beach or dune. The reef, which is designed to be multifunctional, will be built with geotextile tubes filled with sand (Antunes do Carmo, Schreck-Reis, and Freitas, 2010). Numerical studies for this submerged structure have already been performed (Mendonça *et al.*, 2012a,b), and its installation is awaited.

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Figure 16. Reconstructed sand dune system in May 2000. To stabilise the sand, revegetation was performed with transplants of *Ammophila arenaria*.

Figure 17. Protection barrier and toe protection with geotextile tubes. Photo taken in July 2008, 3 years after installation of the geotextile containers. Despite some problems in the application of the geotextile layers, especially in some parts of the three bottom layers, which required an additional intervention with geotextile tubes for toe protection, the front dune is perfectly consolidated along the segment where the intervention has been performed.

FROM ADAPTIVE CAPACITY TO ADAPTATION

Future needs may lead to extreme adaptation measures. It is not too utopian to imagine that a future adaptation measure could involve the general use of floating houses. This accommodation measure is already traditional in some countries, particularly in Asia and in Europe, of which the cases of England and the Netherlands are noteworthy, with decades of experience.

It is understandable that living in the water is increasingly popular in the Netherlands. Because approximately two-thirds of the Netherlands is below sea level, the Dutch have had to find solutions for controlling, living, and working on the water. They have refined the process of building homes on the water, mostly using concrete hulls, over many years (Junak, 2016a). The houseboats at De Omval, Amsterdam, and another set on the River Amstel, just downstream from De Omval, are amongst the growing number of houseboats under construction in the Netherlands.

Also, in England, the construction of houseboats is growing progressively. Two examples of demand are the 60 houseboats situated on the north side of the River Thames, on Battersea Reach, and in the harbour at Bembridge, which is a natural lagoon that is perfect for floating houses, where there are approximately 25 houseboats (Junak, 2016b).

This adaptation measure may comprise relatively sophisticated floating houses, an example of which is the houseboat shown in Figure 19.

DISCUSSION

Once coastal adaptation measures are implemented, there will be considerable interest in how they perform, and policymakers will be keen to demonstrate that the measures are beneficial to the citizenry. All parties will expect the measures to be adjusted if they do not perform according to expectations. As evaluation results become available, policymakers, stakeholders, or the public may be motivated to press for changes in the choice of adaptation measures, their design, or their implementation (Tobey *et al*., 2010a).

For these interventions to be well accepted and proceed without misunderstanding, it is necessary for residents and stakeholders to become involved and accept the risk inherent in any adaptation measure from the outset. Experience has shown that the implementation of adaptation measures creates new challenges and potential conflicts. It must be kept in mind that response options that allow adaptation to climate change on the coast are often unpopular amongst stakeholders. Coastal professionals, stakeholders, and residents must be aware of the potential problems and address them proactively. In this context, there are many questions for which a coastal manager should seek answers, together with all involved actors:

(1) What is and what is not effective in the mid- to long term?
(2) How can residents and stakeholders be convinced to change their opinions or accept the adaptation measures?
(3) How can the financial resources accommodate the necessary investments?

In such a process of analysis and discussion of options, coastal managers should always be available to inform, listen, discuss, and respect all opinions. It is necessary to keep in mind the different perspectives and interests that often make it difficult to find a solution. The perception of risk by local communities tends to influence the design of coastal defence solutions considerably. A commonly widespread idea amongst communities residing within at-risk areas is that hard engineering provides better protection against coastal erosion and the associated risk of coastal flooding (Doody *et al*., 2004).

However, in general, stakeholders are available to support coastal interventions incorporating positive ecological and socioeconomic impacts for the environment and local commu-

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Figure 18. Photos of the dune system front taken in (A) September 2007, (B) February 2009, and (C) January 2013. The erosive effect on the dune front outside the protected segment has become increasingly pronounced over time.

nities. This is attested by a study conducted by Evans *et al*. (2017), which showed that stakeholders support the implementation of multifunctional coastal defence structures in place of traditional single-purpose ones. Still, according to this study, stakeholders recognise that the benefits to society provided by such structures could feasibly attract public funding.

In light of these principles, such procedures of engagement and dialogue with stakeholders and local communities have been adopted in most works conducted recently in the Portuguese coastal zone. The actions carried out in Costa da Caparica, which were described earlier, are a good example of cooperation and success. They show that dialogue among all involved agents (authorities, the contractor, scientists, local communities, and stakeholders) was of utmost importance.

Amongst all possible adaptation measures, a strategy based on artificial nourishment techniques coupled with regular and systematic monitoring is, in principle, a good option. However, to be able to implement a strategy of this nature, identifying sandbars that contain large quantities of sand that has the appropriate quality is indispensable. According to bathymetric surveys conducted on the Portuguese continental shelf at depths greater than the closure depth, which is on the order of 20 m on the Atlantic coast (IH, 2010a,b; Magalhães, 2003), the estimated volumes of sand allow an optimistic perspective on the quality and quantity of existing sedimentary reserves. In any case, in agreement with Santos *et al*. (2014), confirmation of this potential should be reevaluated based on highly accurate bathymetric surveys, lateral scanning sonar surveys, and high-resolution seismic profiles.

Figure 19. A type of houseboat that represents a possible adaptation measure to address coastal hazards and climate change that leads to rising sea level and flooding (Celebrity Sex Tapes, 2016).

Another problem, which is not always properly evaluated, lies in replacement sand added to the beach often being different from the natural beach sand. Small differences in grain size affect the way waves interact with a beach and can cause significant changes in beach shape. In general, the replacement sand that is added is dredged from areas on the continental shelf. This dredged sand may (and usually does) contain sand grains that are smaller or larger in diameter than those occurring on the natural beach. Moreover, after the artificial nourishment process, the sand material that has been added is less consolidated than the natural beach. As a consequence of these cumulative effects, the artificially replaced sand usually erodes faster than the natural sand of the beach.

In energetic coastal zones, such as the Portuguese Atlantic coast, artificial sand nourishment may not be sustainable in itself, at least immediately after the nourishment, and it is often necessary to adopt complementary measures to retain the sand. In Portugal, many of the hard structures (groynes) built in the past (Furadouro, Vagueira, Leirosa, Costa da Caparica, *etc*.) have been maintained or adapted for this purpose. Sand-filled geotextile tubes, either emerged or submerged, have also proven to be effective in the most appropriate settings in relation to the coastline (Narrowneck artificial reef, Young-Jin beach, Pine Cliffs beach, *etc*.).

The coastal anticipatory adaptation to the use of houseboats or other types of houses, such as building on pilings or the use of tidal and floating houses, should be understood as an adjustment by local communities to future changes, because

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of the expected rise in sea level that will lead to flooding, to reduce potential losses.

Apart from a few exceptions, such as those mentioned earlier, the use of houseboats is understood as leisure and for limited periods. At the household level, this adaptation measure is understood to represent a type of accommodation in which the available and pleasant spaces for housing, supporting structures, and existing behaviours are modified.

CONCLUSIONS

The increased risk of violent storms, rising sea levels, flooding, urban and agricultural land losses, and rapid population growth near the coast indicate an urgent need for adaptation measures in coastal areas.

Possible and preferred strategies include planning for climate risk and emergency management. These include nonstructural measures with the aim of managing urban growth that accommodates planned retreat, solving infrastructure issues, planning coastal spaces for adaptation (buffers), building adaptation into structures in low-lying areas, addressing different types of tourism, and planning shelter areas for tidal and floating houses.

The structural measures include protection as a possible type of coastal adaptation; this is the most common approach of adapting to coastal hazards in many regions. In some cases, the risk is so high that retreat may be the only possible option. Accommodation must be conceived as the first adaptation option to be considered. It is an alternative to protection in many regions, with environmental, social, and economic benefits in the midterm (a few years) and long term (more than a decade).

This study emphasizes the importance of integrating the local communities and all stakeholders into the process of decision making. Experience suggests a relational procedure based primarily on three dimensions: integrate, interact, and inform. Thus, the various actors should be considered part of the planning actions. They must be kept informed, be motivated, and stay active during the various stages of definition of the actions and measures to be implemented.

The results obtained in all cases of artificial nourishment of beaches carried out in Portugal in the last 15 years, in particular those described earlier, can be considered successful examples. In addition, the study of dune system rehabilitation conducted on the beach of Leirosa, Portugal, has shown that the strategy tested there has high potential.

Although there are still no sufficiently reliable results from Portugal of the use of geotextiles in submerged structures, whether built with the single purpose of wave energy dissipation (protection) or with multiple purposes (defence, surfing, fishing, diving, *etc*.), the submerged breakwaters built on Young-Jin beach in Korea and the Narrowneck multifunctional reef built in Australia are proof of the high potential of this technology. In addition, the numerical studies on multifunctional reefs conducted for Leirosa are encouraging. The benefits of this technology for coastal areas are recognised. However, taking into account the failures reported in the literature, the need to deepen its installation, develop better criteria and stability formulae, and improve the material characteristics is also recognised.

overall, this work presents several useful aspects for coastal managers that may help coastal communities in carrying out operational coastal management. Accordingly, the following points should be highlighted: (1) current and future vulnerabilities along the European Atlantic coast; (2) recent increases in the number, intensity, and size of storms in the Atlantic Ocean; (3) management tools for decision making in coastal zones; (4) nonstructural and structural adaptation measures in coastal zones; and (5) criteria for decision making.

The last three points are discussed in detail and constitute the important focus and novelty of this work. Participatory and accountable coastal management procedures are also addressed, in close connection with the criteria for deciding the best adaptation option. Finally, the recent paradigm shift in the management model and intervention procedures in the Portuguese coastal zone, with proven beneficial effects, stands out clearly.

ACKNOWLEDGMENTS

The author thanks Mota Lopes (Agência Portuguesa do Ambiente), Alveirinho Dias (Universidade do Algarve), and Carlos Coelho (Universidade de Aveiro) for providing photos and information. The author also thanks five anonymous reviewers for their improvements to this paper.

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