Influence of climate change on the Ria de Aveiro littoral: adaptation strategies for flooding events and shoreline retreat

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ABSTRACT

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Floods and shoreline retreat in coastal areas threaten many millions of people across Europe. Moreover, it is agreed that climate change can amplify the magnitude and frequency of flooding events and accelerate the shoreline retreat. The main goal of this work is to assess flood and shoreline retreat risk, and define adaptation strategies under present conditions and future climate change scenarios on the Ria de Aveiro and its littoral. The hydrodynamic model ELCIRC was implemented for the Ria de Aveiro lagoon and GENESIS (U.S. Army Corps of Engineers) and LTC (Long-Term Configuration) shoreline evolution models for the littoral stretch between Esmoriz and Mira. Numerical results in present and future scenarios were used to map the flooded lagoon extension and the shoreline evolution of this coastal stretch. Analysis showed an increase of the lagoon's flooded area, relative to the present, with regions more exposed to sea level rise being lowland areas located at the margins of the lagoon's deeper channels. Examination of the littoral stretch showed a slight increasing trend of shoreline retreat under predicted future climate change scenarios, thereby increasing the probability of sand spit rupture. Data from numerical predictions were integrated into Geographical Information Systems covering the coastal and lagoon study areas, and produced hazard and risk maps including the identification of regional use and activities. Structural and non-structural measures were subsequently developed in order to mitigate flood and shoreline retreat effects.

ADDITIONAL INDEX WORDS: *Numerical modeling, flood risk, coastal vulnerability, sea level rise. mitigation*

INTRODUCTION

Flood events are part of nature and one of the most common hazards all over the world. The shoreline retreat also endangers coastal areas worldwide. Together they threaten millions of people, goods and ecosystems. Management of flood and coastal erosion risk involves many different public and private entities worldwide, each accountable for different aspects of risk management. Ensuring the emergency services and public knowledge of where and when the flood or coastal erosion will occur and how serious these hazards will be is a very complex task. The minimization of damages caused by floods or coastal retreat involves reducing the likelihood of these hazards and their impacts when they occur. At the same time, there are underlying pressures that are increasing the risk, such as climate change, urban development or changes in land use.

In 2007, the European Union recognized the threats of floods and approved an European Directive (2007/60/EC) on the assessment and management of flood risk. This directive states that all member states must prepare flood hazard maps and flood risk maps for all water courses and coastlines and establish flood risk management plans to reduce the risk, taking into account climate change effects. In response, the scientific project ADAPTARia (http://climetua.fis.ua.pt/legacy/adaptaria/en/index.html) was developed to study the impact of climate change on flooding events and shoreline retreat in the Ria de Aveiro lagoon and its littoral (Figure 1). The lagoon is a shallow coastal system located in central Portugal exposed to fluvial and coastal flooding. The adjacent coastal stretch of Esmoriz to Mira has several coastal erosion problems with a high probability of sand spit rupture. The main goal of this work is to perform flood and shoreline retreat risk assessment and define adaptation strategies under present and future climate change scenarios. To achieve this target, the flood extension in the lagoon and the shoreline position under present (P) and future (F) climate conditions were estimated through numerical modelling. Then, the numerical results were incorporated into a Geographical Information Systems and vulnerability and risk maps were built. Finally, mitigation and adaptation strategies were designed for the region in order to minimise flood and shoreline retreat effects, aiming to reduce risk and mitigate the damages caused by these hazards.

STUDY AREA

The Ria de Aveiro is a shallow coastal lagoon located on the northwest Portuguese coast (40º38'N, 8º45'W). A sand spit separates the lagoon from the ocean in most of its extension,

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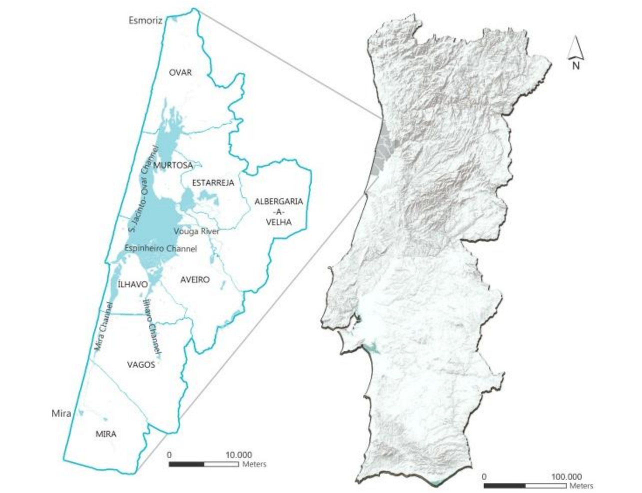

Figure 1. Location of Ria de Aveiro region, indicating the lagoon main channels and its municipalities.

except at the middle where the lagoon connects with the Atlantic Ocean through a single artificial inlet built in 1808. It is 45 km long and 10 km wide and covers an area of 89.2 km^2 in spring tide which is reduced to 64.9 km^2 in neap tide conditions (Lopes *et al*., 2013). The astronomical tidal range varies between a maximum of 3.2 m in spring tide and a minimum of 0.6 m in neap tide (Dias *et al.*, 2000). The meteorological tide, although infrequent, can reach a maximum height of ~ 1 m (Picado *et al*., 2013). When high tides and/or significant meteorological tide occur, certain areas adjacent to the lagoon are flooded, endangering agricultural productivity as well as the local biodiversity. In the Espinheiro channel, the Vouga River enters and represents approximately 2/3 of the overall lagoon fluvial input. The Antuã River enters into the Laranjo bay the, while at the heads of S.Jacinto, Ílhavo and Mira channels, the Cáster, Boco and Ribeira dos Moínhos Rivers enter respectively. The adjacent regions of the Vouga river mouth are flooded when its discharge is high. This area is called *Bloco do Baixo Vouga Lagunar* (BBVL), and presents unique biophysical characteristics that confer to this region high nature conservation and biodiversity values. For these reasons, Ria de Aveiro and its littoral are included in the Natura 2000 network as a Special Protection Zone.

The Esmoriz-Mira stretch is mainly a sandy coastal system, under a very energetic maritime wave climate. The wave climate presents a significant wave height of about 2 or 3 meters, with wave periods between 8 and 12 seconds. The significant wave height during storm events exceeds 8 meters, with wave periods from 16 to 18 seconds (Coelho *et al.*, 2009). Major storms reaching the Northwest Portuguese coast are from the Northwest quadrant. As a consequence of the wave climate, littoral drift currents act mainly in a North-South direction. This can easily be demonstrated by areas of accretion located north of groins and areas of erosion at the south (Coelho and Veloso-Gomes, 2006).

METHODOLOGY

The first step of this study was the application of the 2D hydrodynamic model ELCIRC (Zhang *et al*., 2004) to the Ria de Aveiro lagoon in order to determine the lagoon's flooded area and of the GENESIS (U.S. Army Corps of Engineers) and LTC (Long-Term Configuration) models to the Esmoriz-Mira stretch in order to predict the evolution of the shoreline.

Concerning the lagoon hydrodynamic simulations, the model configuration used was previously calibrated for tidal propagation by Lopes *et al*. (2013). Six runs were defined (Table 1), corresponding to combinations of different tidal ranges (TR), storm surge (SS), mean sea level (MSL) and fluvial flow (FF) conditions. Additionally, the model was run for mean tide conditions, without any other forcing, to define the reference conditions. Mean, spring and equinoctial tide conditions were determined from statistical analysis of tidal gauge data recorded at the lagoon entrance between 1976 and 2005. Storm surge amplitudes of 0.58, 0.84 and 1.17 m determined by Picado *et al.* (2013) for 2, 10 and 100 years return periods, respectively, are used. The fluvial flow for 2, 10 and 100 years return periods was determined at the five most important lagoon tributaries for both climates (Table 2), from daily discharges predicted by the watershed model SWAT. This model was forced with observed precipitation (1932-2010) for the present climate and with forecasted precipitation from ECHAM5 model for the future (2071-2100), considering the SRES A2 scenario from IPCC. A mean sea level rise of 0.42 m was adopted, corresponding to Lopes *et al*. (2011) local estimation for the end of the 21st century considering the SRES A2 scenario from IPCC.

The shoreline evolution simulations include coastal defense works at the studied stretches after all the necessary considerations related to their position, together with wave propagation effects and permeability, thus establishing the most appropriate calibration results. The initial shoreline position, defined as elevation +2.0 m (Cartographic Datum) required some adjustments in bathymetry and topography, being coincident with the position obtained by the satellite image of 2010 (Pereira *et al*., 2013). Two runs were defined, one considering the current mean sea level and wave climate and other considering the future mean sea level (0.42 m) and wave climate. The wave regimes used are presented in Pereira *et al.* (2013) and were determined based on the application of the WW3 wave model to the North Atlantic (Ribeiro *et al*., 2012). The two runs were forced by wind fields generated by the climatic model ECHAM5 for the reference (1971-2000) and future (2071-2100 – IPCC SRES A2 scenario) situations (Ribeiro *et al*., 2012). Following the guidelines of the Decree 115/2010 of October 22 – which transposes the EU Floods Directive (2007/60/EC) to the national law – the data from numerical predictions were introduced into a Geographical Information Systems along with thematic data (such as Census data, land cover, infrastructures, buildings, etc.). The results of the runs of flood extent for the lagoon (Figure 2) and shoreline evolution for the littoral stretch (Figure 3) were analysed and combined, resulting in a present (A) and a future scenario (B). These results were used to map the probability of occurrence, the vulnerability of the territory, and the risk of flooding and shoreline retreat for both scenarios. Finally, based on the risk analysis were proposed interventions to adapt, control, and manage the risk of floods in the lagoon and the risk of shoreline retreat.

Table 1. Summary of boundary conditions used in the hydrodynamic simulations.

	Run1	**Run2**	**Run3**	**Run4**	**Run5**	**Run6**
Tide	Mean	Spring	Equino.	Mean	Spring	Equino.
SS	2	10	100	2	10	100
MSL	P	P	P	F	F	F
FF	P-2	P-10	P-100	F-2	F-10	F-100

RESULTS AND DISCUSSSION

Lagoon marginal flooding

The flood extent maps (Figure 2) result from the identification, in model grid, of cells that were flooded along each tidal cycle. These maps show that changes to the lagoon flooding drivers resulted in different marginal flooded regions. Globally, the margins of the lagoon main channels are flooded under extreme events, mainly at the S.Jacinto and Espinheiro channels given their low altitude and reduced topography. It should be highlighted that under high fluvial discharges the flood extension increases at BBVL, as well as in other lowlands located close to the mouth of the lagoon tributaries. For the future climate, the marginal inundation tends to increase at the lagoon central area and around the lagoon main channels. Close to the mouth of the tributaries, the marginal inundation decreases as a consequence of the predicted reduction in fluvial discharge for the future climate.

Shoreline retreat

The shoreline retreat, the lost territory areas and the alongshore sediment transport volumes in several cross sections were determined from model predictions. An erosion trend was observed for both climates, with few exceptions in very short lengths (Figure 3). Strong erosion downdrift of the groins along this stretch is found for both runs. The maximum retreat after 90 years was recorded in the Labrego-Areão stretch, corresponding to about 400 meters, for the climate change scenario. The lowest retreat rates are located in the confined stretches of smaller extension, being therefore less susceptible to coastal erosion. Comparing the results for present and future runs, a slight clockwise rotation of the shoreline was predicted, increasing the average shoreline retreat rate by about 6% (Figure 3). Regardless of the considered runs, it was found that the areas south of Costa Nova and Labrego (located south of Vagueira) have the higher probability of sand spit rupture and therefore represent the most likely location for opening a new inlet between the lagoon and the ocean.

Vulnerability and flood risk

The first step was to integrate the results of the flood extent for the lagoon and of the shoreline evolution for the littoral stretch. In order to simplify the analysis, the model runs were reduced to a present (A) and a future scenario (B). The scenario A takes into account the current conditions of mean sea level, wave climate, fluvial discharge, storm surge and tidal range. The scenario B considers future climate change scenarios, taking into account the mean sea level rise combined with wave climate and fluvial discharge forecasts for 2100.

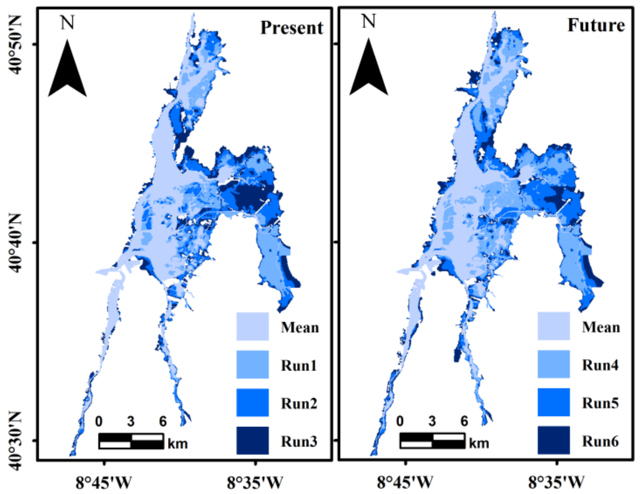

Figure 2. Lagoon flooded extent maps for each model run.

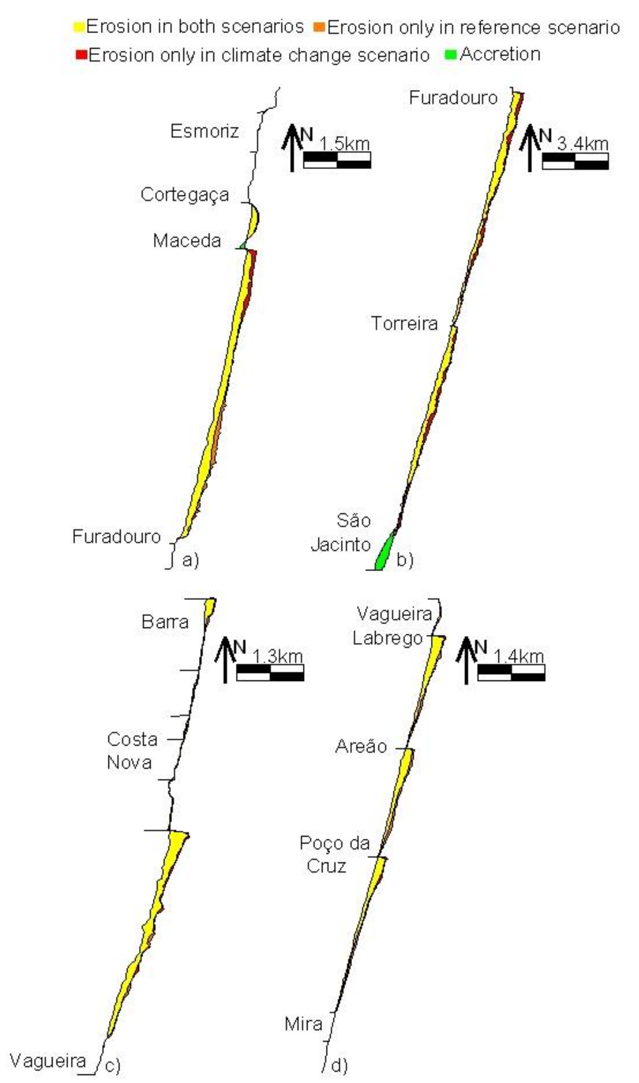

Figure 3. Territory lost until 2100, for both runs: a) Esmoriz-Furadouro; b) Furadouro-São Jacinto; c) Barra-Vagueira; d) Vagueira-Mira.

The probability of occurrence (Figure 4) of flooding in the lagoon was determined based on the return period of fluvial discharge and storm surge. For the coastal area, it was assumed that the largest retreats are less likely to be achieved (shoreline position in 2100 has a lower probability of being reached than the shoreline position in 2070, that has lower probability of being reached than shoreline position in 2040). Probability maps were built for each scenario, combining lagoon and coastal area results.

Vulnerability (Figure 5) is understood as the characteristics of a territory, which make it susceptible to degradation or damage (Barroca *et al.*, 2006; UNISDR, 2009) caused by flooding and/or shoreline retreat. Given the geographic scale of analysis, a correspondence between the degree of vulnerability and the 2006 CORINE Land Cover classes (Caetano *et al.*, 2009) was made. It was assumed that the vulnerability was:

- high in artificial surfaces;
- medium in agricultural, forest and semi natural areas, when they are subject to flooding by salt water, and whenever the shoreline reaches the lagoon;
- low in agricultural, forest and semi natural areas, when they are subject to flooding by freshwater;
- residual in wetlands and water bodies.

The risk map (Figure 5) results from the combination of the probability of occurrence with the vulnerability of the territory. This means that the risk is higher in areas identified with high probability and high vulnerability. This approach integrates both socioeconomic and ecological aspects of the territory.

Mitigation and adaptation strategies

The analysis of present and future flood risk in the lagoon and shoreline retreat risk in the littoral shows:

- increase of the lagoon flooded area – particularly in the alluvial plains – as result of the mean sea level rise, which is not nullified by the predicted decrease in fluvial discharge;
- increase in the average shoreline retreat rate (~6%), also increasing the threatening to the sand spit stability close to Vagueira settlement, as result of mean sea level rise and new wave climate.

Flood risk and shoreline retreat risk can be reduced by managing hazard characteristics, such as flood probability or extent, and/or by reducing the vulnerability of people and territory at risk. There are several measures that can contribute to control, adapt and manage the risk (Klijn *et al*., 2009):

- structural measures – intervene directly in biophysical environment. These can be hard (e.g. dikes, dams, groins), soft (e.g. recovery of water courses, beach nourishment) or mix (where direct physical adaptation interventions into nature structures are done through the application of specialized treatment techniques);
- non-structural measures - comprises the definition of policies and strategies (including the management of water resource), financial instruments (e.g. incentives and penalties) and communication strategies (e.g. public awareness, warning systems).

Table 3 summarizes the proposed interventions to adapt, control, and manage the risk of flooding in the lagoon and the risk of shoreline retreat.

CONCLUSIONS

This multidisciplinary work reports the influence of climate changes on the flooding of the Ria de Aveiro and on shoreline retreat of the adjacent littoral. This also incorporates proposals to reduce their adverse impacts. Globally, the lagoon's flooded area increases under predicted future climate conditions relative to the present; essentially driven by the mean sea level rise predicted for the region. Nevertheless, a reduction of the flooded extension was forecast close to the mouth of the lagoon tributaries, motivated by the reduction of fluvial discharges expected for the future. Regarding shoreline evolution, an increase of about 6% in the average retreat rate for the future, with a slight clockwise rotation of the shoreline is predicted. Erosion problems will induce a high risk of sand spit rupturing in the coastal stretch between Costa Nova and Mira, and consequently the opening of a new inlet in this stretch is predicted.

From the combined analysis of risk of flooding and shoreline retreat, the most critical situations and ensuing strategies to adapt to climate change were identified. These are within the framework of the Portuguese government international responsibilities, and developed in the frame of the national strategy for climate change adaptation. In this context the formulated proposals intend to anticipate the consequences of planned interventions, and incorporate the 'uncertainties' inherent to hazard and risk. This is particularly relevant for areas of significant socioeconomic and

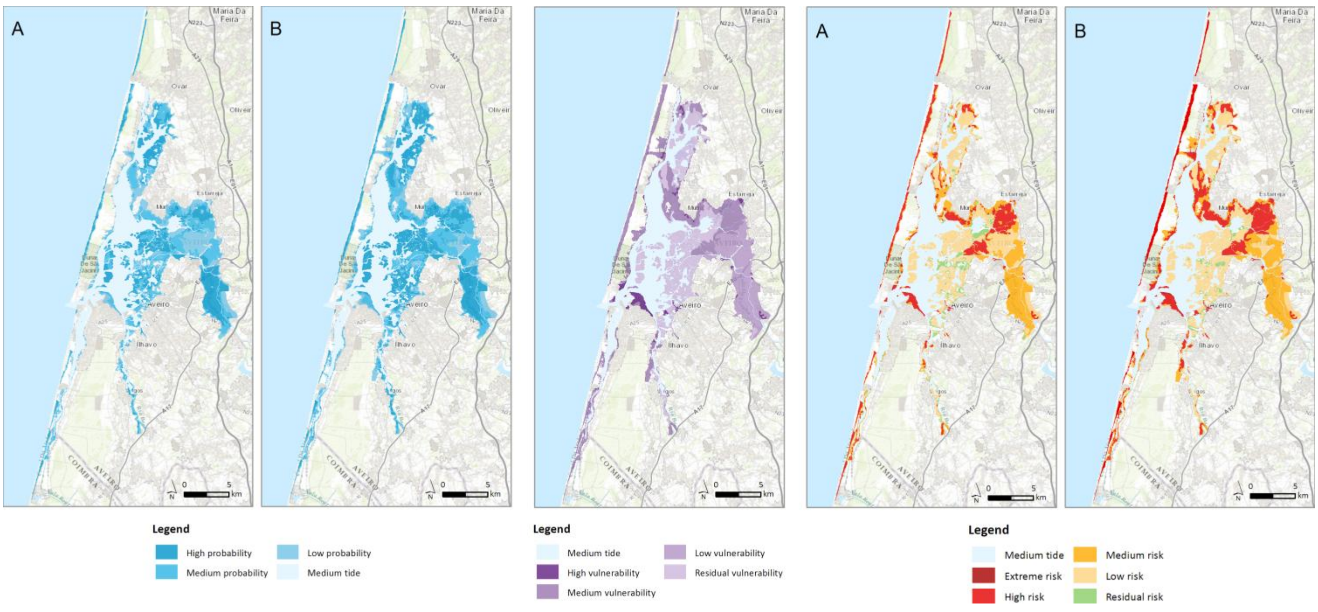

Figure 4. Probability of occurrence in scenarios A and B, global vulnerability of the territory, and flood and shoreline retreat risk maps in scenarios A and B (Source: adapted from Alves and Sousa, 2013).

Table 3. Proposed interventions (Source: adapted from Alves *et al.*, 2013a).

				Type
Structural Measures of Adaptation	***Tide Protection System***			
	'Esteiros' (watercourses)	Recovery and stabilization of watercourses banks through biophysical engineering techniques and establishment of riparian shrub borders in order to avoid uncontrolled overtopping.	Event: Floods, overtopping and bank rupture. Damage: Salinization of agricultural fields and flooding in urban areas.	Mix
	Flood Adaptation System			
	Vouga river	Land surface recovery and biophysical stabilization in and along Vouga river channel through biophysical engineering techniques and establishment of riparian shrub borders in order to avoid uncontrolled overtopping and bank ruptures, characteristic at flood season.	Event: Overtopping, bank rupture and waterlogging. Damage: Flooding of BBVL fields, bank rupture, deposition of unwanted sediments, destruction of agricultural roads and waterlogging (when the drainage is not done on time).	Mix
	Other rivers	Land surface recovery and biophysical stabilization in and along rivers channels through biophysical engineering techniques and establishment of riparian shrub borders in order to avoid uncontrolled overtopping.	Event: Floods, overtopping, bank rupture and waterlogging. Damage: Flooding of agricultural fields and urban areas, bank rupture, deposition of unwanted sediments, destruction of agricultural roads and waterlogging (when the drainage is not done on time).	Soft
Structural Measures of Control	***Tide Protection System***			
	Dikes	Protection of BBVL fields through the extension of a physical main existing structure (dike) against salt water intrusion.	Event: Overtopping and bank rupture. Damage: Salinization of BBVL fields and consequently destruction of cultures and banks.	Hard
	Hydraulic structures	Construction of hydraulic structures constituted by tidal gates, which allow the drainage of excess water to Ria de Aveiro in flood season and constitute a barrier to the entrance of salt water.	Event: Flooding, waterlogging and salinization. Damage: Waterlogging and salinization of BBVL fields and consequently destruction of cultures.	
	Coastal Erosion Protection System			
	Artificial sand nourishment of beaches and reinforcement of dune system	Sand nourishment in Barra, Costa Nova and Vagueira beaches, and in the south dune system of Costa Nova, Vagueira and Areão beaches in order to maintain the environmental and recreational values and to preserve the natural coastal defence systems (beaches and dunes).	Event: Beach area reduction. Damage: Decrease of beach area, losing the recreational and bathing use values.	Soft
	Groins	Construction or extension of a groin in Barra beach, in order to fix the shoreline position and allow filling the eroded beaches by the intersection of longshore sediments transport, with accumulation updrift.	Event: Shoreline retreat and beach area reduction. Damage: Losing of territory, recreational and bathing uses values, damages in infrastructures and properties.	Hard
	Longitudinal revetment works	Construction or extension of longitudinal revetments works in Costa Nova, Vagueira, Areão and Poço da Cruz beaches in order to fix the shoreline position and reduce the wave action by absorption the energy in the structure slope.	Event: Shoreline retreat and waves overtopping. Damage: Territory loss, sandbank rupture, overtopping and floods, damages in infrastructures and properties.	
Non-Structural Measures	***Primary and Secondary Drainage System***			
	Ditches	Ditches cleaning	Event: Clogged ditches and waterlogging. Damage: Poor drainage of excess water in flood season.	Management
	Main Green Structure			
	Hedges	Pruning	Event: Clogged roads. Damage: Difficulties in circulation.	Management
	Hedges	Riparian borders and hedges reinforcement.	Event: Unprotected areas against the advance of water due to the lack of protection shrubs or trees. Damage: Bank ruptures, faster intrusion of salt or fresh water into the fields.	

ecological value at risk, such as Ria de Aveiro lagoon and its coastal zone.

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