Numerical modelling of shoreline evolution in the Aveiro coast, Portugal – climate change scenarios

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ABSTRACT

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In the Northwest coast of Portugal, the shoreline evolution is leading to several problems, such as loss of territory and infrastructural damages, mainly caused by the sea wave's action. This study aims to predict the impacts of climate change on the shoreline evolution in this coastal area. Coastal stretches studied were Esmoriz-Furadouro and Vagueira-Mira, due to their vulnerability related with the low lying sandy coast, the deficit of sediments, the presence of urban waterfronts and the narrow width of the sand spit that separates the ocean from the Aveiro lagoon.
The paper describes the application of two shoreline evolution models (LTC and GENESIS) to the projection of shoreline evolution between 2010 and 2100. A reference scenario considering the present typical wave climate and the mean sea water level was compared with 3 other future scenarios that may result from climate change effects, combining different wave climates and mean sea levels (0.42 and 0.64 m above present level).
Considering the numerical models' results, maps of the shoreline position were represented every 30 years. The results allowed the analysis of the shoreline retreat, the areas of lost territory and the alongshore sediment transport volumes in several cross sections. A strong trend of shoreline retreat was found for all the scenarios, although the retreat rates tend to decrease along time. Comparing the reference scenario with the climate change scenarios, a slight clockwise rotation of the shoreline was predicted, also increasing the average shoreline retreat from 6% to 11%, depending on the considered scenario.

ADDITIONAL INDEX WORDS: *Coastal erosion, sea level rise, wave climate, shoreline retreat, erosion rates, territory lost, sediment transport.*

INTRODUCTION

The Aveiro coastal area is highly vulnerable to erosion, because it is constituted primarily by low-lying lands of sandy sediments that are frequently subjected to severe wave conditions and large tidal amplitudes (Coelho *et al*., 2011), as well as due to the close proximity to the Aveiro lagoon and several urban waterfronts. In this region the problems associated with coastal erosion are often reported and discussed (Coelho, 2005; EUrosion, 2006; Pais-Barbosa *et al*., 2006; Coelho *et al*., 2007), constituting a concern for the local populations and stakeholders. Furthermore, the retreat of the shoreline may imply the breaching of a new entrance to the Aveiro lagoon, which would cause major social, economic and environmental impacts. This breaching has only been avoided by emergency works which have been carried out frequently over the past few years. Increased vulnerability is mainly related to the sedimentary deficit registered in the Portuguese coast, due to the decrease of incoming sediments from river sources (Mota-Oliveira, 1997).

Over the years the Esmoriz-Furadouro and Vagueira-Mira stretches have been affected by flood and erosion processes due to coastal vulnerability to sea wave's action (Figure 1). Considering the expected modifications of the coastal erosion drivers induced by climate changes, it is important to define their potential effects, trying to anticipate hydro/morphodynamics changes in coastal areas, through sea-level rise, increase of storminess and rotations in the wave regime. It is expected that these phenomena will increase coastal flooding of low-plains, houses and infrastructures, causing economic damage and eventual patrimonial, cultural and ecological losses. This work applies numerical models to predict shoreline evolution, in a medium-long term perspective, contributing to establish trends and foresee shoreline position scenarios.

Two models, GENESIS (U.S. Army Corps of Engineers) and LTC (Long-Term Configuration), were applied to anticipate the shoreline position for the year 2100, through the evaluation of four scenarios in a perspective of the effects of different phenomena associated with climate change.

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STUDY AREA

The Portuguese northwest coast faces the Atlantic Ocean with an orientation approximately N21ºE, and is essentially composed by sandy stretches (Figure 2a).

The morphology of the studied stretch is dominated by the proximity to the Aveiro lagoon (Figure 2b) and by the sand barrier that separates the lagoon from the sea, formed by dunes that grew between the 10^{th} and the 19^{th} century. This type of morphology is usually associated with high sedimentary deposition supplied from rivers, which transport large amounts of sediments, especially in flood seasons (Coelho *et al*. 2009).

The study area extends from Esmoriz to Mira, and includes seven coastal municipalities: Espinho, Ovar, Murtosa, Aveiro, Ílhavo, Vagos and Mira (Figure 2b).

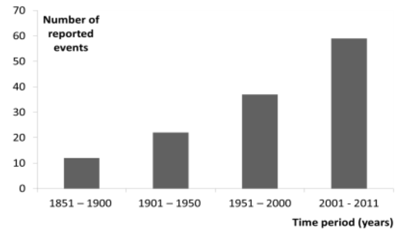

Figure 1. Flood and erosion problems at Aveiro littoral, represented by the number of events registered due to coastal vulnerability to sea wave's action (Pereira and Coelho, 2011).

The Esmoriz-Furadouro stretch (Figure 2c) has a length of approximately 12 km. In this stretch there are 6 groins, which are distributed at the urban waterfront of Esmoriz (2 groins), urban waterfront of Cortegaça (1 groin), Maceda (1 groin) and urban waterfront of Furadouro (2 groins). The position of the shoreline is also fixed with seawalls, mainly located in urban waterfronts, with extensions of about 2100 m between Esmoriz and Cortegaça and about 1100 m in Furadouro.

The stretch Vagueira-Mira (Figure 2d), about 16 km long, has 6 groins and about 850 m of seawall, located in the Vagueira waterfront. The groins are distributed by the urban waterfront of Vagueira (1 groin), Labrego (1 groin), Areão (1 groin), Poço da Cruz (1 groin) and Mira (2 groins). The pressure of the urban waterfronts of Vagueira and Mira over the shoreline, and the proximity to the Aveiro lagoon, especially at Labrego stand out in this area (Figure 2d).

The two main stretches were divided into six smaller stretches, in order to analyse with bigger detail the results of the numerical models: two stretches (Cortegaça-Maceda and Maceda-Furadouro) between Esmoriz and Furadouro and four stretches (Vagueira-Labrego, Labrego-Areão, Areão-Poço da Cruz and Poço da Cruz-Mira) between Vagueira and Mira. This definition considers that groins and seawalls will fix the position of the shoreline during the simulation period.

NUMERICAL MODELS

The numerical models developed to simulate shoreline evolution can establish trends and provide projections of future scenarios, which can be validated by simply observing the actual behaviour of the natural systems under the influence of the wave climate, mean sea level, coastal defence works, etc. The simplest theoretical model is based on the analysis of the sediment budget in a certain period and in a control system. A difficulty in the use of numerical models is the establishment of boundary conditions, calibration coefficients and parameters associated with variables representing the reality of the system, that contribute to the modelling process as well as to predict the most realistic results.

Simulation Set-up

The numerical model GENESIS (U.S. Army Corps of Engineers) was developed to simulate long-term shoreline change on an open coast, produced by spatial and temporal differences in longshore sand transport (Hanson 1989), and has been used since the late 1980's. More recently, the LTC (Long-Term Configuration) shoreline evolution model was proposed. LTC was firstly presented by Coelho *et al*. (2004), and has improved since then (Coelho, 2005; Silva *et al*., 2007; Coelho *et al*., 2007). The main differences between these two models consist in the approach followed to perform the bathymetric and topographic changes in the profile limits during each wave action. For the LTC model, in the vicinity of the depth of closure (DoC), the depth level is constrained by the angle of repose (Φ), in an accretion

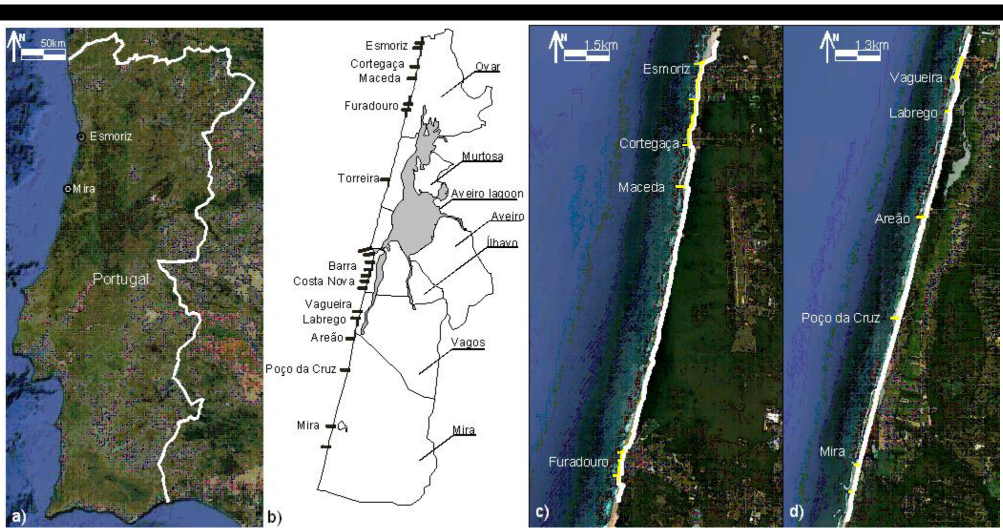

Figure 2. Study Area: a) Esmoriz-Mira stretch; b) coastal municipalities of study area; c) Esmoriz-Furadouro stretch; d) Vagueira-Mira stretch.

Table 1. Wave heights and wave direction distribution.

Wave Climate	*Hs (m)*									
	≤ 0.5	0.5-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	6.5-7.5	7.5-8.5	8.5-9.5
WC1	14.4	46.3	23.5	10.0	3.9	1.3	0.5	0.1	0.0	0.0
WC2	18.1	47.7	21.3	8.2	3.1	1.1	0.4	0.1	0.0	0.0

Wave Climate	*Direction*						
	NNW	NW	WNW	W	WSW	SW	SSW
WC1	7.3	20.5	33.9	25.9	8.2	2.9	1.3
WC2	9.0	21.6	34.7	24.3	6.6	2.4	1.3

situation, and by a user-defined minimum underwater bottom slope, in an erosion situation. In the vicinity of the run-up limit, the controlling parameters are the user-defined minimum beach face slope and Φ, respectively for accretion and erosion (Silva *et al*., 2011).

Spatial Domain

The bathymetric data used to define the numerical spatial domain for modelling the study area were obtained from an offshore Fishing Chart of the Portuguese Hydrographic Institute (24201: Caminha-Aveiro and 24202: Aveiro-Peniche), and was associated to extended topographic data available from an aero photogrammetric survey, conducted in 1996, by the Army Geographic Institute (military charts number: 143, 153, 162-A, 163, 173, 174, 184, 195 and 206).

Shoreline obtained by intersecting the plane of the average sea water level with the coastal terrain (elevation +2.0 m ZH) required some adjustments in bathymetry and topography, to make the shoreline coincide with the position obtained by the satellite image of 2010. The final result was a regular grid representing the spatial domain for modelling, with a resolution of 50 m.

The existing coastal defence works at the study stretches were included in the numerical models, after all the necessary considerations related to their position, wave propagation effects and permeability, allowing to establish the most appropriate calibration results. For GENESIS, the definition of the depth of closure and berm height is required, corresponding to 12 m and 4 m, respectively. In LTC, the depth of closure is calculated internally along the simulation, according to the Hallermeier (1978) formulation. The active profile immersed limit corresponds to the run-up limit, according to Sena (2010). The characteristic sediment diameter, D50, was set to 0.3 mm for the entire study area and for both models.

Wave Climate and Sea Level Rise

The longitudinal sediment transport depends mainly on the waves' characteristics at the surf zone, namely their height and direction. Thus, the shoreline evolution depends on the time series of wave events considered during the simulation. According to the objectives of this study, two distinct offshore wave climates were defined. Based on these, each model proceeds internally to evaluate wave propagation.

WC1 - wave climate characteristic of the 1971-2000 period;

WC2 - wave climate characteristic of the 2071-2100 period.

Both wave regimes were determined based on the application of the WW3 wave model to the North Atlantic (Ribeiro *et al*., 2012). This application is based on the work of Dodet *et al*. (2010), and the model was originally calibrated with available buoy data along the Portuguese coast. The calibrated model was then forced with winds obtained from reanalysis. The two scenarios were forced by wind fields generated by the climatic model ECHAM5 for the reference (WC1) and future (WC2 – IPCC SRES A2 scenario) situations.

Table 1 shows for each wave climate type (WC1 and WC2) the representative wave classes' distribution of heights and directions. The wave heights' analysis exposed in Table 1 shows that WC2 presents fewer occurrences of waves with heights higher than 2.0 meters than WC1. Thus, WC2 is less energetic than WC1, which is consistent with the findings of Ribeiro *et al*. (2012). According to Table 1, WC2 is rotated slightly to the north, when compared to WC1, presenting an increasing number of wave events from NNW, NW, WNW, and decreasing the occurrence of waves from W, WSW and SW.

The smaller wave height of WC2 may result in lower sediment transport capacity, which is balanced by the greater obliquity of the waves with the shoreline. Thus, it is difficult to establish a priori any conclusion about the impact of climate change from WC1 to WC2, relatively to the capacity of longitudinal sedimentary transport.

Coastal erosion may also depend on the mean sea level. Several studies based on tide gauge records showed that the sea level has risen along the Portuguese coast during the 20th century (Antunes and Taborda, 2009). Particularly, for the Aveiro tidal gauge a relative sea level rise rate of 1.15±0.68 mm/year during 1976–2003 was found by Araújo (2005). In the scope of this study two projections of sea level rise for the Portuguese coast were considered (Lopes *et al*., 2011). Values of 0.42 m and 0.64 m above present level were presented by those authors for the A2 SRES (Special Report on Emission Scenarios) scenarios developed by the IPCC (Intergovernmental Panel on Climate Change).

Combining the two wave climates and the three different sea surface levels, four scenarios were established:

Sc1 (reference) - based on WC1 and current level of the sea surface; Sc2 - based on WC2 and current level of the sea surface; Sc3 - based on WC2 and the surface level 42 cm above the current; Sc4 - based on WC2 and the surface level 64 cm above the current one. With these 4 scenarios, shoreline evolution was simulated in the perspective of knowing the effect of different phenomena associated with climate change.

Calibration

Initial shoreline position represents the year 2010 (approximate shoreline position and coastal defence works existing at the time).

In order to achieve the best possible calibration, several simulations were tested considering different parameters of the models (LTC and GENESIS), taking into account the erosion rates recorded in the past (Pereira and Coelho, 2011) as reference values (Table 2). Variations in the shoreline position in the stretches artificialized by groins and seawalls were not considered.

As shown in Table 2, during the calibration process it was impossible to obtain with the same model, satisfactory results for all the stretches. For longer stretches, as Maceda-Furadouro, Labrego-Areão, Areão-Poço da Cruz and Poço da Cruz-Mira, erosion rates obtained with GENESIS were about 70% to 90% lower than the reference values. Regarding LTC, there were

Table 2. Calibration results, considering the average shoreline retreat of each stretch, for a 30 years period, considering the agitation representative of 1971-2000 and the initial shoreline as at 2010. Adapted from Pereira and Coelho (2011).

Stretch	***Stretch's Length***	***Average shoreline retreat of each stretch (m/year)***		
	(m)	*Reference Values*	*GENESIS*	*LTC*
Cortegaça-Maceda	1000	0.9	0.75	- 1.56
Maceda-Furadouro	6570	3.0	0.55	2.91
Vagueira-Labrego	1120	0.2	0.17	7.51
Labrego-Areão	3500	3.3	0.57	3.94
Areão-Poço da Cruz	3350	2.9	0.22	2.45
Poço da Cruz-Mira	4870	2.4	0.62	2.23

difficulties in reproducing the behaviour of the shoreline near the groins, essentially at the updrift side, and this difficulty was more evident in smaller stretches, such as Cortegaça-Maceda and Vagueira-Labrego, where the values obtained differ significantly from the reference value. Thus, the final shoreline presented in this study considered only the results from the model with the best performance for each section, according to the best calibration.

Thus, the Cortegaça-Maceda and Labrego-Vagueira stretches are represented by GENESIS results, which show a relative difference between the modelling results and the literature values of about 16%. For Furadouro-Maceda, Labrego-Areão, Areão-Poço da Cruz and Poço da Cruz-Mira the LTC results were considered, with a relative difference between the model results and the reference values of about 11%. Between Vagueira and Mira, the results updrift of the groins were not considered realistic by either numerical model in the stretches Labrego-Areão, Areão-Poço da Cruz and Poço da Cruz-Mira. Consequently a curve that allows the delimitation of the eroded areas was adopted (figures following, but not considered in the various analyses of results).

RESULTS

Models results represent the shoreline position projections up to 90 years, after each 30 years of evolution, corresponding to 2040, 2070 and 2100.

In each stretch the forecasting of shoreline position was assessed, allowing the analysis of the corresponding erosion rates, as well as the areas of territory lost. Finally, the average volumes of longitudinal sediment transport were also estimated in each coastal stretch. Table 3 presents the results for the 4 scenarios of the shoreline evolution (Sc1, Sc2, Sc3 and Sc4). Figure 3 represents the shoreline position along the simulation period (2040, 2070 and 2100), for the 4 scenarios considered.

An erosion trend was observed in all scenarios, with few exceptions in very short lengths, with heavy loss of territory, representing between 2.62 to 2.86 million square meters of area lost by 2100, increasing from Sc1 to Sc4. In Sc4 there is an increase of almost 9% in the foreseeable loss of territory in 2100, when compared to the area predictably lost in Sc1.Climate change will intensify the average rates of retreat between 6% (Sc2 and

Table 3. Forecast of erosion rates, loss of territory and longitudinal sediments transport.

Stretches	***Erosion rates (m/year)***											
	Sc1			***Sc2***			***Sc3***			***Sc4***		
	2040	***2070***	***2100***	***2040***	***2070***	***2100***	***2040***	***2070***	***2100***	***2040***	***2070***	***2100***
Cortegaça-Maceda	0.75	0.79	0.77	0.69	0.80	0.86	0.66	0.79	0.85	0.72	0.82	0.86
Maceda-Furadouro	2.91	2.45	1.98	2.62	2.37	2.04	2.88	2.38	1.96	2.89	2.35	2.15
Vagueira-Labrego	0.17	0.14	0.12	0.29	0.18	0.14	0.25	0.16	0.12	0.32	0.19	0.15
Labrego-Areão	3.94	3.20	2.58	4.34	3.40	2.77	5.03	3.86	3.12	5.40	4.10	3.39
Areão-Poço da Cruz	2.45	2.38	2.51	2.21	2.19	2.31	2.41	2.38	2.30	2.89	2.61	2.50
Poço da Cruz-Mira	2.23	1.86	1.65	2.17	1.98	1.91	2.40	2.05	1.88	2.42	2.14	1.97

Stretches	***Areas lost ($\times 10^6$ m^2)***											
	Sc1			***Sc2***			***Sc3***			***Sc4***		
	2040	***2070***	***2100***	***2040***	***2070***	***2100***	***2040***	***2070***	***2100***	***2040***	***2070***	***2100***
Cortegaça-Maceda	0.02	0.05	0.07	0.02	0.05	0.08	0.02	0.05	0.08	0.22	0.05	0.08
Maceda-Furadouro	0.54	0.92	1.11	0.49	0.88	1.14	0.54	0.89	1.10	0.54	0.88	1.10
Vagueira-Labrego	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Labrego-Areão	0.24	0.40	0.48	0.27	0.42	0.52	0.31	0.48	0.59	0.33	0.51	0.63
Areão-Poço da Cruz	0.16	0.32	0.51	0.15	0.29	0.47	0.16	0.32	0.46	0.19	0.35	0.51
Poço da Cruz-Mira	0.20	0.33	0.44	0.19	0.35	0.50	0.21	0.36	0.49	0.21	0.37	0.52
Total	1.17	2.03	2.62	1.13	2.00	2.72	1.25	2.11	2.73	1.50	2.17	2.86

Stretches	***Direction***	***Longitudinal sediments transport ($\times 10^3$ m^3/year)***											
		Sc1			***Sc2***			***Sc3***			***Sc4***		
		2040	***2070***	***2100***	***2040***	***2070***	***2100***	***2040***	***2070***	***2100***	***2040***	***2070***	***2100***
Cortegaça-Maceda	North-South	108	104	105	116	125	129	115	125	129	115	125	129
	South-North	17	19	20	11	14	14	11	14	14	11	14	14
Maceda-Furadouro	North-South	1246	1271	1282	1097	1105	1115	1082	1110	1126	1080	1108	1123
	South-North	554	547	552	473	471	477	458	467	472	543	465	468
Vagueira-Labrego	North-South	829	861	862	633	632	632	634	633	632	632	631	631
	South-North	580	509	486	100	100	100	100	100	99	100	100	100
Labrego-Areão	North-South	241	238	240	277	207	211	208	206	207	206	204	207
	South-North	99	98	98	87	87	88	85	86	87	83	84	85
Areão-Poço da Cruz	North-South	229	228	227	206	203	199	205	205	205	200	200	200
	South-North	99	98	99	83	82	84	80	80	80	80	79	80
Poço da Cruz-Mira	North-South	227	228	227	198	201	200	200	204	204	197	201	198
	South-North	104	101	101	88	84	85	84	83	82	85	83	83

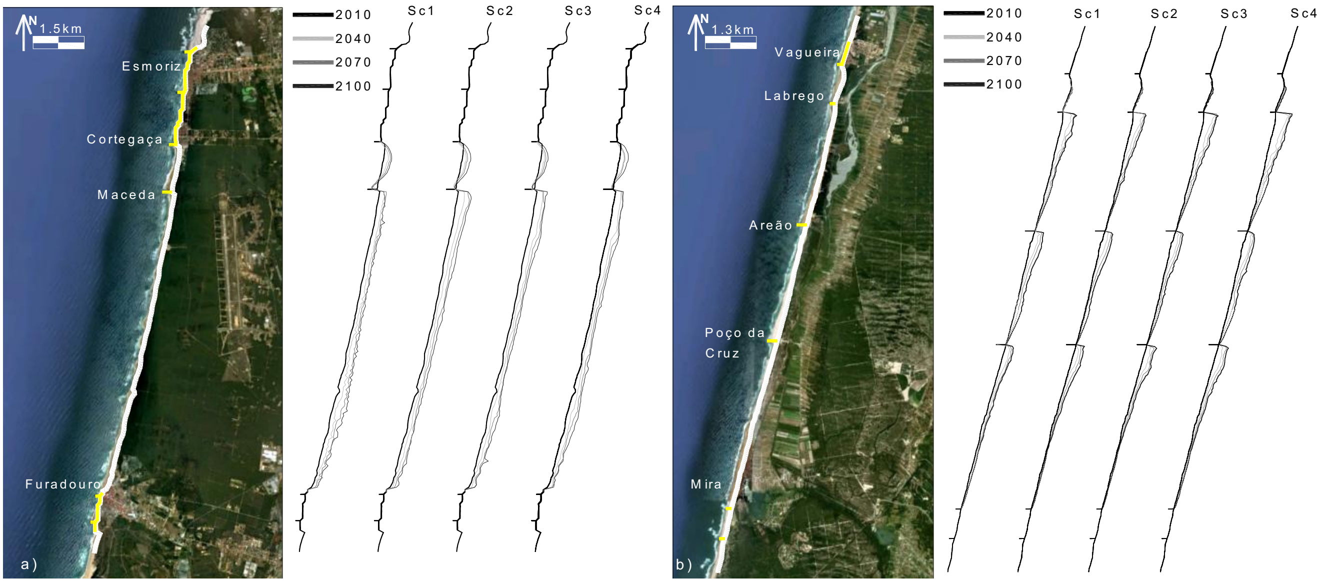

Figure 3. Shoreline position, for each scenario, along time: a) Esmoriz-Furadouro; b) Vagueira-Mira.

Sc3) and 11% (Sc4), relative to the reference situation (Sc1).

The erosion rates decrease over time in all scenarios, approaching a shoreline equilibrium situation at the end of the period under analysis. The loss of territory is regular over time for the 4 scenarios, with a loss of 45% in the first 30 years, 30% in the next 30 years, and 25% in the last 30 years (Figure 3).

For the reference scenario (Sc1) the evolution over time for Esmoriz-Furadouro presents similar retreats along the entire stretch, progressing roughly parallel to the initial shoreline. Areas of major retreat are the middle point between Cortegaça and Maceda and the half south stretch between Maceda and Furadouro. Comparing Sc1 to the other scenarios, a major difference is found, corresponding to greater retreat downdrift of the Maceda groin, and a lower retreat in the south half of Maceda-Furadouro.

As the North stretches, also the Vagueira-Mira evolution presents displacement of the shoreline inwards. This pattern is characterized by strong erosion downdrift of the groins, and is found in all simulated scenarios.

The higher erosion predicted by the models is found for Labrego-Areão, Areão-Poço da Cruz and Poço da Cruz-Mira stretches. The maximum retreat after 90 years was recorded in Labrego-Areão, corresponding to about 475 meters in the Sc4 (5.3 m/year), while in Sc1 the maximum retreat in the same section and period is about 400 m (4.4 m/year). The lowest rates of erosion are found in the stretches Cortegaça-Maceda and Vagueira-Mira,

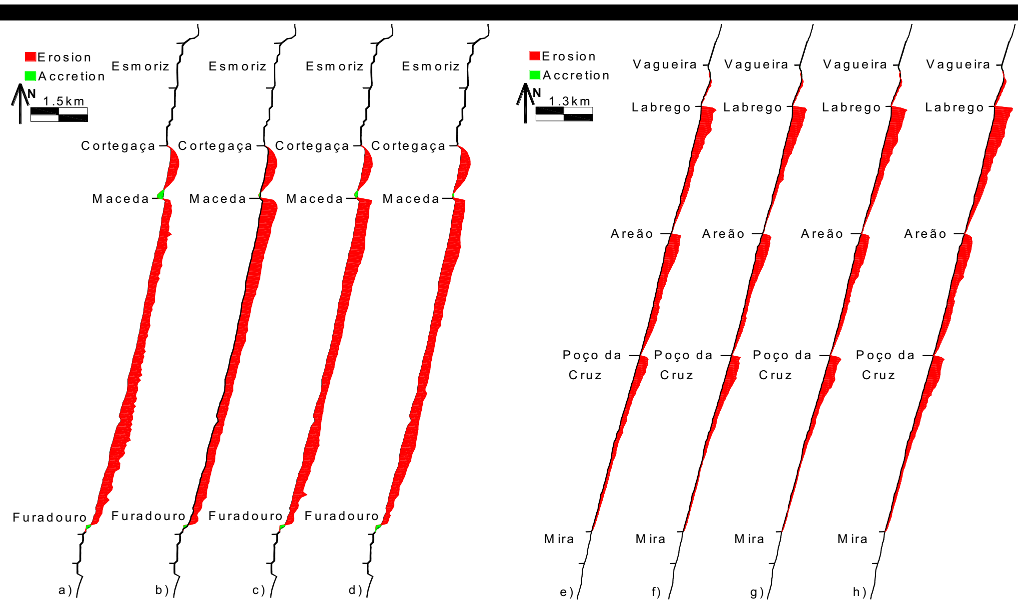

Figure 4. Territory lost until 2100, for each scenario: a) to d) Esmoriz-Furadouro; e) to h) Vagueira-Mira; Sc1 a) and e); Sc2 b) and f); Sc3 c) and g); Sc4 d) and h).

corresponding to confined stretches of small extension, being therefore less susceptible to coastal retreats.

It is anticipated that the highest territorial losses will happen in the southern stretch, which is the less subject to artificialization. It is envisaged that area losses will range between 1.18 and 1.22 million square meters in the northern stretch, while in the south losses will be between 1.44 and 1.68 million square meters (Figure 4).

The results show that the sediments transport is predominantly from North to South along the coastal area under analysis. Noteworthy are the stretches Maceda-Furadouro and Vagueira-Labrego, which present volumes of sediments transported significantly higher than those determined for the other stretches. The values of longitudinal sediment transport are identical for Sc2, Sc3 and Sc4 and slightly lower than for Sc1, which reveals the importance of the wave climate in the sediment transport. Thus, it is understood that in WC2 decreasing wave heights overlaps the rotation of the wave's origin, resulting in decreased sediments transport.

The results analysed show that the sea level rise impact in the sediments transport along the study area is negligible, although it is important on coastal retreat and loss of territory.

CONCLUSIONS

For a better fit between model predictions and the study area reference retreat rates, GENESIS results were adopted in the shorter stretches located at North of the modelled areas, being LTC results adopted in the other stretches.

An erosion trend was observed in all scenarios, with the erosion rates decreasing over time, approaching to a shoreline equilibrium situation.

In the stretch Maceda-Furadouro, the main difference on the future projection considering WC2 resulted in a clockwise rotation of the shorelines, relatively to a fictitious point located halfway between Maceda and Furadouro, resulting in higher losses of territory at the northern part of the stretch and lower losses of territory in the southern. According to the simulated scenarios, the trend of worsening for Vagueira-Mira stretch is not as evident as in the northern stretches, presenting projected shorelines for the year 2100 with traces very similar for the different scenarios. However, in the stretch Labrego-Areão, for all the simulated scenarios, the future shoreline reaches the Aveiro lagoon, at Labrego.

It is also concluded that climate change will aggravate the retreat of the shoreline between 6% (Sc2 and Sc3) and 11% (Sc4), comparing to the reference situation (Sc1). I

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