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Resumo

Este estudo avalia o risco costeiro em Portugal continental ao nível da freguesia, combinando indicadores de perigosidade, exposição e vulnerabilidade social sob diferentes cenários de subida do nível do mar (SLR) para 2040, 2070 e 2100. Os resultados mostram uma expansão significativa das zonas de risco e das áreas urbanas expostas, sendo a exposição o principal fator de aumento futuro do risco. A análise de clusters identifica perfis de vulnerabilidade distintos, destacando a importância de integrar estes indicadores na gestão costeira. As conclusões apoiam políticas adaptativas e equitativas que reforcem a resiliência e reduzam os riscos associados à SLR.

Palavras-chave: subida do nível do mar; risco costeiro; vulnerabilidade social; exposição; resiliência.

Abstract

This study assesses coastal risk in mainland Portugal at the civil parish level, combining hazard, exposure, and social vulnerability indicators under different sea-level rise (SLR) scenarios for 2040, 2070, and 2100. Results reveal that both hazard zones and exposed urban areas are projected to expand considerably, with exposure emerging as the main driver of future risk. Cluster analysis identifies differentiated vulnerability profiles across regions, emphasizing the importance of integrating these indicators into coastal management frameworks. The findings support the design of adaptive and equitable policies to enhance resilience and reduce SLR-related risks.

Keywords: sea-level rise; coastal risk; social vulnerability; exposure; resilience.

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Introduction

Coastal areas are prone to a set of hazards which tend to accentuate under sea level rise (SLR) scenarios. The spatial and temporal distribution of risk, and the consequent losses, in such dynamic areas are explained by complex interactions of human and natural factors, commonly represented as hazard, exposure and vulnerability.

In this article, the assessment of coastal risk due to SLR is represented through a risk index at the civil parish level in mainland Portugal, utilizing scenarios of coastal overtopping and sea-level rise expressing hazard, current exposure, and social vulnerability.

Study Area

The mainland Portuguese coast extends for 987 km, morphologically as diverse as beaches, barrier islands, estuaries, lagoons and cliffs can be found, with varying sedimentary budgets (Figure 1). The coast varies in terms of exposure to storms: the west coast is hit by powerful waves from the North Atlantic, while the south coast is less exposed, with weaker waves. The waves that hit the coast also differ in height and period, decreasing towards the south in height (1.7 to 2.2 m) and period (6.6 to 7.2 seconds). On the south coast, the waves are around 1 m high and have a period of 4.7 seconds (Pinto *et al.*, 2020).

Administratively, the shoreline is touched by 138 civil parishes, aggregated in 52 municipalities. In those municipalities live about ¾ of the c. 10 million Portugal's inhabitants. The distribution of the population is, however, uneven, with the northern coast until Lisbon being more densely – and even so, unevenly - populated than the remaining western Atlantic and southern coast. Major cities along the coast include Porto, Aveiro, Figueira da Foz, Lisbon, Setúbal and Faro (east of Olhos de Água in Figure 1).

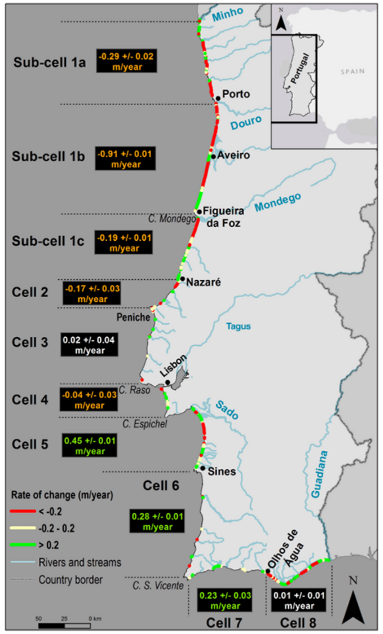

Figure 1. Sedimentary cells of the mainland Portuguese coast, and shoreline rate of change (m/year) as defined in Ponte Lira *et al.* (2016).

In this context, the historical rate of SLR of 2.1±0.1 mm/year between 1977 and 2000 alone was already concerning, to which it adds a projection of mean SLR of 1.14 m by 2100 (Antunes, 2019).

Input Data for Sea Level Rise Risk Profiles

The INFORM risk index-alike formulation was adopted (Marin-Ferrer *et al.*, 2017) considering, however, the classic risk components of hazard (H), exposure (E) and vulnerability represented by social vulnerability (SV) (Eq. 1).

$$\text{SLR risk} = (H^{1/3}) \times (E^{1/3}) \times (SV^{1/3})$$

Hazard

Sea level rise hazard assessment was based on the extent of the intermittent floodable area, where SLR hazard corresponds to the spatial extent of a potentially damaging event with a given magnitude within a specified period and a given location. SLR hazard considers the spatial propensity of a coastal area to be flooded by coastal buildup area overtop or system overwash based on medium- and long-term SLR scenarios (Trindade et al., 2023). The following scenarios were considered: future shared socioeconomic pathways SSP1-2.6, SSP2-4.5, and SSP5-8.5, for the years 2040, 2070 and 2100.

As an illustrative example of result, the current flooded area of 100.66 km^2 will increase 23.5 km^2 from 2011 to 2040 in the SSP5 scenario.

Exposure

The 2011 information on the residential buildings was used to estimate the number of inhabitants and buildings in hazardous areas (INE, 2011), by applying a dasymmetric distribution of residents, that distributes polygonal Census block data to point-type data corresponding to each building, considering the no. of households and the vacant ones (Garcia et al., 2016). The residential population exposed in 2011 was 29,174, which is expected to reach 41,382 by 2100 under SSP5.

Social vulnerability

For the cartographic expression of SV, the conceptual model of Mendes *et al.* (2010, 2019) and Santos *et al.* (2022) was adopted, based on the SoVI statistical steps of Cutter *et al.* (2003). The SV data used refers to a previous analysis done at the civil parish level, with the available data at the time, the 2011 Census (Santos et al., 2022) From an initial set of 24 variables, the final SV principal component analysis retained 15, expressing 4 principal components, interpreted as drivers of SV: PC1 – Age and educational level, PC2 – Economic condition and social dynamism, PC3 – Unfavourable social contexts, and PC4 – Uprooting and internal mobility (Table 1).

Variable	PC1	PC2	PC3	PC4
MeanAge	***0.95***	0.01	-0.09	-0.03
Fam65	***0.91***	0.04	0.03	-0.02
WomAct	***-0.86***	0.25	-0.11	-0.04
Illiter	***0.80***	-0.25	0.17	0.01
PopChan	***0.69***	-0.35	0.14	-0.06
HighEdu	-0.39	***0.76***	-0.19	-0.08
SociVal	-0.16	***0.76***	-0.22	-0.17
5yrMuni	0.03	***0.75***	0.03	0.29
Foreign	-0.10	***0.69***	0.34	0.07
OverCro	-0.48	-0.09	***0.73***	0.11
CarUsag	-0.34	0.01	***-0.66***	-0.09
BasInfr	0.40	-0.30	0.45	0.14
SchLeav	0.04	0.06	0.30	-0.20
OtheMuni	-0.19	0.08	-0.19	***0.84***
Commut	0.18	0.03	0.26	***0.74***
Cardinality	+	Inc.[a]	+	+
% of variance explained	33.5	13.3	11.6	8.0

Table 1. Rotated component matrix of the 2011 SV principal components and the respective explicative variables (loading ≥0,6) in italics and bold. For a description of variables' definition, please see Santos *et al.* (2022) and Annex 1.

Sea Level Rise Risk Profiles

Apart from the calculation of SLR risk, a cluster analysis of the min-max normalized scores of hazard, exposure and social vulnerability was performed. This classification method allowed to understand the existence of distinct profiles of SLR risk, aggregating civil parishes that share the same patterns of H, E and SV (Figure 2).

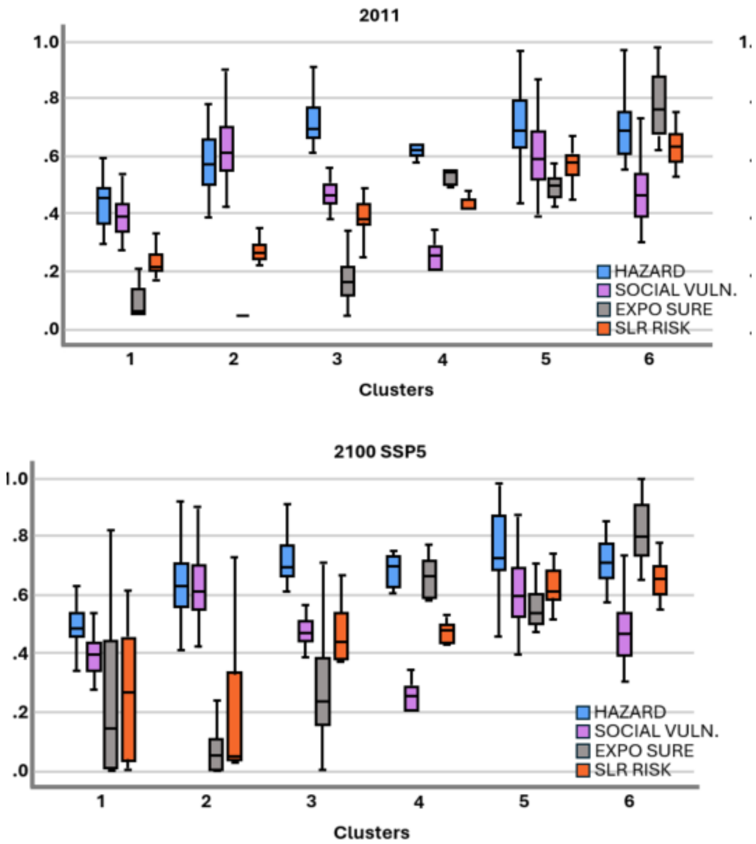

Figure 2. Clusters statistics of SLR risk index for present and future worst-case scenario (2100) under SSP5.

Clusters 1 (24 civil parishes) and 2 (47), for example, gathers the territories with lower risk: the civil parishes in cluster 1 have the lowest average exposure and 10 out of its 24 civil parishes are located in sedimentary cell #7 (cf. figure 1). Although with low risk, cluster 2 represents the highest SV scores found.

High hazard is particularly found in clusters 3 (13 civil parishes) and cluster 5 (19), They are located sparsely along the coastline, except in sedimentary cells #1c, #2 and #7. Clusters 4 and 6 are characterized by low scores of SV.

Conclusion

In this work, we attempted a new method of representing current and future risk to sea level rise, using scenarios of territorial expression of hazardous coastal processes, and of human exposure and built heritage. This is one of the innovative aspects of the methodology in supporting coastal decision-makers. The social vulnerability component cannot be represented in future scenarios due to the complexity of predicting socio-economic and demographic characteristics in the future.

Cluster analysis of risk components identified exposure as a key element in explaining future SLR risk. Accordingly, it is fundamental that mitigation and adaptation policies focus on complementing natural hazards risk management measures with multi-sector wider institutional policies that reduce the PCA-identified drivers of social vulnerability and build resilience and adaptative capacity.

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Annex 1. Variables used in the final model of the social vulnerability assessment.

Variable	Description
MeanAge	Mean age of the resident population (years)
Fam65	Proportion of single person private households with a person aged 65 years old and over (%)
WomAct	Women activity rate (%)
Illiter	Illiteracy rate (%)
PopChan	Variation ratio of resident population between Census (e.g. 2001-2011) (%)
HighEdu	Proportion of resident population with higher education completed (%)
SociVal	Proportion of professionals socially more valued (%)
5yrMuni	Proportion of resident population that 5 years before inhabited outside municipality (%)
Foreign	Proportion of resident population of foreign nationality (%)
OverCro	Proportion of overcrowded living quarters (%)
CarUsag	Proportion of car usage on daily journeys (%)
BasInfr	Proportion of conventional dwellings without at least one basic infrastructure (%)
SchLeav	School leavers rate (%)
OtheMuni	Proportion of resident population that works or studies in other municipality (%)
Commut	Average time spent on commuting (min) of the employed or student resident population

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