Methodology for sea level rise hazard assessment in the exposed coastal zone of the Portuguese mainland

Metodología para la evaluación del riesgo de subida del nivel del mar en la zona costera expuesta del Portugal I

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ABSTRACT

Future scenarios of sea level rise in Portugal are expected to put at risk sensitive areas from a natural and urban point of view. This research proposes a methodology for the assessment of sea level rise Hazard zones using the evaluation of permanent and episodic components as important factors to predict flooding and coastal erosion hazards for the Shared Socioeconomic Pathway 1, 2 and 5 scenarios, in 2040, 2070 and 2100.

Key-words: *sea level rise, hazard, coastal flood, coastal erosion.*

RESUMEN

Se espera que los futuros escenarios de subida del nivel del mar en Portugal pongan en riesgo zonas sensibles desde el punto de vista natural y urbano. Esta investigación propone una metodología para la evaluación de las zonas de riesgo de subida del nivel del mar utilizando la evaluación de los componentes permanentes y episódicos como factores importantes para predecir los riesgos de inundación y erosión costera para los escenarios Shared Socioeconomic Pathway 1, 2 y 5, en 2040, 2070 y 2100.

Palabras clave: *subida del nivel del mar, peligro, inundación costera, erosión costera.*

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Introduction

Coastal zones are facing vast land use management challenges that result from the interactions between the biophysical elements and the built environment. Global human presence in the coastal zone has been increasing and is expected to expand over this century (Brown et al., 2013). Population living and working in coastal areas is expected to grow 50% over the next 40 years in the most conservative scenario (Neumann et al., 2015).

Coastal zones have a high strategic value, concentrating a large part of the population and Gross Domestic Product of coastal nations, productive power and critical infrastructures that need protection against environmental threats, such as the sea level rise (SLR) and associated coastal hazards, which will compromise their resilience in the medium to long term. Although there are many examples of good practices in coastal zone management regarding SLR future impacts, local regulatory measures for preventing coastal hazards can be either absent, lacking in practical implementation, or don't consider future scenarios of SLR and their impacts on the coastal zone.

Western European countries have highly complex land use planning systems, tools, and implementation. These may incorporate prevention measures based on hazard mitigation and adaptation which are typically based on local dimensions of the hazard. But, as SLR and human presence / expansion in the coast are a global concern, strategic coastal zone management regarding coastal hazards must also consider exposure and vulnerability.

Strategic coastal zone management is thus a fundamental mid- to long term hazard prevention tool that needs: (i) to be supported by in depth SLR estimation; and assessment of the related hazards; and (ii) to consider future expected changes in land use and land cover, specifically in-built environments, where human presence is an important driver of coastal processes, as well as community exposure and vulnerability.

The Portuguese mainland coastline stretches for close to 1000 km. Rocky and low-lying sandy systems are predominant, with human presence and related coastal built environments being common because of the higher population density near the coast.

SLR over the last decades (1977 – 2000) is estimated around 2.1±0.1 mm/yr and a rise of 1.14 m is expected for 2100 (Antunes, 2019). Extreme sea levels during storms are also expected to increase both in frequency and magnitude (Oppenheimer, et al., 2019). These trends are accompanied by an expected increase in the concentration of coastal population in Portugal, allowing to anticipate an increase in exposure and vulnerability of the coastal communities in the Portuguese coast.

The hazards resulting from SLR in the Portuguese coast include permanent flooding of estuarine systems, episodic flooding due to wave overtopping of sedimentary barriers and coastal protection structures, erosion and coastline retreat in the low lying sandy coastal zones, and intensification of slope instability in rocky coasts. Pocket beaches, while not overtopped, are likely to become steeper or narrower (Bon de Sousa et al., 2018).

Objective criteria for delineating SLR hazard zones (SLRHZ) are thus an important initial step to be addressed to deliver effective mid- to long-term risk reduction for population, infrastructure, and asset safety. In this context SLRHZ mapping can also incorporate estimations of SLR based on the uncertainties associated with a range of future shared socioeconomic pathways.

Methodological steps for SLRHZ delimitation

This work proposes a methodology for SLR hazard mapping in exposed coastal zones of the Portuguese mainland for 2040, 2070 and 2100. This research is developed under the framework of the R&D project Highwaters: Assessing sea level rise exposure and social vulnerability scenarios for sustainable land use planning.

Permanent components: Coastal geomorphology

Coastal processes that determine first-order coastal hazards are highly dependent on the type or geomorphological characteristics of coastal systems. The impacts of SLR are and will be significantly different in sandy coasts, when compared to the rocky and anthropic coasts, due to their morpho- litho- biological framework. In these areas, the Portuguese coast is expected to experience episodic wave overtopping due to the combined forcing from storm surge and storm waves. As sea level rises wave breaker zones tend to migrate landwards and intensify erosion processes and coastline retreat. This retreat will also promote saltwater intrusion in coastal aquifers (Nicholls & Cazenave, 2010). The same morpho- lithological framework argument can be used for rocky coasts because the landward translation of energetic hydrodynamic processes will allow wave action to reach further inshore and trigger cliff top edge retreat in coastal cliffs and shore platform lowering (Shadrick et al., 2022).

Identification and classification of the coastal systems is thus a fundamental step towards SLRHZ delimitation.

The 0 m orthometric height (corresponding the mean sea level according to the 1938 Cascais altimetric datum) based on 2011 LIDAR data is used in coastal stretches directly exposed to the Atlantic Ocean storm waves as a seaward reference for SLRHZ delimitation. The coastal type of classification system includes sandy and rocky coasts but also areas with strong anthropic intervention (Fig. 1) and uses both bio-physical and land use criteria.

These may include: (i) beach-dune, cliff, and shore platform intertidal and supratidal morphology; (ii) subaerial beach and dune morphology; (iii) presence of plant species characteristic of sandy coastal environments; (iv) land use applies whenever the coastal segment is predominantly occupied by urban features and coastal protection structures.

Permanent components: Tide height, long-term coastline retreat and SLR

Tide height is part of the total water level that can trigger hazardous coastal processes. The magnitude of episodic wave overtopping and storm erosion in beach systems are the most common hazards that depend directly on tide height and stage. It is also a well-known and predictable parameter that can be added to scenarios of SLR. Portugal has a regulatory framework (Law nº. 12/2010, January 25th) with clear criteria for the delimitation of the Highest Astronomical Tide Level (HATL).

HATL validation uses biophysical proxies including presence/absence of plants and specific morphologies attributed to the transition between beach and dune systems, and the position of the base of the cliff face or the presence/absence of slope deposits in rocky systems (Fig. 2).

Long term coastline recession is an important parameter that, indirectly and

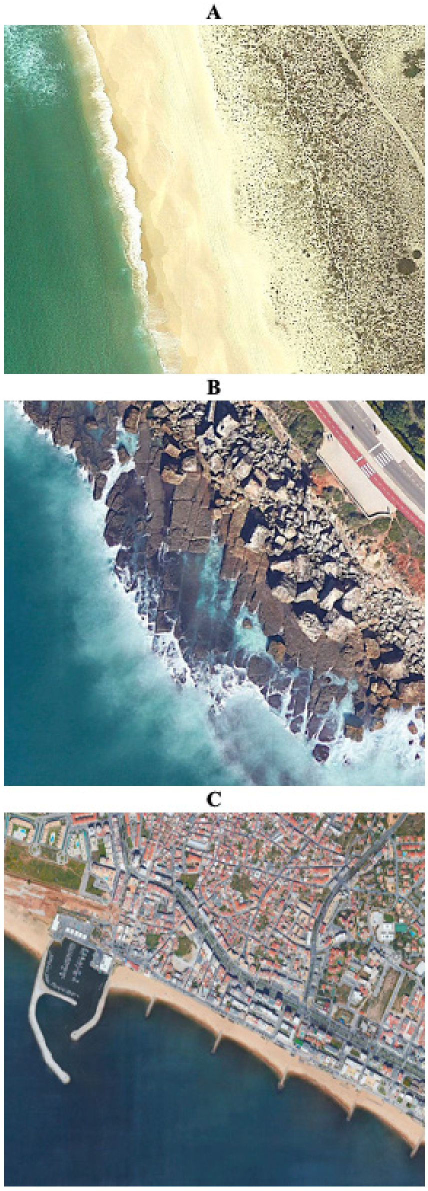

Fig. 1.- Examples of exposed coastal systems in the Portuguese mainland. A) sandy coast; B) rocky coast; C) anthropogenic coast. Image source: Google Earth Pro 7.3.4.8642.

Fig. 1.- Ejemplos de sistemas costeros expuestos en Portugal continental. A) Costa arenosa; b) Costa rocosa; c) Costa antropogénica. Fuente de imagen: Google Earth Pro 7.3.4.8642.

not exclusively, reflects the recent past SLR trends and mainly the lack of sediment supply in the Portuguese coastal area (Ferreira et al., 2008).

Erosional trends were measured in the Portuguese coast using a comparison of successive coastline positions in sandy systems for the period between 1953 and 2010 (Ponte Lira et al., 2016). Rocky and anthropogenic coasts are considered relatively stable systems at the time scale and magnitude of the coastline change considered in this work. Nevertheless, small coastal stretches with highly dy-

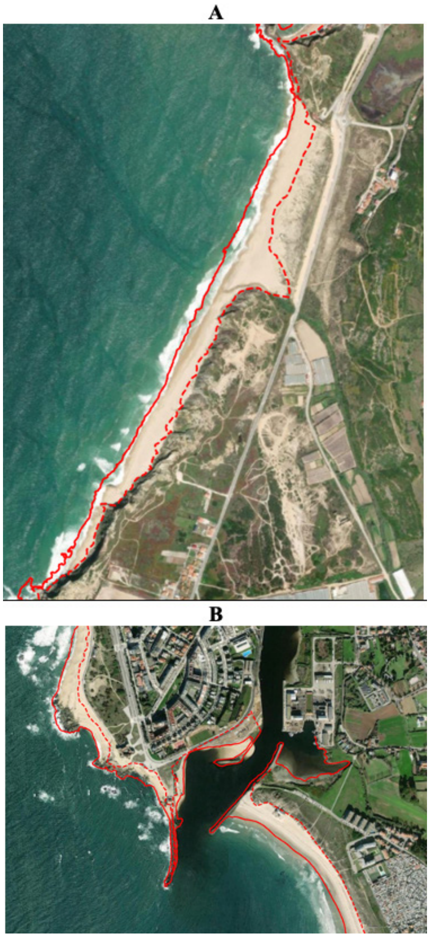

Fig. 2.- HATL delimitation in A) a composite coastal system (Santa Rita Beach, Lourinhã, Western Portugal) and B) in an anthropogenic coast (Vila do Conde, Northwestern Portugal). Solid red line – 0 m orthometric height. Dashed red line – HATL. Image source: Google Earth Pro 7.3.4.8642.

Fig. 2.– Delimitación de HATL en A) un sistema costero mixto (Playa de Santa Rita, Lourinhã, Oeste de Portugal) y B) en una costa antropogénica (Vila do Conde, Noroeste de Portugal). Línea roja continua: 0 m de altitud ortometrica. Línea roja discontinua: HATL. Fuente de la imagen: Google Earth Pro 7.3.4.8642.

namic cliffs are considered on a case-by-case basis.

Local erosion rates are calculated by linear regression and projected to determine shoreline position scenarios for 2040, 2070 and 2100 in areas that have eroded in the recent past (Fig. 3).

The sea level rise expected for 2040, 2070 and 2100 according to the Shared Socioeconomic Pathway (SSP) 1 (2.6), SSP2 (4.5) and SSP5 (8.5) is based on the projections available in the NASA Sea Level Projection Tool global model. This model considers the scenarios proposed by the 6th Assessment Report the Intergovernmental Panel on Climate Change (Fox-Kemper et al., 2021).

Fig. 3.- 2040, 2070 and 2100 scenarios of coastline recession at Costa Nova, Western Portugal. Image source: Google Earth Pro 7.3.4.8642. Ver figura en color en versión web.

Fig. 3.- Escenarios de 2040, 2070 y 2100 de recesión costera en Costa Nova, oeste de Portugal. Fuente de la imagen: Google Earth Pro 7.3.4.8642. See color figure on web.

Episodic components: Storm surge and wave run up

Storms are frequent in the Portuguese coast because most of the coastline is exposed to the North Atlantic and its energetic wave climate during the winter. Between 1994 and 2008 wave buoys located along the western coast recorded 32 storms with significant wave height >5m, mostly from the NW and WNW quadrants (Costa & Esteves, 2010). Their impacts on the shoreline and on the coast are primarily related to episodic coastline retreat and destruction of beach support facilities, coastal protection infrastructures, roads, private property, and other assets. Occasionally there was also life loss, injured and displaced people. These consequences are amplified not only because of the growing urban pressure along the coastal zone and therefore the growing exposure to storm-induced coastal processes, but also when high tides combine with energetic waves leading to extreme runup and storm surge, resulting in an extreme water levels.

Storm surge height is calculated from reconstructed tide gauge time series from 1979 to 2019 (Tadesse & Wahl, 2021). Tide gauges include Vigo (Spain), providing reference values for the Portuguese north-western coastal sector, Cascais (Portugal), with storm surge data representative of the south-western coast, and Lagos (Portugal), for the southern coastal sector.

Wave run up is assumed according to local estimates based on available literature, excluding rocky shores where the HATL directly contacts the cliff base.

Final SLRHZ delimitation

Mapping of SLRHZ scenarios is dependent on the heigh of extreme water levels and predicted coastal recession. Extreme water levels are determined from the sum of the HATL, SLR scenarios, storm surge levels and wave run up. Results of wave extreme water levels along the Portuguese coast show a clear differentiation between the northern and the southern sectors (Fig. 4). Extreme water level values can reach 10.9 m in sandy systems of the northern sedimentary cells while the southern sectors have maximum values of 7.5 m. Lower differences can be observed in rocky coasts.

Because sandy coast morphology can be complex and direct data extrapolation can lead to incorrect results an additional validation criterion is added. If the heigh of the frontal dune top is exceeded by the local extreme water levels or if dune crest is eroded in a mid- long-term scenario, then the local SLRHZ should be extended to the interdune depression.

Conclusion

Mapping SLRHZ in the coastal zone of the Portuguese mainland is fundamental to support coastal decision making.

The criteria for SLRHZ mapping must be differentiated according to the coastal sub-system and the spatial distribution of types of coastal processes

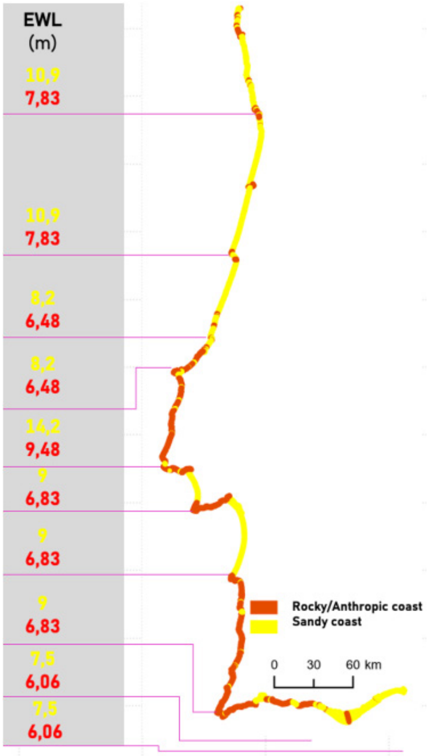

Fig. 4.- Wave extreme water levels (EWL) detailed by sedimentary cell and coastal system, for the Portuguese coast. Ver figura en color en versión web.

Fig. 4. Niveles de agua extremos (EWL) detallados por celda sedimentaria y sistema costero, para la costa portuguesa. See color figure on web.

and hazards, namely extreme water levels and coastline recession.

An effective decision-making support tool for future land use planning the Portuguese coast should include not only the SLRHZ mapping but also should incorporate a more comprehensive risk model that considers future scenarios of exposure, physical vulnerability, social vulnerability, and coping capacity.

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