Article

A Coastal Vulnerability Assessment due to Sea Level Rise: A Case Study of Atlantic Coast of Portugal's Mainland

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Abstract: The sea level rise, a consequence of climate change, is one of the biggest challenges that countries and regions with coastal lowland areas will face in the medium term. This study proposes a methodology for assessing the vulnerability to sea level rise (SLR) on the Atlantic coast of Portugal mainland. Some scenarios of extreme sea level for different return periods and extreme flooding events were estimated for 2050 and 2100, as proposed by the European Union Directive 2007/60/EC. A set of physical parameters are considered for the multi-attribute analysis technique implemented by the Analytic Hierarchy Process, in order to define a Physical Vulnerability Index fundamental to assess coastal vulnerability. For each SLR scenario, coastal vulnerability maps, with spatial resolution of 20 m, are produced at national scale to identify areas most at risk of SLR, constituting key documents for triggering adaptation plans for such vulnerable regions. For 2050 and 2100, it is estimated 903 km² and 1146 km² of vulnerable area, respectively, being the district of Lisbon the most vulnerable district in both scenarios. Results are available through a Web Map Service, for Portuguese public entities, and through a web map viewer for public and communities in general.

Keywords: European Directive 2007/60/EC; sea level rise; coastal vulnerability; GIS; Portugal Coast; WMS; WebViewer;

1. Introduction

The Sea Level Rise (SLR) resulting from climate change is a phenomenon that cannot be prevented. According to [1] it "will continue to rise well beyond 2100 (high confidence) and the increasing global warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure". Areas within 100 km from the coastline comprise the majority of the countries' economic activities as well as most of the world's population (around 40%) [2]. In European Union (EU) approximately half of the population lives within just 50 km of the coastline [3] and 19% (around 86 million people) lives within 10 km of coastal strip [4]. It is likely that such numbers will increase in the future, due to higher migration, industrialization and urbanization trends in coastal areas, increasing human susceptibility to coastal flooding and erosion, especially in low-lying floodplains [5-7]. The susceptibility to SLR can soon imply people and communities' displacement, severely compromising the economic development and undermine the national economic activities. The high demographic exposure of coastal populations and communities sets a high-risk level due to the potential damage of coastal infrastructures and facilities, as well as, a potential real estate economical depreciation. Therefore, the vulnerability assessment of coastal zones to SLR flooding plays a very important role for the assessment of coastal flooding risk and for planning measures of adaptation.

In 2007 the EU published the Flood Directive (Directive 2007/60/CE) which essentially establishes the framework for the assessment and management of all inland and coastal water courses that are at risk of flooding with a purpose to mitigate and reduce the risks to human health, environment, cultural heritage and to economic activity. Determine the entire extent of floodable area due to climate change, its assets and humans at risk are therefore a priority. To comply with this Directive, the EU member states had, in a first phase (until 2011), to identify the river basins and associated coastal areas at risk of flooding. For these areas, the EU Directive recommends the development of flood risk mapping by 2013, as well as the preparation of management plans focused on prevention, protection and preparedness, by 2015 [8]. In Portugal, this Directive had its legal framework in 2010 through the national Decree-Law no. 115/2010 of October 22 and has been subject of study by the Portuguese Environment Agency (APA), which is available online on SNIAmb [9].

Scientific documentation refers to the term vulnerability sometimes in different ways leading to different interpretations. Accordingly, to the Intergovernmental Panel for Climate Change (IPCC) "vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt". On the other hand, IPCC defines the Coastal Vulnerability as the "propensity or predisposition to be adversely affected" by a natural hazard [10].

Over the past two decades, scientists have developed several approaches to identify coastal vulnerability. The most common coastal vulnerability assessment is based on a calculation of an index composed by the aggregation of a set of parameters (variables) which represent several spatial entities (geographic data) that contribute to coastal vulnerability. Gornitz et al. [11] presented the first Coastal Vulnerability Index (CVI), composed by seven variables as indicators of physical vulnerability to the impacts of SLR in the United States of America (USA) coast. These variables consisted of relief (elevation), lithology, geomorphology, erosion/accretion, tidal range, wave height and relative sea level changes. This methodology has been improved by Gornitz et al. [12], that considered thirteen variables grouped into three categories: Erosion (geology, landform, shoreline erosion and wave height), permanent Inundation (elevation and local subsidence) and Episodic Inundation (tropical storm probability, hurricane probability, hurricane frequency-intensity, tropical cyclone forward velocity, extratropical cyclones, hurricane storm surge and tide range). In both methods each variable was rated on a scale of 1 to 5 to express its contribution to coastal vulnerability, with 5 being the highest and 1 being the lowest level. The Gornitz et al. [12] method segments the coastline and assigns the index vulnerability values to each coastal segment and the CVI is defined by the square root of the geometric mean, or through the square root of the product of the ranking factors, divided by the number of variables presented.

After these [11,12] publications, other studies have been produced using specific methodologies to evaluate coastal vulnerability indices applied at regional or local scale (e.g. 13-26).

In Portugal, coastal vulnerability has been studied also at regional and local scales. Coelho [27] proposed a methodology, that has been revised in Coelho et al. [28], to calculate the CVI which is composed by nine vulnerability parameters including geology, geomorphology, land use, anthropogenic actions, elevation, distance to coastline, maximum tidal range, maximum significant wave and erosion rate. Pereira and Coelho [29] calculated the vulnerability within a 2km range from the shoreline between Espinho and Mira (North of Portugal's Mainland), based on the method of [27].

The coastal vulnerability in Ria Formosa (barrier island) (South of Portugal's Mainland) was evaluated by Ceia et al. [30] which identified the areas that are most at risk by assessing the evolution of the Ria Formosa barrier island system (for the time period between 1940 and 2008). In the scope of this study, were also determined which interventions would be necessary to protect those areas. Considering as spatial parameters for their methodology the shoreline evolution, the overwash vulnerability, the occupation, the footpaths, the vegetation and the interventions, the authors divided the study area into fourteen sectors, where each one was rated on a scale from 1 (null) to 5 (extremely high) regarding coastal vulnerability.

Martins et al. [31], has studied the vulnerability of the coastal stretch between Porto de Mós and Falésia beaches in Algarve (South of Portugal's Mainland), corresponding to an area of 52 km length and 500 m width, measured from the coastline to the inland area. This study follows an approach

based on Cellular Automata (CA). A geographical database was created with two types of variables: 1) natural/physical vulnerability (lithology, coastal systems and hydrology) and 2) human factors (highway/railway network, population density, population growth and urban land cover) and is rated on a score/vulnerability degree from1 (very low) to 5 (very high).

The vulnerability and the hazard of flooding by SLR, in the central Algarve (South Portugal's Mainland), between Portimão and Tavira cities, was studied by Martínez-Graña et al. [32]. The vulnerability index was calculated using lithology, geomorphology, slopes, elevations, distances, bathymetry, variations of the coastline, wave height and activity, variations of sea level and tidal range for several time horizons (X0-present, X1-100 years, X2-500 years, X3-1000 year, X4-Stormand X5-Tsunami).

The common dominator of the previously mentioned studies is the spatial unit for the respective CVI calculation considered by all of them, which confined to a strip along the coastline. That is, the coastline is segmented into sectors of equal lengths (e.g. 500 m) and, for each sector, the CVI is determined considering the specific selected parameters. The major limitations of these studies rely on the inability to represent spatially the CVI variability within each sector that results from the lack of spatial detail used. Another limiting aspect is the absence of a prior classification of the study areas into flood or non-flood zones, being the methodology applied equally in both types, with the consequent risk of considering non-flood zones as very vulnerable.

Considering such limitations, the present study defines a methodology to assess Coastal Vulnerability, at national scale, based on projected SLR and extreme flood scenarios forced by extreme events with specific return periods, following the EU Directive guidelines. Coastal vulnerability is calculated on a high spatial resolution basis (20 m), for areas in the Atlantic Coast of Portugal's Mainland (ACPM), that are susceptible to extreme flooding scenarios due to future SLR [33]. In order to make it applicable on a national scale, a Physical Vulnerability Index (PVI) is generated to classify vulnerable areas to coastal flooding, with five levels of importance. The PVI is obtained through the weighted average combination of the Extreme Flood Hazard Index (EFHI) and six physical parameters (hydrographic network, distance to the coastline, coast type, solid geology, drift geology and land use) properly weighted through a multicriteria analysis process. The followed approach to weight parameters was the analytic hierarchy process (AHP), performed by experts and non-experts [34].

This study presents itself as innovative in Portugal not only by the methodological approach for determining coastal vulnerability to SLR, but also because is the first to date study that meets the EU Directive guidelines, with a high spatial resolution, to rigorously study and classify the vulnerability to SLR in the ACPM as a national scale.

The paper is organized as follows: Section 2 presents the study area and dataset, Section 3 describes the methodology, Section 4 presents the results and Section 5 meets the conclusions.

2. Study area and Datasets

2.1. Study area

The ACPM extends from the south of the mouth of Minho river to the western mouth of Guadiana river for about 987 km long. The Portuguese west coast extends approximately in the NS direction, between the mouth of the Minho River (41°52'N, 8°52'W) on the northern border, and Cape St. Vincent (37°01'N, 9°00'W), while the southern coast extends from Cape St. Vincent to the mouth of Guadiana River (37°14'N, 7°22'W) on the eastern border [35] (Figure 1).

The Portuguese coastline contains extensive sandy beaches backed by dunes, high cliffs, bays, estuaries, lagoons and barrier islands, housing near the coast 75% of the population, major political decision-making centers, commercial and industrial hubs and employment opportunities [36].

The main economic activities in these areas are maritime transports, port activities, tourism, bathing and leisure activities, boating, fishing, aquaculture, saliculture, mineral and energy resources. These activities contribute with about 85% of the national Gross Domestic Product (GDP) and as such are highly strategic activities for the country [37].

Figure 1. The Atlantic Coast of Portugal's Mainland with districts and main coastal rivers.

2.2. Datasets

According to the required accuracy and positional detail, the vulnerability study to SLR can be applied at national, regional (district or municipality) or local scale (coastal sector in specific municipality or parish) [38]. Depending on the level of detail, hazards associated to SLR and to extreme coastal flooding should be properly considered as well as the spatio-temporal data availability and its resolution.

Available data strongly determines the methods to be applied to the vulnerability assessment. Thus, in this study, six physical parameters have been selected to assess the PVI. Table 1 shows the data used for this study, the respective data sources and some of its characteristics. All spatial data are referred to PT-TM06, the national cartographic coordinate system referenced to the European geodetic reference system ETRS89.

Data were mostly obtained from public domain sources and from official and unofficial information provided by different national institutions (e.g. Portuguese Environment Agency – APA, Directorate General for Territory – DGT, Hydrographic Institute – IH, Military Geospatial Information Center – CIGeoE and National Statistical Institute of Portugal – INE). A geospatial database, built in a Geographic Information Systems (GIS), was produced to store spatial data

(hydrographic network, administrative units, etc.), as well as alphanumeric information (census data, etc.). The harmonization of the data model has thus been facilitated.

Table 1. Data used in the study, as well as its source and some observations.

Parameter	Data source	Observations
Hydrographic Network	CIGeoE, 2016	Scale: 1:25 000 - Tagus Estuary, Aveiro and Formosa Lagoons; Others: manually vectorized.
Coastline	IH, 2011	Scale: 1:25 000
Lithological chart	APA, 2015	Scale: 1:1 000 000
Land Use (*COS2007*)	DGT, 2014	Level 1 and 2
Administrative Units (*CAOP2015*)	DGT, 2015	Delimitation of the administrative districts.
Statistical Subsection	INE, 2011	Census data from Census2011 (*population and buildings*)

3. Physical Vulnerability Index Assessment

The methodology followed for the PVI calculation combines an Extreme Flood Hazard Index (EFHI) [33], calculated for the ACPM, and a set of physical parameters, considered relevant for the vulnerability analysis at the national scale.

Figure 2 shows the workflow of the methodological followed process. Phases that compose this workflow will be described in the following sections.
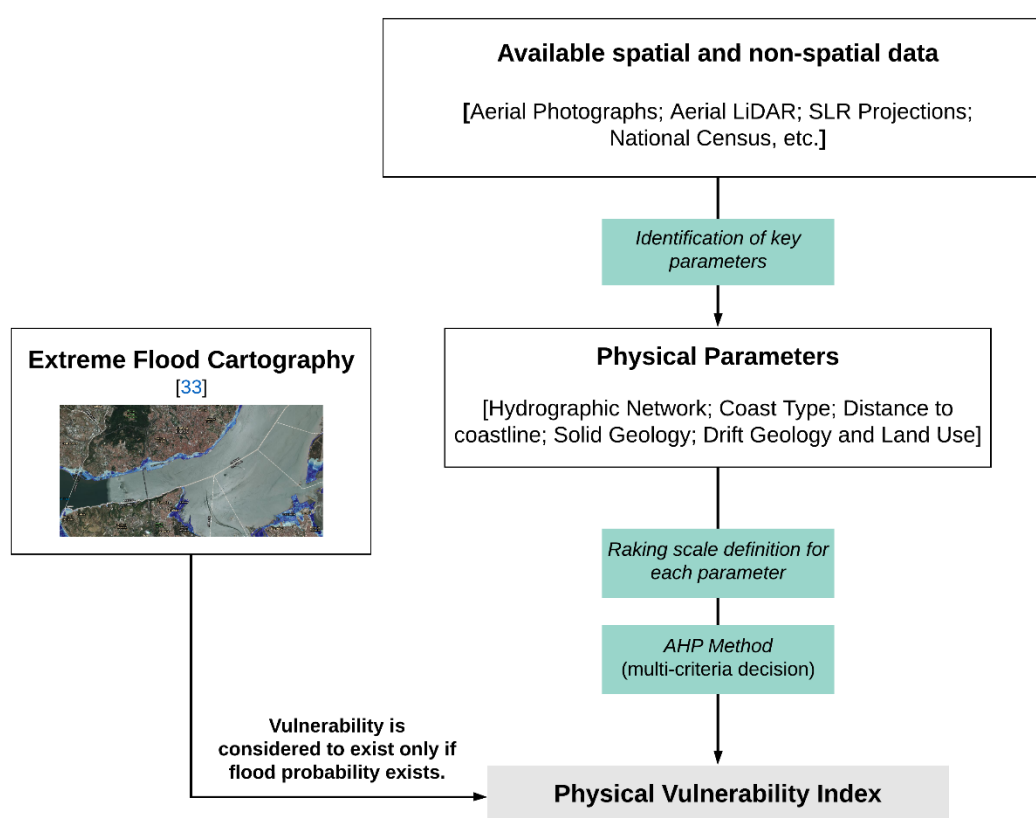
Figure 2. Flow diagram summarizing the methodology adopted in this study for the Physical Vulnerability Index (PVI) in ACPM and based on the Extreme Flood Cartography of [33].

3.1. Extreme Flood Hazard Index (EFHI)

The EFHI is an index that represents the probability of flooding in a specific coastal area [33]. This index was calculated using a probabilistic approach and classified into five classes of flood probability, each one with 20% of interval. The SLR scenarios used to calculate the EFHI were based on the study of Antunes [39]. The EFHI is classified, for an extreme tidal maximum level, by five hazard classes ranging from 1 (Very Low) to 5 (Extreme).

This index serves as the basis for the production of probabilistic flood maps, to which an updated topographic model was used (from aero-photogrametric model of 2008 with 2 m of original spatial resolution - see [33] for more detailed information), without inferring any coastal profile morphodynamics nor considering coastline retreat due to present and future erosion and SLR. The generated maps allowed to quantify and qualify the flooding area for each SLR scenario, thus serving as a basis for the coastal vulnerability assessment study.

The main results in [33] show that, for the year 2050, a total of 903 km2 of the ACPM is potentially affected by extreme flooding due to SLR, being the districts of Lisbon, Faro, and Aveiro the most affected with 221, 182, and 172 km^2 of flooded area, respectively. For 2100 (Figure 3), those values rise to 1146 km^2 of total area and 250, 211, and 219 km^2, respectively, for the same most affected districts.
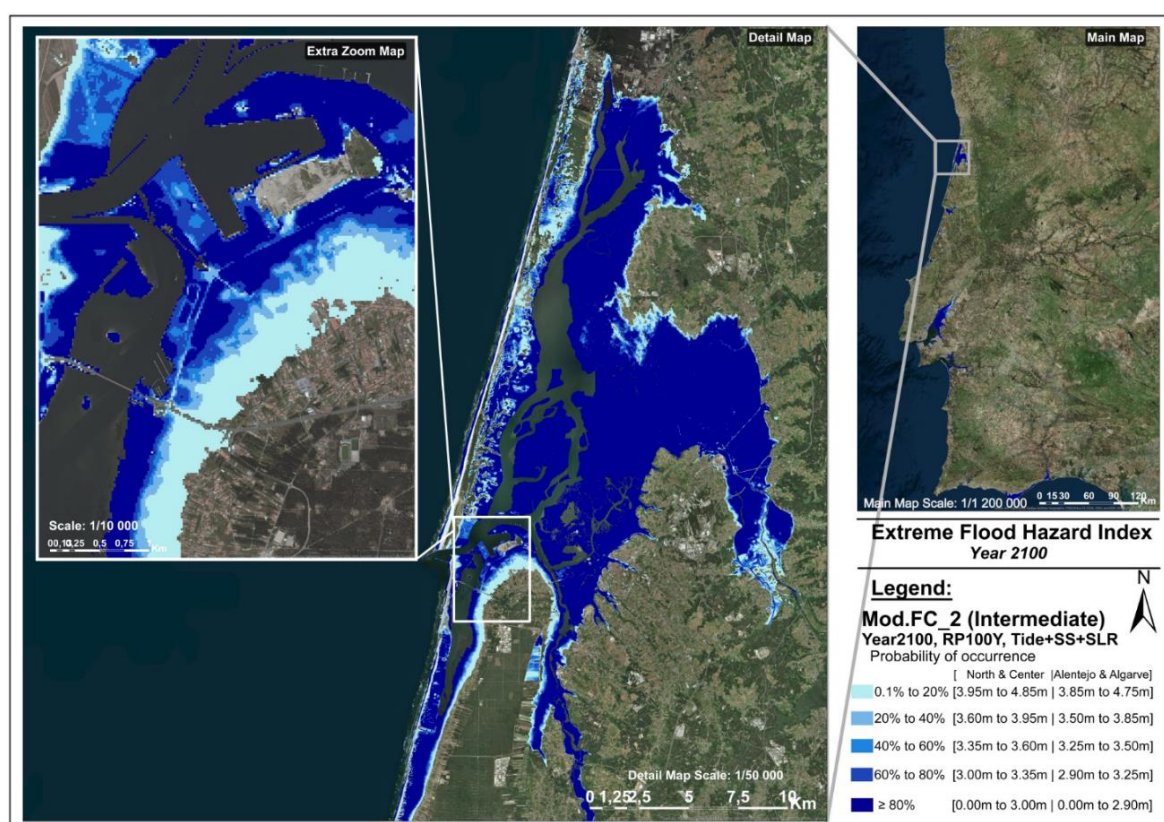
Figure 3. Portuguese coastal flooding extreme scenarios for 2100 SLR and 100-yr RP, within a zoom image of the Aveiro inland lagoon (Ria de Aveiro). Source: [33].

These results were provided, through a WMS, to the Ministry of Environment, under a protocol signed between the General Secretariat of the Ministry of Environment, the Portuguese Association of Insurers and the Research Group "Climate Change Impacts, Adaptation and Modelling – CCIAM" of Lisbon University.

3.2. Physical Parameters

Physical vulnerability focuses on determining the susceptible locations to SLR flood in the coastal environment, which includes the internal and external physical characteristics of the system, defined through coastal characteristics and coastal forcing [38] (the coastal forcing parameter used in the present study is given by the EFHI, which results from the SLR projections described in [33] and [39]).

Different sets of physical parameters can be found or used to determine physical vulnerability, each one with a specific contribution for the susceptibility to extreme and frequent flooding. But, geographical data access and availability, as well as its quality and spatial resolution, determine in most of the cases whether they can or cannot be used and applied. Additionally, the importance or the weight of each parameter must be considered so the results can rely on more realistic assessment.

In the present study, six physical parameters namely, the hydrographic network, the coast type, the distance to coastline, the solid geology, the drift geology and the land use were selected to calculate the PVI. Table 2 shows how each parameter is classified, maintaining the rationale that each parameter must be rated on a scale from 1 to 5 to express its PVI contribution, with 1 corresponding to Very Low and 5 corresponding to Extreme vulnerability.

Table 2. Classification of physical vulnerability parameters for Portugal's Mainland, ranging from 1 (very low) to 5 (extreme).

Physical Parameter		1 – Very Low	2 – Low	3 – Medium	4 – High	5 – Extreme
Hydrographic Network	*Dist.*	200 – 300 m	150 – 200 m	100 – 150 m	50 – 100 m	≤ 50 m
	Slope	≥ 3º	2.0 – 3.0º	1.5 – 2.0 º	0.5 – 1.0º	≤ 0.5º
Coast Type		Rock Cliff Coast				Low and sandy coast
Distance to Coastline		≥ 1000 m	200 – 1000 m	50 – 200 m	20 – 50 m	≤ 20 m
Solid Geology		Plutonic and Volcanic Eruptive Rocks		Sedimentary and Metamorphic Formation		Sedimentary Formation
Drift Geology		Urban or rock	Stone or clay		Beaches or sediments	Alluvium; loose sand or gravels
Land Use (*level 2*)		Water bodies; sparse vegetation; swamp or bare rock	Coastal sands	Forest	Agriculture	Urban and industrial infrastructures

The following sub-sections describe the procedure used in GIS to classify each of these parameters.

3.2.1. Hydrographic Network

The slope of the terrain combined with the distance to the river network enables the identification of areas that are potentially affected by floods, e.g. a river in a valley with a considerable slope has a low vulnerability, unlike a river in a plain, where the slope is relatively small. In the latter, if there is a probability of flooding, there is also a high probability of flooding along shallow flat lands.

Finally, the slope of the terrain enables to assess not only the relative risk of flooding, but also the susceptibility to these flooding event. Thus, regions with the lowest slope should have the most proactive protection and adaptation measures than in the steepest regions [17]. Obtaining the hydrographic network with the required accuracy for this type of studies is an extremely difficult task, since the available data, free and affordable, has a low positional quality due to its cartographic scale. In order to overcome limitations on data quality and data resolution, some efforts have been made to manually vectorized (at a minimum scale of 1:800) the main rivers and water bodies near the coast in ACPM (a total of 34 rivers) except for Aveiro Lagoon, Formosa Lagoon and the Tagus River, where the respective 1:25,000 scale cartography was kindly provided by the CIGeoE.

Figure 4 shows two examples of free data available at Environment Atlas site [9] and some positional problems inherent to the inaccuracy of the data.

Figure 4. Examples of problems found in the online data available at Environment Atlas [10]: a) The hydrographic network of Tagus river valley available in the Environment Atlas represented by supposed axes of water bodies. b) The Alcoa river, near Nazaré city, is represented in the Environmental Atlas by the dark blue line, while the light blue polygon is the manual vectorization of this same river.

3.2.2. Coast Type

The coast type in Portugal's mainland varies according to the nature of its rock materials, and although the Portuguese coast is mainly dominated by beaches, there are predominantly rocky coast areas. Thus, two types of coast can be defined (Figure 5), the cliff coast and the low sandy coast, which are the two types considered for the PVI.

Figure 5. Two type of coast in Portugal's mainland: a) Cliff coast in Albufeira's Falésia beach, Algarve; b) Low sandy coast in Manta Rota beach (Vila Real de Santo António), Algarve. Source: Google Earth Pro.

The parameterization of cost type was defined through a parish analysis, where each predominant coast type was defined. Through the Administrative Units of Portugal (CAOP2015), it was possible to select only the parishes that contain coastal areas classified according to their type of coast. The rock cliff coast is characterized by being high and steep relief and constituted by rock formations more resistant to erosion and to SLR, therefore its vulnerability classification level is 1 (very low). The low and sandy coast allows the sea to advance faster than the previous one, and consequently its vulnerability classification will be maximum level 5 (extreme).
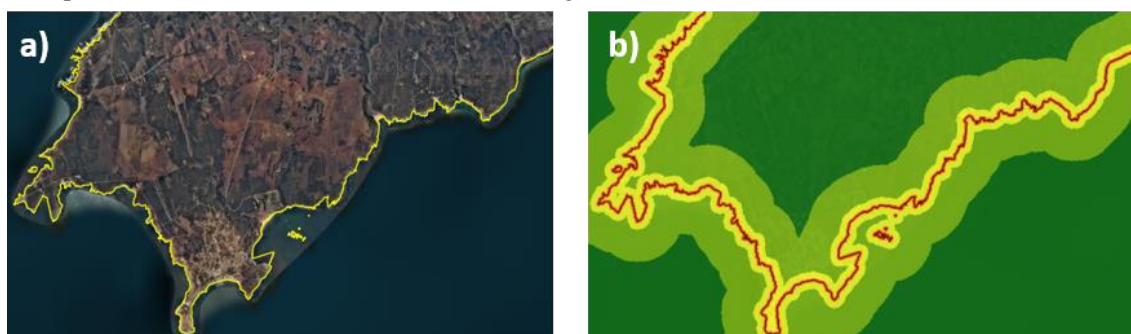
3.2.3. Distance to Coastline

Distance to coastline is an important factor in this analysis, as vulnerability increases with proximity to the sea zone. Under normal conditions, a coastline location is more subject to the ocean energetic forces of the sea, so as the distance to the coastline increases, the erosion and coastal vulnerability decreases.

For the distance to coastline, it was used, as reference line (vector geometry in a shapefile format), the one provided by the National Hydrographic Institute (IH), which includes the coastline of Portugal, Spain and part of Africa. Only the coastline of ACPM was extracted from that file, which according to IH, was obtained mainly from the information of the Portuguese Official Administrative Chart, and it has been further enhanced with information produced by IH in port, rivers and lagoons

areas. Metadata also provides the associated coastline uncertainty, which presents the minimum accuracy on the 1:25,000 scale.

Figure 6 shows an example of the coastline used in the Algarve region (south of Portugal) and the respective distance classes classified according to the values in Table 2.


Figure 6. a) Coastline of Portugal classification in Sagres (Algarve) according IH; b) Distance to coastline with the classification according to Table 2: very low – dark green, low – green, moderate – yellow, high – orange and extreme – red.

3.2.4. Solid Geology and Drift Geology

The cartography of Solid Geology and Drift Geology allows us to evaluate the rocks and sediments nature that form the coastal regions, as well as its classification based on the behavior of those materials when subjected to coastal forcing. For example, magmatic or eruptive rocks are of high hardness and therefore of low vulnerability to erosion, unlike small non-consolidated sediments [27].

The lithological chart of Portugal provides elements about the country's superficial lithology in which the mother rock, as a formation factor, assumes an enormous importance in the characterization and use of soil [9].

The information for these two parameters is available on the Environment Atlas website in a single shapefile containing thirty-four different lithological complexes of Portugal. This chart is based on the Geological Map of Portugal, published in 1972 on a scale of 1: 500,000, including sedimentary, metamorphic and eruptive lithological formations [40]. There are twenty-six complexes belonging to sedimentary and metamorphic rocks and eight belonging to eruptive rocks. The shapefile contains attributes concerning to the mother rock formation type and to the lithological complexes. Both attributes were used to select areas of solid geology and drift geology to rank them on a scale from 1 to 5 (c.f. an example in Figure 7), according to the classification in the Table 2.
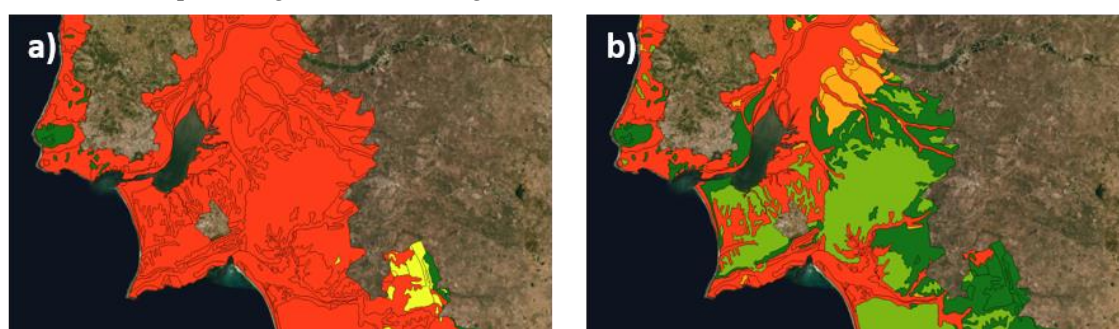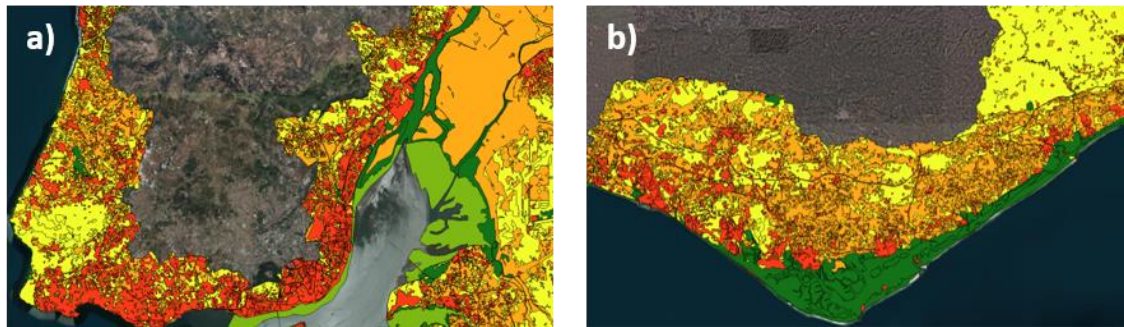

Figure 7. Classification in Lisbon Region, according to Table 2: very low – dark green, low – green, moderate – yellow, high – orange and extreme – red. a) Solid Geology; b) Drift Geology.

3.2.5. Land Use

The morphological characteristics of the coast may also be a result of the type of land use A wooded or a fully paved coast has a distinct behavior in relation to coastal vulnerability. Thus, it is considered that the greater the level of changes in the natural covering state of a soil, the greater is the vulnerability.

Figure 8 shows two examples of the classification in Lisbon (urban area) and in Formosa Lagoon (a Natural Park).

Figure 8. Classification of Land Use according to Table 2: very low – dark green, low – green, moderate – yellow, high – orange and extreme – red. a) Lisbon Region; b) Formosa Lagoon – Algarve.

Land Use information was extracted from the Land Cover Mapping program (COS2007) in Portugal, which is based on the visual interpretation of orthorectified aerial images [41]. COS nomenclature follows a hierarchy that represents land use / occupation at different levels and classes of thematic detail, where level 1 has 5 classes and level 2 has 193 classes.

In the present study, from the five existing levels, only the first and second were used, corresponding to the less detailed levels, but which perfectly fits to the study scale.

3.3. Analytical Hierarchical Process

The Analytic Hierarchy Process (AHP) method was developed by Thomas L. Saaty in 1971-1975. This method is increasingly used in the design work of Decision Support Systems based on a multi-attribute approach since it is easy to implement in computer systems and its mathematical model presents a relatively simple algebraic calculation [34]. This method is used in design studies for decision systems, such mapping of risk zones and landslide susceptibility [e.g. 42-45], earthquake hazard [e.g. 46], flood zones [e.g. 47,48] and coastal vulnerability assessment [e.g. 49-54]. The advantages of this method are pointed out in [34].

According to Saaty [34], the logical consistency of the comparison's matrix is guaranteed by the analysis of the "Consistency Ratio", comparing it with the "Random Consistency". The AHP evaluates the needed weighting factors by means of a preference matrix, where all the selected parameters, considered relevant for the specific study, are compared to each other.

In the present study, a pairwise comparisons was carried out for all the parameters involved in the definition of PVI and the matrix was completed using scores based on their relative importance according to Saaty's rating scale as shown in Table 3.

Table 3. The fundamental scale of AHP [34].

Intensity of Importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored, and its dominance demonstrated in practice

9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix.

Each physical parameter has been rated against every other one by assigning a relative dominant value between 1 and 9, according to the fundamental scale of AHP (Table 4).

Table 4. Pairwise comparison matrix of physical parameters.

Parameter	Extreme Flood Hazard	Hydrographic Network	Coast Type	Distance to coastline	Solid Geology	Drift Geology	Land Use
Extreme Flood Hazard	**1**	2	3	3	5	7	8
Hydrographic Network	1/2	**1**	2	2	3	5	7
Coast Type	1/3	1/2	**1**	1	3	5	7
Distance to coastline	1/3	1/2	1	**1**	3	5	7
Solid Geology	1/5	1/3	1/3	1/3	**1**	3	5
Drift Geology	1/7	1/5	1/5	1/5	1/3	**1**	3
Land Use	1/8	1/7	1/7	1/7	1/5	1/3	**1**

Having a comparison matrix (Table 4), a priority vector, corresponding to the normalized Eigen vector of the matrix, is computed. This is done by dividing each column by the corresponding sum (Table 5).

Table 5. Normalized matrix of physical parameters.

Parameter	Extreme Flood Hazard	Hydrographic Network	Coast Type	Distance to coastline	Solid Geology	Drift Geology	Land Use
Extreme Flood Hazard	0.38	0.43	0.39	0.39	0.32	0.27	0.21
Hydrographic Network	0.19	0.21	0.26	0.26	0.19	0.19	0.18
Coast Type	0.13	0.11	0.13	0.13	0.19	0.19	0.18
Distance to coastline	0.13	0.11	0.13	0.13	0.19	0.19	0.18

Solid Geology	0.08	0.07	0.04	0.04	0.06	0.11	0.13
Drift Geology	0.05	0.04	0.03	0.03	0.02	0.04	0.08
Land Use	0.05	0.03	0.02	0.02	0.01	0.01	0.03

The normalized matrix must be consistent and thus an index of consistency, known as Consistency Ratio (CR), must be computed by Equation (1). If CR satisfy this condition (less than 10%), the matrix is consistent, otherwise the matrix needs to be re-evaluated with different pairwise comparisons and the consistency tested again by the AHP criteria.

$$CR = \frac{CI}{RI} < 10\% \tag{1}$$

where, CI is the Consistency Index (Equation (2)) and RI means a Random Index for different values of n (Table 6).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

Table 6. RI values for each order n of the matrix.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

being λ_{max} the principal eigenvalue of the matrix and n the order of the matrix (Table 7).

Table 7. Computation of consistency ratio (CR).

λ_{max}	n	CI	CR
7.42	7.00	0.07	5.2%

Finally, as the CR satisfy the condition imposed by Equation (1), the weights of each physical parameter are determined and used to calculate the PVI (Equation (3)):

$$\text{PVI} = \frac{EFHI \times 34\% + HN \times 21\% + CT \times 15\% + DC \times 15\% + SG * 8\% + DG * 4\% + LU * 2\%}{100\%} \tag{3}$$

where $EFHI$ is the extreme flood hazard index given by [33], HN is the distance to hydrographic network, CT is the coast type, DC is the distance to coastline, SG is the solid geology, DG is the drift geology and LU is the land use.

4. Results

As a result of PVI determination it is possible to classify the physical vulnerability of the coastal zone of Portugal identifying the susceptible areas to the flooding conditional probability [33] for the future scenarios of SLR, at the time horizon of 2050 and 2100 [39].

With the results of this study, some statistics on the number of people and buildings that will be potentially affected by SLR and extreme events can be performed in the coastal districts of Portugal. The corresponding data of residents and buildings were obtained from the national statistical subsections (Census Data). Since the used Census data is from 2011, and SLR is projected to the end of century, demography statistical estimates will not represent future reality but estimate indicators instead. The number of buildings and residents within the vulnerable areas are estimated by district, for each vulnerability class and for all vulnerable area as can be seen in the following sections.

The PVI classes were defined and determined with five vulnerability levels, as each of the parameters that composes it (Table 8).

Table 8. Color Scheme of results of Physical Vulnerability Index.

Categories	1 – Very Low	2 – Low	3 – Medium	4 – High	5 – Extreme
Color Scheme					

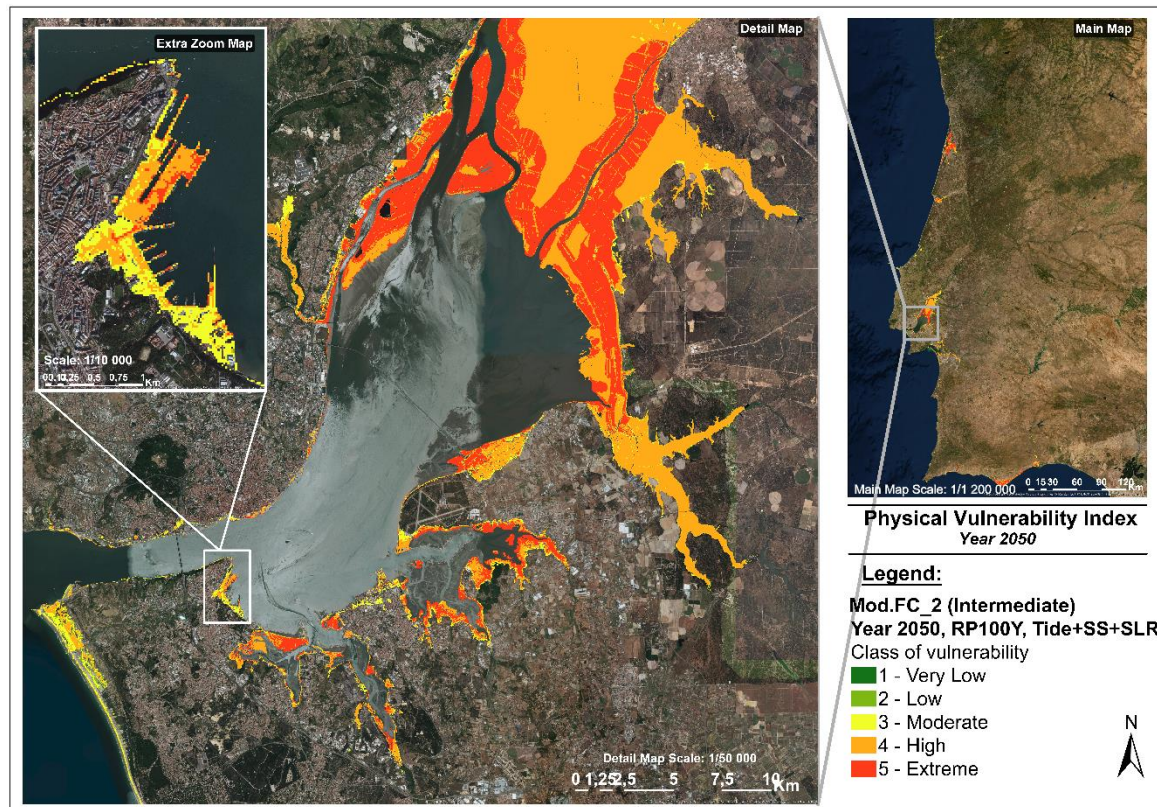*4.1. Physical Coastal Vulnerability Cartography*

4.1.1. Year 2050

In the medium-term future (2050 scenario), considering the Mod.FC_2 SLR projection (44 cm relative to the Cascais1938 vertical datum [39]) at the high-tide and with 100 years return period of storm surge, it is estimated that an area of 903.1 km², comprising with a total of 59,530 buildings and 145,550 residents, will be affected by extreme tide flooding and SLR (Table 9). Demographic statistics, as stated above, are based on current values of Census rather than future projections.

Table 9. Physical Vulnerability areas (in km²) for each class interval and respective number of buildings and residents, for the 2050 SLR extreme flood scenario in each coastal district.

District	1 Very Low	2 Low	3 Medium	4 High	5 Extreme	Total (km²)	Number Buildings	Number Residents
Aveiro	0.0	0.7	12.6	55.1	103.1	171.4	11,480	26,370
Beja	0.0	0.2	1.8	4.4	0.2	6.6	830	920
Braga	0.0	0.1	0.7	1.8	1.1	3.7	1,260	2,200
Coimbra	0.0	0.4	5.5	26.3	9.0	41.1	1,570	3,390
Faro	0.1	2.8	12.0	65.2	102.3	182.3	18,890	36,410
Leiria	0.2	2.4	7.1	10.0	0.6	20.2	2,940	3,800
Lisbon	0.0	0.5	15.6	151.8	53.5	221.4	4,350	16,470
Porto	0.0	0.3	0.9	1.1	0.3	2.5	3,630	11,330
Santarém	0.0	0.5	16.0	55.1	27.5	99.1	1,190	2,150
Setúbal	0.0	4.8	17.4	93.9	20.7	136.8	11,390	38,390
Viana do Castelo	0.0	1.0	4.7	8.0	4.2	17.9	2,000	4120
Total	0.3	13.7	94.3	472.7	322.5	903.0	59,530	145,550

Lisbon is the district with the largest vulnerability area with about 221.4 km², from which 92.7% is classified as high and extreme vulnerability. The district of Faro has the largest number of buildings in vulnerable areas, almost 19,000, while Setubal is the district that has the highest number of residents living (in 2011) in the vulnerable areas to SLR, with above 38,000 people.

Figure 9 shows the PVI calculated for 2050 in ACPM, focusing on a zone of Tagus Estuary and an extra zoom map for the Military Navy Base. This military infrastructure is the land-based unit and the main Portuguese Navy installation and operational base. It comprises a port infrastructures complex, facilities and services in Alfeite and "Doca de Marinha" (Navy Harbor), which the main function is the logistic support to the moored units in Lisbon, to ensure and promote the conservation and maintenance of port facilities, infrastructure and other assigned assets [55]. Such infrastructure, located in a moderate to extreme vulnerability zone, must be adapted to climate change scenarios to maintain its operational function in full time.

Figure 9. Portuguese coastal physical vulnerability for 2050 SLR and 100-year RP, within a zoom image of the Tagus Estuary and an extra zoom map of the Lisbon Naval Base.

3.1.2. Year 2100

In 2100 (Figure 10), a long-term future (2100 scenario), considering the Mod.FC_2 SLR projection (1.15 m relative to the Cascais1938 vertical datum [39]) at the high-tide and with 100 years return period storm surge, it is estimated that an area of 1146 km², comprising with a total of 82,000 buildings and 224,830 residents, will be affected by extreme tide flooding and SLR (Table 10).

Table 10. Physical Vulnerability areas (in km²) for each class interval and respective number of buildings and residents, for the 2100 SLR extreme flood scenario in each coastal district.

District	1 Very Low	2 Low	3 Medium	4 High	5 Extreme	Total (km²)	Number Buildings	Number Residents
Aveiro	0.0	2.7	31.7	74.1	110.1	218.6	15,930	38,040
Beja	0.0	0.4	2.2	4.5	0.2	7.3	890	960
Braga	0.0	0.2	2.9	3.0	1.6	7.6	2,380	4,500
Coimbra	0.1	1.8	7.6	34.5	10.0	54.0	3,020	6,370
Faro	0.1	6.6	22.0	76.0	106.1	210.9	23,190	48,710
Leiria	0.4	4.9	13.9	14.1	0.8	34.0	3,920	5,540
Lisbon	0.0	1.8	16.0	174.9	56.8	249.6	6,250	31,570
Porto	0.1	1.1	2.5	1.6	0.4	5.7	5,430	17,140
Santarém	0.0	1.8	39.5	83.2	28.4	152.9	2,150	4,440
Setúbal	0.4	11.0	27.7	111.0	24.1	174.1	15,350	59,600
Viana do Castelo	0.2	3.3	10.0	12.4	5.2	31.1	3,490	7,960
Total	1.2	35.7	175.9	589.2	343.8	1145.8	82,000	224,830

For 2100 scenario, Lisbon District will be once more with the largest vulnerability area, 221.4 km^2, from which 92.8% is classified with the high and extreme vulnerability levels. The district of Faro has the largest number of buildings in areas considered vulnerable, almost 23,190; and the district of Setubal with the highest number of residents living in areas considered vulnerable to SLR, with around 59,600 people.

As it is evident, in both scenarios (2050 and 2100), inland waters are the most affected areas, corresponding also to areas with the highest level of exposure (people and buildings). Districts that have large estuaries will have their area severely affected in future due to SLR and storm surge flood forcing. This is the case of Faro and Aveiro districts (Figure 10), where the increasing intertidal area is strongly affected by SLR and consequently, the increase of physical vulnerability and high risk caused by a strong urban exposure.
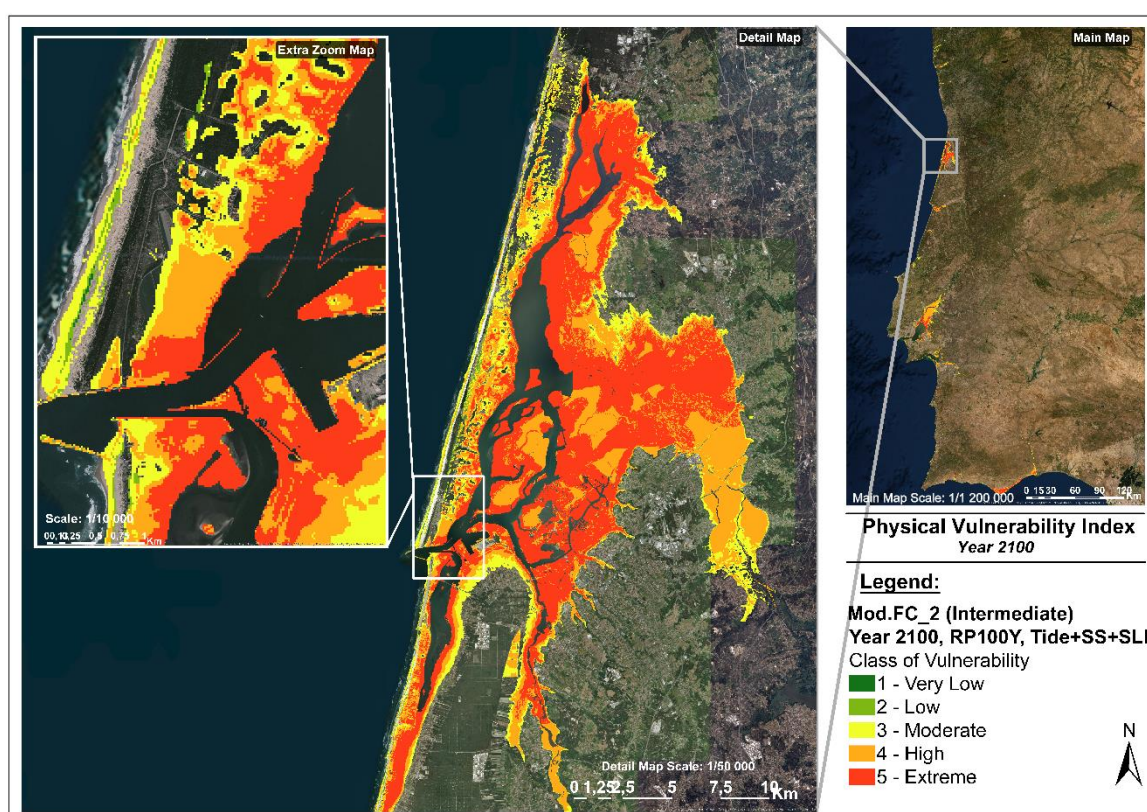
Figure 10. Portuguese coastal physical vulnerability for 2100 SLR and 100-year RP, within a zoom image of the Aveiro inland lagoon.

The set of figures from 11 to 14 show examples of areas containing public and private infrastructures, along the ACMP, classified by moderate to extreme vulnerability levels.

In Figure 11, four cities in Faro district (south of Portugal) having important infrastructure in vulnerable zones, are highlighted in the final vulnerability maps of coastal flooding:

- Figure 11a shows Vila Real de Santo António, in the eastern most city of the Faro district, which is bathed by the Guadiana River and the Atlantic Ocean. Almost the whole city is at the extreme level of vulnerability with 2,700 buildings and 8,900 residents in those areas according to Census2011. This is an example of a city where it is urgent to define and take adaptation measures against SLR.
- The city of Olhão (north of Ria Formosa), in Figure 11b, has the entire downtown classified as extreme level of vulnerability. Many building projects and rehabilitation constructions have been done in this city, but they have not considered the potential extreme events due to climate change, nor the SLR. Olhão municipality is the most vulnerable to SLR in Algarve, since it has the largest number of buildings in areas considered vulnerable, almost 4,100, and more than a

10,400 people lives in those areas. Thus, it is imperative that Olhão municipality quickly take adaptation and mitigation measures to the future impact of SLR.

- Figure 11c shows the Faro international Airport in Formosa Lagoon system, the main and major infrastructures of the region, being also classified by the present assessment with high to extreme vulnerability. This type of infrastructure, which is the lifeblood for the tourism in the region as it is considered the main gateway to the Algarve region (international and domestic flights), can be badly affected by floods and for that reason needs to be adapted to the SLR scenarios.

- Finally, the Figure 11d shows the Lagos city. It is possible to see that Lagos Marina is partially classified with high and extreme vulnerability. On the west side of the river are numerous infrastructures (~1,600 buildings) in the vulnerable area, such as a gas stations, a hospital, the bus station, a church, etc.
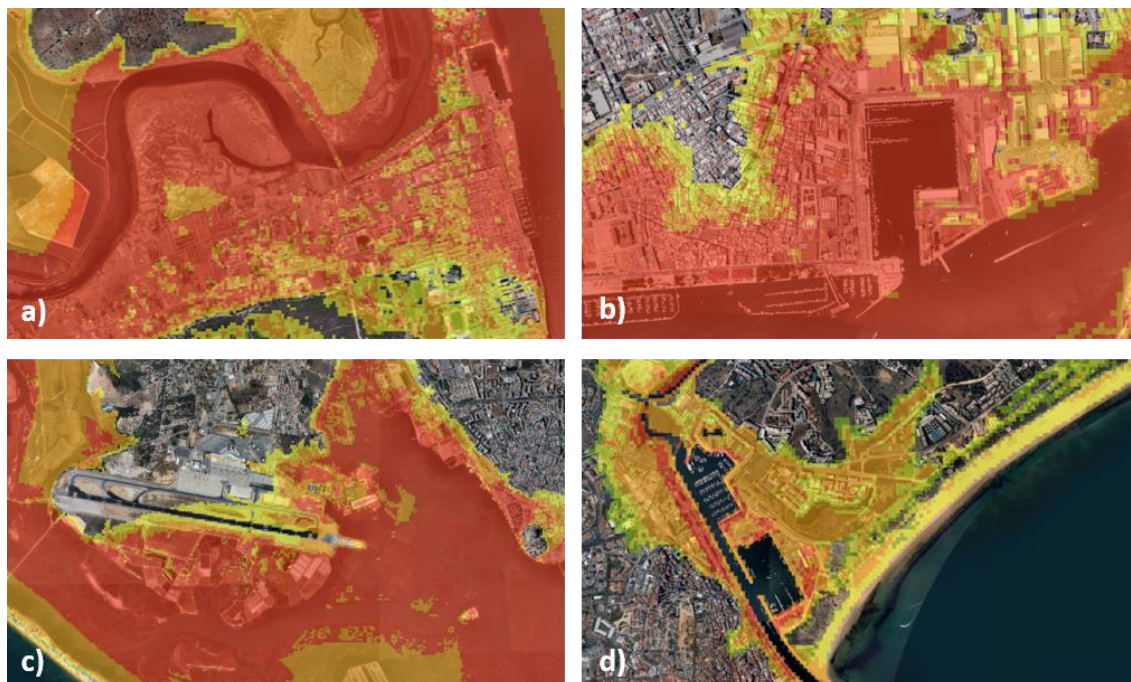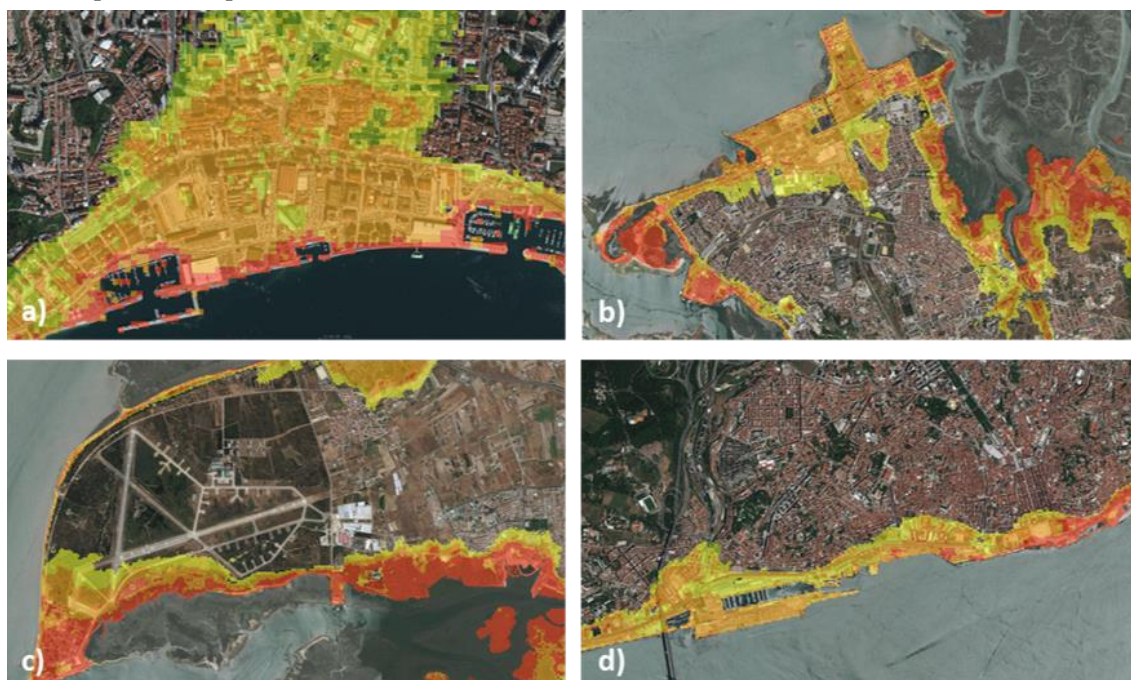

Figure 11. Physical Vulnerability for 2100 in Algarve – Faro district: a) Vila Real de Santo António city; b) Olhão city; c) Faro Airport; d) Lagos city.

Figure 12 shows four cities in Lisbon Metropolitan Region that contain important infrastructure in vulnerable zones:

- In Figure 12a, the city of Setubal is illustrated. The downtown of the city is classified as high to extreme vulnerability level. The Setubal municipality is the second most vulnerable in the district, with a largest number of buildings in areas considered vulnerable, almost 3,000 (including: Judicial Court of Setubal, Municipal Market, Police Station, Schools, Security Infrastructures, Port Administrations, etc.) and more than 12,000 residents.

- In the case of Barreiro (Figure 12b), with strong urban exposure on the southern margin of Tagus estuary, there are almost 1,600 buildings and 9,700 residents in the areas considered vulnerable. In the affected infrastructures list we can highlight schools, museums, supermarkets, the Barreiro fluvial terminal, the industrial zone, part of the railway Sado Line, etc.

- Figure 12c shows Montijo Air Base (BA6), which belongs to the Portuguese Air Force. For this infrastructure it is projected a second Lisbon airport complementary to the main Lisbon airport, which will starts operating commercial flights in 2022 running at least up to 2062.

- The last, Lisbon city (Figure 12d) is one of the most vulnerable cities in the country. Not only for the considerable number of buildings and people living in these areas (~1,600 and 13,500, respectively), but by the buildings and infrastructures value at northern margin of the Tagus estuary. The entire northern riverside area will be severely affected, and as a result, numerous infrastructures that already exist or are designed for construction within the area will be at risk.

Faced with this problem, the municipality has already begun to make relocation plans and placing some restrictions on its Municipal Director Plan for new constructions. However, more serious actions will have to be taken, since as a numerous heritage and important buildings are in the areas of high to extreme vulnerability, such as train lines (Azambuja, Cascais), metro station (Santa Apolónia and Terreiro do Paço), museums, gas station, cruiser terminal, all the marinas and harbors, buildings on Praça do Comércio (Lisbon Court, Ministry of the Sea), Cais do Sodré train station and fluvial station, Time Out Market, Universities, police station, public and private hospitals, Belém Palace, etc.

Figure 12. Physical Vulnerability for 2100 in Lisbon Metropolitan Area: a) Setúbal city; b) Barreiro city; c) Montijo Air Base; d) Lisbon city.

In Figure 13 are presented 4 examples of cities in the Center Region of ACPM which contain also important infrastructure in vulnerable zones:

- In Figure 13a is Peniche Peninsula, the downtown of the city is practically at the medium to high level of vulnerability and has 834 buildings (fire station, bus terminal, Peniche shipyard, etc.) and 2,072 residents in those areas.
- The municipality of Alcobaça (Figure 13b) is also one of the most vulnerable to SLR, accounting for 1,494 buildings and 1,428 residents in the vulnerable areas. Figure 13b shows the parish of São Martinho do Porto, which despite being around a protected bay, may have in the 2100 some of its infrastructures at risk, such as police station, train line - West Line, health center, etc.
- In the case of Figueira da Foz (Figure 13c), with strong urban exposure near the Mondego river, there are almost 1,997 buildings and 4,849 residents in the areas considered vulnerable. From the affected infrastructure list, we can highlight the city council, supermarkets, Figueira da Foz Marina, Mondego shipyard and the urban train line.
- In Espinho municipality, 276 buildings and 747 residents are in vulnerable areas. The Figure 13d shows Engineering Regiment No. 3 (RE3) which is a military unit of the Portuguese Army, installed at the Paramos headquarters in Espinho. This is another of the Portuguese military installations that are in a vulnerable zone to SLR and needs soon to adopt adaptation measures (e.g. relocation).
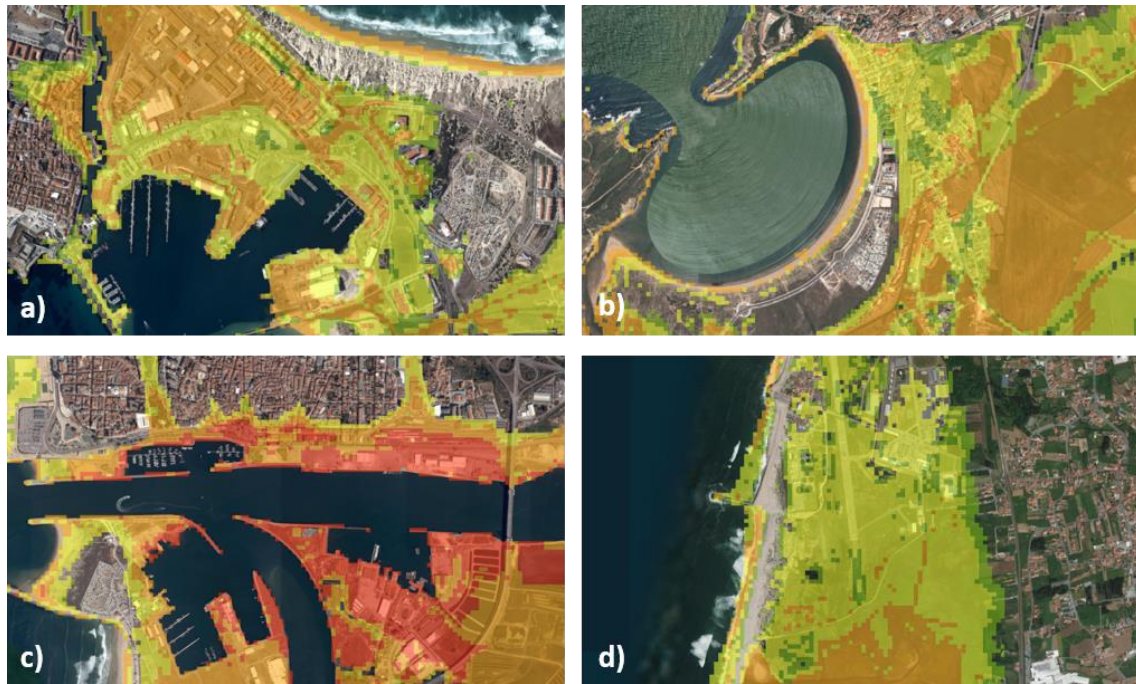
Figure 13. Physical Vulnerability for 2100 in Center Region of ACPM: a) Peniche city; b) São Martinho do Porto city; c) Figueira da Foz city; d) Espinho city.

In Figure 14 it is possible to see 4 examples in the ACPM North Region:
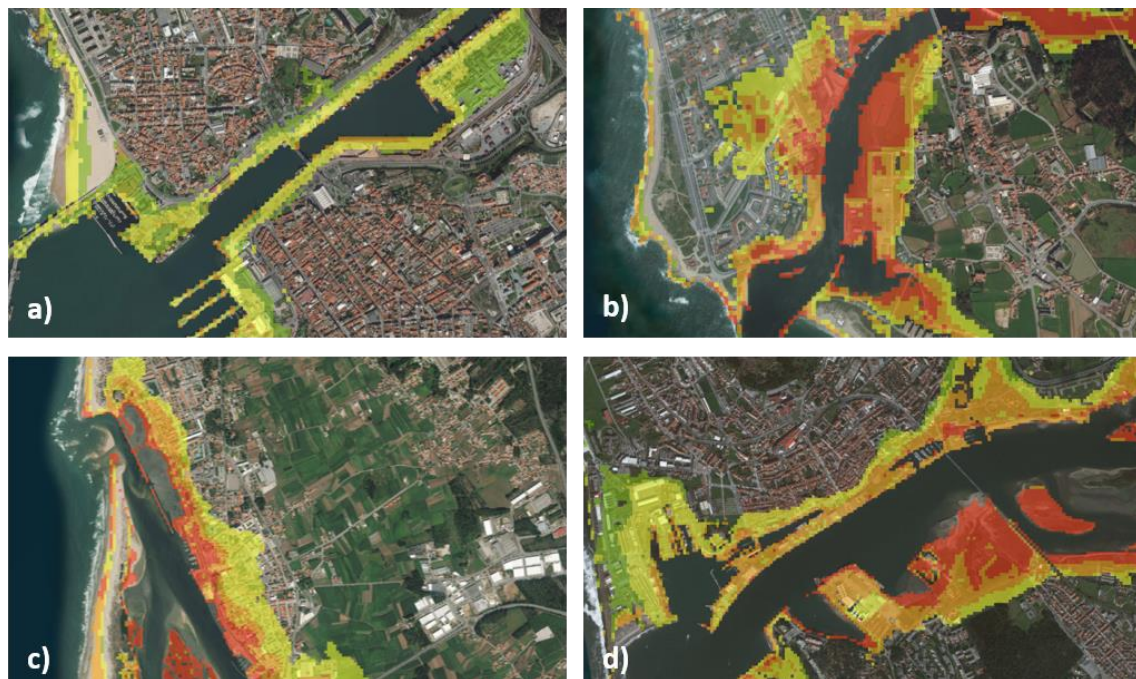
Figure 14. Physical Vulnerability for 2100 in North Region of ACPM: a) Matosinhos city; b) Vila do Conde city; c) Esposende city; d) Viana do Castelo city.

- Matosinhos city is illustrated in the Figure 14a, and is the second most vulnerable in Porto district, with a larger number of buildings in areas considered vulnerable, almost 830 (including the port administration) and more than 2,300 residents.
- The Vila do Conde municipality in Figure 14b, is the most vulnerable to SLR in Porto district, with the largest number of buildings in areas considered vulnerable, almost 1,470 and more than 5,000 people living actually in those areas. Thus, it is important that the Vila do Conde municipality quickly take adaptation and mitigation measures to SLR.

- In Figure 14c, Esposende city is the most vulnerable in Braga district, with strong urban pressure near Cávado river. There are almost 2,250 buildings and 4,000 residents in the areas considered vulnerable. From the affected infrastructure list, we can highlight schools, the hospital, the municipal market, the fire station, the marina and museums.
- Finally, Figure 14d shows Viana do Castelo, the capital of district. On the Lima River bank side it is possible to see classified zones with high to extreme vulnerability, counting with 1,466 buildings and 4,236 residents in those areas.

4.2. Web-Viewer: Sea Level Rise for Portugal

All results produced within the scope of this work are available through a Web Map Service (WMS) for Portuguese public entities, and through a web viewer for civil community and public in general, available in www.snmportugal.pt [56].

The purpose of this Web Viewer is to share the present study results and making them freely available to disseminate the research and alert the Portuguese's community (politicians, municipalities, institutions, stakeholders and the public) to the SLR issue and its impact in the Atlantic coast of Portugal's Mainland.

The website has three main tabs, one providing a preliminary look at SLR and coastal flooding impacts, allowing users to see the results of extreme flooding for each future SLR scenarios (2025, 2050 and 2100) and by comparison of scenarios (Figure 15a). The same structure is available for physical vulnerability on a second tab as a group scenarios (Figure 15b) or individually (Figure 15c). Finally, some demographic statistics are provided for the vulnerable area, in a third tab, particularly the number of houses and the number of residents per district and municipality affected in each scenario, considering data from Census2011 (Figure 15d).
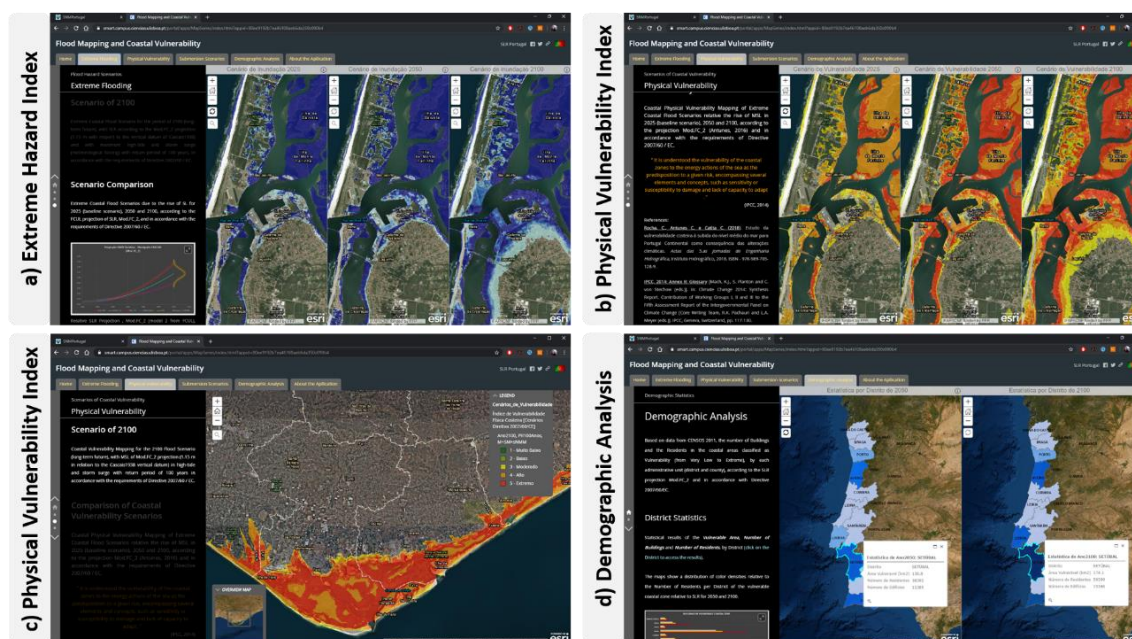
Figure 15. The SNMPortugal Website [56] created to share the results of this study. a) examples of Extreme Flood Hazard Index for 2025, 2050 and 2100 in Aveiro Lagoon; b) Physical Vulnerability Index for all temporal scenarios, also for Aveiro Lagoon; c) Physical Vulnerability Index for Formosa Lagoon in 2100; and c) shows some demographic statistics that can be accessed per district or municipality, selecting the corresponding polygon.

At the web viewer, the maps are available and provided "as they are", without warranty to their performance, merchantable state, or fitness for any particular purpose. This tool should be used strictly as a navigation tool and without permission or other legal purposes.

4. Discussion and Conclusion

The present study defines a methodology to characterize, identify and quantify the affected areas vulnerable of ACPM to coastal flooding in 2050 and 2100, with different scenarios of extreme flooding based on SLR projections and extreme events with different return periods. For this purpose, a coastal Physical Vulnerability Index is determined at national scale.

Areas where PVI classes are highest, and consequently most affected by SLR and extreme events, are areas associated to high anthropogenic pressure. In 2050, considering the Mod.FC_2 SLR projection with 44 cm relative to the Cascais1938 vertical datum [39], a vulnerable area of 903.1 km² for ACPM was determined. In addition, this study shows that several infrastructures in these vulnerable areas, containing a total of 59,530 buildings and 145,550 residents, are at risk. It is also identified that the district of Lisbon is the most susceptible to SLR impact, having about 221.4 km² of vulnerable area, and being about 92.7% classified as high and extreme vulnerable. In 2100, a long-term future, considering the Mod.FC_2 SLR projection with 1.15 m relative to the Cascais1938 vertical datum [39] at the high-tide and with 100 years return period storm surge, the estimated vulnerable area for Lisbon district is about 1146 km2, comprising a total of 82,000 buildings and 224,830 residents.

This study proves also that the quality of the results is highly dependent of data quality. Access to good data was one of the most challenging factors throughout the work since the available data, free and affordable, has poor positional accuracy and little detail due to the scale that have been produced or made available. In these circumstances, it is necessary to perform numerous processes of transformation/digitalization in some data sources, in order to turn its use viable (e.g. as it is done for hydrographic network).

Despite these limitations, the national DTM used to calculate the EFHI which was validated on 134 national geodetic marks [33], proved to be sufficiently accurate to obtain the results at national scale with a spatial resolution of 20 m. To prove this added value, the results of the present study were compared with the results of the study in Kulp and Strauss [57], which uses a Coastal DEM, not validated for Portugal, with 30 m of spatial resolution. Table 11 shows significant differences of both studies, mainly in the estimated number of people affected in Portugal in 2050 and 2100. Comparing Kulp and Strauss [57] results with SLR projections of Koop et al. [58] (RCP 4.5 – DP16) for 2050, which also corresponds to the 99th percentile of Antunes [39] used in this study, a total of about 80,000 people, living on coastal flood areas, will be affected by SLR. These values represent 45% less than those in this study for 2050, while for 2100, [57] estimated a total of ~140,000 of people affected, representing 62% less than the present work results.

Table 11. Comparison of results for the affected population for Portugal in 2050 and 2100 presented in [57] with the results obtained in present study.

Projections	2050		2100	
	GMSL (m)	Population estimated	GMSL (m)	Population estimated
RCP4.5 – ModFC_2	0.11 – 0.51 [39]	145,550	0.10 – 1.80 [39]	224,830
RCP4.5 – K14	0.15 – 0.41 [58]	*N/D1*	0.26 – 1.28 [58]	100,000 [57]
RCP8.5 – K14	0.17 – 0.46 [58]	80,000 [57]	0.40 – 1.59 [58]	120,000 [57]
RCP4.5 – DP16	0.10 – 0.52 [58]	80,000 [57]	0.39 – 1.80 [58]	140,000 [57]

RCP=Representative Concentration Pathway; GMSL=Projections of Global-Mean Sea-Level; ModFC_2=Antunes [39] Projection for Portugal; K14=sea-level model employs a probabilistic approach and includes very little contribution from Antarctica in its central projections [58]; DP16=sea-level model links physical models of ice sheet loss to the projection framework established in K14, thus emphasizing the possibility of early onset Antarctic instability [58]. 1 The study [57] does not show the affected population for this projection.

In short, the methodological approach is simple, robust (uses the physical parameters accepted by most of the scientific community), and easy to implement since it is based on well-defined criteria. It is known that more research is required to observe, measure, and assess adaptation and mitigation

measures to SLR in the country to improve resiliency. Although, the presented results reveal an important contribution in the identification of coastal vulnerability constituting an essential instrument of support for decision-makers with responsibilities on management and planning of areas exposed to sea energy actions.

We have to keep in mind that if the 2ºC climate change mitigation target is missed, according to Jevrejeva et al. [59], the global annual flood costs, without adaptation, are projected to be US$ 14.3 trillion per year, which account for 2.5% of GDP for the median SLR scenario RCP8.5_J14 (0.86 m), and up to US$ 27.0 trillion per year for the respective 95th percentile (1.80 m), accounting for 4.7% of global GDP. Considering Portugal part of the upper middle-income countries, without any adaptation efforts, the coastal flooding, from RCP8.5_J14 SLR, at the end of the 21st century, could correspond to an annual cost of 7.2% of national GDP, according [59]. But on the contrary, making adaptation efforts, costs could come down to 0.3% per year of national GDP. Such potential costs related to coastal flooding reinforce the importance of the present work, contributing for a better coastal risk assessment, helping on the design and implementation measures development for coastal flooding adaptation. Without such vulnerability assessment, adaptation cannot be implemented in time and economic further impacts will be consequent avoiding flooding cost's reduction.

Although there is still much to do, and further detailed studies will need to be carried out in each of the areas identified with high and extreme vulnerability. Therefore, some perspectives of future work may be raised from this study: a) Apply and test the methodology, using a DTM with a better spatial resolution and compare the results with those presented here. Will the results be much different if using a higher resolution DTM?; b) For the areas classified as being highly vulnerable, could be interesting apply socioeconomic vulnerability models, creating a multi-scale approach; c) Implement shoreline retreat/accretion rates to the vulnerability model, or include morphodynamical modeling, making it a dynamic rather than static model; d) Incorporate LiDAR data into offshore bathymetry, making it possible for each local vulnerability model to incorporate beach slopes and include Total Runup as a coastal forcing parameter and incorporate coastal protection structures into the vulnerability model; and e) Develop and strengthen cooperation with decision makers of coastal management and planning to produce all the background information required for this type of study.

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