

## Article

# Hazards, Vulnerability, and Risk Analysis on Wave Overtopping and Coastal Flooding in Low-Lying Coastal Areas: The Case of Costa da Caparica, Portugal

José Carlos Ferreira <sup>1,\*</sup>, Fábio Santos Cardona <sup>2</sup>, Catarina Jóia Santos <sup>1</sup> and José António Tenedório <sup>3</sup>

<sup>1</sup> MARE—Marine and Environmental Sciences Centre, Department of Environmental Sciences and Engineering, NOVA School of Science and Technology, NOVA University Lisbon, Campus da Caparica, 2829-516 Caparica, Portugal; csj.santos@campus.fct.unl.pt

<sup>2</sup> ENA—Energy and Environment Agency of Arrábida, Avenida Belo Horizonte, Edifício Escarpas Santos Nicolau, 2910-422 Setúbal, Portugal; fabio.cardona@ena.com.pt

<sup>3</sup> CICS.NOVA—Interdisciplinary Centre of Social Sciences, NOVA School of Social Sciences and Humanities, NOVA University Lisbon, Av. de Berna, 26-C, 1069-061 Lisbon, Portugal; ja.tenedorio@fcsh.unl.pt

\* Correspondence: jcrf@fct.unl.pt

**Abstract:** Coastal areas are densely populated areas, and they have been experiencing increasing pressures as a consequence of population growth, but also because of climate change aggravation. For this reason, hazard, vulnerability, and risk indexes have been becoming more recurrent, especially to study and analyze low-lying coastal areas. This study presents an analysis on wave overtopping and coastal flooding, using an Analytic Hierarchy Process (AHP) multicriteria methodology, in Costa da Caparica (Portugal). The definition of the different criteria, as well as their respective weighting for the overall problem and index calculation, was carried out with the help of experts in the subject. By following this methodology, and by using Geographic Information Systems (GIS), hazard, vulnerability, and risk indexes were obtained. The most hazardous areas are located closest to the sea, where the elevation is the lowest, whereas the most vulnerable areas are in neighborhoods with specific socioeconomic characteristics (high urban and economic density). Overall, around 30% of the study area displays moderate to very high risk regarding the occurrence of overtopping and flooding events. The results of this study will be helpful in decision-making processes in matters of coastal zone management and monitoring.

**Keywords:** coastal risk; coastal hazard; coastal vulnerability; multicriteria analysis; analytical hierarchy process



**Citation:** Ferreira, J.C.; Cardona, F.S.; Jóia Santos, C.; Tenedório, J.A. Hazards, Vulnerability, and Risk Analysis on Wave Overtopping and Coastal Flooding in Low-Lying Coastal Areas: The Case of Costa da Caparica, Portugal. *Water* **2021**, *13*, 237. <https://doi.org/10.3390/w13020237>

Received: 21 December 2020

Accepted: 16 January 2021

Published: 19 January 2021

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Risk, hazard, and vulnerability studies in coastal areas have been gaining importance due to the increasing pressure on these areas. Coastal areas are densely populated, therefore being subject to natural and, more importantly, anthropogenic pressures [1]. Such pressures have been intensified because of both population growth as well as the increase in greenhouse gas emissions, which lead to climate change aggravation [1,2].

The Intergovernmental Panel on Climate Change (IPCC) [3] refers to climate change as a “change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity”. According to the United Nations (UN) [4], climate change means “a change of climate, which is attributed directly or indirectly to human activity, that alters the composition of the global atmosphere”.

Climate change is a reality. In fact, the global average surface temperature is increasing: according to NASA/GISS [5], in 2017 the temperature increased by 0.9 °C in comparison with the 1951–1980 average temperatures (in 1880, the global average surface temperature

was  $-0.19\text{ }^{\circ}\text{C}$ ). This increase leads to thermal expansion, changes in ocean mass due to ice loss from ice sheets and glaciers, and the intensification of storm surges, resulting in global sea level rise [6].

The main trends and effects on coastal areas resulting from climate change are [7]:

- Sea level rise: coastal flooding, coastal overtopping, submergence of low-lying coastal areas, erosion, salinization of coastal aquifers, rise in groundwater level causing problems in drainage systems, loss of wetlands;
- Storms (increased frequency and intensity): sea level rise, storm surges, overtopping, astronomical tides, coastal flooding, salinization of coastal aquifers, groundwater level rise causing problems in drainage systems, loss of wetlands, infrastructures, buildings, and coastal defenses destruction;
- Winds: rising water phenomena, high currents, coastal defenses destruction;
- Waves: coastal erosion, coastal overtopping and coastal flooding;
- Ocean surface temperature: changes in water stratification and water movement, thermal expansion of the oceans, increasing defrost, death of corals, ecosystems changes;
- Change in the chemical composition of the water: ocean acidification, PH reduction,  $\text{CO}_2$  increase, desalination, deoxygenation.

According to Santos and Miranda [8], as a consequence of the climate change impacts, extreme events in the Portuguese coastal areas will increase in frequency, duration, and intensity. These extreme events will, consequently, increment coastal erosion, coastline retreat, and sea level rise episodes, which may lead to saline intrusion in coastal land, and high sedimentation in estuarine and lagoon bodies [9]. Moreover, for the period between 1980 and 2100, the climate change consequences predicted for Portugal include: an increase in average temperature, an increase in temperature range, an increase in thermal gradient between the ocean and the continent, an increase in heatwaves ( $>35\text{ }^{\circ}\text{C}$ ), an increase in tropical nights ( $>20\text{ }^{\circ}\text{C}$ ), an accentuated decrease in the number of very cold days ( $\leq 0\text{ }^{\circ}\text{C}$ ), and a decrease in the average precipitation and duration of rainy seasons, predicting an increase in precipitation in the winter and a strong decrease in the remaining seasons [10].

In addition to climate change, many anthropogenic actions play a key role in increasing coastal risk [11–14]. The bed regularization works and hydraulic utilization are two of the main activities responsible for the sedimentary deficit in the littoral [9,15,16]. It is estimated that hydroelectric uses are accountable for the retention of more than 80% of the volumes of sand that were transported to natural rivers [17]. Furthermore, port dredging is one anthropogenic action that could result in high impacts on the hydraulic dynamic and coastal drift retention [18]. Dredging activities, along with removing sediments that could be sent to the beaches by natural action, also increase pollution problems. The removal of sediments alters the physicochemical patterns of the water because, as they are being stirred, they release pollutants which have been deposited in depth. These changes have significant impacts on local biotic communities [19].

In order to protect coastal areas and defend coastal communities from sea action, numerous hard infrastructure defenses have been designed and installed. Nonetheless, it is now increasingly recognized that these defenses are unsustainable, as they lead to the loss of intertidal habitats [12–14,20], and the natural protection it provides promotes the downdrift site erosion [21], most of this erosion being caused by the reflective nature of the defense structures [22].

As a consequence of these threat factors, it is necessary to know and identify the areas at risk, and to understand the factors that contribute to the identification of natural and anthropogenic risks to support options in urban planning, land use planning and necessary action plans for the adequate prevention and protection of the affected population.

This article aims to increase awareness of coastal erosion dangers on a low sandy shore, as well as to increase the tools to support decision-making in issues related to urban planning and security. Additionally, the main objectives of this article are to develop a model that identifies the overtopping hazards and areas affected by the consequent flooding

in a storm situation, using offshore sea agitation data, projecting them to the surf zone and swash zone, and to develop a methodology for calculating the hazard, vulnerability, and risk of overtopping and coastal flooding. This methodology will use numerical models, wave propagation models, such as WAVEWATCH III (WWIII) and Simulating Waves Nearshore (SWAN), and will use GIS and a multicriteria Analytic Hierarchy Process (AHP) analysis to obtain risk, hazard, and vulnerability indexes. Table 1 displays several multicriteria AHP analysis methods, which use GIS.

The WWIII and SWAN models have been used by several authors with great results, both in predicting offshore agitation (WWIII) and projecting the values closer to the shoreline (SWAN) [23]. Both models have been applied and used at geomorphological sites identical to the study area (low sandy coastal areas), namely in the coastal area adjacent to the Diogo Lopes Estuary (Brazil) and on the north coast of Rio Grande, Brazil, by Matos et al. [24]. Raposeiro and Ferreira [25] applied and validated the SWAN model in the sea agitation characterization in Vale de Lobo Beach, Algarve, Portugal, from 6–12th March 2012 and during 1998–2007, and concluded that the SWAN model reliably produced the significant wave height. Raposeiro et al. [26], Neves et al. [26], Poseiro et al. [27], and Fortes et al. [28] and Ferreira [13] used the WWIII model to predict sea agitation at the São João da Caparica Beach (Portugal) and the urban beaches of Costa da Caparica (Portugal), and compared and correlated these numerical results with the data measured in the ondographic buoy, allowing the validation of the data from WWIII, which allowed their later use in the SWAN model and to calculate the sea agitation at São João da Caparica Beach. Poseiro et al. [29] and Poseiro et al. [30] carried out two field campaigns between Cova do Vapor and Rainha Beach, in Costa da Caparica, to survey the updated beach profiles, and they concluded that there were not significant differences between the results obtained by the numerical model used and the ondographic buoy results, having a good correlation between numerical and measured results.

**Table 1.** Multicriteria analysis methods using GIS.

Methodology	Definition
<b>Coastal Vulnerability Index (CVI)</b>	Classifies the study area according to variables that substantiate the problem under study using GIS [13,31–37].
<b>Social Vulnerability Index (SoVI)</b>	It classifies the social vulnerability of a study area and uses a multicriteria analysis model with social and economic variables to assess the vulnerability. Although, in reality, the different social factors display different degrees of social importance, in this model, all the variables exhibit the same degree of importance [13,38].
<b>Overall Place Vulnerability Index (PVI)</b>	It results from the sum between the coastal vulnerability index and the social vulnerability index. This index identifies the areas at coastal risk, integrating the physical factors of the study area with the socioeconomic indicators of the community [39]. Although the physical, social, and economical factors contribute to coastal risk at different degrees of importance, they display the same contribution to the global index calculation. This index is an indicator of the static risk of physical and socioeconomic conditions in a given location, since it allows for scenarios. Mitigation factors, such as the defense structures present at the site, are not considered. Ecological factors are not considered as well.

Table 1. *Cont.*

Methodology	Definition
<b>Simple Multi-Attribute Rating Technique</b>	This index is based on the identification of relevant factors or criteria of the problem to be identified (danger, risk, vulnerability), and their weighting (carried out by specialists) in relation to their importance for the problem to be assessed and the respective classification in the study area [40].
<b>Classification of vulnerability, exposure, and risk of sea action</b>	Weighted Analytic Hierarchy Process methodology (AHP) for the classification of vulnerability, exposure, and risk of sea action, with the aim of delimiting risk areas. It does not take into account several important variables for the study of coastal risk, such as: historical data on overtopping and flooding; existing species and ecosystems on the coast; existing cultural heritage; wave period and frequency of sea actions [13,41].
<b>Development of an Information Technology Tool for the management of European southern lagoons under the influence of river-basin runoff—Decision Support System (DITTY-DSS model)</b>	Risk analysis model which uses a Decision Support System (DSS) approach and a weighted multicriteria analysis (AHP). The DSS system is represented by mathematical and analytical models and the multicriteria analysis is applied to evaluate and classify alternatives based on the values of indicators and interaction with the decision-maker [42].
<b>Community Vulnerability Assessment Tool Methodology</b>	Methodology for analyzing the risks and vulnerabilities of communities using GIS. It analyzes infrastructure, environmental vulnerability, social vulnerability, economic vulnerability, as well as mitigation opportunities. The hazard identification process uses objective and qualitative variables to classify the total hazard, not evaluating the probabilities or frequencies of the problematic events [43].
<b>Vulnerability to disaster mapping method in densely populated coastal communities</b>	It is a decision support model that assesses the risk of climate change at the regional level. The model is based on a multicriteria analysis (AHP) and uses GIS to identify the hazard, exposure, susceptibility, risk and damage assessment from climatic scenarios and the physical, environmental, and socioeconomic characteristics of the study area. High resolution numerical models are used to analyze the risk [44].
<b>Coastal Zone Simulation Mode (COSMO)</b>	It is a GIS model used to support decision-making and it allows for the assessment of potential management strategies under different long-term scenarios, including climate change, local economic development, or the development of other uses. This model has interactive tools that allow coastal managers to assess the impacts of development projects and environmental and coastal protection measures. It makes it possible to relate climate change to its adaptation in coastal areas and to identify the advantages and disadvantages of each strategy [45,46].

Table 1. *Cont.*

Methodology	Definition
<b>Decision Support System for Coastal Climate Change (DESYCO)</b>	DESYCO is a GIS model and it works as a decision support system that assesses the risk of climate change at the regional level and defines the context for planning strategic adaptation measures on the coast. This model is based on a weighted multicriteria analysis of decision, whose aim is identifying the danger, exposure, susceptibility, risk and damage assessment from climatic scenarios and the physical, environmental, and socioeconomic characteristics of the study area. Risk analysis uses data from climate simulations and simulations of physical processes performed by high resolution numerical models for the study area. The simulations can be related to different scenarios of greenhouse gas emissions and aerosols. For hazard scenarios, data from time series of climatic variables and extreme events are required. The vulnerability analysis analyzes four main categories of factors: susceptibility, value, mitigation and forcing. This model integrates multidisciplinary and heterogeneous information from environmental and socioeconomic scenarios in a multicriteria analysis structure based on the judgment of experts and key actors. It has already been applied to different European projects, which proves its flexibility [47].
<b>Dynamic and Interactive Vulnerability Assessment (DIVA)</b>	The DIVA method was developed to facilitate the integration of multidisciplinary knowledge from specialists to create vulnerability calculation tools. This tool consists of three major components: a coastal database; an integrated model of modules with natural and social knowledge of coastal subsystems; a graphical user interface for selecting data and scenarios, running model simulations, and analyzing results. This model predicts the impacts of sea level rise scenarios on natural and human systems, as well as the effects of the human response to these impacts through adaptation measures. It is a robust tool for assessing vulnerability on a global, national, or regional scale. It does not, however, consider ecologically based adaptation measures [48–51].

As already mentioned, the methodology of this paper is based on the work established by Ferreira [13], and intends to develop a procedure to evaluate the hazards, vulnerability, and risks associated with oceanic and coastal flooding on a low sandy coast, Costa da Caparica, in Portugal, through an Analytic Hierarchy Process (AHP), using numerical models and Geographic Information Systems (GIS), with the support of national experts in the coastal risk scientific investigation. The result will be a georeferenced hazard, vulnerability, and risk map. However, it is first necessary to clarify the concepts of hazard, vulnerability, and risk that will be used throughout this paper, as several definitions of these concepts can be found in the scientific bibliography.

Therefore, in this paper, vulnerability is understood as the degree of loss of a given element or set of elements at risk (population, property, economic activities, among others) as a result of the occurrence of a manifestation of a certain magnitude [52]. Vulnerability is the product of “social vulnerability”, related to the social, economic, and political organization of a community, and of “biophysical vulnerability”, related to the physical



and ecological elements of the territory. Vulnerability is closely related to the organization of a community that can minimize or potentiate losses to a dangerous event [13,53–57].

Moreover, in the present paper, hazard is considered to be a natural, technological or mixed process that can cause losses and damages [58], such as loss of life, injury or other health impacts, property damage, habitats and services loss, social and economic degradation or environmental damage [57]. Natural hazards are seen as external to the system or elements at risk but can be modified and enhanced by human activity [54,59].

Risk is considered to be the probability of a dangerous action occurring and its consequences on people, goods or the environment, expressed in personal damages and/or material and functional losses, direct or indirect [58,60]. In other words, it can be defined as the product of danger's probability and its consequences, considering the vulnerability of the exposed elements within a period, with a given frequency and using scenarios [13,54,61,62].

The present article is divided into six different sections. In the present section (Introduction), the subject of the work and its relevance were introduced. The next section includes a short description of the study area (Costa da Caparica, Portugal) and of its vulnerabilities. The third chapter (Methods) includes the methodological steps followed for the calculation and weighting of both the hazard and vulnerability factors, for the consequent risk index calculation. In the fourth and fifth sections (Results and Discussion), the hazard, vulnerability and risk indexes, and the distribution of each level throughout the study area, are presented and discussed. Finally, the last chapter (Conclusions) encompasses the conclusion of the paper and its relevance to scientific research and to adaptation strategies research.

## 2. Study Site

Costa da Caparica is a sandy and low coastal plain located on the European Atlantic seaboard, in Portugal, on the south bank of the Tagus estuary, west in the Municipality of Almada [63] (Figure 1).



**Figure 1.** Location of the study site (Costa da Caparica, Portugal).

The Costa da Caparica coastal plain is characterized geomorphologically by the beach, beach-dune, and fossil cliff systems. This plain was selected as a study case because it is an area generally affected by winter storms. These storms lead to significant erosive phenomena in the frontal dune, with erosion scarps formation, beach profile retraction, frontal dune retreat, and overtopping accompanied by flood events on the urban front, resulting in damage to coastal protection infrastructures, seaways, accesses to the beach, parking lots, beach bars and camping sites, especially the worsening of the damage to adherent defense (rhombuses) and outcropping of the infrastructure foundation [13,63].

### 3. Methods

The calculation of the hazard, vulnerability, and risk of overtopping and flooding in Costa da Caparica was carried out by Ferreira [13], applying the principles of AHP through a multicriteria analysis developed by Saaty [64], while also using GIS (on ArcGIS). For this purpose, a set of hazard and vulnerability criteria were selected and consequently classified, with the aim of producing mapped global hazard, vulnerability, and risk indexes.

The criteria classification, namely the division of the criteria into hazard and vulnerability classes, was carried out with the contributions of a national expert group in coastal risk scientific research. These specialists came from universities and public institutions to cover the national territory and the different formations and specialties.

The risk and vulnerability rating ranges from 1 (very low) to 5 (very high), and every section of the study area was classified according to this rating, for each hazard and vulnerability factor, based on the information in Sections 3.1 and 3.2. According to Saaty [64], the criteria should be classified in odd numbers to have an intermediate value. In this study, the interval between 1 and 5 was chosen to facilitate the assignment of values to the criteria. In order to differentiate the importance of each factor for the study index (hazard or vulnerability), different weightings were assigned. These weights were attributed considering the coastal risk specialists' input, using the Saaty [64] comparison peer-to-peer methodology. After the criteria were identified and weighted, the study area was classified using GIS, and maps of vulnerability, hazard, and risk index were produced through the AHP method.

All the data used for the hazard and vulnerability criteria were based on works developed within the Hidralerta project [23,28,30,37], and considered the last 35 years of data available.

#### 3.1. Hazard Factors

The hazard factors/criteria chosen were: distance from flooded areas, altimetry, lithology, geomorphology, erosion/accretion rates, aspect-slope (or slope and slope exposure), sea level rise (SLR), and sea agitation (see Figure 2).

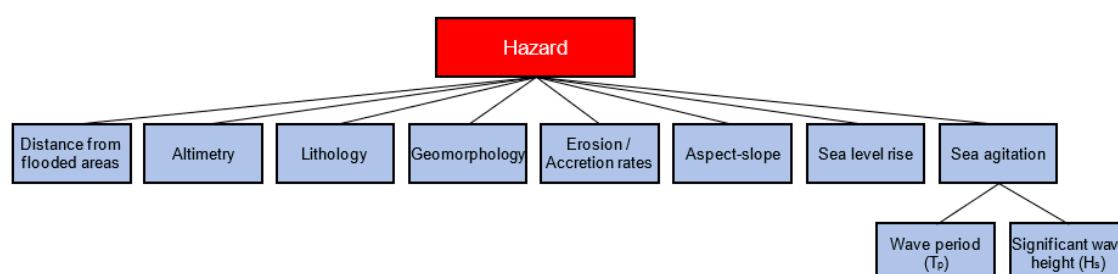


Figure 2. Hazard flow chart with their factors.

The factors directly related to the sea (erosion/accretion rates and sea agitation) were classified only up to 100 m away from the flooded areas over the last 35 years, since areas with a higher distance are not directly influenced by these factors.

### 3.1.1. Distance from Flooded Areas

The hazard of overtopping and flooding varies according to the distance from the sea. Under normal and identical conditions, a site near the coastline is more subject to the energetic forces of the sea than a location far from it. Thus, as distance increases, the hazard associated with coastal flooding decreases.

To obtain the flooded areas in the last 35 years, the methodology of Ferreira [13] was used. This methodology characterizes the wave climate in the area through the numerical modelling of wave propagation from offshore to the coastline, and calculates the corresponding wave overtopping on the beach. The sea-wave climate near the beach was characterized using the forecast provided by the model WAVEWATCH III, developed by the Marine Weather Service (USA), and the wave propagation was calculated by the Simulating Waves Nearshore (SWAN) model, developed by Delft University of Technology. The empirical formula of Stockdon et al. [65] was used to calculate the run-up, i.e., the maximum vertical extent of wave uprush on a beach or structure above the still water level [13].

The formula of Stockdon et al. [65] was selected after evaluating and comparing several empirical formulas in Ferreira [13]. It is the formula that best corresponds to the reality of the low sandy coastal territories with the geographical conditions of the coastal plain of the Costa da Caparica in extreme storm conditions.

After analyzing the flooded areas in the last 35 years, the hazard index was attributed [13]. These areas were classified with the maximum hazard classification for this criterion, considering them as the area where wave overtopping and flooding were most likely to occur. Following this area, hazard classes were defined according to the distance from the flooded areas, using GIS. The farthest ranges have lower hazard ratings and are less likely to occur in a flood event. Table 2 shows the hazard classification given.

**Table 2.** Hazard classification concerning the distance from flooded areas in the last 35 years hazard factor.

Hazard Factor	Hazard Classes				
	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Distance from flooded areas in the last 35 years (m)	>300	100–300	50–100	<50	Flooded areas in the last 35 years

### 3.1.2. Altimetry

Altimetry is one of the most important parameters in the hazards related to wave overtopping and coastal flooding studies. Areas with low altitudes are more susceptible to wave overtopping and coastal floods than areas with high altitudes, thereby increasing the inundation probability.

The hazard classification for the different altitudes of the study area can be seen in Table 3. This classification considered the terrain characteristics of the study area. Areas with an altitude lower than 3 m (6% of the study area) were considered areas of low altitude. These areas include beaches, drainage ditches, and interdune depressions, which are classified as very high hazard areas [13]. The areas between 5–7 m of altitude are dune systems [13]. The areas with an altitude between 7 m and 10 m are frontal dune systems—dune systems in the south study area and an area at the bottom of the fossil cliff (in the zone corresponding to the existence of the slope deposits) [13]. The areas with



altitudes greater than 10 m correspond to the area between the base of the fossil cliff and its crest [13].

**Table 3.** Hazard classification concerning the altimetry hazard factor.

Hazard Factor	Hazard Classes				
	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Altimetry	>10	7–10	5–7	3–5	<3

The earth's surface altimetry analysis of the study area was carried out using the digital model of the bathymetric and topographic terrain, acquired with Light Detection and Ranging (LIDAR) technology provided by the General Directorate of the Territory (Direção Geral do Território).

### 3.1.3. Lithology

The knowledge of the lithological nature of the coastal zone allows us to ascertain its hardness and behavior on coastal flooding and wave overtopping. The study area is generally constituted by sedimentary rocks. Sedimentary rocks have less hardness than metamorphic rocks and magmatic rocks and are, therefore, more susceptible to coastal erosion. Although the predominant lithology in the study area is sedimentary, there are differences in terms of hardness and susceptibility to erosion. Thus, the higher the clay content, the less susceptible the rocks are to erosion [13].

The lithology analysis of the study area resulted from the aggregation of information from the Geological Chart of Portugal, Folha 34-C (Cascais) and Folha 34-D (Lisbon). Table 4 displays the hazard classification concerning the lithological nature's factor.

**Table 4.** Hazard classification concerning the lithology hazard factor.

Hazard Factor	Hazard Classes				
	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Lithology	Clays and landfill (coastal defense infrastructure)	Conglomerates with clay intercalations	Limestone, sand, sandstones, and marly limestones	Scree, feldspathic sand, incoherent or compact, sandy conglomerate	Beach sand, dunes sand, and alluvial soil

Although lithology is a factor more commonly used to characterize coastal erosion, this factor can, too, be used to describe the hazards of wave overtopping and coastal flooding. During storm events, the lower the hardness of the rocks, the greater their consequent rupture, and, therefore, the more intense the wave overtopping and consequent flooding events will be.

### 3.1.4. Geomorphology

The geomorphology factor is used to study the earth's surface landform. Table 5 shows the hazard classification on wave overtopping and coastal flooding concerning the geomorphology. This classification only considered the geomorphological characteristics of the study area.

**Table 5.** Hazard classification concerning the geomorphology hazard factor.

Hazard Factor	Hazard Classes				
	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Geomorphology	Cliff and coastal defenses	Slope deposits (cliff base)	Coastal plain and interior dunes	Drainage ditches	Beaches, waterline and frontal dunes

The beaches, the waterline, and the frontal dunes are classified as the highest hazard category because they are the areas most influenced by the sea and, consequently, they have a higher danger for wave overtopping and coastal flooding. Drainage ditches are classified in the high hazard class because, although they are included in the coastal plain, they are more susceptible to flooding. The coastal plain and the interior dunes were considered to be the moderate danger class. The cliff base is classified as the low hazard class, and the cliff and coastal defense infrastructures are classified in the very low hazard class because they are the areas least susceptible to wave overtopping and coastal flooding.

### 3.1.5. Erosion/Accretion Rates

The erosion and accretion rates were measured as the retreat or advance (in meters) of the maximum high tide line of equinoctial living waters (LMPAVE) per year. These rates were calculated using the DSAS software. By marking the points where the LMPAVE is located annually, the DSAS software created linear regressions of the rates of change of the LMPAVE, i.e., of the indentation or advance rates. These included statistical analyses adjusting a linear regression by the least squares method for all points of the coastline for a particular transect, minimizing the sum of the square residues, i.e., minimizing the square of the differences between the estimated value and the observed data. A linear regression with a 95% confidence interval was used. The points that distinguished the coastline were marked with the aid of the land use maps of 1958, 1980, 2008 and 2013.

For the hazard classification of the erosion/accretion rates, the Thieler and Hammar-Klose [36] classification was used, as seen in Table 6. If the erosion rate exceeds 1 m/year, it is classified as having a high or very high hazard factor. Consequently, if the accretion rate exceeds 1 m/year, it is considered a low or very low hazard situation. Finally, if the erosion and/or accretion events are below 1 m/year, the system is considered in balance and, therefore, the hazard classification is moderate.

**Table 6.** Hazard classification concerning the erosion/accretion rates hazard factor.

Hazard Factor	Hazard Classes				
	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Topographic elevation in relation to the hydrographic zero	>+2	+2 to +1	+1 to −1	−1 to −2	<−2
	Accretion		Equilibrium		Erosion

### 3.1.6. Slope and Slope Exposure

The coastal slope is defined as the ratio between the altitude and the horizontal distance between two points perpendicular to the coastline. The hazard associated with coastal flooding depends on the coastal slope, as a steep emerged coast is considered less susceptible to flooding events when compared to an emergent coast with gentle slopes [13,32,36,66,67].

The slope orientation/exposure was also taken into account when calculating the hazard in this criterion, since a steep slope can be either favorable to or not favorable to the occurrence of flood episodes, depending on its orientation. The coastline in the study

area is an arc with an approximately north-south orientation. The sea is located west of the coastline. Thus, a slope orientation to the west will decrease susceptibility to overtopping and flooding; an orientation to the east will increase the susceptibility to overtopping and flooding; and a north or south orientation which, although does not enhance inland flooding, may do so with local flooding. Since steep slopes with orientations to the west display lower hazard, steep slopes with orientations to the east have high hazard, and steep slopes with orientations predominantly to the north or south have high flooding hazard. In Table 7, the hazard classification of the slope and slope exposure combination is shown.

The slope and slope exposure values were calculated using ArcGis software and digital terrain maps of the study area provided by the General Directorate of the Territory (Direção Geral do Território).

**Table 7.** Hazard classification concerning the slope and slope exposure hazard factor.

Hazard Factors		Slope (%)				
		<2	2–5	5–10	10–15	>15
Slope exposure	Northwest					
	West	Moderate 3	Moderate 3	Low 2	Low 2	Very low 1
	Southwest					
	Northeast					
	East	Moderate 3	Moderate 3	High 4	High 4	Very high 5
	Southeast					
	North	Low 2	Moderate 3	Moderate 3	High 4	Very high 5
	South					

### 3.1.7. Sea Level Rise (SLR)

Sea Level Rise (SLR) causes the coastline to recede. Thus, the higher the rate of the annual SLR, the greater the likelihood of overtopping and flooding, and, therefore, the greater the hazard. To classify the hazard in relation to the SLR indicator, the Thieler and Hammar-Klose [36] classification was used, as seen in Table 8.

**Table 8.** Hazard classification concerning the sea level rise (SLR) hazard factor.

Hazard Factor	Hazard Classes				
	Very Low 1	Low 2	Medium 3	High 4	Very High 5
SLR Increase (mm/year)	<1.8	1.8–2.5	2.5–2.95	2.95–3.16	>3.16

### 3.1.8. Sea Agitation

The higher the sea agitation, the greater the hazard of overtopping and coastal flooding. Consequently, maritime agitation was considered to be a hazard criterion in this study. This criterion was divided into two sub-criteria: the wave period and the significant wave height, as they are two of the parameters that best characterize sea agitation.

A high wave period increases the overtopping and consequent coastal flooding hazard because the longer the period of a wave, the greater its energy. The greater the significant wave height, the greater the danger of overtopping and flooding. In this study, it was considered that the two sub-criteria have equal weight, meaning they represent equal importance in sea agitation study.

In order to obtain nearshore maritime agitation data, it was necessary to correlate them with offshore maritime agitation data. The offshore maritime agitation data were obtained through the statistical analysis of data collected from the European Centre for Medium Range Weather Forecast, using the Wave Atmospheris Model (WAM) and the

geographic coordinates 38°15'0'' N 9°45'0'' W, during the period between January 1979 and March 2014, at 6 h intervals. The nearshore sea agitation data were obtained by simulating the wave conditions in the 10 m bathymetric across 16 beach profiles throughout the study area with a numerical wave model (SWAN) [13].

The SWAN model data and the European Centre for Medium-Range Weather Forecasts (ECMWF) data display a strong positive correlation, according to the statistical analysis of Pearson's correlation coefficient ( $r_{p3} = 0.83$ ;  $r_{p7} = 0.84$ ;  $r_{p13} = 0.82$ ) with an overall ratio of 1:2.5, showing that the significant wave height decreases moderately when reaching the coast.

The quantile (the quantile classification assigns the same number of data values to each class. It is an adequate classification for a linear data distribution) method was then applied to the 2% of the highest data, to create classes of significant wave height and wave period. For the classification of each beach profile in terms of the significant wave height and wave period, the average of the 2% of the highest data was calculated. In Tables 9 and 10, the classification of the sea agitation sub-criteria (wave period and significant wave height) is shown, regarding the hazard of overtopping and coastal flooding. The beaches were classified considering the average of the 2% of the highest data.

**Table 9.** Hazard classification concerning the significant wave height hazard subfactor.

Hazard Factor	Hazard Classes				
	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Significant wave height (m)	<2.7	2.7–3.0	3.0–3.3	3.3–3.6	>3.6

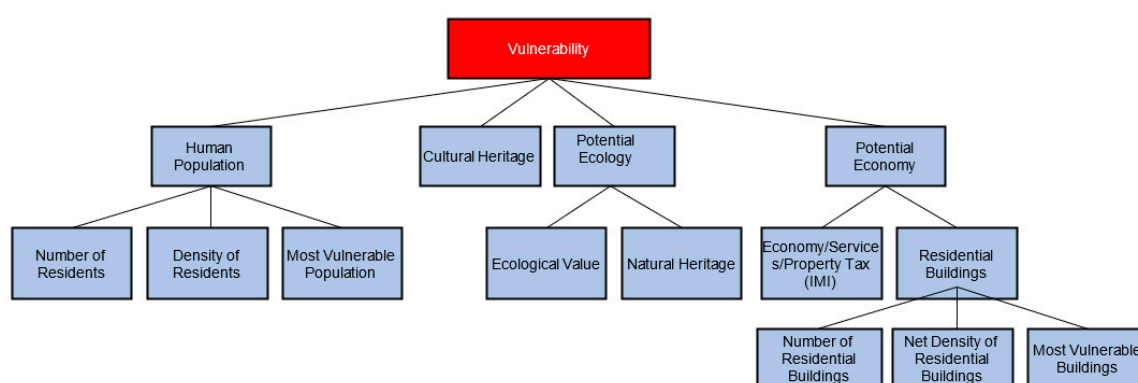
**Table 10.** Hazard classification concerning the wave period hazard subfactor.

Hazard Factor	Hazard Classes				
	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Wave period (s)	<14.1	14.1–14.3	14.3–14.6	14.6–15.0	>15.0

### 3.2. Vulnerability Factors

The vulnerability parameters were divided into factors and sub-factors. The factors considered to characterize vulnerability were human population, cultural heritage, potential ecology, and potential economy. These were further divided and subdivided into subfactors that characterize the criteria, as clarified in Figure 3.

The background information used to classify the human vulnerability and residential buildings criteria was provided by the 2011 Census subsections, which included the study area, from the National Statistics Institute (INE). It should be noted, however, that not all subsections were completely contained in the study area. Therefore, it was necessary to make correlations between the INE data and the existing buildings in the territory to make estimates to fit such data to the study area under analysis. These estimates were based on the observation of the map of ESRI's ArcGis software from an aerophotogrammetric survey of 2013, in which, by interpreting the occupation of the territorial mosaic, a percentage of the subsection cluster contained in the study site was attributed.



**Figure 3.** Vulnerability flow chart with their factors.

### 3.2.1. Human Population

The human population factor assesses the human “value” and “sensitivity” in the study area. This criterion is characterized by the following sub-factors:

- Number of residents (INE defines “residents” as the people who live at their usual residence for a continuous period of at least 12 months prior to the observation moment): the estimated number of residents in the statistical subsection located in the study area;
- Net density of residents: the ratio between the number of residents in the statistical subsection located in the study area and the residential area of the respective subsection. It should be noted that the area considered in this calculation is not the total area of the subsection, but only the residential area of the respective subsection.
- Most vulnerable population: the ratio of the population residing in the statistical subsection under the age of 10 years and over 64 years, with the total number of residents of the respective sub-section.

For the creation of classes for vulnerability classification in the sub-factor of human population, a histogram with the data was developed, using ArcGis. This histogram was then divided into 5 classes by the quantile classification, apart from the least vulnerable class, which always has null data.

### 3.2.2. Potential Economy

This criterion assesses the value of economic potential, buildings, and the existence of services in the study area. It is divided into two different sub-criteria: economy/services/property tax (IMI) and residential buildings. It should be noted that for the calculation of the residential buildings sub-criterion, the estimates referred to in sub-chapter Vulnerability Factors were used. This sub-criterion is then divided into three additional factors:

- Number of residential buildings: the number of classic buildings (INE defines “classic buildings” as a building whose structure and materials used in its construction are non-precarious and expected to last at least 10 years) in the subsection located in the study area;
- Net density of residential buildings: the ratio between the number of residential buildings present in the statistical subsection and the residential area of the respective subsection. The area used in this calculation is not the total area of the subsection, but only the residential area;
- Vulnerable buildings: the ratio between the number of residential buildings with less than 2 floors (inclusive) in the subsection and the total number of residential buildings in the respective subsection.



For the creation of vulnerability classification classes within the residential buildings sub-criterion, a histogram with the data was created, using ArcGis, which was divided into 5 classes by the quantile classification, except for the least vulnerable class that always has null data.

The economy/services/property tax (IMI) sub-criterion evaluates the economic value of buildings (based on the Municipal Property Tax/IMI), the potential value of services, and the value or contribution to the local economy. This sub-criterion was rated from 1 to 5, with the value “1” contributing the least to the local economy or essential services to the population, and the value “5” contributing the most.

The geographic information with the local economy and services in the study area was prepared based on the information provided by both the SMAS (Municipal Water and Sanitation Services) of the Almada Municipality and the cartographic information of 2011.

Table 11 shows the vulnerability classification in relation to the contribution to the local economy, the value of buildings and the existence of essential services for the population.

**Table 11.** Vulnerability classification concerning the contribution to the local economy, services, and Municipal Property Tax (IMI) vulnerability factors.

Vulnerability Factor	Vulnerability Classes				
	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
<b>Local Economy</b>	Areas with no economic activities	Warehouses Fuel deposits Bus/Truck termination station Train station Road network and paths Hotel construction area Urban park	Coastal defense structures Banks Social center Sports areas Campsites Parking spaces/lots	Golf course Gas stations Shopping center Residentials Electrical transformation stations Train pathways Inatel Complex Market	Shelters and fishing spaces Greenhouse Surf Hotels Ditch water pumping station Beach supports
<b>Services</b>	Areas with no services	Post office	Parish council Military area	Health center Schools Nursing homes	Republican National Guard (GNR) Fire departments
<b>Municipal Property Tax (IMI)</b>	Non-residential areas	IMI = 1.6 IMI = 1.55 IMI = 1.4 Coastal barracks	IMI = 1.85	IMI = 2	n/a

### 3.2.3. Potential Ecology

The potential ecology criterion assesses the ecological or natural value of the study area. This factor is characterized by the sub-factors: natural heritage and ecological value.

In the natural heritage sub-criterion, territorial management instruments and the restrictions and conditions of public utility were considered, as well as the most relevant ecosystems in the study area, namely, beaches, dunes, and riverside ecosystems. Table 12 displays the vulnerability classification for the natural heritage sub-criterion.

**Table 12.** Vulnerability classification concerning the natural heritage vulnerability subfactor.

Vulnerability Factor	Vulnerability Classes				
	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
<b>Natural heritage</b>	Areas with no natural heritage	n/a	Protected landscapes National Ecological Reserve (REN) Water domain Natura 2000	Riverside ecosystems (drainage ditches, waterlines)	Beach and dune ecosystems

As its name indicates, the ecological value sub-criterion evaluates the intrinsic ecological value of the study area. The vulnerability classification of this subfactor is shown in Table 13.

**Table 13.** Vulnerability classification concerning the ecological value vulnerability subfactor.

Vulnerability Factor	Vulnerability Classes				
	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
<b>Ecological value</b>	Habitats with no ecological value	Shrubby vegetation or areas occupied by habitats in poor phytosanitary conditions (green areas in general, natural herbaceous vegetation, invasive species, golf course, Inatel, urban park, artificial dunes on the urban front)	Areas with shrubby vegetation and areas with low ecological value (acacial, dense scrub, artificial dunes)	Areas with high ecological value (maritime pine forest, river, drainage ditch)	Very high ecological value (beaches and dunes, pine forest and <i>Juniperus</i> spp.)

### 3.2.4. Cultural Heritage

The cultural heritage factor evaluates the cultural “value” of the study area. The vulnerability classification for this criterion can be seen in Table 14.

**Table 14.** Vulnerability classification concerning the cultural heritage vulnerability factor.

Vulnerability Factor	Vulnerability Classes				
	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
<b>Cultural heritage</b>	Absent	Coastal sheds	Chapel Graveyards Statues/Monuments New church Beaches	Agricultural lands Railways	Old church Fishing shelters

Coastal sheds/barracks were considered to have cultural value due to their antiquity and their respective landscape value. Nevertheless, the value is still low. The old church has a cultural value superior to the new church, since it is a rather old church, dating from the first buildings of Costa da Caparica, with historical and cultural value. The agricultural lands of Terras da Costa were considered to have value because they were transformed from swamps into agricultural land. Cultural value was also attributed to the railway due to its cultural potential. The beaches and fishing shelters have cultural value because they are associated with the traditional fishing activity, the Xávega art.

### 3.3. Weighting of the Hazard and Vulnerability Factors

The weighting process consists of the attribution of weights to each factor. The weight indicates the relative importance of each factor (and consequent sub-factors) to the evaluation under analysis. Thus, the higher the weight of a criterion, the greater its importance for the hazard and vulnerability index, and, consequently, to the risk index as well.

The methodology used to weight the criteria was developed by Saaty [64]. In order for a multidisciplinary analysis to take place, the opinion of different experts in coastal risk was considered. Each expert attributed a weight to each factor. The weights ranged between 0 and 1 and can be translated to a percentage, indicating how much each factor contributes to the overall object of study. Since there were 12 experts, it was then necessary to calculate the geometric mean weight of each factor to obtain the final weighting.

This technique was applied by Cardona [20] on a smaller scale (Continental Portugal) and with the objective of assessing the risk of erosion, with excellent results. In this work, however, the methodology was applied to a larger scale, using a more complex model due to the high number of variables considered and the complex nature of the overtopping and flooding phenomena, which puts in evidence a set of more dynamic and more complex relationships.

With the mean weights attributed to each hazard and vulnerability factor, it was then possible to obtain the hazard and vulnerability indexes, according to the methods explained in Section 3.4.

### 3.4. Attaining Hazard, Vulnerability, and Risk Indexes

The georeferencing of the hazard and vulnerability indexes is performed through spatial analysis in GIS environment with the support of a spreadsheet according to the following phases:

1. Construction of a digital georeferenced database in the study area with the criteria and sub-criteria defined in Section 3.1. and Section 3.2. of the present work, with a view to spatial analysis in a GIS environment. The criteria mapped in the study area in vector form;
2. Conversion of vector data to raster data, so that they can be analyzed matrix-wise and so that mathematical operations between them are possible. When converting these data, we transfer the classification information of the criteria from the vector file to the raster file. As a result of this step, there is a georeferenced raster file for each hazard and vulnerability factor, where each pixel refers to a classification between 1 and 5, according to the classification mentioned in Sections 3.1 and 3.2;
3. Obtaining the hazard and vulnerability index. The values (between 1 and 5) referring to each factor are crossed with the respective weighting, using the Raster Calculator™ tool, which, through spatial matrix analysis, adds the weighted value of each factor equation (Equations (1) and (2)), resulting in an index. This means these equations are applied to each pixel of the georeferenced raster image, resulting in a value between 1 and 5 for each pixel. This method of obtaining hazard and vulnerability indexes, using the weighted sum, was recommended by Gornitz et al. [33] and used by Yin et al. [68].

$$\begin{aligned} \text{Hazard Index} = & \text{distance from flooded areas} \times W + \text{altimetry} \times W + \text{lithology} \times W \\ & + \text{geomorphology} \times W + \text{erosion|accretion rates} \times W + \text{slope and slope exposure} \\ & \times W + \text{SLR} \times W + \text{sea agitation} \times W = \sum_{i=1}^n P_i \times W_i \end{aligned} \quad (1)$$

where,

- *distance from flooded areas*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to this criterion, present in the study area;

- *altimetry*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to this criterion, present in the study area;
- *lithology*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to this criterion, present in the study area;
- *geomorphology*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to this criterion, present in the study area;
- *erosion/accretion rates*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to this criterion, present in the study area;
- *slope and slope exposure*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to this criterion, present in the study area;
- *SLR*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to this criterion, present in the study area;
- *sea agitation*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to this criterion, present in the study area;
- *W*: weighting factor attributed to the criterion for the pixel under analysis;
- *P*: hazard classification of the criterion for the pixel under analysis.

#### Vulnerability index

$$\begin{aligned}
 &= \text{res.} \times W + \frac{\text{res.}}{\text{area}} \times W + \text{vuln. pop.} \times W + \text{economy|services|IMI} \times W + \text{build.} \times W \\
 &+ \frac{\text{build.}}{\text{area}} \times W + \text{vuln. build.} \times W + \text{eco. value} \times W + \text{nat. heritage} \times W \\
 &+ \text{cult. heritage} \times W = \sum_{i=1}^n V_i \times W_i
 \end{aligned} \quad (2)$$

where,

- *res.*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Number of Residents, present in the study area;
- *res./area*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Density of Residents, present in the study area;
- *vuln.pop.*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Vulnerable Population, in the study area;
- *economy/services/IMI*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Economy/Services/IMI, present in the study area;
- *build.*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Residential Buildings, present in the study area;
- *build./area*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Net Density of Residential Buildings, present in the study area;
- *vuln.build.*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Density of Vulnerable Buildings, present in the study area;
- *eco.value*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Ecological value, present in the study area;

- *nat.heritage*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Natural Heritage, present in the study area;
  - *cult.heritage*: The value (between 1 and 5) of the pixel under analysis of the georeferenced raster file was classified, according to the sub-criterion Cultural Heritage, present in the study area;
  - *W*: weighting factor attributed to the criterion for the pixel under analysis;
  - *V*: vulnerability classification of the criterion for the pixel under analysis.
4. Obtaining the risk index through the weighted sum between the hazard index and the vulnerability index. A weighting of 80% was attributed to the hazard, whereas a 20% weighting was attributed to vulnerability, since in the peer-to-peer classification it was considered that the hazard would have an intermediate value between the “strongly important” and the “most important” when compared to vulnerability. Hence, the risk index map results from the weighted sum of vulnerability and danger, obtained with the aid of the Raster Calculator<sup>TM</sup> of ArcGis. Table 15 shows the classification matrix for the risk of overtopping and coastal flooding in the study area (Costa da Caparica) resulting from the weighted sum between the hazard index and the vulnerability index (Equation (3)). The colors were added to facilitate the identification of the different levels for each index, as they will be represented in the resulting indexes.

$$R = 0.8 \sum_{i=1}^n P_i \times W_i + 0.2 \sum_{i=1}^n V_i \times W_i \quad (3)$$

where R: risk for the pixel under analysis; W: weighting factor attributed to the criterion; P—hazard classification of the criterion for the pixel under analysis; V: vulnerability classification of the criterion for the pixel under analysis.

**Table 15.** Classification Matrix for the risk of overtopping and flooding in the study area (Costa da Caparica).

		Vulnerability Index					Risk Index
		Very Low 1	Low 2	Moderate 3	High 4	Very High 5	Very High V
Hazard Index	Very low 1	I	I	I	II	II	High IV
	Low 2	II	II	II	II	III	Moderate III
	Moderate 3	III	III	III	III	III	Low II
	High 4	III	IV	IV	IV	IV	Very low I
	Very high 5	IV	IV	V	V	V	

In addition to the global risk index for overtopping and coastal flooding, it is possible to produce specific risk indexes for overtopping and coastal flooding, such as: the risk in human occupation; the risk to economic activities; residential building risk; the risk to cultural heritage; the risk to natural heritage; the risk to ecological value; or the risk of any vulnerability sub-criterion [13]. For this, Equation (3) is used and the sum of the vulnerability criteria is replaced by the vulnerability index of the sub-criterion to be assessed, i.e., if the objective is to obtain the risk of overtopping and coastal flooding in economic activities, then the weighted sum between the hazard and the vulnerability of economic activities is calculated.



#### 4. Results

By applying the AHP principles through the Saaty [64] multicriteria analysis, while also using the ArcGIS software, it was possible to classify the distinct areas of the study site, according to the different hazard and vulnerability classes. Additionally, by employing Equations (1)–(3), mapped global hazard, vulnerability and risk indexes were obtained.

##### 4.1. Weighting of the Hazard and Vulnerability Factors

The hazard and vulnerability indexes obtained for Costa da Caparica are the result of integrating a wide range of variables and the weighting of the criteria and sub-criteria carried out by the consulted specialists [13]. The experts consulted are national experts on coastal overtopping risk (real names were replaced by letters for confidentiality reasons), with extensive experience in the field (Table 16).

**Table 16.** Experts on coastal overtopping risk consulted for the weighting of the hazard and vulnerability criteria and sub-criteria.

Experts	Institution
A	Portuguese Environment Agency
B	University of Aveiro, Civil Engineering Department
C	University of Lisbon, Faculty of Sciences
D	NOVA University Lisbon, NOVA School of Science and Technology
E	University of Porto, Faculty of Engineering
F	University of Azores, Biology Department
G	University of Lisbon, Geography and Territorial Planning Institute
H	National Laboratory of Civil Engineering
I	Portuguese Environment Agency, ARH Tejo
J	University of Algarve, Faculty of Sciences and Technology
L	University of Lisbon, Instituto Superior Técnico
M	National Laboratory of Civil Engineering

The experts were consulted in order to classify the hazard and vulnerability criteria and sub-criteria, according to their importance for the problem in question. The criteria were weighted, and the weightings were averaged to obtain a hazard and vulnerability index for each criterion. Tables 17 and 18 show the mean of the weights attributed to each hazard and vulnerability criteria, respectively. In the present study, the means were calculated according to a geometric mean. The geometric mean was interpolated for easy understanding by the reader.

**Table 17.** Arithmetic mean, geometric mean, and interpolated geometric mean from the weighting of the hazard criteria, carried out by the consulted specialists.

Hazard Factors	Arithmetic Mean	Geometric Mean	Geometric Mean (Interpolated)
Distance from flooded areas in the last 35 years	0.18	0.17	0.19
Altimetry	0.19	0.17	0.20
Lithology	0.05	0.05	0.05
Geomorphology	0.07	0.07	0.08
Erosion/Accretion rates	0.16	0.13	0.15
Slope and Slope Exposure	0.12	0.09	0.10
SLR increase	0.08	0.07	0.07
Sea agitation	0.15	0.13	0.15
Total	1.00	0.88	1.00

**Table 18.** Arithmetic mean, geometric mean, and interpolated geometric mean from the weighting of the vulnerability criteria, carried out by the consulted specialists.

Vulnerability Factors	Vulnerability Sub-Factors	Arithmetic Mean	Geometric Mean	Geometric Mean (Interpolated)
<b>Human population</b>	Number of residents	0.17	0.13	0.16
	Density of residents	0.17	0.12	0.15
	Most vulnerable population	0.15	0.14	0.16
<b>Potential Economy</b>	Economy/Services/Property Tax (IMI)	0.10	0.09	0.11
	Number of residential buildings	0.03	0.03	0.03
	Net Density of residential buildings	0.04	0.03	0.03
	Most vulnerable buildings	0.04	0.03	0.04
<b>Potential Ecology</b>	Natural heritage	0.09	0.07	0.09
	Ecological value	0.09	0.08	0.09
<b>Cultural heritage</b>		0.12	0.11	0.13
<b>Total</b>		1.00	0.82	1.00

#### 4.2. Hazard Factors

To obtain the hazard, vulnerability, and risk indexes, it was necessary to georeferentiate the hazard and vulnerability criteria and sub-criteria with the respective classification, according to the presented methodology.

The criteria and hazards considered were: distance from flooded areas in the last 35 years, altimetry, lithology, geomorphology, erosion/accretion rates, slope/slope exposure, SLR increase, and sea agitation (wave period and significant wave height). The maps of the hazard criteria can be found in Ferreira [26].

##### 4.2.1. Distance from Flooded Areas

The distance from the flooded areas (or overtopped areas) is one of the most important criteria according to the experts (Table 17), with 19% of the global weight of hazard to overtopping and coastal flooding. The hazard decreases as the distance from these areas increases. Table 19 shows the areas and respective percentage of the study area that this hazard factor represents.

**Table 19.** Areas and percentages of the study area classified as each class of the distance from flooded areas hazard factor.

Hazard Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Distance from flooded areas (m)</b>	562	63	134	15	35	4	38	4	121	14

##### 4.2.2. Altimetry

Altimetry is one of the most important criteria in hazard studies on overflow and coastal flooding, as seen in Table 17, with 20% importance for the global hazard index. The study area is a very low area, where more than 80% of the study area is below the 10 m level, 67% of the area is below 6 m, and 11% of the area is below the 2 m level [13].

In terms of altimetry, according to Table 20, the most representative class for the study area is the “very high” hazard class, expressed by 37% of the area (about 329 ha). The least dangerous areas are located mainly on the fossil cliff, on the promontory that started the development of the village of Costa da Caparica, and in the area covered by coastal defense and dunes. The high classification of this factor is due to the low altitude of the study area.

This is one of the variables that most characterizes the coastal plain of Costa da Caparica and highlights the importance of the dune system and coastal defense in protecting against overflows and floods of oceanic origin.

**Table 20.** Areas and percentages of the study area classified as each class of the altimetry hazard factor.

Hazard Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Altimetry</b>	168	19	81	9	97	11	214	24	329	37

#### 4.2.3. Lithology

In this area, dune and beach sands predominate (85% of the study area). There are two large units, determined by the type of dominant lithology: the coastal plain, where sands and dunes predominate (Holocene), and the fossil cliff, where there are mainly limestone and muddy complexes (Jurassic and Miocene) on the north of the highway (IC1), and, in the south, there is a prevalence of unconsolidated sands of the Pliocene, interspersed by conglomerates of the Plio-plistocene, and fine and marginal limestone sandstones of the Myocene. Holocene deposits are deposited at the base of the fossil cliff [13].

Since most of the study area consists of sands, this is an area associated with a high hazard level. Only the fossil cliff, its base and heavy coastal defenses are not classified with a high hazard level, according to the lithology criterion. The areas and percentages of the study area for each hazard class of the lithology criterion can be found in Table 21.

**Table 21.** Areas and percentages of the study area classified as each class of the lithology hazard factor.

Hazard Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Lithology</b>	21	2	17	2	61	7	35	4	756	85

#### 4.2.4. Geomorphology

The study area consists of four large geomorphological units: the continental shelf, the coastal plain, the fossil cliff and the coastal shelf. Most of the study area, however, comprises the coastal plain.

The areas and percentages of the study area for each hazard class of the geomorphology criterion can be found in Table 22. The areas with a “very high” hazard classification are the beaches, whereas the areas with the lowest hazard level are the areas of the fossil cliff and the heavy artificial coastal defense structures (groins and longitudinal adherent defense).

**Table 22.** Areas and percentages of the study area classified as each class of the geomorphology hazard factor.

Hazard Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Geomorphology</b>	124	14	21	2	626	71	1	0	117	13

#### 4.2.5. Erosion/Accretion Rates

The northern sectors of the study area, along the coastline, namely Cova do Vapor beach and São João beach, are the beaches most affected by erosion, with maximum retreat rates of 5.13 m/year. The erosion rate decreases towards the south of the study area.

The beaches with a very high hazard classification are located north of the urban beaches, except for the Cova do Vapor beach, displaying a moderate hazard level. However, there is a cluster in the Cova do Vapor beach, which classifies as a “very high” hazard level. The urban beaches are classified as having a “high” hazard level, whereas the beaches south of these have a moderate hazard level. Table 23 shows the areas and percentages of the study area classified according to each class of the hazard factor in question.

**Table 23.** Areas and percentages of the study area classified as each class of the erosion/accretion rates hazard factor.

Hazard Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Erosion/Accretion rates</b>	695	78	n/a	n/a	44	5	99	11	50	6

#### 4.2.6. Slope and Slope Exposure

The areas and percentages of the study area classified according to the slope and slope exposure criterion can be found in Table 24. In general, the study area displays a moderate hazard classification according to this factor.

The areas with the highest hazard levels are located on the beaches, due to the very gentle slope and respective orientation. The areas that are immediately after the natural and artificial coastal defenses, i.e., the areas further inland from the continent, also have a very high and high hazard classification because of the steep slope with mostly eastern orientation (E), as they promote flooding in the event of a breach of the respective coastal defense or overtop over structures.

**Table 24.** Areas and percentages of the study area classified as each class of the slope and slope exposure hazard factor.

Hazard Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Slope and slope exposure</b>	62	7	163	18	558	63	46	5	60	7

#### 4.2.7. Sea Level Rise (SLR) Increase

The SLR increase is homogeneous throughout the study area, as well as its respective hazard classification. Therefore, the entire study area is classified as having a moderate hazard level.

#### 4.2.8. Sea Agitation

The sea agitation criterion has two sub-criteria: significant wave height and wave period, as both are the variables that best characterize the energetic magnitude of the wave. In this criterion, it was considered that the areas over 100 m away from historically overturned areas would have a “very low” hazard classification, as these areas are not directly influenced by wave force.

The wave period sub-criterion was classified in the whole area with direct maritime influence as having a “high” hazard level (195 hectares, 22% of the study area) because in

this whole area, the values of the wave period are very similar and have been deemed to belong to the same hazard class.

Regarding the sub-criterion significant wave height, the respective areas and percentages of the study area for each hazard class can be consulted in Table 25. The beaches classified as having a “high” or “very high” hazard level are located north of the São João beach (including São João itself). The beaches with a “moderate” hazard classification are the urban beaches, located between São João and Praia da Mata. The beaches with a reduced hazard level are located south of Praia da Mata. Therefore, it is possible to conclude that the hazard associated with the significant wave height decreases as we move south in the study area.

**Table 25.** Areas and percentages of the study area classified as each class of the significant wave weight hazard sub-factor.

Hazard Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Significant wave height	695	78	85	10	59	7	38	4	14	1

#### 4.3. Vulnerability Factors

The criteria considered to assess vulnerability were Human Population, Potential Economy, Potential Ecology, and Cultural Heritage. These were then divided into sub-criteria for further evaluation.

##### 4.3.1. Human Population

The Human Population criterion is divided into the sub-criteria: number of residents, density of residents, and vulnerable residents.

##### Number of Residents

The areas and percentages of the study area for each class of vulnerability of the human population criterion, namely the sub-criterion number of residents, can be consulted in Table 26. The areas considered to be of very high and high vulnerability are located in Cova do Vapor and Torrão, in the urban areas of São João, Quinta de Santo António, and Costa da Caparica.

**Table 26.** Areas and percentages of the study area classified as each class of the number of residents vulnerability sub-factor.

Vulnerability Sub-Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Number of residents	759	85	34	4	33	4	33	4	31	3

##### Density of Residents

The classification of vulnerability regarding the density of residents shows a very similar behavior to the classification of vulnerability of the number of residents, although with some differences in the spatial distribution.

The standout areas with high and very high vulnerability are in the Torrão neighborhood, and further south, in some areas of São João, Quinta de Santo António, and Costa da Caparica. These areas, although having identical values of density of residents, display very different characteristics, as the Torrão neighborhood is a neighborhood of



illegal genesis, with precarious constructions, whereas the high-density neighborhoods of São João and Costa da Caparica are made up of vertical buildings (buildings) with good habitability conditions.

#### Most Vulnerable Population

The areas and percentages of the study area for each class of vulnerability of the human population criterion, namely the sub-criterion of vulnerable residents, can be consulted in Table 27. The areas classified with high and very high vulnerability are located to the north, in a small strip in front of the Tagus estuary in Bairro do Torrão, and in some areas of São João, Quinta de Santo António, Costa da Caparica, and some areas of Terras da Costa.

**Table 27.** Areas and percentages of the study area classified as each class of the most vulnerable population vulnerability sub-factor.

Vulnerability Sub-Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Most vulnerable population</b>	759	85	32	4	34	4	29	3	35	4

#### 4.3.2. Potential Economy

The Potential Economy criterion consists of the sub-criteria Economy/Services/IMI and Residential Buildings. The latter sub-criterion is further divided into: number of residential buildings, net density of residential buildings, and most vulnerable buildings.

##### Economy/Services/IMI

Table 28 shows the areas and percentages of the study area for each class of vulnerability of the Potential Economy criterion, more specifically, the Economy/Services/IMI sub-criterion.

The areas with economic activities and provision of services to the community fall on the beach supports, being most vulnerable to overtopping and to the consequent flooding events. They are, therefore, classified as areas with very high vulnerability. São João, Quinta de Santo António, and Costa da Caparica also display very high vulnerability, as they have high values of IMI. The areas closest to the sea, such as beach supports, fishing supports, and the dock, also exhibit very high vulnerability.

**Table 28.** Areas and percentages of the study area classified as each class of the economy/services/IMI vulnerability sub-factor.

Vulnerability Sub-Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Economy/Services/IMI</b>	386	43	130	15	119	13	102	12	153	17

##### Residential Buildings

The sub-criterion of Residential Buildings is further divided into three more sub-criteria: number of residential buildings, net density of residential buildings, and vulnerable buildings.

##### Number of Residential Buildings

The areas and percentages of the study area for each class of vulnerability of the sub-criterion residential buildings—number of residential buildings—are displayed in

Table 29. The areas classified with very high vulnerability correspond to Cova do Vapor, a small strip in Bairro do Torrão, a strip in São João, the built area near the base of the fossil cliff in Quinta de Santo António, some areas of Costa da Caparica and some areas in Terras da Costa.

**Table 29.** Areas and percentages of the study area classified as each class of the residential buildings (number of residential buildings) vulnerability sub-factor.

Vulnerability Sub-Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Number of residential buildings	759	85	41	5	36	4	27	3	27	3

#### Net Density of Residential Buildings

The areas with the highest density of residential buildings and, therefore, classified with a very high vulnerability are located throughout the Cova do Vapor, in Bairro do Torrão, in some areas of Quinta de Santo António and São João, in the center of Costa da Caparica, and in Terras da Costa.

#### Most Vulnerable Residential Buildings

The areas and percentages of the study area for each class of vulnerability of the residential buildings—most vulnerable residential buildings—sub-criterion can be consulted in Table 30. The most vulnerable areas correspond to areas with buildings with mostly one or two floors. These areas are located throughout Cova do Vapor, Bairro do Torrão and Terras da Costa. In Costa da Caparica, there are also areas with very high vulnerability, especially the oldest areas, such as Bairro dos Pescadores. In São João, in the housing areas, there are some high vulnerability zones. It should be noted that the areas along the coast are extremely vulnerable, such as Cova do Vapor, Bairro dos Pescadores, and the buildings next to the Barbas Restaurant.

**Table 30.** Areas and percentages of the study area classified as each class of the vulnerability subfactor, residential buildings (most vulnerable residential buildings).

Vulnerability Sub-Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Most vulnerable residential buildings	775	87	16	2	20	2	26	3	53	6

#### 4.3.3. Potential Ecology

The Potential Ecology criterion is divided into two sub-criteria: Natural Heritage and Ecological Value.

##### Natural Heritage

The areas and percentages of the study area for each class of vulnerability of the potential ecology criterion, namely the natural heritage sub-criterion, can be consulted in Table 31. The areas with very high vulnerability correspond to the beaches and frontal dune system, which is why they are represented by such a high percentage. The areas with high vulnerability have little expression since only the drainage ditches and the riparian system of Foz do Rego were considered. The territory was mostly classified with moderate vulnerability, as it is represented by areas with environmental constraints, such as Protected

Landscapes and National Ecological Reserves. The areas displaying a low vulnerability correspond to urban areas and buildings, as they have no natural heritage.

**Table 31.** Areas and percentages of the study area classified as each class of the natural heritage vulnerability sub-factor.

Vulnerability Sub-Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Natural Heritage</b>	237	27	n/a	n/a	533	60	2	0	117	13

#### Ecological Value

Table 32 displays the areas and percentages of the study area, for each class of vulnerability, regarding the Ecological Value sub-criterion.

**Table 32.** Areas and percentages of the study area classified as each class of the ecological value vulnerability sub-factor.

Vulnerability Sub-Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Ecological Value</b>	489	55	160	18	39	4	16	2	186	21

The areas classified with very high vulnerability correspond to beaches, frontal dunes, stone pine forests (in Mata dos Franceses, in São João, and at the top of the fossil cliff) and areas with *Juniperus* spp. (Mata dos Franceses and along the fossil cliff, in deposits and at the top).

The areas classified with high vulnerability have less expression and correspond to the Pinheiro Bravo forest (located in the slopes of the fossil cliff), to the Foz do Rego stream and the drainage ditch system.

#### 4.3.4. Cultural Heritage

The areas and percentages of the study area for each class of vulnerability of the cultural heritage criterion can be found in Table 33.

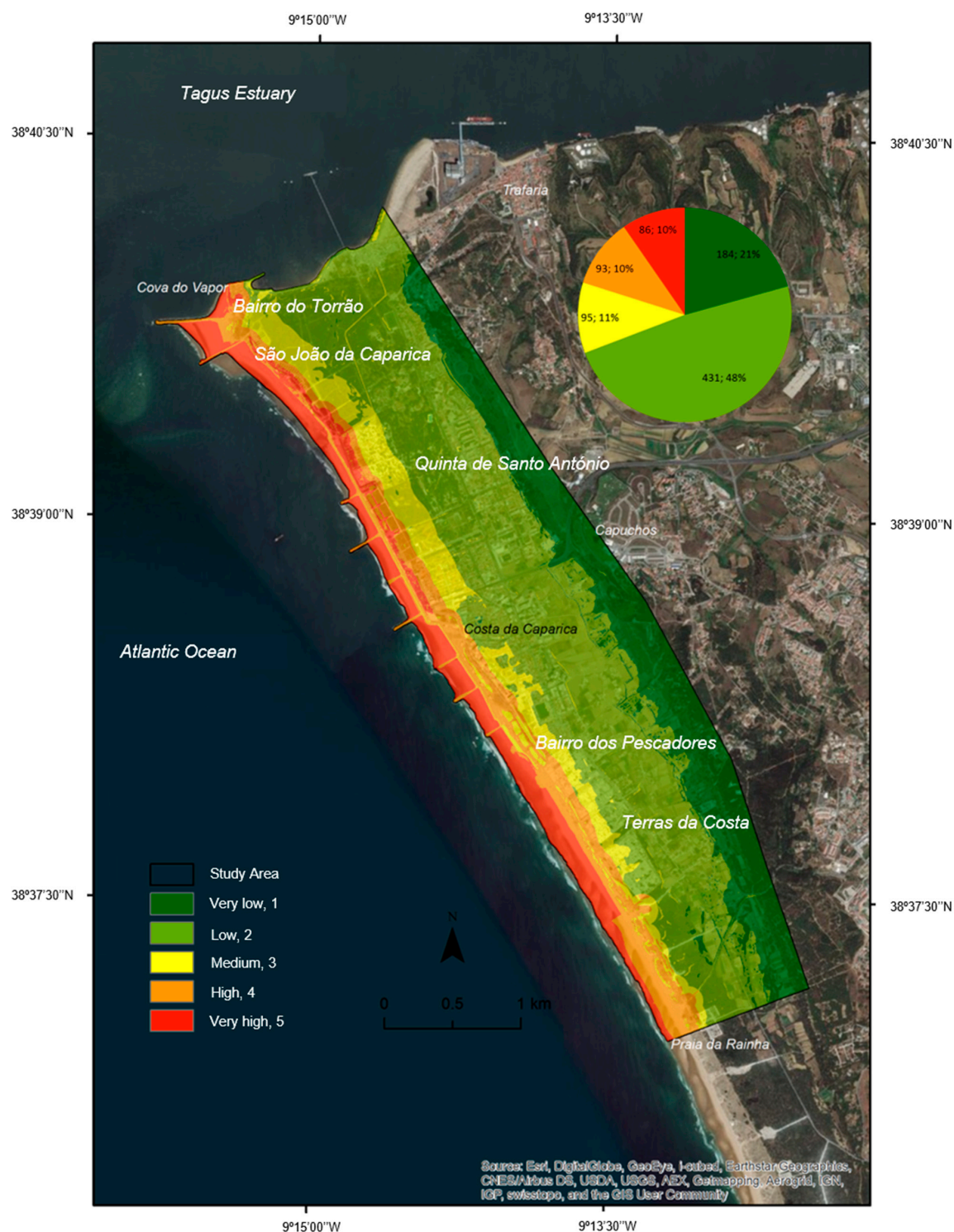
**Table 33.** Areas and percentages of the study area classified as each class of the cultural heritage vulnerability factor.

Vulnerability Factor	Very Low 1		Low 2		Medium 3		High 4		Very High 5	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
<b>Cultural Heritage</b>	649.3	73	0.2	0	93.3	11	146.6	16	0.6	0

The areas classified with very high vulnerability correspond to fishing supports and the Old Church of Costa da Caparica and have very little expression due to their reduced dimensions. The areas classified with high vulnerability have great expression, corresponding to about 147 hectares of the study area, since the agricultural areas of Terras da Costa are included. The areas with moderate vulnerability have a significant expression, due to the dimensions of the elements present, namely the beaches. In this criterion, a lot of importance was given to the cultural elements corresponding to the activities of fishing and agriculture.

#### 4.4. Global Hazard Index to Overtopping and Coastal Flooding

The global hazard index of the global ocean overtopping and consequent flooding for Costa da Caparica was obtained through Equation (1), with the weightings attributed by the consulted specialists and following the previously presented methodology. The map of the global hazard index can be seen in Figure 4.



**Figure 4.** Map of the hazard index to coastal overtopping and consequent flooding in the study area, Costa da Caparica, with the graph with the areas (ha) and percentages of each class of vulnerability. The coordinate system used was the Datum73 Transverse Mercator.

The areas most subject to overtopping and consequent flooding on the coastal plain of Costa da Caparica are concentrated close to the coastline, where there are areas subject to very high (10% of the study area with 86 ha) and high (10% of the 93 ha area) hazard.

The entire coastline between Cova do Vapor and Ribeira da Foz do Rego is subject to a high or very high overtopping hazard, namely beaches, frontal dune systems, coastal defense structures, car parks and parking lots, beach supports, fishing supports, camping sites, the Cova do Vapor cluster, some dwellings, shops, and services on the urban front of Costa da Caparica. These areas are the ones closest to or in contact with the ocean, being, therefore, the most pressured by erosive phenomena of coastal origin, by the sea level rise increase, and by the fact that they have very sensitive geomorphology and lithology characteristics.

The hazard of overtopping and consequent flooding decreases as we head south within the study area. The urban agglomeration in the study area most affected by ocean overtopping corresponds to Cova do Vapor, and it should be noted that the global hazard index is sensitive to this fact as it classifies this area with very high hazard. The beach supports most affected by ocean overflows are the beach supports north of the study area in São João and Restaurante Barbas (immediately north of the urban beaches).

The area with the lowest hazard index is mainly located in the fossil cliff. This is a direct consequence of its location, as it represents a cliff located quite far from the coastline.

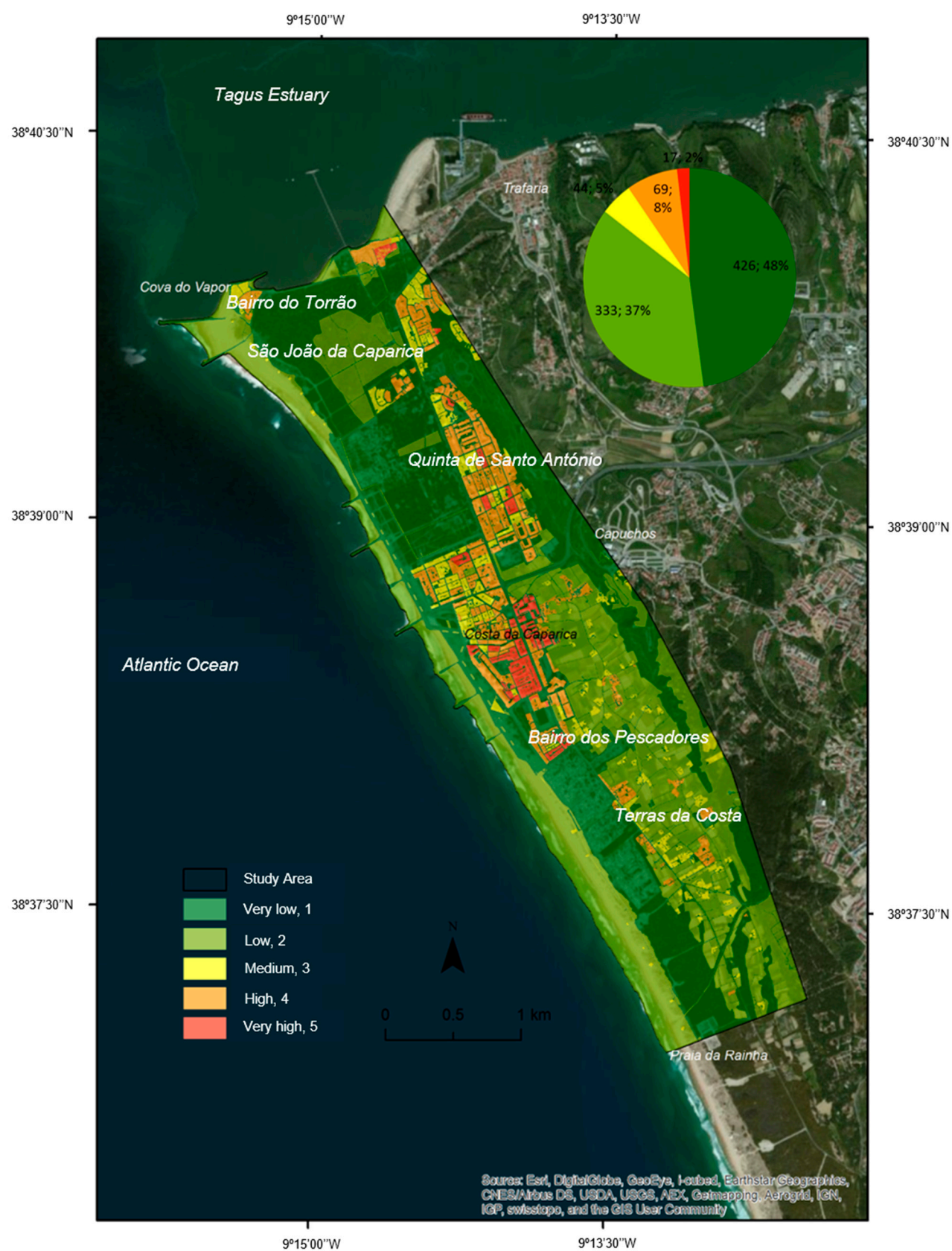
#### *4.5. Global Vulnerability Index to Overtopping and Coastal Flooding*

The global vulnerability index of ocean overtopping and consequent flooding for the coastal plain of Costa da Caparica was attained through Equation (2), with the respective weightings attributed by the consulted specialists, according to the method detailed in the methodology section. The map of the global vulnerability index is shown in Figure 5.

The most vulnerable areas to overtopping and coastal flooding, classified with very high vulnerability, comprise a total of 17 hectares, representing about 2% of the study area, and are located mostly in the city center of Costa da Caparica. This assessment results from the high urban and economic density present in the city center and because the experts have given a high weight to the criteria related to residents and the economy. In São João, some clusters with very high vulnerability are visible. However, they are quite far from the sea. In the neighborhoods of Torrão and Bairro dos Pescadores, areas with very high vulnerability are also visible, as they are areas with vulnerable buildings and a high density of residents.

The urban front of Costa da Caparica, closer to the water line, is practically classified in its entirety with high vulnerability due to the high density of residents, buildings, and economic services.





**Figure 5.** Map of the vulnerability index to coastal overtopping and consequent flooding in the study area, Costa da Caparica, with the graph with the areas (ha) and percentages of each class of vulnerability. The coordinate system used was the Datum73 Transverse Mercator.

#### 4.6. Global Risk Index to Overopping and Coastal Flooding

The global risk index of ocean overtopping and consequent flooding for Costa da Caparica was obtained through Equation (3), with the weightings of the consulted specialists, according to the method explained in detail in the methodology. The map with the risk index can be seen in Figure 6.

The areas with the greatest risk of overtopping and consequent coastal flooding on the coastal plain of Costa da Caparica, according to the weighing attributed by the experts and the methodology presented in Section 3, are located along the entire coastal strip (beaches) between Cova do Vapor and Ribeira Foz do Rego.

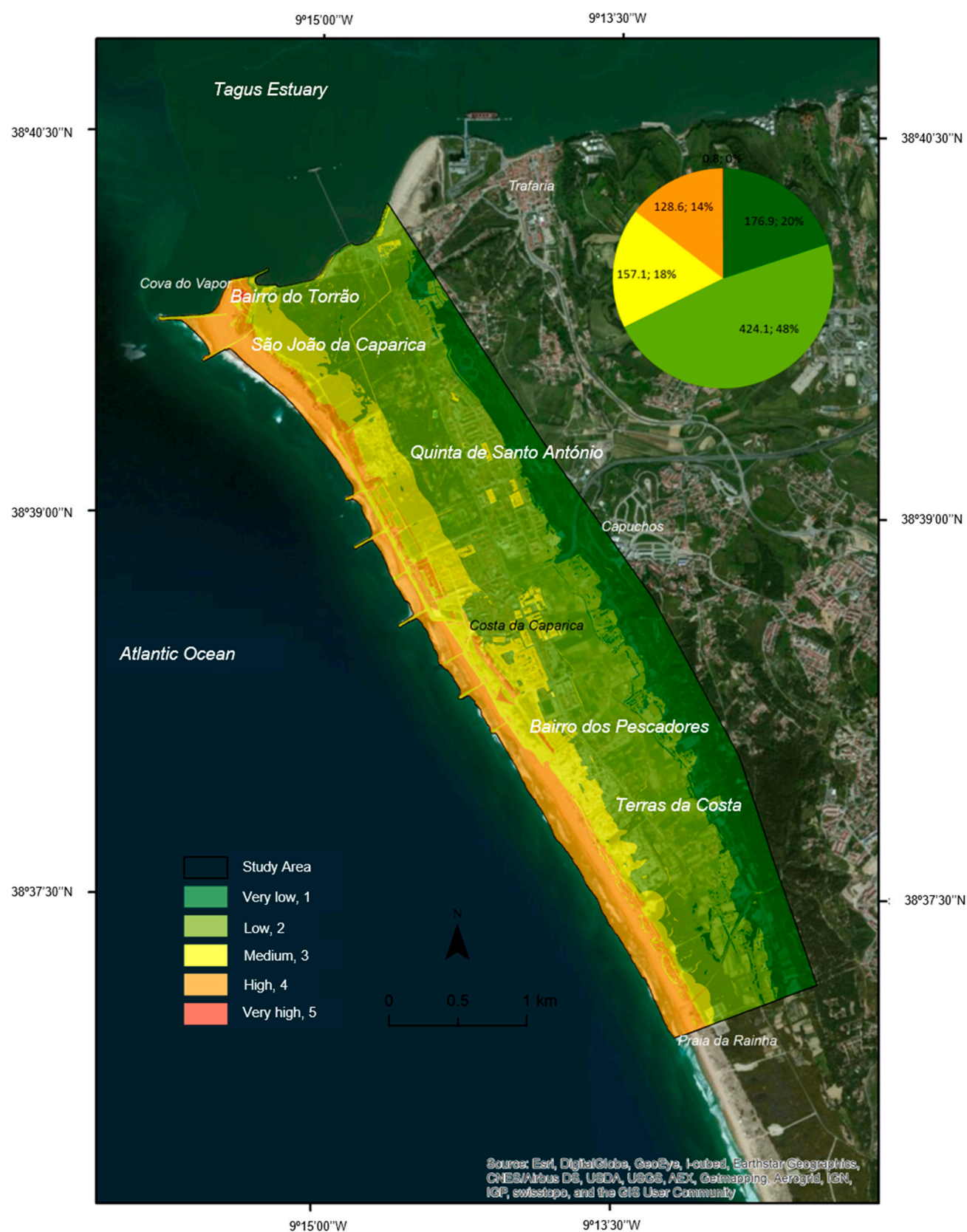
The highest risk classes (moderate/medium risk, high risk, and very high risk) represent about 32% of the study area, totaling about 287 hectares. The very high risk class, although with very little representation (0.8 ha), occurs in the urban area of Cova do Vapor and covers some areas on the beach of São João, namely the beach supports and the respective accesses.

The high risk class (14% of the study area, 129 ha) occurs mainly on beaches, frontal dunes and beach supports throughout the studied coastline and in areas with a higher concentration of vulnerable buildings on the urban front of Costa da Caparica (support fishing, auction, buildings with commercial activity).

Further inland, the risk decreases in intensity, but still displays values that determine the existence of a moderate risk. This area has about 157 hectares and represents 18% of the study area, occupying a continuous area between the forests of São João and the Foz do Rego riverside, covering campsites, parking lots, residential areas, commercial and service areas, only interrupted by the quota increase in the central area of Costa da Caparica, next to the oldest church in Costa da Caparica, and in the area occupied by the first inhabitants of Costa da Caparica. The first occupants of Costa da Caparica settled in an area with reduced risk and relatively close to the sea.

The coastal territory covered by the highest classes (moderate/medium, high and very high risk) should be subject to a territorial planning process based on this assessment of the risk of overtopping and ocean flooding, as well as to adequate management of the risk levels.

The risk index reveals itself as a versatile and robust tool for risk analysis in the coastal plain of Costa da Caparica, and allows for more specific analysis, such as assessing risk, taking into account specific vulnerabilities, such as the risk of overtopping and flooding in areas representative of economic activity. In these cases, global hazard is crossed with the vulnerability of economic activities.



**Figure 6.** Map of the risk index to coastal overtopping and consequent flooding in the study area, Costa da Caparica, with the graph of the areas (ha) and percentages of each risk class. The coordinate system used was Datum73 Transverse Mercator.



## 5. Discussion

In this work, the AHP methodology confirmed its versatility and suitability to develop hazard, vulnerability, and risk indexes.

The tables that provided the areas and percentages of the study site classified as each class of the hazard and vulnerability factors allowed for an overview of the most worrisome factors considered.

In terms of hazard factors, the ones with the highest percentages of the study site, classified with the “very high” classification stamp, were altimetry and lithology. This is because Costa da Caparica is, for most of its extension, considered a coastal plain. Low areas, especially low sandy areas, are more prone to the occurrence of flooding and overtopping events, hence the classification. Complementarily, the consulted experts attributed the highest weights to the “distance from flooded areas” and “altimetry criteria”, automatically meaning that the areas closest to the sea would be the most affected, according to the hazard index. In fact, Figure 4 displays this by classifying the lowest areas, closest to the sea, as the most hazardous.

On the other hand, considering the vulnerability factors and subfactors, none displayed the highest percentage of area associated with the most vulnerable class. In fact, most of the vulnerability factors were classified with a “very low” classification for the majority of the Costa da Caparica area. Nonetheless, as the consulted experts considered the “human population” factor and the “economy/services/IMI” sub-factor as the most relevant, the areas with a higher vulnerability classification are in neighborhoods with a high population and economic density (Quinta de Santo António, São João, and the city center of Costa da Caparica). Additionally, “cultural heritage” was also one of the most important factors, as considered by the experts, meaning neighborhoods with extremely specific socioeconomic characteristics, such as Bairro do Torrão and Bairro dos Pescadores, were also vulnerable.

The combination of the hazard and vulnerability indexes resulted in the risk index, displayed in Figure 6. By analyzing the risk index, it is possible to understand that the class distribution displays more similarities with the hazard index, rather than with the vulnerability index. This is because the hazard index was considered more significant (with a relative weight of 80%) to the calculation of the risk index when compared with the vulnerability.

While most of the area was classified as having “very low” and “low” risk, the “moderate”, “high”, and “very high” risk areas still corresponded to approximately 1/3 of the study site, meaning that the areas closest to the sea, those with high population and economic density, and those with specific socioeconomic characteristics (i.e., low income) should be continuously monitored.

## 6. Conclusions

This work aimed to propose a model for the identification and classification of hazards, exposed and vulnerable areas, and areas at risk of coastal overtopping and flooding at the local level, namely in Costa da Caparica. A series of criteria were selected to characterize the problem, and the coast of Costa da Caparica was classified according to the same criteria.

Eight hazard criteria were selected, taking into account the characteristics of the site: distance from flooded areas, altimetry, lithology, geomorphology, erosion/accretion rates, slope and slope exposure, SLR increase, and sea agitation. The latter was divided into two sub-criteria, significant wave height and wave period, both equally weighted.

Similarly, four vulnerability criteria were selected: human population, potential economy, potential ecology, and, finally, cultural heritage. The human population criterion was divided into three sub-criteria: number of residents, net density of residents, and most vulnerable population. The criterion potential economy was divided into two sub-criteria: economy/services/IMI and residential buildings. The latter was then further divided into three more sub-criteria: number of residential buildings, net density of residential

buildings, and most vulnerable buildings. Finally, the potential ecology criterion was divided into two sub-criteria: ecological value and natural heritage.

The classifications of the hazard criteria were based on historical sea agitation data, historical data on the position of the coastline, the digital terrain model, historical data from the SLR in Cascais, and the digital geological map of Lisbon and Cascais. The classifications of the vulnerability criteria were based on: data from the censuses of the National Statistics Institute (INE), namely the number of residents, age group of residents, number of buildings and number of floors of buildings; the 2014 land occupation and land use maps, shared by the Almada City Council (CMA); a map of the National Ecological Reserve (REN); a map of the National Agricultural Reserve (RAN) and, finally, a map of the Protected Areas/Protected Landscapes in Portugal.

The criteria were classified on a numerical scale between 1 (very low) and 5 (very high). The criteria were weighted by a group of national experts on overtopping and coastal flooding, using Saaty's peer-to-peer weighting methodology [64].

The vulnerability, hazard and risk indexes to coastal overtopping and flooding resulted from a weighted multicriteria analysis (AHP) adapted from Saaty [64], using the ArcGIS to georeference the criteria and the respective indexes. The classification of these indexes was made on a scale between 1 (very low) and 5 (very high), following the classification distribution of the respective criteria.

Considering the vulnerability index, it was found that about 2% of the study area, totaling 17 hectares, corresponds to areas with very high vulnerability, and these are mainly located in the city center of Costa da Caparica. The high urban and economic density present in this area and the high weight attributed by the experts to the criteria related to human population and the economy justify the very high classification of vulnerability in this area. Other areas with very high vulnerability are in São João, Bairro do Torrão and Bairro dos Pescadores, although with smaller areas. The urban front of Costa da Caparica, closest to the coastline, is classified as having high vulnerability.

Regarding the hazard index, it was found that 10% of the study area is classified as having a very high hazard, totaling about 86 hectares. The areas closest to the sea are naturally more prone to overtopping and, therefore, were classified with a very high hazard index, regardless of whether activities, buildings or natural features with high value were present. These are the areas closest to sea pressure, more pressured by erosive phenomena of coastal origin, more pressured by the SLR increase, and which lithology and geomorphology characteristics indicate are more sensitive to overtopping events. The areas with a very high hazard index are in the urban agglomeration of Cova do Vapor and the beach supports located on the beaches of São João. This classification is due to the natural characteristics of the place, reflected in the assessed hazard criteria. It appears that the hazard levels are decreasing as we go further south in the study area.

Regarding the risk of overtopping and coastal flooding, only 0.8 hectares were classified as having very high risk. These areas are in the urban agglomeration of Cova do Vapor and on the beach supports of São João. Only these areas were classified with very high risk because they are the areas with economic, social, or natural value closest to the sea, and, therefore, more subject to overtopping and erosion events.

As expected, the risk decreases as we head south from the study area, mainly due to the decrease in hazard. Approximately 14% of the study area, totaling 129 hectares, is classified as having high and very high risk, comprising fishing supports, beach supports, auction, and buildings with commercial activity close to the coastline.

The moderate risk area is about 157 hectares and represents 18% of the study area, occupying an area between the forests of São João and the Foz do Rego riverside, including campsites, parking lots, and residential, commercial and services areas, only being interrupted by the oldest part of Costa da Caparica, where the Old Church is located and where the first inhabitants of Costa da Caparica settled. It should be noted that our ancestors already knew the best place to settle, without being hit by the force of the sea and erosive phenomena.

While the methodology applied in this article is not new, the use of such a variety of descriptive indicators (associated with wave overtopping and coastal flooding) is very innovative. In fact, the work carried out involved the use of economic, social and environmental indicators, which will prove to be a useful, effective, and simple tool for the identification of sensitive areas and to assist in decision-making processes in matters of coastal zone planning and management. The work developed can be adapted to other realities and spatial scales, since the methodology followed has proved to be successfully replicable.

Moreover, it is important to understand that the work carried out in this study is not finished. In order to make the study even more robust, an additional number of indicators can be used, such as the hydraulic risk as a hazard indicator, among others [69]. Complementarily, the calculation of the risk index for the Costa da Caparica area allowed us to start developing a methodology to calculate the economic costs associated with the defense/protection, accommodation and relocation strategies, which should be implemented as a response to the results of the present study, as done by Cardona et al. [70].

**Author Contributions:** Conceptualization, methodology, and writing were carried out by J.C.F., F.S.C., C.J.S. and J.A.T. reviewed and edited previous draft versions and provided supervision. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors acknowledge the financial help of the Portuguese Foundation for Science and Technology (FCT) project To-SEAlert (PTDC/EAM-OCE/31207/2017). This work is financed by national funds through FCT - Foundation for Science and Technology, I.P., within the scope of the project UIDB/04292/2020 of MARE—Marine and Environmental Sciences Centre, and UIDB/04647/2020 of CICS.NOVA—Centro Interdisciplinar de Ciências Sociais da Universidade Nova de Lisboa.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Acknowledgments:** The authors would like to thank the specialists on coastal overtopping risk, consulted for the weighting of the hazard and vulnerability criteria and sub-criteria: Juana Fortes (LNEC), Maria Teresa Reis (LNEC), Rui Capitão (LNEC), Pedro Poseiro (LNEC), Marta Martinho (FCT NOVA), Paulo Raposeiro (FCT NOVA) and Susana Ferreira Silva (FCT NOVA) for the help during the entire process.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Duarte, C.M.; Ferreira, J.C.; Fortes, J. Risk modelling in urban coastal areas to support adaptation to climate change and extreme weather events: Early warning, emergency planning and risk management system. *J. Coast. Res.* **2020**, *SI95*. [CrossRef]
2. Hunter, J. Estimating sea-level extremes under conditions of uncertain sea-level rise. *Clim. Chang.* **2010**, *99*, 331–350. [CrossRef]
3. Reay, D.; Sabine, C.; Smith, P.; Hymus, G. *Intergovernmental Panel on Climate Change; Fourth Assessment Report; Inter-Governmental Panel on Climate Change*; Geneva, Switzerland; Cambridge University Press: Cambridge, UK, 2007; ISBN 9291691224. Available online: [www.ipcc.ch](http://www.ipcc.ch) (accessed on 5 September 2020).
4. United Nations and Canada. *United Nations Framework Convention on Climate Change*; United Nations, General Assembly: New York, NY, USA, 1992.
5. NASA/GISS Long-Term Warming Trend Continued in 2017: NASA, NOAA. Available online: <https://climate.nasa.gov/news/2671/long-term-warming-trend-continued-in-2017-nasa-noaa/> (accessed on 5 September 2020).
6. Howard, T.; Pardaens, A.K.; Bamber, J.L.; Ridley, J.; SPada, G.L.; Hurkmans, R.T.W.; Lowe, J.A.; Vaughan, D. Sources of 21st century regional sea-level rise along the coast of northwest Europe. *Ocean Sci.* **2014**, *10*, 473–483. [CrossRef]
7. Wong, P.P.; Losada, I.J.; Gattuso, J.P.; Hinkel, J.; Khattabi, A.; McInnes, K.L.; Saito, Y.; Sallenger, A. Coastal Systems and Low-Lying Areas. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; pp. 361–409. ISBN 9781107415379.
8. Santos, F.D.; Miranda, P. *Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação. Projeto SIAM II*, 1st ed.; Gradiva Publicações, Lda.: Lisbon, Portugal, 2006; ISBN 989-616-081-3.
9. Dias, J.A.; Ferreira, Ó.; Pereira, A.R. *Estudo Sintético de Diagnóstico da Geomorfologia e da Dinâmica Sedimentar dos Troços Costeiros Entre Espinho e Nazaré*; ESAMIN—Estudos de Ambiente e Informática, Lda.: Lisbon, Portugal, 1994.



10. Ribeiro, J.L. *Cadernos Técnicos PROCIV: Riscos Costeiros—Estratégias de prevenção, mitigação e protecção, no âmbito do planeamento de emergência e do ordenamento do território*; Autoridade Nacional de Protecção Civil, Ed.; ANPC: Carnaxide, Portugal, 2010; pp. 1–156.
11. Ferreira, J. Coastal zone vulnerability and risk evaluation: A tool for decision-making (an example in the Caparica Littoral-Portugal). *J. Coast. Res.* **2004**, *39*, 1590–1593.
12. Raposeiro, P.D.; Reis, M.T.; Fortes, C.J.; Ferreira, J.C. Methodology for estimating run-up and flooding at the costal zone using the GUIOMAR system: Application to Vale do Lobo beach. In Proceedings of the Conference: CoastGIS 2009, Oeiras, Portugal, 13 November 2009; Volume 2.
13. Ferreira, J.C.R. Ordenamento Ambiental de Frentes Urbanas Litorais em Áreas Baixas de Elevado Risco e Vulnerabilidade ao Galgamento Costeiro. 2016. Available online: <http://hdl.handle.net/10362/19883> (accessed on 5 September 2020).
14. Turner, R.K.; Burgess, D.; Hadley, D.; Coombes, E.; Jackson, N. A cost-benefit appraisal of coastal managed realignment policy. *Glob. Environ. Chang.* **2007**, *17*, 397–407. [CrossRef]
15. Cooper, J.A.G.; McKenna, J. Social justice in coastal erosion management: The temporal and spatial dimensions. *Geoforum* **2008**, *39*, 294–306. [CrossRef]
16. Dias, J.A. Evolução da Zona Costeira Portuguesa: Forçamentos Antrópicos e Naturais. *Encontros Científicos Turismo Gestão Fiscalidade* **2005**, *1*, 7–27.
17. Dias, J.A. A Evolução Actual do Litoral Português. *Geonovas* **1990**, *11*, 15–29.
18. Yuhi, M. Impact of Anthropogenic Modifications of a River Basin on Neighboring Coasts: Case Study. *J. Waterw. Port Coast. Ocean Eng.* **2008**, *134*, 336–344. [CrossRef]
19. Newell, R.C.; Seiderer, L.J.; Hitchcock, D.R. The impact of dredging works in coastal waters: A review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. *Oceanogr. Mar. Biol.* **1998**, *36*, 127–178.
20. Cardona, F.M.S. *Avaliação do Risco de Erosão, Galgamento e Inundação Costeira em Áreas Artificiais de Portugal Continental: Estratégias de Adaptação Face a Diferentes Cenários de Risco (Relocalização, Acomodação e Protecção)*; Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa: Caparica, Portugal, 2015; p. 206.
21. French, P.W. *Coastal Defences: Processes, Problems and Solutions*, 1st ed.; Routledge: Abingdon, UK, 2001.
22. Bernatchez, P.; Fraser, C. Evolution of coastal defence structures and consequences for beach width trends, Québec, Canada. *J. Coast. Res.* **2012**, *28*, 1550–1566. [CrossRef]
23. Martinho, M.F.M.A. *Avaliação e Gestão de Riscos em Áreas Litorais. Contributo para o Desenvolvimento de um Sistema de Previsão e Alerta de Inundação em Zonas Costeiras*; Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa: Caparica, Portugal, 2014; p. 131.
24. Matos, M.D.F.A.D.; Fortes, C.J.E.M.; Amaro, V.E.; Scudelari, A.C. Análise Comparativa da Agitação Obtida com o Modelo Numérico (SWAN) na Modelagem de Ondas do Litoral Setentrional do Rio Grande do Norte, Brasil e Dados de Campo. *Rev. Gestão Costeira Integr.* **2013**, *13*, 283–299. [CrossRef]
25. Raposeiro, P.D.; Ferreira, J.C. Evaluation of Coastal Flood Risk Areas and Adaptation Strategie for a Sustainable Planning. *J. Coast. Res.* **2011**, *SI 64*, 1896–1900.
26. Neves, P.; Poseiro, P.; Fortes, C.J.; Reis, M.T.; Capitão, R.; Antunes do Carmo, J.S.; Raposeiro, P.; Ferreira, J.C. O Projeto Hidralerta—Sistema de Previsão e Alerta de Inundações Costeiras e Portuárias. In Proceedings of the 8<sup>as</sup> Jornadas Portuguesas de Engenharia Costeira e Portuária, Lisboa, Portugal, 10–11 October 2013.
27. Poseiro, P.; Fortes, C.; Reis, M.; Santos, J.; Reis, R. Aplicações Do Sistema De Previsão E Alerta Do Risco De Galgamentos Em Zonas Costeiras E Portuárias: Costa Da Caparica E Praia Da Vitória. *Rev. Eng. E Tecnol.* **2014**, *7*, 77–91.
28. Fortes, C.J.E.M.; Reis, M.T.; Poseiro, P.; Santos, J.A.; Pinheiro, L.; Craveiro, J.; Rodrigues, A.; Sabino, A.; Silva, S.F.; Ferreira, J.C.; et al. HIDRALERTA Project: A Flood Forecast and Alert System in Coastal and Port Areas. In Proceedings of the IWA—World Water Congress & Exhibition, Lisbon, Portugal, 21–26 September 2014. [CrossRef]
29. Poseiro, P.; Capitão, R.; Fortes, C.; Silva, S.; Ferreira, J.C. *Relatório do Levantamento de Perfis Morfológicos do Sistema Praia-duna da Costa da Caparica, entre Cova do Vapor e Ribeira Foz do Rego 29 e 30 de abril de 2014*; Laboratório Nacional de Engenharia Civil: Lisbon, Portugal, 2014; p. 78.
30. Poseiro, P.; Reis, R.; Ferreira, J.C.; Fortes, C.; Capitão, R. *Sistema de Previsão e Alerta de Inundações em Zonas Costeiras e Portuárias ptdc/aac-amb/120702/2010—Relatório do Levantamento de Perfis Morfológicos do Sistema Praia-duna da Costa da Caparica, entre Cova do Vapor e Ribeira Foz do Rego*; Laboratório Nacional de Engenharia Civil: Lisbon, Portugal, 2014; p. 37.
31. Denner, K.; Phillips, M.R.; Jenkins, R.E.; Thomas, T. A coastal vulnerability and environmental risk assessment of Loughor Estuary, South Wales. *Ocean Coast. Manag.* **2015**, *116*, 478–490. [CrossRef]
32. Gornitz, V. Global coastal hazards from future sea level rise. *Palaeogeogr. Palaeoclim. Palaeoecol.* **1991**, *89*, 379–398. [CrossRef]
33. Gornitz, V.M.; White, T.W. A coastal hazards data base for the U.S. east coast. *Environ. Sci. Div.* **1992**, *174*. [CrossRef]
34. Kantamaneni, K. Counting the cost of coastal vulnerability. *Ocean Coast. Manag.* **2016**, *132*, 155–169. [CrossRef]
35. Shaw, J.; Taylor, R.B.; Forbes, D.L.; Solomon, S.; Ruz, M.H. *Sensitivity of the Coasts of Canada to Sea-Level Rise*; Natural Resources Canada: Ottawa, QC, Canada, 1998; ISBN 0-660-17569-X.
36. Thieler, E.R.; Hammar-Klose, E.S. National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the U.S. Atlantic Coast U.S. Geological Survey Open-File Report 99–593. Available online: <https://pubs.usgs.gov/of/1999/of99-593/> (accessed on 5 September 2020).

37. Silva, S.F.; Martinho, M.; Capitão, R.; Reis, T.; Fortes, C.J.; Ferreira, J.C. An index-based method for coastal-flood risk assessment in low-lying areas (Costa de Caparica, Portugal). *Ocean Coast. Manag.* **2017**, *144*, 90–104. [\[CrossRef\]](#)
38. Cutter, S.L.; Boruff, B.J.; Shirley, W.L. Social vulnerability to environmental hazards. *Soc. Sci. Q.* **2003**, *84*, 242–261. [\[CrossRef\]](#)
39. Boruff, B.J.; Emrich, C.; Cutter, S.L. Erosion hazard vulnerability of US coastal counties. *J. Coast. Res.* **2005**, *21*, 932–942. [\[CrossRef\]](#)
40. Gardiner, P.C.; Edwards, W. Public values: Multiattribute-utility measurement for social decision making. In *Human Judgment and Decision Process, Academic Press Series in Cognition and Perception*; Kaplan, M.F., Schwartz, S., Eds.; Academic Press: New York, NY, USA, 1975; pp. 1–37.
41. Coelho, C.D.B. *Riscos de Exposição de Frentes Urbanas para Diferentes Intervenções de Defesa Costeira*; Universidade de Aveiro: Aveiro, Portugal, 2005.
42. Marcomini, A.; Suter, G.W.; Critto, A. *Decision Support. Systems for Risk-Based Management of Contaminated Sites*; Marcomini, A., Critto, A., Sutter, G.W., II, Eds.; Springer: Berlin, Germany, 2009; ISBN 978-0-387-09721-3.
43. Flax, L.K.; Jackson, R.W.; Stein, D.N. Community Vulnerability Assessment Tool Methodology. *Nat. Hazards Rev.* **2002**, *3*, 163–176. [\[CrossRef\]](#)
44. Sherly, M.A.; Karmakar, S.; Parthasarathy, D.; Chan, T.; Rau, C. Disaster Vulnerability Mapping for a Densely Populated Coastal Urban Area: An Application to Mumbai, India. *Ann. Assoc. Am. Geogr.* **2015**, *105*, 1198–1220. [\[CrossRef\]](#)
45. Taal, M. The cosmo-line: Interactive tools for ICZM. In *Concepts, Tools and Measures—Climate of Coastal Cooperation*; Misdorp, R., Ed.; Coastal and Marine Union: Leiden, The Netherlands, 2011; pp. 142–143. ISBN 978-90-75502-09-1.
46. UNFCC. *Decision Support Models: COSMO (Coastal Zone Simulation Model)*; UNFCC: Rio de Janeiro, Brazil, 2014.
47. Torresan, S.; Critto, A.; Rizzi, J.; Zabeo, A.; Furlan, E.; Marcomini, A. DESYCO: A decision support system for the regional risk assessment of climate change impacts in coastal zones. *Ocean Coast. Manag.* **2016**, *120*, 49–63. [\[CrossRef\]](#)
48. Hinkel, J. DIVA: An iterative method for building modular integrated models. *Adv. Geosci.* **2005**, *4*, 45–50. [\[CrossRef\]](#)
49. Hinkel, J.; Klein, R.J.T. DINAS-COAST: Developing a Method and a Tool for Dynamic and Interactive Vulnerability Assessment. *Land-Ocean Interact. Coast. Zone* **2003**, *27*, 1–8.
50. Hinkel, J.; Klein, R.J.T. Integrating Knowledge for Assessing Coastal Vulnerability to Climate Change. In *Managing Coastal Vulnerability: An Integral Approach*; McFadden, L., Nicholls, R.J., Penning-Rowsell, E.C., Eds.; Emerald Group Publishing, Ltd.: Bingley, UK, 2008; pp. 1–20.
51. Hinkel, J.; Nicholls, R.J.; Vafeidis, A.T.; Tol, R.S.J.; Avagianou, T. Assessing risk of and adaptation to sea-level rise in the European Union: An application of DIVA. *Mitig. Adapt. Strateg. Glob. Chang.* **2010**, *15*, 703–719. [\[CrossRef\]](#)
52. Zêzere, J.L. *Movimentos de Vertente e Perigosidade Geomorfológica na Região a Norte de Lisboa*; Faculdade de Letras da Universidade de Lisboa: Lisbon, Portugal, 1997.
53. Bankoff, G. Vulnerability as a Measure of Change in Society. *Int. J. Mass Emerg. Disasters* **2003**, *21*, 5–30.
54. Birkmann, J. Risk and vulnerability indicators at different scales: Applicability, usefulness and policy implications. *Environ. Hazards* **2007**, *7*, 20–31. [\[CrossRef\]](#)
55. Shepard, C.C.; Agostini, V.N.; Gilmer, B.; Allen, T.; Stone, J.; Brooks, W.; Beck, M.W. Assessing future risk: Quantifying the effects of sea level rise on storm surge risk for the southern shores of Long Island, New York. *Nat. Hazards* **2012**, *60*, 727–745. [\[CrossRef\]](#)
56. UN/ISDR. *Living with Risk: A Global Review of Disaster Reduction Initiatives*, 1st ed.; United Nations: Geneva, Switzerland, 2004; ISBN 92-1-101050-0.
57. UN/ISDR. *2009 UNISDR Terminology on Disaster Risk Reduction*; International Strategy for Disaster Reduction: Geneva, Switzerland, 2009.
58. Julião, R.; Nery, F.; Ribeiro, J.; Branco, M.; Zêzere, J. *Guia Metodológico Para a Produção de Cartografia Municipal de Risco e Para a Criação de Sistemas de Informação Geográfica (SIG) de Base Municipal*; Autoridade Nacional de Proteção Civil, Ed.; ANPC: Carnaxide, Portugal, 2009; ISBN 978-989-96121-4-3.
59. UNDP. *Reducing Disaster Risk: A Challenge for Development—a Global Report*; United Nations Development Programme—Bureau for Crisis Prevention and Recovery: New York, NY, USA, 2004; ISBN 9211261600.
60. Ni, H.; Chen, A.; Chen, N. Some extensions on risk matrix approach. *Saf. Sci.* **2010**, *48*, 1269–1278. [\[CrossRef\]](#)
61. Carter, D.A.; Hirst, I.L.; Maddison, T.E.; Porter, S.R. Appropriate risk assessment methods for major accident establishments. *Process. Saf. Environ. Prot. Trans. Inst. Chem. Eng. Part. B* **2003**, *81*, 12–18. [\[CrossRef\]](#)
62. WMO. *Comprehensive Risk Assessment for Natural Hazards*; World Meteorological Organization—Hydrology and Water Resources Department: Geneva, Switzerland, 2006.
63. Santos, C.J.; Andriolo, U.; Ferreira, J.C. Shoreline response to a sandy nourishment in a wave-dominated coast using video monitoring. *Water* **2020**, *12*, 1632. [\[CrossRef\]](#)
64. Saaty, T.L. How to make a decision: The analytic hierarchy process. *Eur. J. Oper. Res.* **1990**, *48*, 9–26. [\[CrossRef\]](#)
65. Stockdon, H.F.; Holman, R.A.; Howd, P.A.; Sallenger, A.H. Empirical parameterization of setup, swash, and runup. *Coast. Eng.* **2006**, *53*, 573–588. [\[CrossRef\]](#)
66. Mani Murali, R.; Ankita, M.; Amrita, S.; Vethamony, P. Coastal vulnerability assessment of Puducherry coast, India, using the analytical hierarchical process. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 3291–3311. [\[CrossRef\]](#)
67. Mihoubi, M.K.; Belkessa, R.; Latreche, M.A. Study of the Vulnerability of Coastal Areas of the Algerian Basin with the GIS. *Int. J. Environ. Sci. Dev.* **2014**, *5*, 522–526. [\[CrossRef\]](#)

- 
68. Yin, J.; Yin, Z.; Wang, J.; Xu, S. National assessment of coastal vulnerability to sea-level rise for the Chinese coast. *J. Coast. Conserv.* **2012**, *16*, 123–133. [[CrossRef](#)]
  69. Bruno, M.F.; Saponieri, A.; Molfetta, M.G.; Damiani, L. The DPSIR approach for coastal risk assessment under climate change at regional scale: The case of apulian coast (Italy). *J. Mar. Sci. Eng.* **2020**, *8*, 531. [[CrossRef](#)]
  70. Cardona, F.S.; Ferreira, J.C.; Lopes, A.M. Cost and Benefit Analysis of Climate Change Adaptation Strategies in Coastal Areas at Risk. *J. Coast. Res.* **2020**, *95*, 764–768. [[CrossRef](#)]