Universidade de Aveiro Departamento de Engenharia Civil
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PEDRO MIGUEL FRAGOSO NARRA

CERA: ANÁLISE DE RISCO À EROSÃO COSTEIRA BASEADA EM SISTEMAS DE INFORMAÇÃO GEOGRÁFICA

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Civil, realizada sob a orientação científica do Doutor Carlos Daniel Borges Coelho, Professor Auxiliar do Departamento de Engenharia Civil da Universidade de Aveiro, e coorientação científica do Doutor Francisco Eduardo da Ponte Sancho, Investigador Auxiliar do Departamento de Hidráulica e Ambiente do Laboratório Nacional de Engenharia Civil.

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Dedico este trabalho aos meus pais, irmão e namorada.
Obrigado por tudo.

o júri

presidente

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agradecimentos

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palavras-chave suscetibilidade, vulnerabilidade, exposição, perigo, Aveiro, Macaneta, Quintana Roo

resumo

As zonas costeiras são locais de grande importância para o desenvolvimento humano, proporcionando inúmeros benefícios económicos e sociais. Por outro lado, estas zonas estão sujeitas a vários perigos naturais. Portanto, a identificação de zonas de perigo é essencial para uma gestão costeira apropriada e consequente mitigação de potenciais danos.

Ao longo dos anos, várias metodologias de risco costeiro foram desenvolvidas com o intuito de apoiar gestores das zonas costeiras no processo de decisão. Estas metodologias variam no tipo de perigo em análise, no conceito e produto final determinado, na extensão de linha de costa a que podem ser aplicadas e na escala temporal em análise. Este trabalho procura contribuir para o progresso das metodologias de risco costeiro com o desenvolvimento do CERA (*Coastal Erosion Risk Assessment*). O CERA foi desenvolvido com o intuito de analisar o risco à erosão costeira a médio prazo (10 a 20 anos). A metodologia deve ser aplicável a uma grande variedade de ambientes costeiros e escalas, com uma considerável assertividade e eficiência. O principal público alvo para a utilização do método são instituições governamentais de países ou regiões onde exista fraca informação e resultados de gestão costeira. Para a conceção do CERA, foi feita uma extensa revisão de literatura, identificando metodologias de risco costeiro existentes. Esta tarefa proporcionou um melhor conhecimento relativo à aplicação das metodologias, identificação de indicadores mais comuns, bem como as escalas temporais e espaciais mais usadas. Das metodologias identificadas e estudadas, cinco foram aplicadas aos locais de estudo definidos para este trabalho: Aveiro (Portugal), Macaneta (Moçambique) e Quintana Roo (México).

Os métodos aplicados (CERA1.0; CVI; Smartline; RISC-KIT CRAF1; e CHW) variam em termos de objetivo específico dentro da temática de risco costeiro, indicadores considerados, procedimentos e resultados. Consequentemente, os resultados dos vários métodos não são concordantes no nível de perigo atribuído a cada local. No entanto, os locais de maior perigo dentro de cada área de estudo são similares.

A aplicação destes métodos permitiu o desenvolvimento de uma série de diretrizes a serem seguidas durante o desenvolvimento da nova proposta.

A nova metodologia (CERA2.0) segue o modelo conceptual *Source-Parthway-Receptor-Consequence*, avaliando a propagação de risco em quatro módulos: suscetibilidade, valor, exposição e erosão costeira. Posteriormente, estes módulos são combinados de forma a obter resultados de vulnerabilidade, consequência e risco. A utilização do CERA2.0 requer um total de 12 indicadores. Para uma fácil aplicação da metodologia, foi desenvolvido um *plugin* no programa QGIS. Introduzindo os dados necessários, o *plugin* executa todos os processos previstos no CERA2.0 e providencia os resultados georreferenciados. O novo método foi igualmente aplicado aos casos de estudo, obtendo-se um conjunto de resultados mais realistas.

keywords susceptibility, vulnerability, exposure, hazard, Aveiro, Macaneta, Quintana Roo

abstract

Coastal areas are important in human development, providing numerous economic and social benefits. On the other hand, these areas are affected by several natural hazards. Therefore, the identification of endangered areas is essential to a thoughtful coastal management and to mitigate potential damages.

Through the years, several methodologies of coastal risk assessment have been developed to support coastal managers in decision making. These methodologies assess areas for various types of coastal hazards, for variable extents and time scales, and return different final products often based on different conceptions. This work intends to contribute for further progress of coastal risk assessment methodologies with the development of CERA (Coastal Erosion Risk Assessment). CERA is a methodology developed to evaluate coastal erosion risk for a medium-term horizon (10 to 20 years). The methodology should be applicable in a wide range of coastal environments and scales, with considerable accuracy and efficiency. This method mainly targets governmental institutions from countries and regions where there is a lack of data and results of coastal management.

For the development of CERA, an extensive literature review of existent coastal risk methodologies was performed. This task allowed to gain knowledge on how to apply the methodologies and to identify most common indicators, and adopted spatial scales and time frames. From the analysed methods, five were applied to the selected study sites within this work: Aveiro (Portugal), Macaneta spit (Mozambique) and Quintana Roo (Mexico).

The applied methods (CERA1.0; CVI; Smartline; RISC-KIT CRAF1; and CHW) varied in terms of specific objective within coastal risk assessment, indicators considered, procedure and outputs. Consequently, the results of various methodologies disagree on the hazard level attributed for the study areas. However, they generally agree in the identification of most endangered locations of each study area. The application of these methods provided specific takeaways to be followed in the development of the new proposal.

The new methodology (CERA2.0) follows closely the Source-Parthway-Receptor-Consequence model by evaluating risk propagation in four modules: susceptibility, value; exposure; and coastal erosion. Subsequently, these are combined to generate vulnerability, consequence and risk results. A total of 12 indicators are included. For easier application of the methodology, a QGIS plugin was developed. Given the required inputs, the plugin computes all CERA2.0 procedures and provides the results in a georeferenced format. The new procedure was also applied to the three case studies, obtaining a more realistic set of results.

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ACRONYMS

APA	Agência Portuguesa do Ambiente
APFyF	*Áreas de Protección de Flora y Fauna*
ASMITA	Aggregated Scale Morphological Interaction between Tidal inlets and the Adjacent coast
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASV	Approximated Social Value
AVVA	Aerial Videotape-Assisted Vulnerability Analysis
CAOP	*Carta Administrativa Oficial de Portugal*
CERA	Coastal Erosion Risk Assessment
CF	Critical Facilities
CHW	Coastal Hazard Wheel
CI	Coastal Index
CIESIN	Center for International Earth Science Information Network
CLC	Corine Land Cover
CLIMBER	CLIMate and BiosphERe Model
CLMS	Copernicus Land Monitoring Service
CM	IPCC Common Methodology
CMCC	Euro Mediterranean Centre for Climate Change
COMASO	Coastal Management Solutions
CONANP	*Comisión Nacional de Áreas Naturales Protegidas*
CRAF	Coastal Risk Assessment Framework
CRAF1	Coastal Risk Assessment Framework phase 1
CRS	Coordinate Reference System
CSD	Collateral Social Damages
CVI	Coastal Vulnerability Index
CVRA	Coastal Vulnerability and Risk Assessment
CZMS	Coastal Zone Management Sub-group

DEM	Digital Elevation Model
DESYCO	Decision Support System for Coastal Climate Change Impact
DGT	*Direção Geral do Território*
DHI	Danish Hydraulic Institute
DIVA	Dynamic and Interactive Vulnerability Assessment
DRR	Disaster Risk Reduction
DSAS	Digital Shoreline Analysis System
DSGCIG	*Direção de Serviços de Geodesia, Cartografia e Informação Geográfica*
DSS	Decision Support System
EC	European Commission
EEA	European Environmental Agency
ESRI	Environmental Systems Research Institute
EU	European Union
EVI	Environmental Vulnerability Index
EWS	Early Warning System
GDP	Gross Domestic Product
GHS	Global Human Settlement
GIS	Geographic Information System
GPW	Gridded Population of the World
GRASS	Geographic Resources Analysis Support System
GUI	Graphical User Interface
ICNF	*Instituto da Conservação da Natureza e das Florestas*
ICZM	Integrated Coastal Zone Management
IH	*Instituto Hidrográfico*
INE	*Instituto Nacional de Estatística*
INEGI	*Instituto Nacional de Estadística y Geografía*
IPCC	Intergovernmental Panel on Climate Change
ISDR	International Strategy for Disaster Reduction

ISO	International Organization for Standardization
LiDAR	Light Detection and Ranging
LTC	Long-Term Configuration
MAMAOT	*Ministério da Agricultura, do Mar, do Ambiente e do Ordenamento do Território*
MARN	*Ministério do Ambiente e Recursos Naturais*
MCA	Multi-Criteria Assessment
MCDA	Multi-Criteria Decision Analysis
METI	Japan's Ministry of Economy, Trade and Industry
N2K	Natura 2000 Network
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
OSM	OpenStreet Maps
PI	Potential Impact
PN	*Parques Nacionales*
RB	*Reservas de la Biosfera*
RISC-KIT	Resilience-Increasing Strategies for Coasts - toolKIT
RNAP	*Rede Nacional de Áreas Protegidas*
RRA	Regional Risk Assessment
SC	SimCLIM
SIC	*Sítios de Interesse Comunitário*
SIPA	*Sistema de Informação para o Património Arquitetónico*
SL	Smartline
SLR	Sea-level Rise
SNIG	*Sistema Nacional de Informação Geográfica*
SPRC	Source-Pathway-Receptor-Consequence
SRES	Special Report on Emission Scenarios
SWAN	Simulating Waves Nearshore
TCS	Tyndall Coastal Simulator

UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USACE	U.S. Army Corps of Engineers
USAF	United States Air Force
XD-COAST	Xpress Design of Coastal Structures
ZPE	*Zonas de Proteção Especial*

1. INTRODUCTION

Coastal areas have always been important in human development, providing numerous economic and social benefits. Consequently, a great number of urban settlements are found along the coast. Over the years, the number of people living in coastal areas has grown rapidly, leading to an increase in the number and sophistication of infrastructures and a rise in the socio-economic value of these areas. For instance, 10% of the world´s population live in coastal areas that are less than 10 m above sea-level (McGranahan *et al.*, 2007).

One the other hand, many of these coastal zones are exposed to numerous natural hazards. Natural hazards are physical phenomena that expose the coastal zone to risk of property damage, loss of life or environmental degradation (Gornitz, 2005). These can be high intensity, short-term events, such as hurricanes or cyclones that lead to floods and overtopping, or long-term events that act continuously, such as coastal erosion or sea-level rise. This work is mainly focused on coastal erosion (Figure 1.1). The lack of sediment sources, sea-level rise, sand mining, increasing human occupation in littoral zones, the construction of artificial barriers that reduce or capture the natural sediment fluxes (littoral drift) and the destruction of natural defence lines (beaches and dunes) are some of the underlying reasons for coastal erosion (Mangor *et al.*, 2017).

The high urban occupation in coastal areas associated with the presence of natural hazards creates the necessity for implementation of adequate coastal management plans. These are not only recommended to assess coastal risk for urban areas near the coastline, where there has been great investment and where the population density is high, but also to prevent the expansion of urban and touristic developments to exposed areas.

From the IPCC Common Methodology (IPCC CZMS, 1992) to the RISC-KIT project (van Dongeren *et al.*, 2018), several coastal hazard assessment methodologies and tools have been developed over the years to support coastal managers in their work

(Leatherman *et al.*, 1995; Thieler and Hammar-Klose, 1999; Coelho and Arede, 2009; Hinkel and Klein, 2009; Warrick, 2009; Torresan *et al.*, 2010; Mokrech *et al.*, 2011; Lins-de-Barros and Muehe, 2013; Zanuttigh *et al.*, 2014; Appelquist *et al.*, 2016; Christie *et al.*, 2018). These tools assess coastal areas for various types of coastal hazards and/or multi-hazards, such as flooding, overtopping and coastal erosion, aiming to estimate the associated impact, vulnerability and/or risk. The outputs of these assessments help coastal managers and stakeholders in decision making, planning and, ultimately, safeguarding structures and human lives.

Figure 1.1. Example of coastal erosion hazard (Esmoriz – Furadouro, Portugal).

Despite all efforts in the scientific community, gaps regarding coastal assessments still exist and should be addressed. Most methodologies developed in the last two decades are focused on coastal risk due to climate change events. The increased probability of extreme events due to climate change (Stocker *et al.*, 2013), such as storms and hurricanes, pose a serious problem for coastal living societies, given the potentially devastating consequences that they have. However, the focus on these highly threatening events made the assessment of other hazards, such as coastal erosion, less of a priority. Consequently, this hazard is often included as an additional module in multi-hazard assessments, lacking dedicated methodologies to coastal erosion assessment. Some methodologies consider specifically coastal erosion, but in the context of short-term storm related coastal erosion, not considering its medium to long-term effects.

Furthermore, the most recent methodologies frequently rely on simulation and modelling. Although considered very important in risk assessments and research in general, modelling is accompanied by a series of setbacks. Generally, these models are data demanding and resource intensive (Zanuttigh *et al.*, 2014; CLIMsystems, 2018), which reduces the possibility to be applicable in underdeveloped areas, with less institutional capacity. Also, given the complexity of the process, they are not applicable to large scale assessments, since they usually are applied to dozens of kilometres (Mangor *et al.*, 2017).

Finally, most coastal risk assessment methodologies/tools provide limited accessibility to the general user. They are recurrently unavailable to the public, only offer a demo with limited functionalities, require the payment of fees for their application or require adjacent programs (Iyalomhe *et al.*, 2013). Again, this type of approach is not compatible with underdeveloped locations, not promoting a thoughtful coastal management when these eventually expand.

1.1. OBJECTIVES

With the previous shortcomings in mind, the work developed in this thesis intends to address them with the development of a new methodology dedicated to coastal erosion risk assessment. The new methodology, called CERA (Coastal Erosion Risk Assessment), was developed with the objective to assess coastal erosion risk for a medium-term horizon (10 to 20 years). The methodology should be applicable in a wide range of coastal environments, although this work's development focused mainly on sandy coastal zones, where erosion is more prominent. The methodology should also be applicable at several spatial scales (from local to national) with a considerable accuracy and efficiency. The methodology is intended to be mainly targeted to developing countries or to respond to requests from governmental and regional institutions, which often require large scale assessments in short time spans to be included in coastal management plans. Hence, the methodology should have a low cost of application and do not require large amounts of data and human resources to be applicable. Complex numerical modelling is to be avoided, as it is not compatible with the aforementioned objectives.

To achieve the main goal, several secondary objectives were defined. These objectives have worked as milestones for CERA development, or improvements of knowledge on relevant subjects. The secondary objectives are the following:

- Identification and characterization of existent methodologies and tools to evaluate coastal hazards, in general, and coastal erosion risk, in particular, including appraisal of most common indicators, procedures, time spans and scales adopted for the analysis;
- Definition and clarification of risk and related concepts (*e.g.* vulnerability, hazard, exposure, etc.) to be considered in the context of the CERA methodology;
- Research, selection and characterization of study areas for application, and test of coastal hazard assessment methodologies;
- Selection and application of methodologies considered relevant for CERA methodology development to the study areas. These methodologies should be selected based on having application of procedures that could be followed by CERA, have similar objectives, or include coastal erosion in the assessment;
- Application of Geographic Information Systems (GIS) technology to the selected methodologies;

- Development of a GIS-based application for CERA methodology. The application should take advantage of free and open-source software in order to be easily accessible by potential users;
- Development of CERA, a simple methodology to estimate coastal erosion risk. The most used, pertinent and accessible indicators identified in previous methodologies should be favoured and the technical knowledge required to apply this methodology should be reduced;
- Application of CERA to the selected study areas to test the performance of the new proposal.

1.2. STRUCTURE

The development process and achievement of objectives is described in detail throughout this document. The thesis is divided in 8 chapters that, for the most part, follow the order of works done during development. As already presented, this chapter frames the problematic of coastal hazards in general, and coastal erosion in particular, mentions the reasons behind the development of a new coastal erosion risk assessment, states the objectives of this thesis, and describes the structure of the document.

The second chapter presents a literature review regarding different types of coastal risk assessments. First, the definition of risk and related concepts is explored. A literature review is done, showing that these concepts are not always consensual or easy to understand. Next, a literature review of existent coastal risk assessment methodologies is presented. These vary considerably in its approach, data required and results. A characterization of 12 methods is done in more detail and a preliminary discussion regarding most commonly used data, and intended spatial scale and time frame is presented.

The third chapter focus on the presentation of the main characteristics of three selected study areas. The study areas are Aveiro (Portugal), Macaneta spit

(Mozambique) and Quintana Roo (Mexico). The characterization of Macaneta and Quintana Roo study areas counted with the support of local experts from Eduardo Mondlane University and National Autonomous University of Mexico, respectively. Moreover, the data considered for coastal risk assessments of each area is described.

The forth chapter presents a first iteration of CERA. CERA1.0 (Narra *et al.*, 2017) is based on the Coastal Vulnerability and Risk Assessment approach developed by Coelho (2005). The improvements relative to the original methodology are the integration with GIS technology, with the development of a dedicated plugin for QGIS (2018) and the revision and adjustment of several indicators, in order to make the methodology applicable to a wider range of locations. Additionally, CERA1.0 is applied to the study sites and its results are discussed, allowing a first insight on the performance of the method.

The fifth chapter expands the application of coastal assessment methodologies started in the previous chapter, with the application of four different methodologies to the study sites. The methodologies are the Coastal Vulnerability Index (Thieler and Hammar-Klose, 1999), Smartline (Lins-de-Barros and Muehe, 2013), RISC-KIT Coastal Risk Assessment Framework phase 1 (Viavattene *et al.*, 2018) and the Coastal Hazard Wheel (Appelquist and Halsnæs, 2015). Considering the specific characteristics of the methods and study sites, 9 different coastal assessments were performed. Following the application and results of each method, a discussion of results and procedures takes place. From that, important takeaways for the new proposal are outlined.

The sixth chapter is where the final proposal for CERA is presented and detailed. CERA2.0 is based on the risk related concepts detailed in chapter 2, and on ideas and accumulated experience from the application of other methodologies. Each indicator is described in detail, as well as recommendations on where to get the necessary information. The chapter ends with sensitivity analysis of the results, obtained by applying Monte Carlo simulations to the combination and classification of indicators in the new proposal.

The seventh chapter tests CERA2.0 by applying it to the study sites featured in this work. The results are then discussed, including comparisons with results from the sensitivity analysis, previous methodologies and existent literature about the study areas. Additionally, CERA2.0 procedure is compared with the other methods, and the takeaways concluded in chapter 5 are addressed.

Finally, the eighth chapter presents a brief summary of contents, accompanied by the main conclusions. Additionally, possible future developments to continue CERA are outlined.

2. Coastal risk assessment review

In practice of coastal management, the definition of risk and related concepts often appears as a source of discussion. Regardless of the subject or science, a universal and clear vision of risk definition, principles and fundamental concepts does not exist (Andretta, 2014). Therefore, the following section describes risk definitions and related concepts adopted by this work. Moreover, this chapter overviews most notable coastal flooding/erosion risk assessments methods available in literature, seeking to identify different approaches, used indicators, application scale and targeted time frame regarding each method.

2.1. Risk and related concepts in coastal management

Depending on the science and context that is studying risk, the interpretation process of this concept takes numerous outcomes. The perspective of risk terminology has been evolving along the years (Aven, 2012), mainly revolving around concepts of probability, uncertainty and expected consequences. The most core and widely accepted definition of risk is to be understood as the expected consequences associated with a given event (Faber, 2012). On the other hand, the ISO31000:2009 (ISO, 2009) defines risk as the effect of uncertainty on objectives. This publication also states that risk is often characterized by reference to potential events or consequences, or a combination of both. The United Nations supports this definition by stating that risk is a combination of the probability of an event and its negative consequences (ISDR, 2009). Smith and Petley (2008) state that risk is the actual exposure of something of human value to a hazard, but they also state that is often measured as the product of probability and loss.

In risk management, concepts of coastal vulnerability, exposure, susceptibility, among others, join the intricacy of risk definitions, leading to difficulties and variations in their understanding and relation to each other's. Vulnerability is defined by the United Nations as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (ISDR, 2009). Moreover, Sarewitz *et al.* (2003) describes vulnerability as inherent characteristics of a system that create the potential for harm, but are independent of the probabilistic risk of occurrence. Samuels and Gouldby (2009) define vulnerability as a characteristic of a system that describes its potential to be harmed. However, the term vulnerability is often used in a broader sense depending on the subject. Füssel (2007) identifies four categories of vulnerability by dividing it in socioeconomic and biophysical domain, and internal and external sphere. The inclusion of external factors and division between social and physical vulnerability is noticeable in some assessment methodologies in the following section.

The remaining concepts are more consensual in their meaning. ISDR (2009) defines hazard as a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. Exposure is defined by Samuels and Gouldby (2009) as the quantification of the receptors that may be influenced by a hazard, while the ISDR (2009) considers it as the people, property, systems or other elements present in hazard zones that are thereby subject to potential losses.

To define the terminology considered in this work and to understand connections between risk definition and related concepts, the Source – Pathway – Receptors – Consequence (SPRC) model (Samuels and Gouldby, 2009) was adapted from coastal flooding to coastal erosion. This model is used to link various components of a system, helping in the identification of how risk propagates. Therefore, for risk to arise, it must exist a source that triggers the hazard, a pathway that the hazard takes until reaches the receptor, which may be harmed by it, culminating in the consequence provoked by the hazard.

Using the SPRC model, each part of the model corresponds to a component of risk estimation (Narayan *et al.*, 2014). Therefore, an assessment on source conditions should be done to evaluate the hazard probability. A pathway assessment correlates to the degree of exposition and a study of the receptor is required to evaluate how susceptible they are to the hazard. The consequence will vary depending on the value present in the study area.

Considering the linkage between the SPRC model and risk related concepts, this work considers the following definitions:

- Hazard – a physical event, phenomenon or human activity with the potential to result in harm. A hazard does not necessarily lead to harm (Samuels and Gouldby, 2009);
- Exposure – Quantification of the receptors that may be influenced by a hazard (Samuels and Gouldby, 2009);
- Susceptibility – The propensity of the people, property or other receptors to experience harm (Samuels and Gouldby, 2009);
- Value – Monetary, social and/or environmental valorisation of the receptor;
- Vulnerability – The characteristics and circumstances of a receptor that make it susceptible to the damaging effects of a hazard (ISDR, 2009). This definition identifies vulnerability as an intrinsic characteristic of the receptor, which is independent of its exposure or hazard conditions. This can be considered as a combination of susceptibility and value;
- Consequence (or impact) – An impact such as economic, social or environmental damage. May be expressed quantitatively, by category or descriptively (Sayers *et al.*, 2003). Potential consequences are evaluated by combining elements of exposure and vulnerability;
- Risk – the combination of the probability of an event and its negative consequences (ISDR, 2009). Samuels and Gouldby (2009) deconstruct this definition by stating that risk is a function of probability, exposure and vulnerability. Therefore, this work considers that risk can be assessed by multiple combinations of concepts (Figure 2.1).

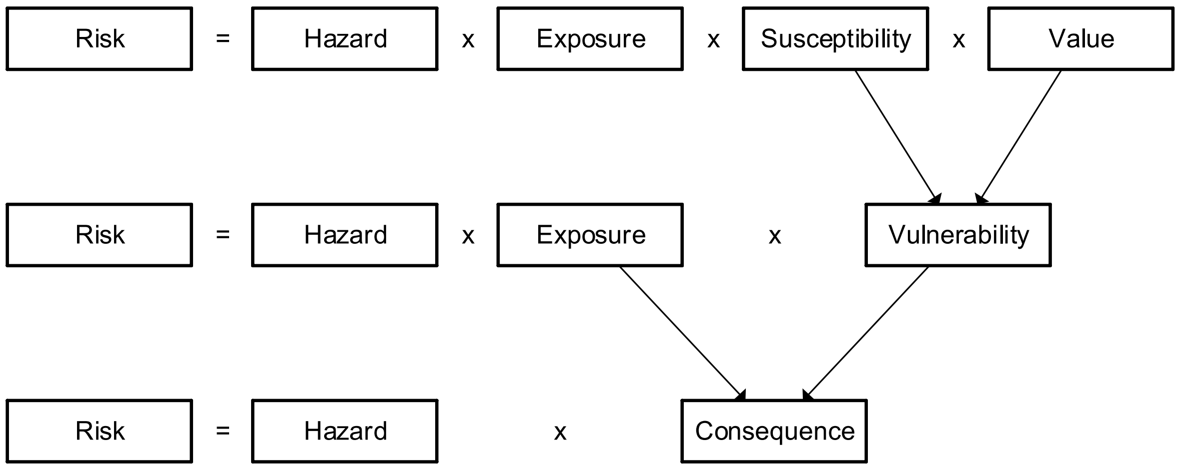

Figure 2.1. Diagram of interconnection between concepts.

Considering the risk terminology and the SPRC model presented above, the adaptation of these concepts to coastal erosion risk is proposed. The components of the SPRC model for coastal erosion (Figure 2.2) are:

- Source – sea action (*i.e.* waves, currents, storms, sea-level rise): the wave climate conditions that are capable of inducing erosion. An increase in the intensity of these erosive agents can represent higher shoreline retreat rates. Also, the lack of sedimentary sources can induce shoreline erosion;
- Pathway – distance from the area in study to the shoreline: the shoreline is where the coastal erosion actuates. Thus, the distance from the shoreline to the territory under assessment is the pathway that coastal erosion must pass to be able to affect that area;
- Receptors – territory and people: considering erosion as the hazard, any part of land can be the receptor that can potentially be lost. The study area is defined by the user performing the assessment;
- Consequence – loss of territory: the propagation of coastal erosion eventually leads to the consequence for the study area, which is the disappearance of that area. The consequences of losing the territory vary depending on the type of receptor that is contained in it (*e.g.* urban centres, rural areas, critical infrastructures).

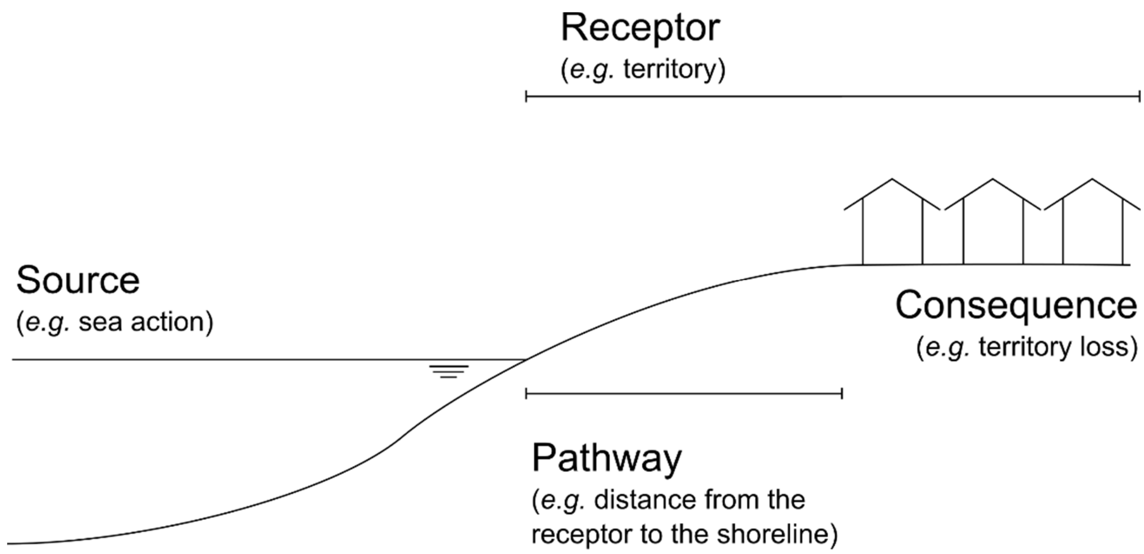

Figure 2.2. 1-dimention SPRC model for coastal erosion.

Therefore, this work considers the understanding of risk related concepts in context of coastal erosion as the following:

- Hazard – intensity and/or likelihood of coastal erosion and/or driving sources of coastal erosion (waves, sea-level rise, extreme events);
- Exposure – quantification of the receptors that are within range of potential land loss. The exposure assessment can be executed into levels of exposure, classifying receptors from highly exposed to low exposition;
- Susceptibility – intrinsic characteristics of the land that makes it predisposed to be eroded by action of wave climate. The susceptibility is independent of the wave conditions at the study area;
- Value – valorisation of the territory, depending on economic, social and/or environmental factors;
- Vulnerability – the amount of potential damage caused by coastal erosion. Therefore, vulnerability is dependent of the soil predisposition to erode (susceptibility) and the value attributed to that same area. Vulnerability is independent of coastal erosion conditions and exposure level affecting the study area;

- Consequences – potential harm if coastal erosion affects the study area. Here, exposure and vulnerability are combined (Figure 2.1). Contrary to vulnerability, which is independent of exposure, the consequences include exposure to estimate the amount of area that is going to be affected by coastal erosion;
- Risk – a combination between the potential damage that erosion can cause and the likelihood/intensity that coastal erosion affects the study area.

2.2. Coastal risk assessment methods

In this section, a review of coastal assessment methodologies that have been proposed is presented. As mentioned in the last section, the definition of risk related concepts varies depending on the methodology. Thus, describing each methodology, this thesis respects the nomenclature given by the original authors, while provides a connection with definitions considered in the previous section.

The oldest coastal assessment methodology found in the literature was presented in 1991 (IPCC CZMS, 1992) by the Intergovernmental Panel on Climate Change (IPCC). Since then several methodologies were developed, mainly focused on sea-level rise (SLR) and its consequences for coastal zones around the world.

In the last decade, in addition to the more traditional methodologies to evaluate coastal risk, several GIS-based (Geographic Information System) coastal risk assessment tools were developed, mainly to evaluate the impacts of sea-level rise in coastal areas. These GIS-based applications are commonly known as Decision Support Systems (DSS) and aim to help coastal managers in the process of decision making, based on the outputs of the applications.

A total of 12 methodologies are thoroughly explained in the following sections. These were mainly chosen based on the widespread availability of detailed literature. Also, the presence of coastal erosion processes in the methodologies contributed for their inclusion.

2.2.1. IPCC Common Methodology

In 1992, the IPCC published the latest version of a Common Methodology for assessing the vulnerability of coastal areas to sea-level rise (IPCC CZMS, 1992). The IPCC Common Methodology (CM) defined vulnerability as the degree of capability to cope with the consequences of climate change and accelerated sea-level rise (IPCC, 2001). The methodology was drafted to assist countries in making first-order assessments of potential coastal impacts of sea-level rise and adaptation measures that should be taken into consideration (Klein and Nicholls, 1999). The methodology is applicable at a global, national, regional or local scale.

The IPCC Common Methodology refers the completion of 7 consecutive analytical steps:

- Delineate the case study area;
- Evaluate study area characteristics;
- Identify the relevant socioeconomic development factors;
- Assess the physical changes;
- Formulate response strategies;
- Assess the vulnerability profile;
- Identify future needs.

The result of this methodology is a vulnerability profile report, including impacts of sea-level rise, such as land loss, and the associated value of this land. The report should also include a list of future policy measures. The methodology does not explicitly state how to perform the analysis. Thus, the user needs to have considerable knowledge on a range of techniques for estimating biophysical and socioeconomic impacts of sea-level rise (UNFCCC, 2008).

Despite its generic nature, this methodology was widely applied around the world, contributing to the understanding of the consequences of sea-level rise and encouraged long term thinking about coastal zones (UNFCCC, 2008).

2.2.2. Aerial Videotape-Assisted Vulnerability Analysis

The Aerial Videotape-Assisted Vulnerability Analysis (AVVA) was created in 1992 (Leatherman *et al.*, 1995), responding to the necessity of a new and cost-effective methodology to assess coastal vulnerability to sea-level rise. Most existent topography maps only had 10 to 100 m contour intervals, insufficient for a quality assessment of the impacts of a sea-level rise scenario and digital elevation data or satellite imagery was expensive and not available on many developing countries. Therefore, videotaping the coastline at a low altitude captures the relative aspect (compass direction that the slope is facing) of the land to the sea, coastal geomorphology, coastal land use, building density, etc., becoming a viable alternative, considering the lack of topographic data and the large length of the coastline to be assessed (Leatherman *et al.*, 1995). AVVA provided the ability to survey considerable stretches of the coastline with limited budget, while also provided a historical record that can be used to monitor future changes in geomorphology or land use, especially in developing countries, where such data rarely exists.

The AVVA approach involves a combination of unrectified oblique aerial video-recording of the coastline, limited ground-truth information, archival exploration and analysis of these data in conjunction with simple land loss and response models. To apply the analysis, Leatherman *et al.* (1995) proposed a set of guidelines composed by 6 steps, which were developed based on the first comprehensive study in Senegal, in 1990, and had been revised with posterior projects in Nigeria, Argentina, Uruguay and Venezuela. The steps are: (a) pre-trip preparation; (b) videotape data acquisition; (c) videotape data review; (d) ground-truth data acquisition; (e) socio-economic data collection; and (f) detailed analysis.

In the last step, the data collected is used to estimate sea-level rise and possible consequences of that hazard, considering the approaches described by Nicholls *et al.* (1995), which can be summarized by the following steps:

- On coasts subject to erosion, the Bruun Rule (Bruun, 1988) is used to estimate land loss;
- On low-lying coasts, including coastal wetlands, is used a combination of existing maps with spot heights, ground-truthing, videotape and expert judgement, as appropriate, to estimate likely inundation;
- Estimate present market value of land and buildings that would be lost;
- Estimate the implications of the response options in terms of land loss prevented, market value of land and buildings saved and response costs. Other values, such as coastal ecosystems can be qualitatively assessed.

Although Leatherman *et al.* (1995) stated that additional alternatives could be developed, in the studies previously mentioned, three response options were considered:

- No Protection – assume that there is no protection;
- Important Areas Protection – assume that all important areas will be fully protected;
- Total Protection – assume that areas along the coast with population superior to 10 person/km^2 will be protected.

The AVVA approach was considered a quick, useful and cost-effective tool for assessing sea-level rise impacts in developing countries. Leatherman *et al.* (1995) mention similarities between AVVA and the Common Methodology (IPCC CZMS, 1992). Moreover, AVVA can be a method to obtain data for analysis using the Common Methodology.

2.2.3. Coastal Vulnerability Index

The Coastal Vulnerability Index (CVI) was introduced by Thieler and Hammar-Klose (1999). The method was based on work by Gornitz (1991) and uses the sensitivity index employed by Shaw *et al.* (1998). The CVI shows the relative vulnerability of the coast to changes due to sea-level rise.

To compute the CVI, six indicators related to the physical characteristics of coastal areas and the coastal waters/dynamics are evaluated on a scale from 1 to 5 (Table 2.1). These indicators were considered to assess the Atlantic coast of the USA (Thieler and Hammar-Klose, 1999), the Pacific coast of the USA (Thieler and Hammar-Klose, 2000a) and the Gulf of Mexico (Thieler and Hammar-Klose, 2000b). However, the criteria used to evaluate some indicators suffers a slight variation depending on the purpose of the assessment: the indicators related to coastal slope, relative sea-level change and mean wave height.

Table 2.1. Ranking of coastal vulnerability index variables for U.S. Atlantic Coast (Thieler and Hammar-Klose, 1999).

Variable	Very low 1	Low 2	Moderated 3	High 4	Very high 5
Geomorphology	Rocky cliffed coasts Fjords	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	> 0.2	0.2 – 0.07	0.07 – 0.04	0.04 – 0.025	< 0.025
Relative sea-level change (mm/year)	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	> 3.16
Shoreline erosion/accretion (m/year)	> 2.0	1.0 – 2.0	-1.0 – 1.0	-1.0 – -2.0	< -2.0
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	< 1.0
Mean wave height (m)	< 0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	> 1.25

The CVI does not contain socio-economic indicators in its vulnerability assessment. On the other hand, hazard related indicators, such as sea-level rise, tidal range and wave height are included. For this reason, this work considers the CVI definition of vulnerability more in line with the hazard definition given in section 2.1.

After every individual indicator evaluation, Thieler and Hammar-Klose (1999) compute the vulnerability score using the CVI formula (Eq. 2.1). Each letter represents one different variable (a: geomorphology; b: coastal slope; c: relative sea-level rise rate; d: shoreline erosion/accretion rate; e: mean tide range; f: mean wave height). Next, the CVI scores are split into 4 categories, based on quartile ranges of the dataset obtained.

$$\mathrm{CVI} = \sqrt{\frac{a.\,b.\,c.\,d.\,e.\,f}{6}} \tag{2.1}$$

This classification along the shoreline identifies hotspots with higher relative vulnerability on a given coastal stretch. Unfortunately, this classification does not allow comparison between the different assessments due to relative results and varying thresholds. All results of CVI applications give the study area roughly 25% for each class, regardless of whether the area is effectively threatened by coastal hazards or not. For the U.S. Atlantic Coast (Thieler and Hammar-Klose, 1999), 9472 km of shoreline were ranked using CVI. From this total, 27% of the shoreline was classified with very high vulnerability, 22% with high vulnerability, 23% with moderate and 28% with low vulnerability. Later, this methodology was also applied to Assateague Island, in United States (Pendleton *et al.*, 2004). This study area is much smaller than the one in the previous studies, with only about 60 km of shoreline. Also, other authors adapted the methodology to their own study areas, such as Abuodha and Woodroffe (2006) for Illawarra beaches, Australia, and Ojeda *et al.* (2009) for Andalusia coast.

2.2.4. Coastal Vulnerability and Risk Assessment

The Coastal Vulnerability and Risk Assessment (CVRA) methodology proposed by Coelho (2005) incorporates a total of 9 parameters that influence coastal erosion vulnerability: distance to shoreline (defined as the shortest linear distance from any land point to the shoreline), topography, geology, geomorphology, land cover, anthropogenic actions, maximum significant wave height (within a representative data period), maximum tidal range and average erosion/accretion rates (Table 2.2).

Table 2.2. Classification of vulnerability parameters (Coelho *et al.*, 2007).

Parameters	Very low 1	Low 2	Moderated 3	High 4	Very high 5
Distance to shoreline (m)	>1000	]200, 1000]	]50, 200]	]20, 50]	≤ 20
Topography (m)	> 30	]20, 30]	]10, 20]	]5, 10]	≤ 5
Geology	Magmatic rocks	Metamorphic rocks	Sedimentary rocks	Non-consolidated coarse sediments	Non-consolidated fine sediments
Geomorphology	Mountains	Rock cliffs	Erosive cliffs Sheltered beaches	Exposed beaches Coastal plains	Dunes River mouths Estuaries
Ground cover	Forest	Vegetation cultivated	Non-covered	Rural urbanized	Urbanized Industrial
Anthropogenic actions	Shoreline stabilization intervention	Intervention without sediment sources reduction	Intervention with sediment sources reduction	Without interventions or sediment sources reduction	Without interventions and with sediment sources reduction
Maximum significant wave height (m)	< 3.0	[3.0, 5.0[	[5.0, 6.0[	[6.0, 6.9[	≥ 6.9
Maximum tidal range (m)	< 1.0	[1.0, 2.0[	[2.0, 4.0[	[4.0, 6.0[	≥ 6.0
Average erosion / accretion rates (m/year)	> 0.0 Accretion	[0.0, -1.0[Erosion	[-1.0, -3.0[Erosion	[-3.0, -5.0[Erosion	≤ -5.0 Erosion

For each parameter, a classification from 1 to 5 is attributed based on different criteria, as presented in Table 2.2. The definition of thresholds in each classification parameter was presented by Coelho *et al.* (2007, 2009b) and Coelho and Arede (2009) based on previous literature, namely findings of Gornitz *et al.* (1997), and on questionnaires with experts on the subject. Later, each parameter was represented on a georeferenced map for the study area. Distance to shoreline, topography, geology, geomorphology and ground cover are classified at the entire defined study area (at every latitude/longitude point), while the other parameters are only classifiable along the shoreline, due to its characteristics. The classification of the later parameters is extrapolated to inland areas, attributing to these the same classification as that of the closest point at the shoreline (Narra *et al.*, 2015b).

The vulnerability at each point is computed by calculating the weighted average of the nine parameters according to the weights presented in Table 2.3. The quantification of each weight was defined by Coelho *et al.* (2007) and applied by Coelho and Arede (2009), Coelho *et al.* (2009b) and Pereira and Coelho (2013a). The weight proposed for each parameter results from testing 13 different combinations of weights, based on a multi-criteria analysis done with several coastal experts. The weight of each parameter changes with increasing distance to the shoreline. Topography, geology and distance to shoreline were chosen as the most influential factors (each accounting for approximately 21% of the total weight within the first 100 m of the coastal stripe), since they have a direct impact in the vulnerability of the study area. However, as the assessment is computed for points located in landward areas, the impact of the distance to shoreline parameter in the overall rating of vulnerability increases, peaking at 88% in the final classification for distances greater than 5 km, while all other parameters decrease its impact in the overall classification. The weighted average according to Table 2.3 results in a vulnerability map with values from 1 to 5 (decimal values are rounded to unity).

Table 2.3. Weight of each parameter in the global classification of vulnerability, depending on the distance to shoreline (Coelho *et al.*, 2009b).

Parameters	Distance to shoreline (m)		
	< 100	[100; 5000]	> 5000
Distance to shoreline (m)	0.214	$\frac{6}{28}+\frac{0.665(d-100)}{4900}$	0.879
Topography (m)	0.214	$\frac{6}{28}-\frac{0.665(d-100)}{4900}\frac{6}{22}$	0.033
Geology			
Geomorphology	0.071	$\frac{2}{28}-\frac{0.665(d-100)}{4900}\frac{2}{22}$	0.011
Ground cover			
Maximum significant wave height (m)			
Average erosion / accretion rates (m/year)			
Maximum tidal range (m)	0.036	$\frac{1}{28}-\frac{0.665(d-100)}{4900}\frac{1}{22}$	0.005
Anthropogenic actions			

The consequence assessment is performed in a similar way as the vulnerability assessment. Coelho (2005) selected 4 parameters to evaluate consequences: population density, economy, ecology and heritage (Table 2.4), which are also rated from 1 to 5. The criteria for the limits in the classification of consequence parameters were defined by Coelho (2005) and Coelho and Arede (2009) based on questionnaires and previous literature (*e.g.* Andrade *et al.*, 2002). To obtain the final map of consequences, the average of the 4 maps is computed. In this case, all parameters have the same weight. However, the final class of the consequence cannot be lower than the class attributed for the population density (Pereira and Coelho, 2013a), enhancing thus this parameter.

Table 2.4. Classification of consequence parameters (Coelho, 2005; Coelho and Arede, 2009).

Parameters	Very low 1	Low 2	Moderated 3	High 4	Very high 5
Population density (inhabitant/km^2)	< 500	[500, 1000[	[1000, 2000[	[2000, 4000[	≥4000
Economy (number of employments)	0	]0, 10]	]10, 30]	]30, 50]	> 50
Ecology	No ecological relevance	Agricultural national reserve	Ecological national reserve	Zones of ecological protection	Natural reserve
Historical Heritage	No heritage to preserve	There are some constructions not typical	Constructions and typical activities of a place	Historical regional constructions	Historical national monuments

To obtain the classification map of coastal erosion risk, the vulnerability and consequence maps are combined using the risk matrix presented in Table 2.5. Risk is defined in 5 different classes: "I" represents a very low risk and "V" represents very high risk. The risk matrix is symmetric, considering both vulnerability and consequence of equal importance.

Table 2.5. Risk matrix (Coelho, 2005).

		Consequence				
		I	II	III	IV	V
Vulnerability	I	I	I	I Very low	II	III
	II	I	I	II Low	III	IV
	III	I	II	III Moderate	IV	V
	IV	II	III	IV High	V	V
	V	III	IV	V Very high	V	V

2.2.5. SMARTLINE

The Smartline approach (SL) was firstly introduced by Sharples (2006) with the initial objective of creating a database of coastal geomorphology for the Tasmanian coastline, Australia. Later, the Smartline approach was refined and expanded for application to the entire coast of Australia. The aim was to create a national scale of coastal landforms with a consistent format and classification, using Geographic Information Systems, which would be used for coastal vulnerability assessment (Sharples *et al.*, 2009). The data is stored in a single georeferenced line that divides the coastline into segments according to characteristics such as backshore, intertidal and geology type. Sharples (2006) describes the vulnerability assessment as composed by three broadly-defined levels of detail and confidence.

The first level is an Indicative Assessment and aims to simply identify the shores whose basic geological and geomorphological characteristics, called by the author as *fundamental vulnerability factors*, make them potentially vulnerable to coastal hazards, regardless of the level of vulnerability of the locations.

The second level is a Regional Assessment and uses the available data regarding the characteristics of the coastal zone, such as wave climate, tidal range and geomorphological data to develop an initial ranking of differing degrees of vulnerability along large stretches of the coast. This level of assessment allows for a general overview of the vulnerability in a large stretch of the coastline. However, a regional assessment of this site is also subject to numerous exceptions resulting from site-specific geomorphologic variables that cannot be integrated into a regional-level assessment.

The third level is a Site-Specific Assessment, which identifies all relevant geological, geomorphologic, topographic, oceanographic and climatic factors influencing a local coastal system to assess coastal vulnerability at a local scale. These local assessments should integrate the Regional Assessment to increase or decrease the level of vulnerability based on this new information.

Sharples (2006) reinforces that these three levels should not be alternative methods of vulnerability assessment, but rather as three logical stages in an integrated vulnerability assessment.

To apply the described methodology, Sharples (2006) mapped the key elements for the vulnerability assessment of the coastline of Tasmania. The authors chose to represent the elements and results as a line along the coast rather than a polygon covering areas due to funding and time limitations. However, this format proved to have advantages in simplifying data analysis and querying procedures for purposes that require identifying coasts having any combination of geomorphologic attributes encoded in the GIS data. Moreover, the adaptation of a line map format allows the creation of a complete coastal map much faster than would have been possible through polygonal mapping.

Lins-de-Barros and Muehe (2013) adapted the Smartline approach to assess physical vulnerability (understood by the authors as hazard assessment) and social vulnerability, and combined them to assess risk to coastal hazards on a stretch of the coastline in Rio de Janeiro state, Brazil. The study area, part of the so-called Região dos Lagos, covers five municipalities and extends along almost 100 km of shoreline. These authors followed the three-step approach explained by Sharples (2006), and added a fourth step, by including social data, which allows coastal risk to be assessed.

Lins-de-Barros and Muehe (2013) considered indicative variables, such as coastal features, beach material and backshore and hinterland characteristics, for the first stage. Next, the regional assessment included wave climate, shore exposure and beach morphodynamics. Lastly, the site-specific assessment included dune and beach ridge height, bottom slope, wave refraction and areas under wave overwash.

The vulnerability assessment of each stage and their combination is explained by Lins-de-Barros (2010). Regarding coastal erosion, the assessment is performed by combining the indicators of two sub-indexes. The first sub-index evaluates erosion resistance capacity (Table 2.6) and combines the median grain size with the presence of dunes (Lins-de-Barros, 2010). The resulting classification divides the study area into 4 classes.

Table 2.6. Sub-index of resistance to erosion (Lins-de-Barros, 2010).

Grain size	Dune presence	Resistance to Erosion
Fine	no dunes	Very Low
Fine	dunes without vegetation	Low
Medium	no dunes or dunes without vegetation	Moderate
Medium	vegetated dunes	High
Coarse	dunes without vegetation or vegetated cliff	High

The second sub-index is called the potential magnitude of shoreline retreat. Table 2.7 shows a streamlined version of the sub-index criteria in Lins-de-Barros (2010). This sub-index includes coastal slope, backshore features and backshore topography to evaluate the potential shoreline retreat when a storm occurs, and has 5 levels of classification.

Table 2.7. Potential magnitude of shoreline retreat (adapted from Lins-de-Barros, 2010).

Slope (in degrees)	Backshore features	Backshore topography (m)	Retreat magnitude
---	coastal plain	---	Very High
< 0.25	others	≤ 4	Very High
< 0.25	others	> 4	High
[0.25; 1]	others	≤ 4	High
[0.25; 1]	others	> 4	Moderate
> 1	others	≤ 6	Moderate
> 1	others	> 6	Low
---	cliffs, mountain or seawalls	---	Very Low

Finally, the combination of the previous sub-indexes with the nearshore wave height and relative shoreline changes yields the final classification of vulnerability to coastal erosion (Table 2.8).

The method divides the shoreline into 6 classes of physical vulnerability classification (A to F), where A is the lowest vulnerability and F is the highest. These classes can be interpreted as: A – Stable shoreline with low vulnerability; B – Stable shoreline with moderate vulnerability; C – Stable shoreline with high vulnerability or retreating shoreline with low vulnerability; D – Retreating shoreline with moderate vulnerability; E – Retreating shoreline high vulnerability; F – Retreating shoreline with very high vulnerability.

Table 2.8. Vulnerability matrix for coastal erosion (adapted from Lins-de-Barros, 2010).

Potential Retreat Magnitude	Wave Exposure	Retreating shoreline Resistance to Erosion				Stable shoreline Resistance to Erosion			
		High	Mode.	Low	V. Low	High	Mode.	Low	V. Low
Very High	Very high	E	E	F	F	C	C	E	F
High		E	E	F	F	C	C	E	E
Moderate		D	E	E	F	B	C	C	E
Low		D	D	E	E	B	B	B	E
Very low		D	D	E	E	B	B	B	B
Very High	High	E	E	F	F	C	C	C	E
High		D	E	F	F	B	C	C	E
Moderate		D	D	D	F	B	B	B	E
Low		B	D	D	D	A	B	B	C
Very low		B	B	C	C	A	A	B	B
Very High	Moderate or Low	C	C	D	D	B	B	B	C
High		C	C	C	D	A	B	B	C
Moderate		C	C	C	C	A	B	B	B
Low		B	C	C	C	A	A	B	B
Very low		B	B	B	B	A	A	A	A

2.2.6. TYNDALL COASTAL SIMULATOR

Other relevant tool in the assessment of coastal risk is the Tyndall Coastal Simulator (TCS), which incorporates a framework for coastal flooding and erosion hazards. This tool was developed by the Tyndall Centre for Climate Change Research, in the UK, using the coast of Norfolk, in East Anglia, as case study. This coastal simulator project addresses the necessity for better and longer-term management planning for flood and erosion hazards in this country. Determining the geomorphological response to climate change and its effects on coastline evolution is the main aim of the Tyndall Coastal Simulator (Mokrech *et al.*, 2011).

The development of the TCS has taken place in two phases. In phase 1 (2000 to 2006), most focus was on discrete scenarios of climate change. Phase 2 (2006 to 2009) explored probability density functions of future climate scenarios and uncertainty analysis of its implications (Nicholls *et al.*, 2009; Mokrech *et al.*, 2011).

The TCS integrates a range of coastal models to support a long-term assessment of coastal risk and decision making. The aim is to create a generic, integrated framework that links appropriate scenarios of climate and socio-economic changes with coastal processes. Using the framework, a series of linked models, capable of simulating these drivers and their consequences in terms of changing flood and erosion risk and ecosystem changes, can be developed as a tool to investigate a range of management options and their wider implications (Mokrech *et al.*, 2011).

The integrated framework of the TCS includes three distinct scales, starting in global future scenarios and downscaling to a regional scale and subsequently, to a local scale, where coastal management can be applied. At a global scale, socio-economic future scenarios and anthropogenic actions were factors to be considered, as well as information from ocean-atmosphere coupled with the Global Climate Model. This information is downscaled to a regional scale using a Regional Climate Model, providing wind forcing for surge and wave models (Mokrech *et al.*, 2011). At a local scale, several physical and non-physical factors link to each other's to determine the expected change in the coastal zone.

Despite being considered a useful tool in the decision-making of coastal management, the Tyndall Coastal Simulator lacks a dedicated classification for risk levels, as other methodologies have, making it more suitable to coastal experts that can use the complex models and interpret its results.

2.2.7. Dynamic and Interactive Vulnerability Assessment

The Dynamic and Interactive Vulnerability Assessment model (DIVA) is a software tool that enables its users to produce quantitative information on a range of coastal vulnerability indicators, for user-selected climatic and socio-economic scenarios and adaptation strategies, on national to global scales, covering all coastal nations (Hinkel and Klein, 2009). DIVA is co-developed by several European research institutions, such as the Global Climate Forum, University of Southampton, Kiel University, University of Sussex and Cambridge University.

Hinkel and Klein (2009) describe the DIVA tool as composed by four main components:

- A detailed global database with biophysical and socio-economic coastal data;
- Global and regionalized sea-level and socio-economic scenarios until the year 2100;
- An integrated model, consisting of interacting modules that assess biophysical and socio-economic impacts and the potential effects and costs of adaptation;
- A graphical user interface for selecting data and scenarios, running model simulations and analysing the results.

The database used for DIVA contains around 80 biophysical and socio-economic parameters of worldwide coast. The data was assigned to seven different types of geographic features: coastal segments, administrative units, countries, rivers, tidal basins, world heritage sites and 5 by 5-degree grid cells. Most data were assigned to coastal segments, resulting in a total 12 148 segments worldwide. The inclusion of this data as a pre-processing input shortens the computation time of the model, contributing for the objective of developing a fast model (Hinkel, 2005).

The global and regional scenarios present in the model have information about sea-level rise, land-use change and socio-economic development, which are based on scenarios of the IPCC Special Report on Emission Scenarios (SRES; IPCC, 2000). For each SRES emission scenario, 6 sea-level scenarios were produced, using the climate model CLIMBER-2 (Petoukhov *et al.*, 2000).

The DIVA model consists in an integration of several separate modules that were developed by various project partners, each one representing different coastal subsystems and parameters (Table 2.9). The challenges of the development of a module based tool led to the development of DIVA method, an interactive method for building integrated models by distributed partners. This method allows for researchers of different fields to harmonize their conceptualizations of the system to be modelled without the need to have profound knowledge on the whole system (Hinkel and Klein, 2009).

Table 2.9. Modules of DIVA (Hinkel and Klein, 2009).

Module name	Description
Relative sea-level rise	Creates relative sea-level rise scenarios by adding vertical land movement to the climate-induced sea-level rise scenarios.
River effect	Calculates the distance from the river mouth over which variations in sea-level are noticeable.
Indirect erosion	Calculates the loss of land, the loss of sand and the demand for nourishment due to indirect erosion in tidal basins. This is a reduced version of the Delft Hydraulics ASMITA model.
Total erosion	Calculates direct erosion on the open coast based on the Bruun rule. Sums up direct erosion and indirect erosion for the open coast, including the effects of nourishment where applied.
Wetland change	Calculates area change due to sea-level rise, sea dike construction and possible wetland nourishment for six types of wetlands.
Flooding	Calculates flooding due to sea-level rise and storm surges, considering sea dikes.
Wetland valuation	Calculates the value of different wetland types as a function of GDP, population density and wetland area.
Tourism	Calculates number of tourists per country.
Costing and adaptation	Calculates socio-economic impacts of the geodynamic effects, considering preset and/or user-defined adaptation options.

Using the sea-level scenarios as input, four types of biophysical impacts are assessed: land loss, flooding, salinity intrusion and wetland change. Land loss happens due to submergence and coastal erosion. The effect of sea-level rise on coastal erosion is estimated using the Bruun rule (Bruun, 1988) and a simplified version of ASMITA model (van Goor *et al.*, 2003) to estimate the amount of sediments trapped in tidal basins due to sea-level rise, which contribute to coastal erosion. Flooding of coastal zone areas due to sea-level rise and storm surges were estimated for return period from 1-in-1 to 1-in-1000 years. Salinity intrusion and coastal wetlands are also estimated with sea-level rise as input.

DIVA model also includes socio-economic consequences of the physical impacts described above. Social consequences are measured by three indicators: coastal floodplain population, which gives the number of people that live below the 1000-year storm-surge level; expected number of people subject to annual flooding; and forced migration, which gives the number of people that had to migrate from land that would be permanently lost due to erosion and submergence. Economic consequences are expressed in terms of damage costs and adaptation costs. For each coastal subsystem, several adaptation measures are considered to perform cost-benefit analysis.

The biophysical impacts of DIVA model have a wide range of components. Hence, they cannot be objectively compared and are unsuitable for aggregation into a single measure. Therefore, DIVA does not produce a single measure or index of vulnerability. The comparison of the various components of the output is left to the user's own judgement (Hinkel and Klein, 2009).

DIVA's graphical user interface allows the user to choose different scenarios and adaptation strategies, to run the model and to analyse and compare results for different regions, time steps, scenarios and adaptation strategies. The results can be visualized in tables, graphs, charts or maps and can be exported to different formats (Hinkel and Klein, 2009).DIVA 1.0 was released in 2004. However, this tool is no longer available due to a lack of resources for maintaining and supporting the software. The underlying DIVA model has been substantially further developed into a state-of-the-art research model applicable for assessing coastal impacts and adaptation at global and national scales. Several studies of vulnerability to sea-level rise were conducted using DIVA model both at a global scale (Vafeidis *et al.*, 2008; Hinkel *et al.*, 2013, 2014) and at a national scale, such as countries of the European Union (Hinkel *et al.*, 2010) and Africa (Hinkel *et al.*, 2012). Recently, the DIVA was applied to the Emilia-Romagna coast (Wolff *et al.*, 2016), a smaller scale site when compared with the previous studies.

2.2.8. Decision Support System for Coastal Climate Change Impact

Since 2005, the Euro-Mediterranean Centre for Climate Change (CMCC), an Italian research centre devoted to the study of climate change and its impacts, has been developing the Decision Support System for Coastal Climate Change Impact

(DESYCO) for the assessment and management of multiple climate change impacts on coastal areas and related ecosystems at a regional/subnational to local scale. This tool was firstly applied to the coast of the North Adriatic Sea, in Italy, namely the coastal zone of Veneto and Friuli-Venezia Guilia regions (Torresan *et al.*, 2010).

DESYCO is composed by four main components: a geodatabase for storage of biophysical and socio-economic data; multi-scale scenarios provided by numerical model simulations or time series analysis; the integration of the Regional Risk Assessment methodology (RRA); and a Graphical User Interface (GUI) to facilitate interaction with the user (Torresan *et al.*, 2013).

For the generation of hazard scenarios for the coast of the North Adriatic Sea, a chain of models was developed. The chain of models includes, among others, a suite of higher resolution models able to simulate ocean dynamics and circulation, biogeochemical and transport processes. Within DESYCO, the proposed model chain allows the investigation of different climate change impacts including regional inundation processes and increased storm surge flooding due to sea-level rise, erosion processes due to wind, waves and tide, water quality variations due to the concentration of nutrients and contaminants (Torresan *et al.*, 2010).

These hazard scenarios feed the core component of DESYCO, the Regional Risk Assessment methodology (RRA). The RRA is defined as a risk assessment procedure which considers the presence of multiple habitats, multiple sources releasing a multiplicity of stressors impacting multiple endpoints (Landis, 2005). The RRA is based on the Multi-Criteria Decision Analysis (MCDA) framework. Therefore, the method is capable to include multiple sustainability spheres (social, economic, environmental) and stakeholders in the assessment process (Torresan *et al.*, 2016).

Torresan *et al.* (2016) proposes a distinction between two major determinants of risk: climate change hazard and vulnerability of a system. The climate change hazard analysis refers to the assessment of the sources (see section 2.1) that contribute to increasing probability of a hazardous event. The vulnerability of the system encompasses the assessment of four main categories of factors: susceptibility factors, value factors, attenuation factors and pathway factors. The definitions of the DESYCO project are similar to the definitions presented in section 2.1, differentiating slightly in the definition of vulnerability, by including pathway factors (which correspond to exposure indicators) in the vulnerability assessment. All these factors are combined using MCDA techniques to evaluate and rank targets, areas and risks from climate change at the regional scale.

The RRA application is done in 5 phases. The Hazard scenario assessment characterizes climate change hazard that impact the system. Then, the Exposure assessment identifies and classifies areas where the hazard can affect the receptor. Next, the Susceptibility assessment phase evaluates the degree to which the receptors could be affected by a given climate change impact, based on site-specific territorial information. The Risk assessment phase integrates the information of the exposure and susceptibility assessments to identify and prioritize areas and targets at risk in the study area, attributing a relative risk score. Finally, the Damage assessment phase aggregates the results of the risk assessment with the environmental and socio-economic value of a receptor to estimate potential loss (Torresan *et al.*, 2016).

The main output of the Regional Risk Assessment is the production of GIS-based raster maps. RRA maps include hazard, exposure, vulnerability, risk and damage representations. The hazard maps allow the analysis of climate and environmental change scenarios, presenting geographical patterns and quantitative indicators of climate related pressures. Hazard maps are useful to inform the user of the most significant sources of hazard. The exposure maps show potential pathways of contact between the hazard and the receptors. These maps consider territory landforms (elevation and distance from the hazard source) and attenuation factors (*i.e.* coastal defences) to provide a normalized exposure score. The susceptibility maps allow the identification and ranking of the receptors based on their propensity to be impacted by a given hazard. The risk maps integrate the exposure and susceptibility maps to identify and rank the areas and receptors at greater risk from climate change related impacts. Finally, the damage maps provide a normalized scale with an estimation of expected damages associated with a given hazard for the areas at risk (Torresan *et al.*, 2016).

DESYCO and the RRA approach proved to be innovative tools to study climate change impacts on coastal zones at the regional scale and support the development of effective adaptation strategies and sustainable Integrated Coastal Zone Management (ICZM), considering the increasing issues related to climate change. The inclusion of a multi-model chain allows the downscaling of information provided by climate models at the global and sub-continental scale and the investigation of cascading processes at a regional level. However, building this kind of computational structure requires great initial effort in terms of time and resources, and the tool is only applicable for the study area of concern. On the other hand, the Regional Risk Assessment methodology provides a series of outputs that are potentially very useful to coastal managers and stakeholders. The DESYCO tools are currently being used by several projects around the Mediterranean sea and other locations around the world (Torresan *et al.*, 2016).

2.2.9. SimCLIM

SimCLIM (SC) is a software tool designed to facilitate the assessment of risks from climate change (CLIMsystems, 2018). The purpose of SimCLIM is to link and integrate complex arrays of data and models in order to simulate, temporally and spatially, bio-physical impacts and socio-economic effects of climatic variations, including extreme climatic events (Warrick *et al.*, 2005). The SimCLIM system combines complex arrays of data and models. It has a vertically-integrated, "top-down" structure that links global, local and sectorial models and data for examining impacts on agriculture, health, coasts or water resources (Warrick, 2009).

Some of the main advantages of SimCLIM for performing risk assessment are the "open-framework" features, giving users the flexibility to import their own data and customize the software for their own purposes. Also, the geographical scale is a matter of user choice, given that the computational demands and data required are available.

Warrick (2009) considers that SimCLIM includes two core features relevant to risk-based climate impact assessments: the scenario generator and the extreme event analyser. The scenario generator extrapolates standardized spatial patterns of climate change from a complex General Circulation Model considering time-dependent (*e.g.* year-by-year) projections of global-mean climate changes. The scenario generator is used to change the present climate and create climate scenarios, either spatially (time slice) or in time (for selected sites). SimCLIM is also capable of evaluate extreme events by identifying extreme values in a set of data. Then, these extreme values are plotted and fitted to a General Extreme Value distribution. From this function, return periods for extreme values specified by the user can be estimated. Also, the extreme event analyser is linked to the scenario generator so that user-specified scenarios of climate change is used to perturb time-series data.

Regarding coastal modelling, SimCLIM includes a modified version of the Bruun rule (Bruun, 1988). The option of using the Bruun rule instead of a full-fledged model is justified by the requirement of high quality and high-resolution data for a range of variables and parameters, which is often not available for the studied area. Moreover, the more complex coastal models are not well suited for issues of sea-level rise due to different time and spatial scales involved (CLIMsystems, 2018). The Bruun rule was modified to address its setbacks, such as the result being the “equilibrium” state of the coastline, and to take in consideration the occurrence of extreme events, which often cause severe coastal erosion.

SimCLIM is currently available to the public in its 4.0 version. The software can perform spatial and site-specific scenarios, site specific sea-level rise and analysis of extreme events, with or without climate changes. Several models can be developed, such as site-specific coastal erosion models. The user interface is efficient and customizable to the user and outputs are easily extracted. SimCLIM presents itself as a very useful tool in coastal risk assessment for stakeholders and experts. However, the application does not provide a dedicated risk classification, instead relying on the expert knowledge to accurately interpret the results and assess the coastal risk based on them.

2.2.10. THESEUS

THESEUS is an integrated project within coastal risk assessment and mitigation funded by the European Commission, involving 31 partner institutes (THESEUS, 2015). The main goal of the project was to provide an integrated methodology for planning sustainable defence strategies for the management of coastal erosion and flooding, addressing technical, social, economic and environmental aspects (Zanuttigh, 2011). Within the project, a Decision-Support System (DSS) tool was developed, aiming to support decision-makers and practitioners to develop sustainable coastlines by performing analysis of vulnerability, impacts and risks, and the identification and evaluation of related management options.

According to Zanuttigh *et al.* (2014), this tool is intended as a vehicle for communication, training, forecasting and experimentation. The key features for the THESEUS DSS are: seamless integration across disciplines (physics, engineering, ecology, social sciences and economy); intermediate spatial scales (10–100 km) and short-, medium- and long-term time spans (1–10–100 years); diverse portfolios of mitigation options such as engineering defences (*i.e.* barriers, wave farms), ecologically-based solutions (*i.e.* biogenic reefs, sea-grasses) and socio-economic mitigations (*i.e.* insurance, change of land use); support of decision-making based on a balance between deterministic models and expert, discussion-based assumptions; open source approach to maximize the availability and uptake of the tool.

The DSS is based on a model for coastal risk assessment proposed in THESEUS project. This model follows the Source-Pathway-Receptor-Consequence (SPRC), which was already presented in section 2.1. The SPRC-based model provides an integrated framework which is used to assess and combine physical, ecological (habitat) and socio-economic aspects of a study site.

To analyse the physical component, a simple GIS-based flood model is used to assess the flood extent, instead of more complex and computationally expensive models, which were considered impractical for THESEUS DSS. The model performs flood mapping through the spreading of water levels or volumes in a Digital Elevation Model (DEM).

At the ecological level, THESEUS developed an Environmental Vulnerability Index (EVI) for 10 coastal habitats within THESEUS study areas, representing key coastal ecosystems across Europe. In each of these habitats, features such as habitat extent, protected sites, key species and commerce were evaluated. An Environmental Vulnerability Index is calculated considering the habitats/species present in each habitat. For the assessment of social vulnerability, two main aspects are considered: the damages to Critical Facilities (CFs); and the expected number of fatalities. CFs are defined as "the primary physical structures, technical facilities and systems which are socially, economically or operationally essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency" (ISDR, 2009). The impact of flooding on CFs is estimated by three steps: rank critical facilities with an Approximated Social Value (ASV), with values from 1 (low) to 5 (high); estimate physical damage for structures, following the method by Schwarz and Maiwald (2008); and definition of touristic impact. The Collateral Social Damages (CSD) are an overall combination of possible intangible damages, in the range 0 to 100. According to Zanuttigh *et al.* (2014), the CSD maintains a high level of uncertainty, but it is one of the first attempts to provide to end users the possible effects of floods on the community and individuals. On the other hand, the estimation of social damages was based on a function of life losses and injuries from Penning-Rowsell *et al.* (2005). The overall Economic Consequences (EC) of flood in terms of flood depth and flood duration are estimated considering the values of land uses from census statistical data, flood duration and depth for storms with 100-year return period, resilience of the study area and normalised income. Experts related to each of the three impacts (*i.e.* ecology, society, economy) defined one or more quantitative indexes to be applied: ecologists suggested an EVI index [0, 3], sociologists developed one indicator in [0, ∞[for the affected population and one indicator in [0, 10] for CF, and economists relied on land use values in euro/m^2 in [0, ∞[. The relative weight of each impact in the overall assessment is defined by stakeholder's preferences and other user specified weights and by normalizing all values estimated by experts.

Given the fundamental interaction of the user, THESEUS DSS tool was built considering two key points: intuitive and interactive design on the Graphical User Interface (GUI); and a balance of simplified modelling assumptions and speed to promote the use of the tool for testing different combinations of mitigation options.

Each study site requires a Digital Elevation Model, hydraulic structures and infrastructures position and geometry; map of land-use and of critical facilities; list and/or map of geo-referenced social and economic indicators, such as: age, gender, employment, occupation, population health, etc.; geo-referenced maps of habitat types and species.

With the input data, climate, environmental, economic and social scenarios are built, mitigation options are considered and models for flood and erosion are developed. The final output are economic, social and ecological vulnerability maps. A normalization procedure of each map is carried out to obtain a 1 to 4 scale (1 = low, 2 = medium, 3 = high and 4 = very high impact). This normalization is done by dividing the local values of the consequences by the corresponding site-specific thresholds. By its turn, the thresholds are obtained by comparing the consequences of different scenarios with historical experience or data available in the site. Social, economic and ecological vulnerability maps are then combined through a weighted procedure, to obtain the overall risk map (Zanuttigh *et al.*, 2014).

The THESEUS project performed exploratory risk assessments in 8 study sites across Europe (Penning-Rowsell *et al.*, 2014), with involvement of stakeholders and users in each study site. Although THESEUS DSS proved to be a very complete tool to perform an assessment of coastal risk, its development faced several practical and conceptual challenges, such as the more simplistic approach taken by the tool in some components, leading to less scientific support in the results and to difficulties to coastal managers and stakeholders to trust in its reliability. Also, in many cases, topographic, social, economic and ecological high spatial resolution data that are required for applying the tool may not be available. A cost-benefit analysis is not considered in THESEUS DSS, mainly due to difficulties in the assessment of costs and the non-linearity of the benefits of a combination of measures.

2.2.11. Coastal Hazard Wheel

The Coastal Hazard Wheel (Figure 2.3; CHW) is a tool for coastal assessment which combines multi-hazard scenarios. The system seeks to be an alternative to complex coastal hazard assessments that often require a large amount of input data and expert knowledge (Appelquist and Halsnæs, 2015).

The initial version of the tool was made public in 2012 (Appelquist, 2013) and has since been refined to version 3.0, and has the support of the United Nations Environment Programme (Appelquist *et al.*, 2016). CHW 3.0 is represented by a circle consisting of 6 indicators: geological layout, wave exposure, tidal range, vegetation, sediment balance and storm climate (Figure 2.3). These indicators are considered the most important bio-geophysical components for a generic coastal environment (Appelquist and Halsnæs, 2015). The classification of a given coastal area is made by sequentially classifying each indicator, starting in the centre of the circle. The classification of each component can be done using Google Earth images and timeline functions, and basic information of wave data (Appelquist *et al.*, 2016).

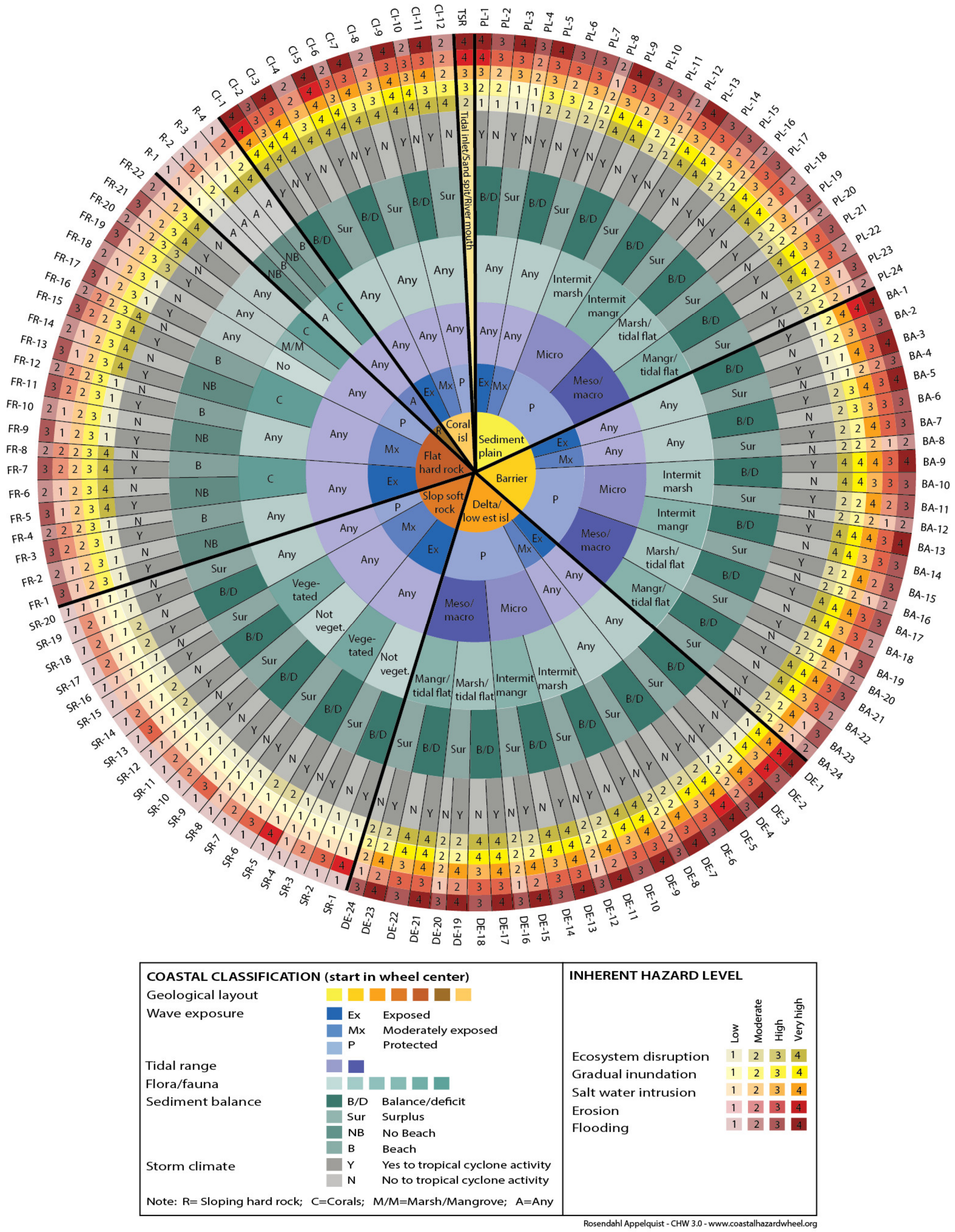

Figure 2.3. Coastal Hazard Wheel 3.0 consisting of six coastal classification circles, five hazard circles and the coastal classification codes (Appelquist *et al.*, 2016).

The CHW distinguishes between 131 combinations of coastal environments and scenarios, and attributes a hazard level for each scenario. The assessed hazards are five: ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. Each hazard is classified from 1 to 4 (Low, Moderate, High and Very High). The levels were based on scientific literature review of the characteristics of the world's coastal environments and their susceptibility to climate related parameters.

Additionally, the CHW platform (http://coastalhazardwheel.org) created a set of tools to help coastal managers using their resources efficiently. The required documentation is publicly available, as well as templates to facilitate its use with GIS systems. The Coastal Hazard Wheel App is also being developed. This application is a GIS-based web viewer that utilizes world databases to provide global coastal classification information and adaptation guidance with low to moderate accuracy. So far, only erosion hazard is assessed. Moreover, higher accuracy is intended in the future, as additional local classification become available (Deltares *et al.*, 2017).

2.2.12. RISC-KIT Coastal Risk Assessment Framework phase 1

RISC-KIT was an EU-funded project for developing risk management tools, constituted by 17 partners and with coordination of Deltares (van Dongeren *et al.*, 2016). Within the project, a set of open-source and open-access methods, tools and approaches to evaluate and reduce risk to extreme events in coastal zones was developed. The final product was the RISC-KIT toolkit, which is comprised by five elements (van Dongeren *et al.*, 2018):

- Storm Impact Database contains data on historical impacts of storms for the study areas, including physical, socio-economic, cultural and environmental interface. Around 300 storm events are stored in the database for the RISC-KIT case study sites (Ciavola *et al.*, 2018);
- Coastal Risk Assessment Framework (CRAF) provides a methodology to identify the areas of increased risk (hotspots) of a case study. The method is composed by phase 1, a combination of several hazard and exposure indicators to form a coastal index, and phase 2, where more advanced hazard and impact

assessment models are applied to the hotspots identified in phase 1 (Viavattene *et al.*, 2018);

- Web-based Management Guide of Disaster Risk Reduction (DRR) measures that help coastal managers on which measures to implement and how they can be implemented, taking in account technical, social, cultural and historical aspects (Martinez *et al.*, 2018);
- Hotspot Tool for assessing effectiveness of potential DRR measures and provide users with advanced early warning of impeding hazards. For assessment of DRR measures, simulations of flood and erosion behaviour are done with and without DRR measures and a framework (Cumiskey *et al.*, 2017) identifies primary measures that have potential to contribute to risk reduction. The results are stored in a Bayesian-based Decision Support System that gives the end user insight in how DRR measures affect the overall risk. The Early Warning System (EWS) provides predictions of local hazards and impacts by coupling the Bayesian network of the DSS with forecasts of large-scale process-based models, thereby eliminating the need to computationally-expensive modelling;
- Multi-Criteria Assessment (MCA; Barquet and Cumiskey, 2018) to enable users from different backgrounds to discuss the selected DRR measures. The use of a MCA approach with stakeholders and end-users facilitate knowledge sharing and encourages local-expert interaction in the decision making.

From all tools provided, this work focuses on the Coastal Risk Assessment Framework phase 1 (CRAF1), namely, on erosion hazard assessment, as this is comparable with other methodologies and with the aim of this literature review.

CRAF1 aims to identify potential hotspots of risk by making a simplified risk assessment for each kilometre of the coastline and by grouping together high-risk segments. The approach combines 5-class rankings of hazard and exposure with equal weight to calculate a Coastal Index (CI) for each kilometre (Eq. 2.2):

$$\mathrm{CI} = (\mathrm{i}_{\mathrm{hazard}} \times \mathrm{i}_{\mathrm{exposure}})^{1/2} \tag{2.2}$$

For the hazard assessment, each hazard is assessed individually and receive a unique index. Viavattene *et al.* (2018) considers that a single coastal index for all hazards might be misleading, since they are dependent of different geomorphologic and physical constrictions. Within CRAF1, various methods are proposed to assess different hazards. For erosion, the method proposed was developed by Mendoza and Jiménez (Mendoza and Jiménez, 2006). The method requires a representative cross-shore profile of the study area, a long time-series of wave climate (real or hindcast) and general characteristics of the study area (sediment grain-size, beach profile coastal slope and berm height). The aim is to correlate cross-shore eroded volume under a storm event, obtained by numerical model simulations with a coastal morphodynamic parameter, JA (explained further in section 5.3), for each simulation. The resulting expression allows to predict the eroded volume in the study area, for a given extreme event. This result is then classified from 0 to 5 (as it is with any other hazard in CRAF1), with 0 corresponding to no erosion, and other classes corresponding to user-defined thresholds of shoreline retreat.

On the other hand, exposure is scored from 1 to 5, by combining the geometric mean with equal weighting of all exposure indicators (Eq. 2.3):

$$\mathrm{i}_{\mathrm{exposure}} = (\mathrm{i}_{\mathrm{exp1}} \times \mathrm{i}_{\mathrm{exp2}} \times \ldots \times \mathrm{i}_{\mathrm{expn}})^{1/\mathrm{n}} \tag{2.3}$$

where 1 to *n* refers to the exposure variables considered in the assessment. The variables were not established with the intention of consider different exposures for each type of hazard. Viavattene *et al.* (2018) considers a single coastal exposure index for all hazard might be misleading. Hence, the coastal managers should be responsible to identify exposure variables, taking in consideration the expected responses, mitigations and management approaches of their study areas. The exposure variables can include land use, population, transport, critical infrastructures and business (Ferreira *et al.*, 2016).

The RISC-KIT project applied their tools to 10 case studies in Europe with different forcing, morphological and exposure/vulnerability conditions. Van Dongeren *et al.* (2018) concludes that the tool prove to be effective and broadly applicable.

2.3. PRELIMINARY DISCUSSION

The methodologies described in the previous section present a wide range of processes, indicators and scope, both in time and spatial scale, to assess coastal risk, hazards and/or vulnerability. This variety is worth analysing to identify the most relevant indicators, and most used time and spatial scales in coastal risk assessment. This exercise was used as a stepping stone in the development of a new methodology, the intended objective of the present thesis. Therefore, the most used risk indicators by the methodologies presented previously are reviewed, as well as the spatial scale that each methodology focuses on its intended time frame. Table 2.10 presents an overview of the reviewed methodologies (with respective acronym), known year of development, main consulted reference and stated objective.

Beyond indicators, spatial and temporal scales, the methodologies analysed also differ in many other points. The increase of complexity is noticeable along time. CM and AVVA are essentially guidelines that lean on local expert knowledge to perform first-order assessments on vulnerable areas. Then, CVI, CVRA and the Smartline use a series of established physical, social and environmental indicators to perform the assessment. However, the output differs in the range of classes and in the meaning of those outputs. CVI presents 4 levels of relative vulnerability, while CVRA considers 5 levels of vulnerability, value and risk output. On the other hand, the Smartline has 6 levels of physical vulnerability and 4 risk levels. Finally, the remaining 7 methodologies go beyond the development of a framework and incorporate software-based tools to assess coastal risk. These methods are mainly based on chains of models that simulate the coastal risk propagation. Although there are some exceptions (*i.e.* SimCLIM), these models are usually simplified to save on computational costs and due to the data requirements of more complex models.

Table 2.10. Review of methodologies and their correspondent objective.

Name	Year	Reference	Objective
IPCC Common Methodology (CM)	1991	IPCC CZMS (1992)	Assessment of potential coastal impacts of sea-level rise and adaptation measures
Aerial Videotape-Assisted Vulnerability Analysis (AVVA)	1992	Leatherman *et al.* (1995)	Assessment of coastal vulnerability to sea-level rise
Coastal Vulnerability Index (CVI)	1999	Thieler and Hammer-Klose (1999)	Assessment of relative vulnerability of the coast to changes due to sea-level rise
Coastal Vulnerability and Risk Assessment (CVRA)	2005	Coelho (2005)	Assessment of coastal vulnerability and risk to coastal erosion
Smartline (SL)	2006	Lins-de-Barros and Muehe (2013)	Physical and social vulnerability assessment to coastal erosion and flooding and resulting coastal risk
Tyndall Coastal Simulator (TCS)	2000	Mokrech *et al.* (2011)	Determining geomorphological response to climate change and its effects on coastline evolution
Dynamic and Interactive Vulnerability Assessment (DIVA)	2004	Hinkel and Klein (2009)	Assessment of coastal vulnerability for user-selected climatic, and socio-economic scenarios and adaptation strategies
Decision Support System for Coastal Climate Change Impact (DESYCO)	2005	Torresan *et al.* (2016)	Assessment of climate change impacts on coastal areas and related ecosystems
SimCLIM (SC)	2005	Warrick (2009)	Simulation of bio-physical impacts and socio-economic effects of climatic variations
THESEUS DSS	2009	Zanuttigh *et al.* (2014)	Assessment of vulnerability, impacts and risks of coastal areas and identification and evaluation of coastal adaptation options
Coastal Hazard Wheel (CHW)	2012	Appelquist *et al.* (2015)	Assessment of coastal hazard level for multi-hazard scenarios
RISC-KIT Coastal Risk Assessment Framework 1 (CRAF1)	2013	Viavattene *et al.* (2018)	Assessment of hazard, exposure and risk of coastal zones for identification of high-risk segments

Despite all methods seek to assess coastal hazard impacts in some way, they vary slightly in the motivation and specific objective for that assessment (Table 2.10). Moreover, the difference in the purpose and nomenclature for vulnerability, impact, hazard or risk assessment is noticeable for each methodology. Some methodologies focused only on physical and geomorphological factors (IPCC; AVVA; CVI; TCS) and call themselves vulnerability or hazard assessments. Others (CVRA; Smartline; DESYCO; CRAF1) consider socio-economic indicators, making it possible to perform a risk assessment. As stated previously, the risk related definitions are associated with the nomenclature given by each methodology output but might not follow exactly the same interpretation as the one followed by this work. Other point to highlight is the fact that seven of the total methodologies explicitly state the objective of assessing coastal hazard impacts and risk due to sea-level rise or climate changes. Others, while not directly acknowledging climate change as the driving force behind the development of the methodology, also present indicators or scenario simulations that assess the climatic change. This fact reveals a trend to study and assess coastal environments with the increasing relevance of climate change subject. Coastal erosion is rarely mentioned in an explicit way as the hazard or risk to be assessed.

The following sections assess the data and/or indicators required, targeted application scale and time frame for the application of each methodology.

2.3.1. Common indicators and data requirements

The reviewed methodologies make use of a set of indicators to perform the coastal assessments. In this section, the indicators for each methodology are identified. It is expected that this identification will contribute to select the most common indicators and the ones with greater importance in a coastal assessment. Although most methodologies do not focus on coastal erosion hazard specifically, but rather in multi-hazard assessments or hazards derived to sea-level rise, they usually incorporate components of coastal erosion. Therefore, the most used indicators can be considered for implementation in the development of the new methodology, as they certainly have an important role in coastal erosion risk assessment.

Looking at Table 2.11, which identifies indicators used for each methodology, it is evident that wave climate data, geomorphologic data and socio-economic data are the most used indicators for coastal risk assessments. The identification of these types of data ties in with the SPRC model described in section 2.1. The wave climate data is used to assess sources, geomorphologic data to assess the pathway and socio-economic data to assess the receptors. On the other side of the spectrum, the least used indicators, such as sediments' grain size, beach profile slope or bathymetry, are very specific, which makes its data difficult to obtain due to the scarce amount of available information and the cost of producing that data, which is already represented by some other parameters with broader meaning (*e.g.* coastal slope can be integrated in topography).

Table 2.11. Indicators/data considered by each methodology. CM is not included since it relies on expert knowledge to identify the relevant indicators.

Indicators	AVVA	CVI	CVRA	SL	TCS	DIVA	DESYCO	SC	THESEUS	CHW	CRAFI	Total
Tidal Data	x	x	x	x	x	x	x	x	x	x	x	11
Wave Data	x	x	x	x	x	x	x	x	x	x	x	11
Geomorphology	x	x	x	x	x	x	x	x	x	x		10
Geology	x		x	x	x	x	x	x	x	x	x	10
Topography	x		x	x	x	x	x	x	x		x	9
Land Use	x		x		x	x	x	x	x	x	x	9
Sea-level Rise	x	x		x	x	x	x	x	x			8
Economic Data	x		x	x	x	x	x		x		x	8
Social Data	x		x	x	x	x	x		x		x	8
Coastal Interventions	x		x		x	x	x	x	x			7
Storm Surge				x	x	x	x	x	x			6
Shoreline Change Rates	x	x	x	x		x				x		6
Heritage Data	x		x		x	x			x		x	6
Ecological Data	x		x			x			x		x	5
Bathymetry	x			x							x	3
Coastal Slope		x		x							x	3
Sediment Grain Size				x							x	2
Distance to Shoreline			x									1

This work intends to produce a methodology that could allow to perform a quick assessment on coastal erosion risk without the need of much detailed data. Therefore, the assessment on how frequently these parameters are used is very important in the decision of each ones should be incorporated in the methodology. The use of broader parameters is preferred, as the information is easier to find, making it more suitable for developing countries, although it could potentially damage the accuracy of the results. The methodology should be useful for a first assessment, followed by a more detailed analysis if the previous results are concerning.

2.3.2. Spatial scale

The spatial scale that each methodology can cover is an important feature. On one hand, assessing a large area means getting information about coastal risk for a much larger community. Also, being capable of evaluating different environments on the same assessment brings benefits in terms of classification comparison and prioritization of hotspots for the application of mitigation measures. The capacity of assessing large areas is good for national land-use planning, which usually require assessments for large areas with limited deadlines. However, assessing coastal risk at a global scale can lead to a lack of detail and inaccurate or outdated data regarding certain areas, resulting in a less accurate risk evaluation on those areas.

On the other hand, developing a methodology specific at a local scale can produce a highly detailed risk assessment, offering great support to decision by coastal managers, regarding coastal defences and interventions. However, those methodologies require a tailored assessment for the specific area, requiring detailed data for that location. These assessments usually take more time to develop, require more expert knowledge, and are more computational-expensive and data demanding. Table 2.12 presents and overview of the spatial scale that each methodology adopts.

The 4 categories presented in the table are not well defined, but are the scales more often presented in the literature and allow an abstract idea of the area that is possible to apply each methodology. Table 2.12 shows that most methodologies favour a regional assessment (tens to hundreds of kilometres). Only 3 methodologies target a global scale: CM; DIVA; and CHW. From those, only DIVA and CHW are truly targeted at a global scale. The IPCC Common Methodology, being composed by guidelines based on expert knowledge, can also adopt a global scale, as well as any other scale, depending only of the user objectives. The AVVA methodology is mainly targeted at a sub-national and regional assessment, as the aerial data required is not adequate for a global scale and is not required for local scales (few tens of kilometres). The CVI is also targeted at national to sub-national scales, presenting few indicators and a relative vulnerability output. The TCS, CRVA, DESYCO and SimCLIM are assessments that require modelling or a considerable amount of data, being therefore focused on a regional scale. The Smartline approach was applied at a national and regional level in different parts of the world (Australia and Brazil) and is simplified enough to be applicable on those scales, despite having some very specific indicators in its formulation. The THESEUS methodology is mainly focused on regional to local scale. This method was tested in 8 different locations across Europe, which indicate enough flexibility to be applicable to several types of environment. Finally, CRAF1 is also a methodology with study sites around Europe at a regional scale.

Table 2.12. Scales adopted for each reviewed methodology.

Methodology	Global	National	Regional	Local
CM	x	x	x	x
AVVA		x	x	
CVI		x	x	
CVRA			x	
SL		x	x	x
TCS		x	x	x
DIVA	x	x		
DESYCO			x	x
SimCLIM		x	x	x
THESEUS			x	x
CHW	x	x	x	x
CRAF1			x	x
Total	3	8	11	8

This work intends to produce a methodology that can be applicable in areas with hundreds of kilometres, at a sub-national scale. However, the outputs of the methodology should also make sense at smaller scales, providing that the data is sufficiently accurate. The user should be able to provide highly accurate data for a great extent of coastline, although this process should be highly data demanding and computational expensive.

2.3.3. Time frame

Regarding the time frame used by coastal risk methodologies, two major approaches are noticeable. The methodologies that rely on scenario generators to assess both physical, environmental and social factors aim at medium to long-term time spans.

For example, the DIVA model presents its results for the year of 2100, having the sea-level rise as major intervenient in coastal risk evolution. Also, the TCS and the SimCLIM integrate models that evaluate scenarios for medium and long-term periods. The THESEUS project is more flexible regarding time scales, presenting the possibility of results for 1, 10 and 100 years. CRAF1 does not specify a time scale, but the return periods used for the definition of extreme events vary from medium to long-term (*i.e.* 50 to 100 years).

The coastal risk assessment in a medium and long-term period could provide the information for a more thoughtful coastal management, supporting the execution of coastal interventions aiming at long-term development of the area. However, the inclusion of modelled data increases the degrees of freedom and complexity of the framework, with possible no gains in the assessment reliability.

On the other hand, methods such as the CM and AVVA, which mainly present guidelines supported on expert knowledge, do not specify any time frame. Methodologies based on the assessment of indicators and field data, such as CVRA, CVI, Smartline or CHW focus on coastal risk for current time. The absence of a time frame could mean the results are valid only for short-term periods. However, considering that coastal erosion is mainly a medium to long-term process, the assessment of indicators in its current state can be considered valid for these time frames. Therefore, even if a methodology assesses coastal risk in short-term period, the results lead stakeholders to consider mitigation strategies that lead to medium to long-term benefits.

This work proposes to use present data to assess coastal erosion risk instead of relying on complex models to estimate future behaviour of a coastal zone. This approach will not allow long-term scenario generation, but will provide decision support for proper coastal management in its current state, mainly for developing countries, where complex models can be difficult to apply.

3. STUDY AREAS

In order to test the existent coastal hazard and risk methodologies, as well as the new proposal method presented in this work, three study areas are considered: Aveiro (Portugal); Macaneta (Mozambique); and Quintana Roo (Mexico). These study areas were chosen throughout the development process, as opportunities with partners appeared, which gave the required support for development of the assessments. The areas present similarities regarding geomorphology, being all mostly low-lying sandy coasts, but also have differences in terms of spatial scale, anthropogenic occupation and wave climate conditions. The following sub-sections show the general characteristics of the study areas and the data gathered to perform the coastal risk assessments. The required data is mostly available to the public, such as land use, geomorphology or topography (a minimum of 2 km inland was collected). Also, data regarding wave climate is required. This one is not always available through public entities, requiring other approaches, such as partnerships with local entities. Other indicators were collected, which are detailed in their respective sections.

3.1. AVEIRO, PORTUGAL

The first case study considered in this work is the Aveiro district coastline, in Portugal. The coastline is approximately 75 km long and is located at the Portuguese northwest coast (Figure 3.1; OpenStreetMaps as basemap, like in all figures in this work), approximately N21°E oriented. Aveiro coastline includes areas from the following seven municipalities (from north to south): Espinho, Ovar, Estarreja, Murtosa, Aveiro, Ílhavo and Vagos. The study area is mainly an open sandy coast, exposed to high-energy wave climate from Atlantic Ocean, frequently incident from northwest.

Beaches on Aveiro coastline are classified as intermediate to reflective, according to Short (1999) classification. The mean significant wave height is around 2 m (Narra *et al.*, 2015a), although during storms, wave height can reach 8 m (Costa *et al.*, 2001). Commonly, storms last for less than 2 days. However, storms that persist for up to 5 days were already registered (Costa *et al.*, 2001). For a storm defined as a wave field with significant wave heights greater than 3 m, the average storm duration is 60 hours (Sancho *et al.*, 2016). The tide is semi-diurnal and ranges between 2 m, at neap tide, and 4 m, at spring tide.

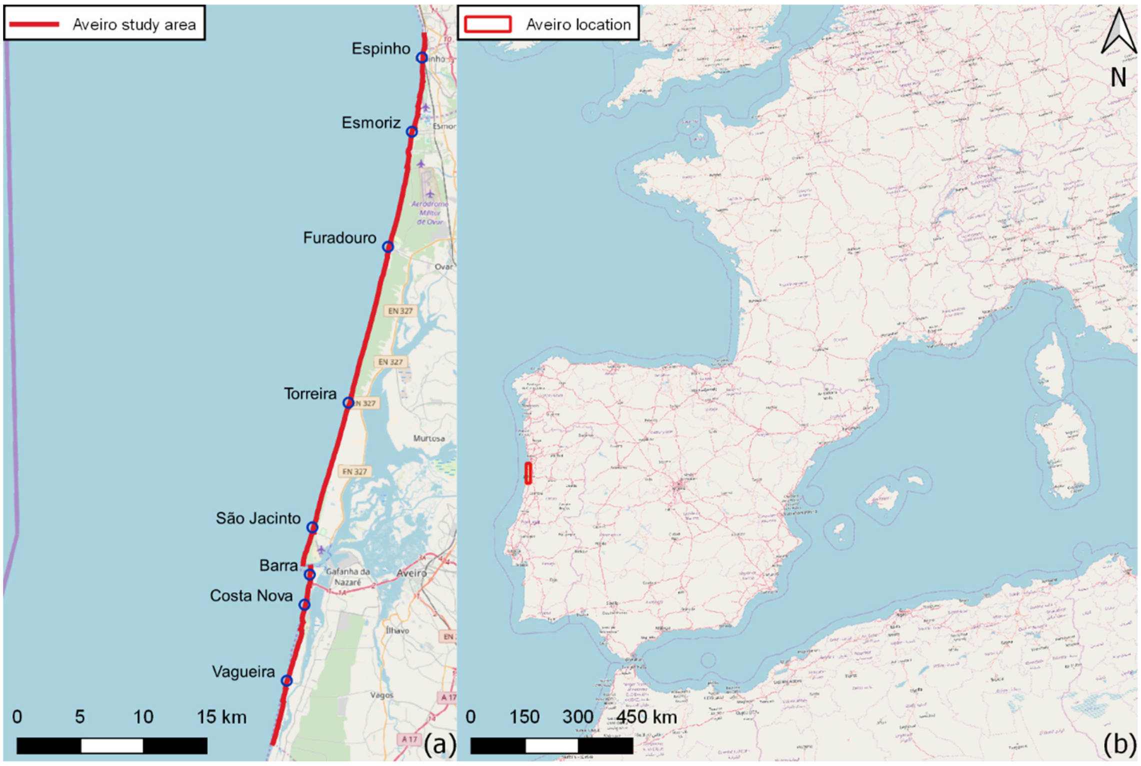

Figure 3.1. Aveiro study area (a) extent and (b) location, Portugal (OSM, 2018).

In the last decades, this coast has been facing shoreline retreat problems due to exposition to highly energetic wave climate, non-consolidated sediments that compose the soil, harbour infrastructure construction and expansion, and, most significantly, due to decrease of the updrift river sediment supplies (Bettencourt, 1997). According to Lira *et al.* (2016), in the last 50 years, this transect suffered from erosion rates that reached 8 m/year. Additionally, events of flooding and overtopping are frequent (*e.g.* the storm events of 2014, which produced significant damages in both coastal defence structures and infrastructures). Along the years, starting mainly in the 1970's, several coastal defence structures were implemented to hold the shoreline and prevent coastal erosion. A total of 23 groynes and 13 longitudinal rocky revetments were built in this study area (Costa and Coelho, 2013; Pereira and Coelho, 2013a).

For the Aveiro coast, most required data is available through national or European organizations, or was found in previous research (Narra *et al.*, 2017). The use of openly available data is preferable for the objective of this work, since it facilitates future applications of the new coastal erosion risk classification proposal in under developed areas.

Data regarding shoreline position and evolution was obtained by Lira *et al.* (2016). This dataset (Figure 3.2) was produced by mapping the shoreline based on the foredune toe, which is less susceptible to short-term changes.

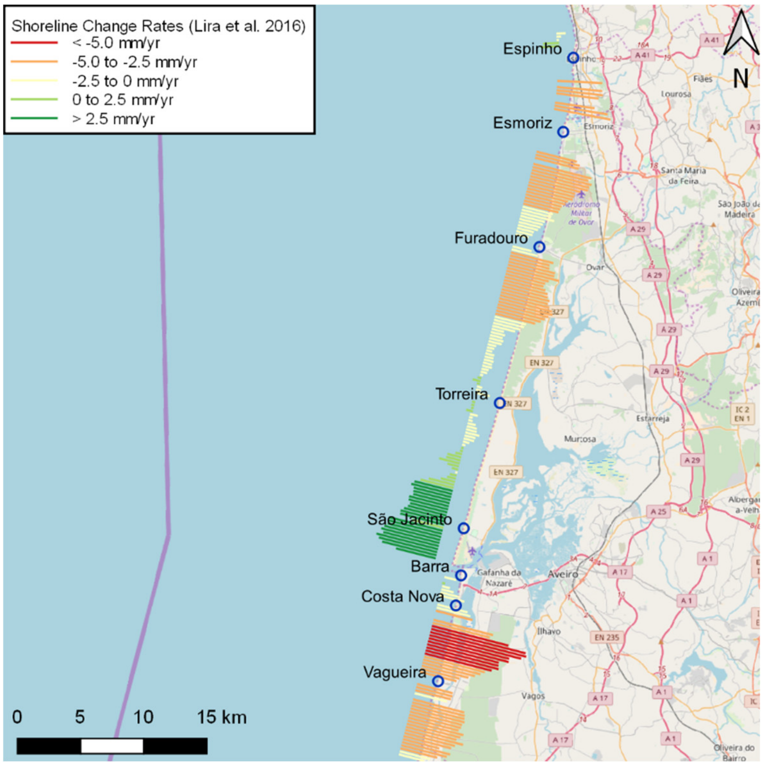

Figure 3.2. Shoreline change rates for Aveiro study area (Lira *et al.*, 2016).

The shoreline mapping was done for 1958, using digital aerial photographs from USAF (United States Air Force), with a 0.5 m/px resolution, and for 2010, using digital ortophotomaps from DGT (*Direção Geral do Território*), with 0.2 m/px resolution for the entirety of Portugal mainland. The dataset produced by Lira *et al.* (2016) is composed by two polyline sets mapping 1958 and 2010 shoreline, one polyline representing long-term change rates between those dates and a table with minimum, maximum and mean evolution rates considering measurements each 250 m along the shoreline. Lira *et al.* (2016) highlights the coastal stretches Espinho – Torreira and Costa Nova – Mira, which are within this study area, as having major coastal erosion issues, with shoreline retreat rates up to 7.4 m/year.

Elevation data was collected from the EU-DEM dataset (EEA, 2016a). The EU-DEM (Figure 3.3) is part of the Copernicus Land Monitoring Service (CLMS), a European land monitoring service managed by the European Environment Agency (EEA) that provides geographical information on land cover and related information, useful for a variety of domains (CLMS, 2018).

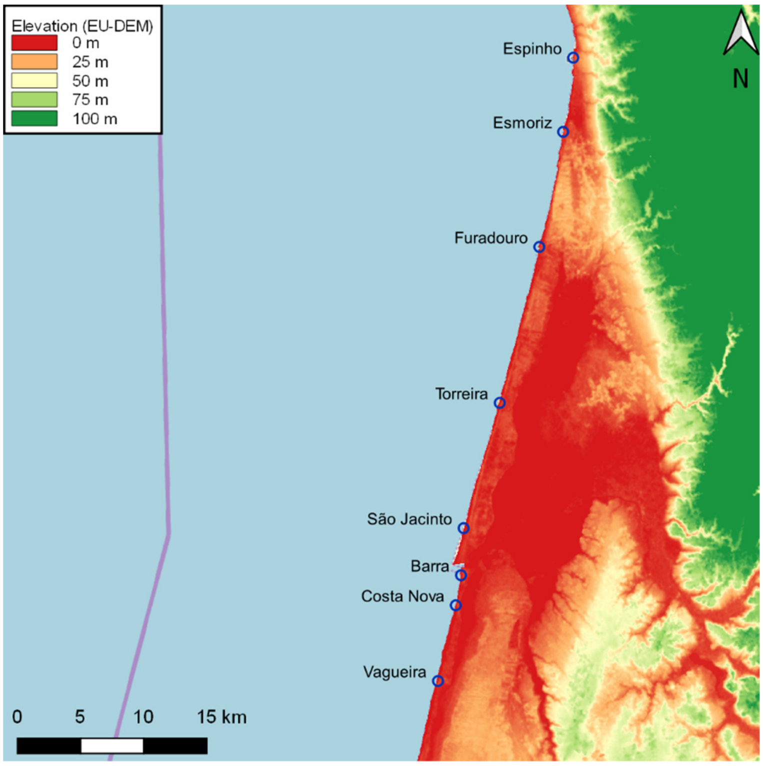

Figure 3.3. Elevation data for Aveiro study site (EEA, 2016a).

The EU-DEM is a Digital Elevation Model (DEM) produced by fusing data of several data sources into a single elevation dataset, covering a total of 33 country EEA members. The coordinate reference system (CRS) is the ETRS89-LAEA (EPSG: 3035) and has a pixel size of 25 m resolution with an approximate vertical accuracy of 7 m (CLMS, 2017a). Although this accuracy is not ideal for a topography assessment, it was the most adequate information that covers the study area up to 2 km inland. The dataset from DSGCIG (2011) was also considered for the topography assessment. This dataset was done using LiDAR technology, covering the coastal zones of Portugal (until 600 m offshore and 400 m inland) with a resolution of 2 m/px. Despite the much higher detail, this dataset did not cover the entirety of the study area. Thus, EU-DEM remained the dataset of preference. However, the DSGCIG (2011) was used to compute beach slope using GIS software. Slope is computed using *r.slope* from GRASS GIS within QGIS (QGIS, 2018). There is no consensus in the scientific community on a single definition of beach slope, as the initial and end points of a beach profile are open to interpretation (Sunamura, 1984; Kriebel *et al.*, 1991; Kamphuis, 2000; Jewell, 2012). In this work, to maintain consistency, the author resampled the available DEM to have slope estimates in a buffer zone roughly 50 metres seawards and landwards from the shoreline defined by Lira *et al.* (2016). This method was used to improve the efficiency of GIS processing regarding the estimated beach slope parameter. The lithological information for Aveiro (and other study sites) were gathered using the Global Lithological Map (GLiM; Figure 3.4), produced by Hartmann and Moosdorf (2012).

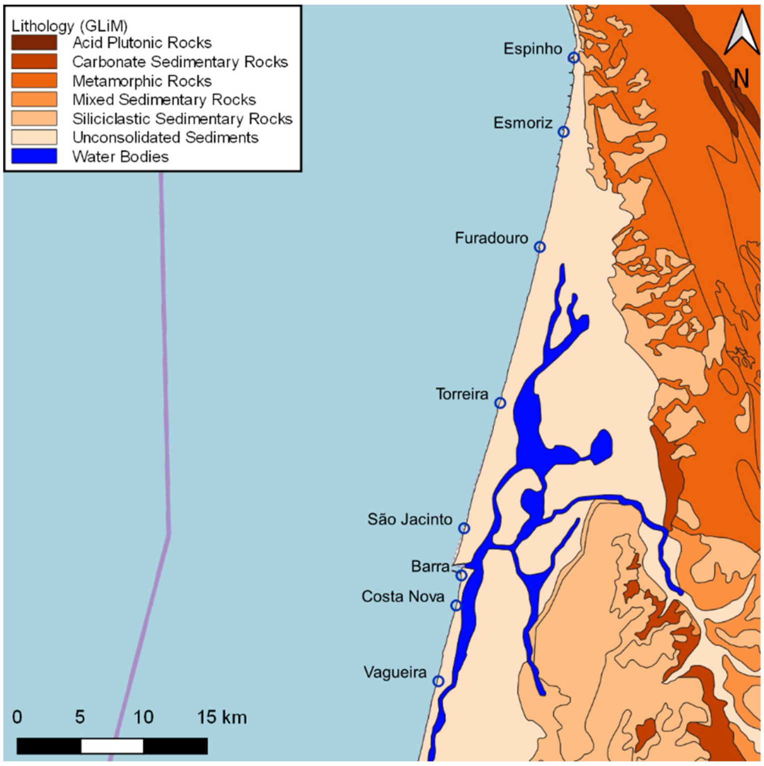

Figure 3.4. Lithological data for Aveiro study site (Hartmann and Moosdorf, 2012).

GLiM is a high-resolution representation of the rock types of the Earth surface. A combination of 92 regional lithological maps was used to produce this dataset. The resulting map has an average scale of 1:3750000, and classifies the world surface in 16 different classes. For Aveiro region, most area is composed by unconsolidated sediments, accompanied by siliciclastic sedimentary rocks and metamorphic rocks.

The land use data was gathered using the Corine Land Cover 2012 (CLC2012; Figure 3.5) dataset (EEA, 2016b). This data is essential for several indicators considered in the methodologies application, such as land cover, geomorphology or infrastructures/heritage. The CLC2012 is also a product of Copernicus programme and is the forth revision performed to represent land cover in Europe, following 1990, 2000 and 2006. This map was first produced to support environmental policy development. Aerial images acquired by Earth Observation satellites were used as main source of data to assess land cover and land use information.

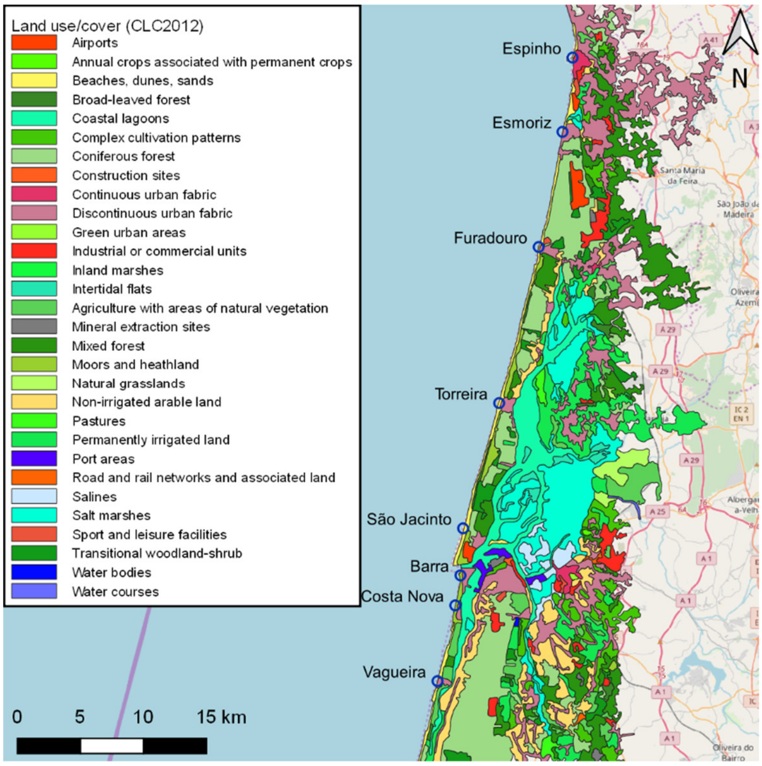

Figure 3.5. Land use/cover for Aveiro study site (EEA, 2016b).

The CLC2012 has a pixel resolution of 25 ha, a positional accuracy better than 100 m and a 1:250000 scale. The nomenclature has 44 classes of land use/cover in total, which are hierarchized in 3 levels. The categories of the broader level are: artificial surfaces; agricultural areas: forests and semi-natural areas; wetlands; and water bodies. The Corine Land Cover project had the participation of 39 countries in 2012 (CLMS, 2017b). In Portugal, the *Direção Geral do Território* (DGT) was responsible for their execution. In Aveiro, most coastline is composed by agriculture or natural areas, with some area presented as discontinuous urban fabric, representing the villages near the coast.

Protected areas at ecological level are also important for land valorisation. In Portugal, there are several types of classification promoted by ICNF (*Instituto da Conservação da Natureza e das Florestas*). The RNAP (*Rede Nacional de Áreas Protegidas*), the Ramsar Convention areas and the Natura 2000 network (N2K) areas are represented in Aveiro study site (Figure 3.6).

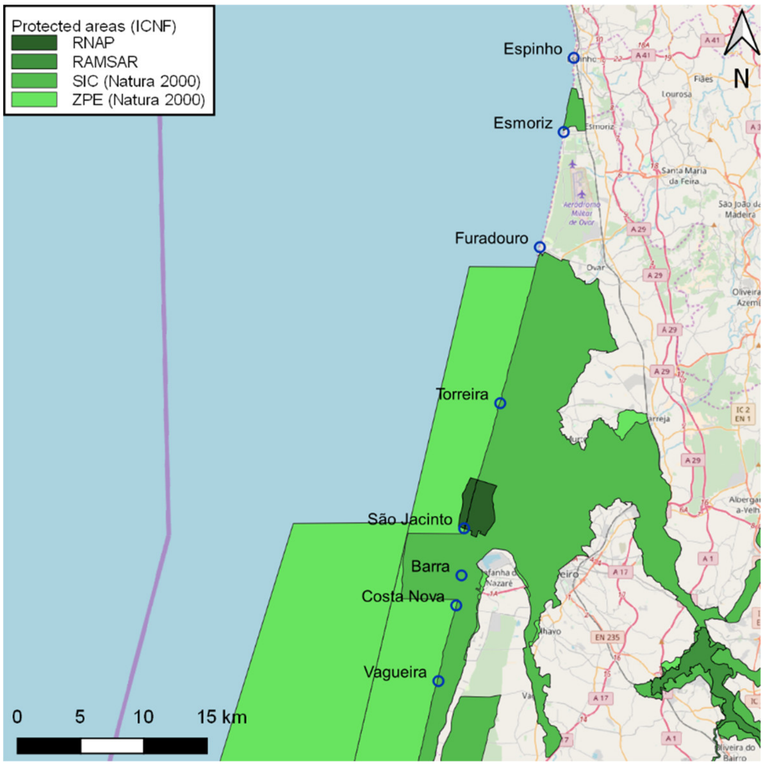

Figure 3.6. Ecological relevant areas in Aveiro study site (SNIG, 2018).

The RNAP (ICNF, 2018) is composed by maritime or land areas that have an important scientific, ecologic, social or scenic value due to biodiversity or natural features, with the aim of giving it legal protection for the maintenance of its value. In

Aveiro region, São Jacinto dunes are included in this classification, representing the highest ecological value in this study area. The Ramsar Convention (UNESCO, 1971) areas are part of an intergovernmental treaty for the conservation and wise use of wetlands and their resources. Finally, the N2K (EC, 2008) is a network of core breeding and resting sites for rare and threatened species, and rare natural habitats. This network is coordinated by the European Commission and has 28 participating countries. In Portugal, this network is divided in two types of classification: SIC (*Sítios de Interesse Comunitário*) and ZPE (*Zonas de Proteção Especial*). The SIC classifies ecological habitats that represent high social importance for the community. In Aveiro, the Barrinha de Esmoriz and Ria de Aveiro are classified as SIC. The ZPE establish areas of high interest for bird conservation and their habitats. Ria de Aveiro is also established as a ZPE. The data to support this map classification was collected from iGeo portal (SNIG, 2018), a web service that provides open GIS data in Portugal, with the objective of contributing and disseminate the use of GIS data.

Population density data for Aveiro was gathered using the GHS (Global Human Settlement; Figure 3.7) resident population grid (Freire *et al.*, 2016). The GHS grid was produced based on Census datasets for 2011, Corine Land Cover Refined 2006 (CLC06Rv2) and European Settlement Map 2016 (ESM2016). The dataset presents the number of persons per hectare in the coordinate reference system ETRS89-LAEA. This dataset represented a step forward in the representation of population density, as in the beginning of this work, the population density used was based on the total population per parish, given by Census 2011. Overall, Aveiro district does not have a highly populated coastline, which agrees with the land use presented previously, only with peaks in population density in the villages near the coastline.

Other relevant data to develop coastal risk assessments is the presence of coastal defence structures along the shoreline, wave climate characteristics and local sea-level trends. This information was not gathered in GIS-format but rather on literature or other types of datasets. The information on coastal defences was taken from previous literature (Costa and Coelho, 2013; Pereira and Coelho, 2013a) and identified using Google Earth (2018).

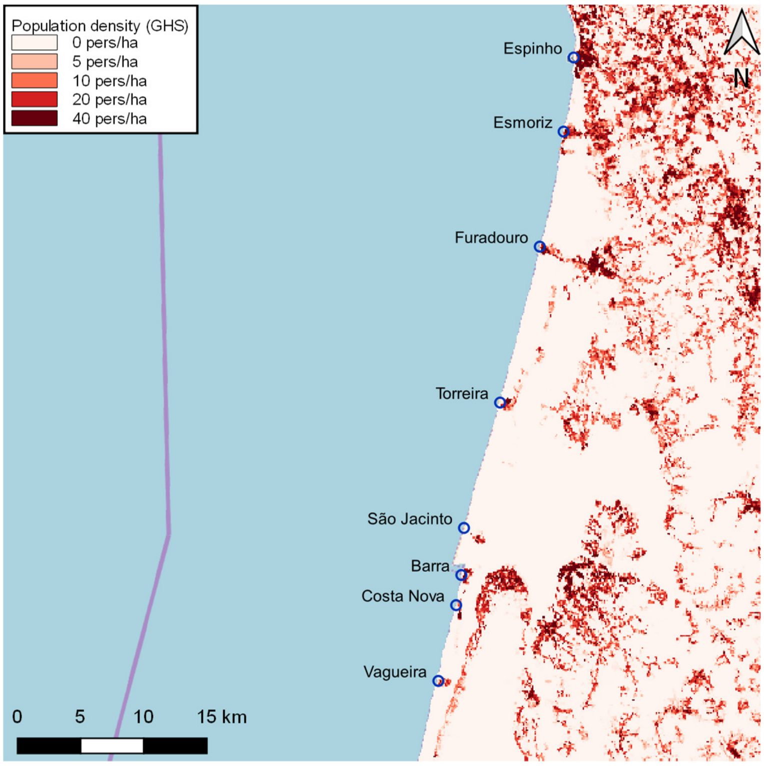

Figure 3.7. Population density for Aveiro study site (Freire *et al.*, 2016).

The wave climate data used is the same as in Narra *et al.* (2015a). In that work, data collected from IH (Instituto Hidrográfico) over 8 months was analysed, taking a mean significant wave height (H_s) of 2.16 m, but reaching a maximum of 9.5 m. This data is in accordance with other publications, such as Costa *et al.* (2001), which identifies a mean H_s of 2.2 m, with storm H_s passing 7 m frequently. Additionally, the data resulting from hindcast simulation near Espinho (Sancho *et al.*, 2013; Heitor, 2014) was also considered. The hindcast used SWAN (Booij *et al.*, 1999) for computing significant wave height, wave peak period and wave direction between 1962 and 2009. This data was used for the identification of extreme events (*i.e.* storms) in the study area.

Regarding sea-level rise (SLR), NOAA (2018a) estimates a rise of 1.27 mm/year for Cascais, in Portugal, which was considered representative of the SLR for Aveiro. This value was computed based on monthly mean sea-level data from 1882 to 1993. This value is in the same order of previous publications (Alveirinho-Dias and Taborda, 1988; Antunes and Taborda, 2009). Alveirinho-Dias and Taborda (1988) considered registers from other locations. Leixões (near Aveiro) registered a sea-level rise of 0.6 mm/year, but only 30 years of data was considered, not enough to estimate a reliable trend.

Finally, to characterize sediment grain size, the research previously carried out by Narra *et al.* (2015a) indicates that the grain size representative of a beach is found at the upper foreshore limit at high tide. Thus, the mean d_{50} considered was 0.36 mm, corresponding to the profile regarded as the most representative by that work. This value corresponds to a medium sand according to Wentworth (1922) classification.

3.2. Macaneta, Mozambique

The second study site considered in this work is the Macaneta spit, located circa 30 km north of Maputo City, Mozambique (Figure 3.8). The study site northern boundary is the Macaneta Holiday Resort and the southern boundary is the inlet and delta of the Incomáti River, limiting the Maputo bay to the north. The east side faces the Indian Ocean, while the Incomáti River estuary is on the west side.

The study area has around 12 km of coastline, the spit varies between 50 m and 600 m wide, and vegetated dunes are present along almost all spit formation. The pattern is interrupted at the narrower parts, where the possibility of breaching is present. Macaneta spit has around 20 scattered summer houses available only for seasonal rental, mainly in the northern part of the spit. The beach is an attractive destination for tourists due to its clean sandy beach. The construction of a bridge that connects this area to Maputo will improve its accessibility, boosting its touristic value. Currently, the economic activities are restricted to some fishery activities, besides the already mentioned house rental (Palalane *et al.*, 2016).

Due to the absence of publicly available national or regional necessary information, the data used to assess the Macaneta study site was mainly collected through local knowledge and from technical and scientific publications. Karlsson and Liljedahl (2015) investigated and quantified the sediment transport and coastal evolution of Macaneta. They collected data on six cross-shore profiles, including topography and sediment sampling. This information, in conjunction with contents of Google Earth (2018), contributed for the estimation of the shoreline position.

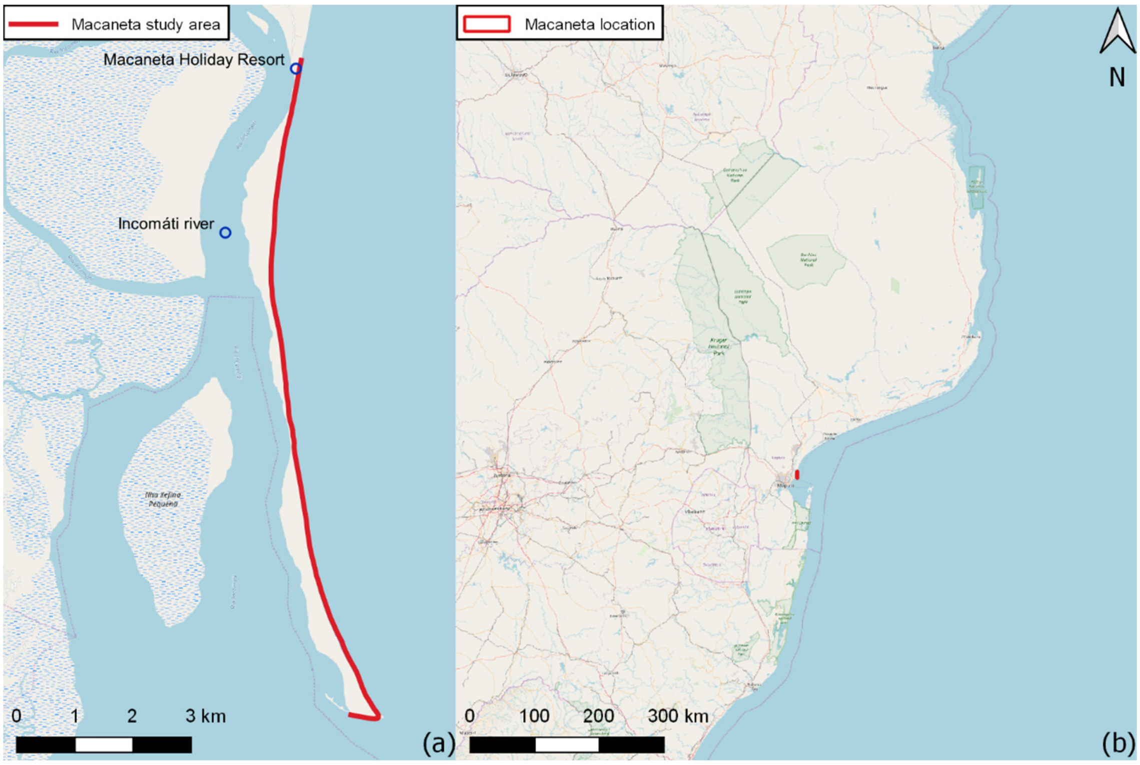

Figure 3.8. Macaneta spit (a) extent and (b) location, Mozambique (OSM, 2018).

The cross-shore profiles were also useful to produce a DEM, but this was later replaced by data from ASTER GDEM2 (NASA and METI, 2011), as they provide better accuracy than data from Google Earth. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM2) was released in October 2011 and is a joint effort from the United States National Aeronautics and Space Administration (NASA) and the Ministry of Economy, Trade and Industry (METI) of Japan to produce a global DEM (coverage spans from 83° north latitude to 83° south latitude). The data has a resolution of 1 arc-second. The projection for a compatible CRS (UTM36) translates that resolution in around 30 m/px. As shown in Figure 3.9, the spit is mainly a low-lying area, only with few higher areas representing dunes. Slope computation was also done for this DEM, using the same process as described for Aveiro site.

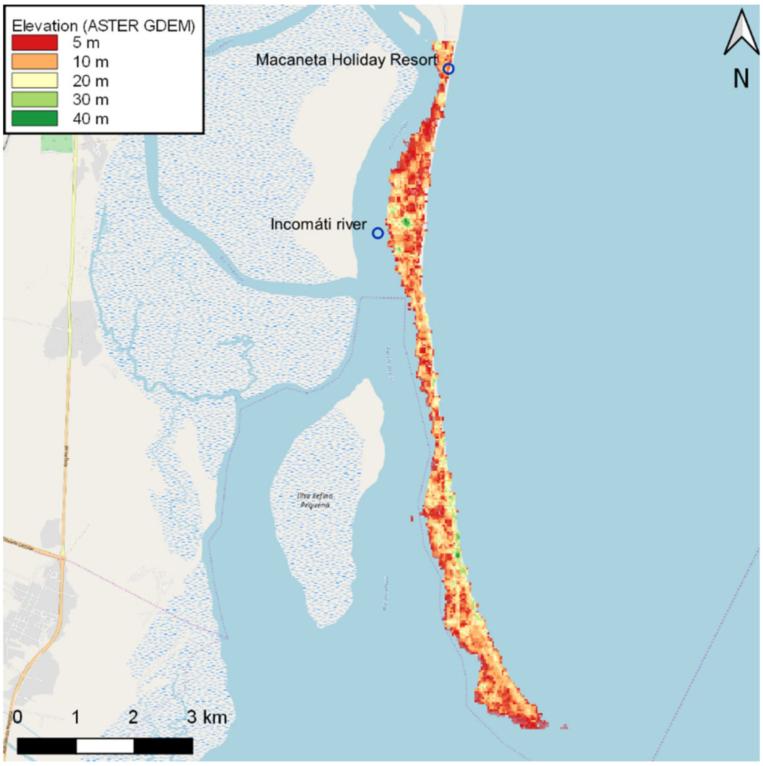

Figure 3.9. Elevation data for Macaneta spit (NASA and METI, 2011).

The north-south spit development indicates that the growth of Macaneta spit was due to a longshore sediment transport directed southwards. However, during the last decades the spit has not experienced a substantial growth as the gradient in the longshore transport is small (DHI, 2013; Karlsson and Liljedahl, 2015; Palalane *et al.*, 2016). Palalane *et al.* (2016) suggests that most significant changes in beach profile are caused by cross-shore processes such as erosion and overwash linked to storms. For the northern section of the spit, from a comparison of rectified old aerial photographs (from 1989 to 2011), DHI (2013) indicates the possibility of slight erosion being occurring at a rate not exceeding 0.1 m/year. According to this report, the main reason for this low value lays on the fact that the shoreline orientation is nearly equal to its equilibrium value for the incoming waves. For the southern section, Karlsson and Liljedahl (2015) indicates that a slightly eastwards migration of the spit (towards the sea) is occurring, pointing to an accretion of the beach.

Like in Aveiro, GLiM (Hartmann and Moosdorf, 2012) was used as source of lithologic information. In this case, the area is completely composed by unconsolidated sediments. Karlsson and Liljedahl (2015) collected sediment samples along the six cross-shore profiles. The mean value of d_{50} for all samples is 0.59 mm. The mean values of d_{50} by cross-shore location is 0.44 mm in the foredune, 0.58 mm in the berm, 0.96 mm in the swash zone and 0.38 mm in the breaker zone. Using the same criteria as for Aveiro, the sediment grain size of the berm was used as representative, as this is the closest location to the upper foreshore limit at high tide. The mean of d_{50} in the berm (0.58 mm) corresponds to coarse sand, according to Wentworth (1922) classification.

Accordingly to a report from DHI (2013), Maputo experiences semi-diurnal tides, with a spring tidal range varying between 2 m and 3 m. Wave data at an offshore point of Inhaca Island was obtained from the global wave model Wavewatch III (Tolman, 2009), and the nearshore wave conditions were calculated by DHI (2013) using MIKE 21 SW. It was concluded that the nearshore waves are mainly NEE to SEE oriented and present an annual maximum significant wave height at Macaneta spit equal to 2 m, although offshore significant wave height frequently exceeds 3 m. One reason behind the wave height reduction is a partial natural sheltering of the spit provided by the Dannae shoal. Finally, the local SLR estimated by NOAA (2018a) is 1.4 mm/year for Durban, South Africa, considering the monthly sea-level rise from 1971 to 2016. This value was considered representative of Macaneta spit.

3.3. QUINTANA ROO, MEXICO

The state of Quintana Roo is in the southeast of Mexico, in the Yucatán peninsula, facing the Caribbean Sea. The study site covers the coastal area of three municipalities of the state, with around 250 km of coast – 140 km on the peninsula and 110 km for the perimeter of Cozumel Island (Figure 3.10). The coastline of Quintana Roo has an extensive variety of morphologic formations, with beaches and coastal lagoons (Martell *et al.*, 2010).

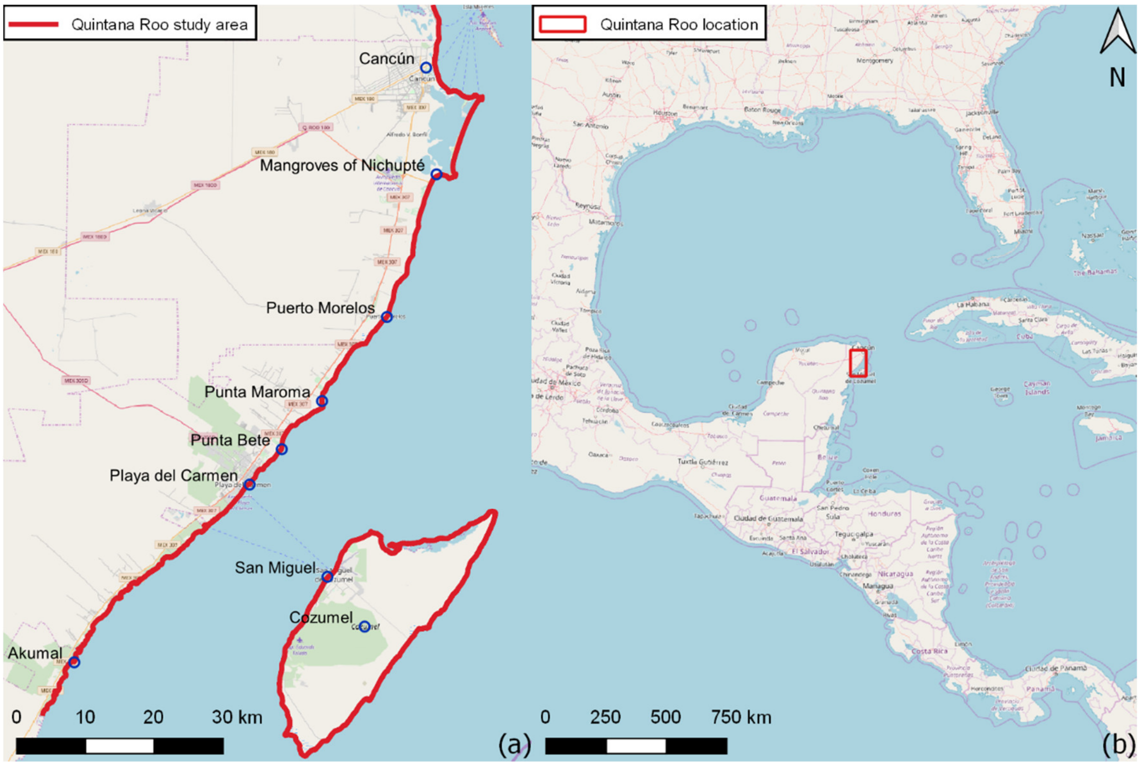

Figure 3.10. Quintana Roo study site (a) extent and (b) location, Mexico (OSM, 2018).

Due to the lack of georeferenced data of shoreline position, this feature had to be manually digitized. The shoreline position in 2006 and 2016 were drawn from Google Earth (2018) satellite images to evaluate the shoreline change rates of the study area. This process also considered information of Silva *et al.* (2007) and Escudero *et al.* (2014) to validate the output. Since the area has a microtidal regime, tides were not considered to influence the upper foreshore limit, so the wet/dry line was used as reference for the shoreline position. The shoreline position change rates were computed using the Shoreline Analyst plugin for QGIS (Lima *et al.*, 2016) and later refined using the DSAS for ArcGIS (Thieler *et al.*, 2009). Despite having some areas suffering from coastal erosion, in general, the shoreline position presented minimal changes. Contributing for that are the several coastal defences near urban areas that hold the shoreline position, also identified on Google Earth.

The tidal range was based on measurements taken at Puerto Morelos (Figure 3.10) from 2007 to 2011, which identify the site as microtidal, with a mean amplitude of 0.15 m and a maximum value of 0.3 m. Villatoro *et al.* (2015) recorded slightly greater tidal ranges, but in the microtidal regime nonetheless, with 0.2 m for neap tide and 0.6 m for spring tide.

The wave climate in Quintana Roo is moderate, but with a frequent presence of extreme events. Odériz *et al.* (2014) states that the modal significant wave height is inferior to 1.5 m. Odériz *et al.* (2014) also describe the sporadic summer extreme events (hurricanes), which can produce significant wave heights of 13 m. Villatoro *et al.* (2015) also present a similar description of the wave climate, stating that the prevailing significant wave height varies between 1 m and 1.5 m with a wave period of 4 - 9 seconds. They also refer to extreme events with characteristics similar to Odériz *et al.* (2014), adding that the storm surge from these hurricanes can be up to 2 m height. Data from hindcast simulation produced by Silva *et al.* (2008) was used for identification of extreme events. The model registered hourly significant wave heights from 1948 to 2010. The mean significant wave height was 1.2 m, but the maximum registered was 13.1 m, due to the summer hurricanes that are frequent in the region, which is validated by authors referenced previously.

Quintana Roo state has a wide variety of georeferenced data publicly available from governmental entities. The georeferenced information used for Quintana Roo was mainly produced by INEGI (*Instituto Nacional de Estadística y Geografía*), including a DEM and land cover information. The DEM was produced using LiDAR information (INEGI, 2012). This dataset covers most Mexico municipalities with topographic information at a horizontal resolution of 5 m. The scale is 1:10000, using the coordinate reference system ITRF92. As shown in Figure 3.11, the elevation on Quintana Roo is generally the lowest of the three study sites, with elevations reaching around 15 m maximum, even in inland areas. This information was used for topographic and slope assessments, using the same process previously described for Aveiro.

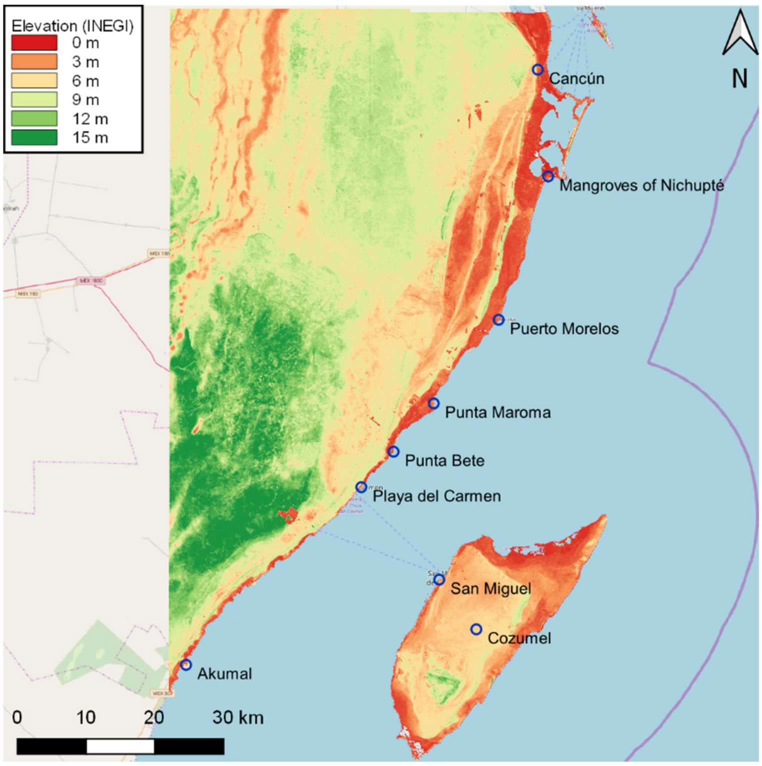

Figure 3.11. Elevation data for Quintana Roo study site (INEGI, 2012).

The land use/cover information (Figure 3.12) was the 5th (from 2013) and later the 6th (from 2016) series maps produced by INEGI (2016).

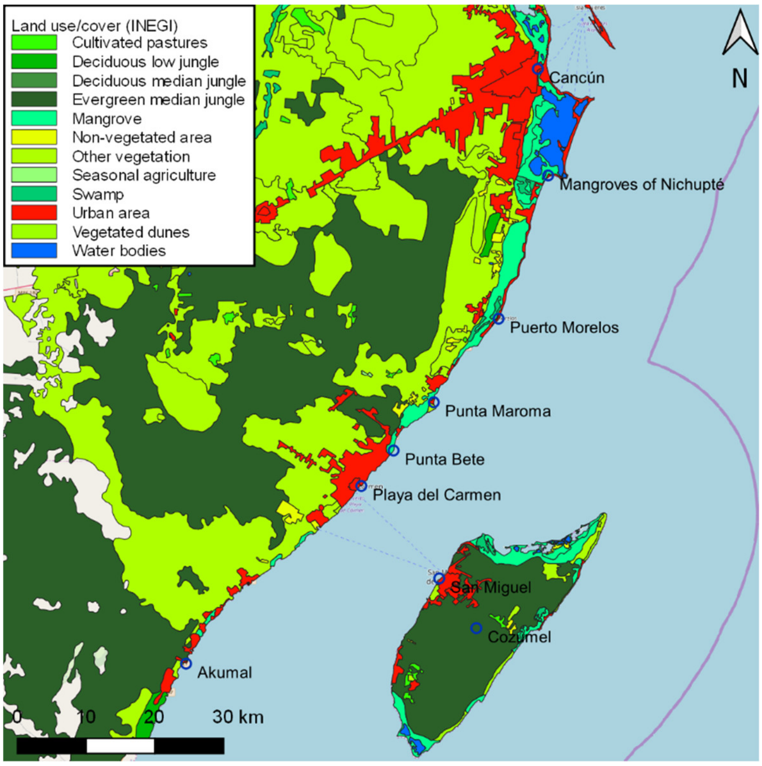

Figure 3.12. Land use/cover for Quintana Roo study site (INEGI, 2016).

This dataset covers the entirety of Mexico at 1:250000 scale in a vector format. The latest series was based on information from the previous series and data collected throughout 2014 and 2015. The CRS is the WGS84 with a resolution of 0.017°/px. Mexico is divided in 33 main classes, which are then divided in several subclasses. Quintana Roo is mainly composed by jungle and other vegetation (Figure 3.12), but has significant urban presence near the coastline, potentially exposed to coastal hazards. The presence of mangroves is also noticeable in the study area's coastline.

The Global Lithological Map (Hartmann and Moosdorf, 2012) was also used as source for information regarding lithology. Contrary to the previous study sites, the coastline of Quintana Roo is not mainly composed by unconsolidated sediments, presenting also a considerable length of coastline containing sedimentary rocks (Figure 3.13).

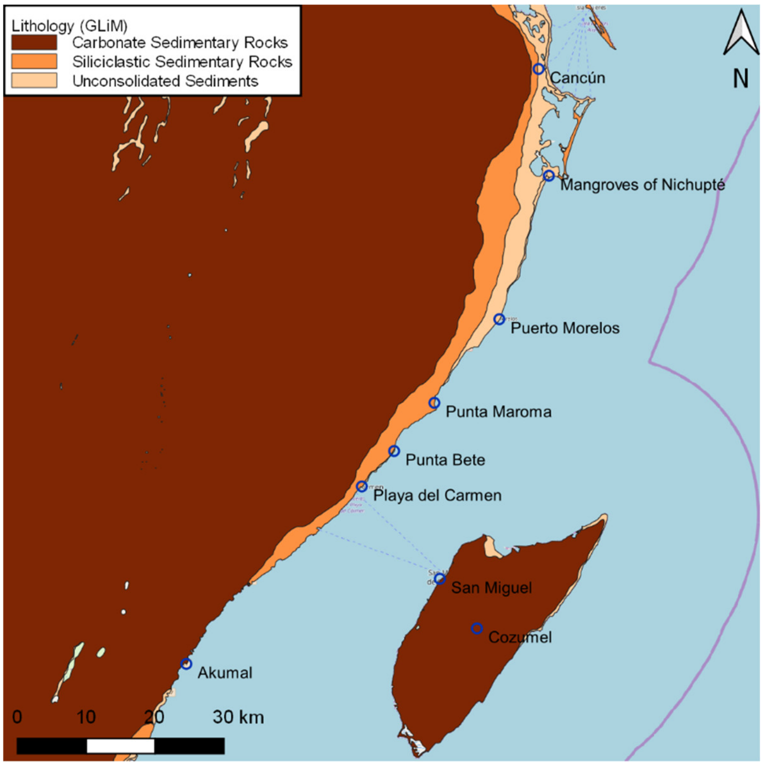

Figure 3.13. Lithology data for Quintana Roo study site (Hartmann and Moosdorf, 2012).

The coastal geomorphology of the area corroborates with the lithologic composition. The presence of sandy beaches is less common, giving place to indented coasts, mainly in the south part of the study area. The estimation of sediments' grain size was based on Odériz *et al.* (2014), which present relevant sediment parameters for several locations between Punta Maroma and Punta Bete. The samples taken yielded a d_{50} between 0.3 mm and 0.4 mm. This size corresponds to medium sand, according to the Wentworth (1922) classification.

The identification of ecological relevant areas in Quintana Roo was executed considering data from CONANP (*Comisión Nacional de Áreas Naturales Protegidas*; 2017). In Mexico, CONANP distinguishes areas in 6 different typologies. In the considered study area, only 3 are present (Figure 3.14): APFyF (*Áreas de Protección de Flora y Fauna*); PN (*Parques Nacionales*); and RB (*Reservas de la Biosfera*). A considerable area in the Caribbean Sea was classified as a biosphere reserve (RB), covering almost the entire coastline of the study area. Moreover, the mangroves of Nichupté and the northern coastline of Cozumel are protected areas for flora and fauna (APFyF). These areas are also included in the Ramsar areas mentioned previously for wetland areas. Finally, the reefs of Cozumel and Puerto Morelos are considered national parks (PN) due to the presence of endangered marine fauna and flora. These areas are also included in the Ramsar Convention.

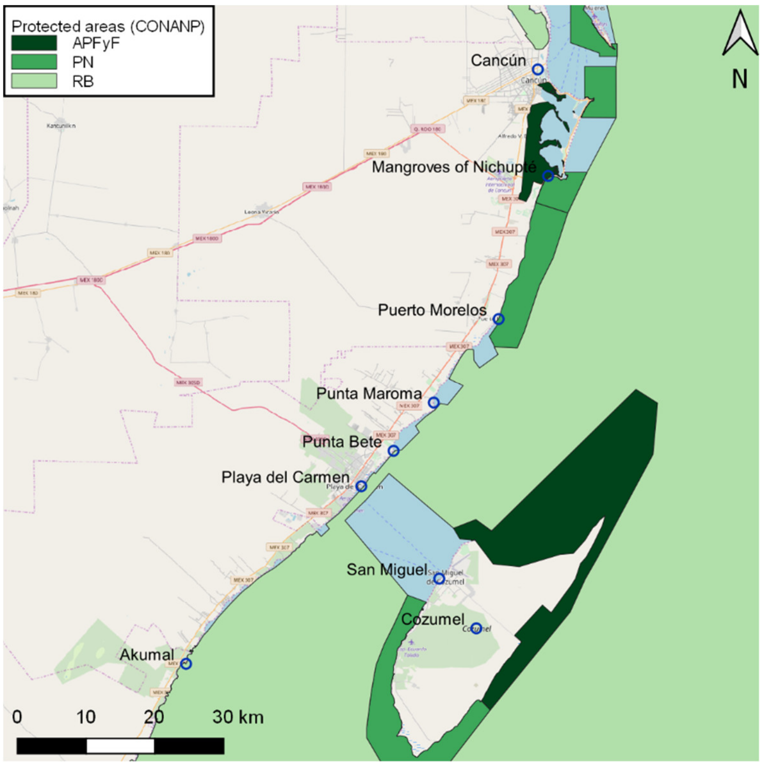

Figure 3.14. Ecological relevant areas in Quintana Roo study site (CONANP, 2017).

The dataset for population density used in Quintana Roo is the GPWv4 (Gridded Population of the World, Version 4; CIESIN, 2017). This dataset consists of an estimate of human population density (in persons/km^2) based on national censuses and population registers for the years 2000, 2005, 2010, 2015 and forecasted population density for 2020. In this work, the population of 2015 was considered (Figure 3.15). The population data collected at a national and sub-national administrative units was allocated to 30 arc-second grid cells. The data file was created with the same resolution, which corresponds to approximately 1 km at equator. The lower resolution comparatively with Aveiro gives less detailed data, namely on smaller urban areas, which can be identified in the land use map (Figure 3.12). However, the larger urban areas correspond to high population densities, with more than 2000 persons/km^2.

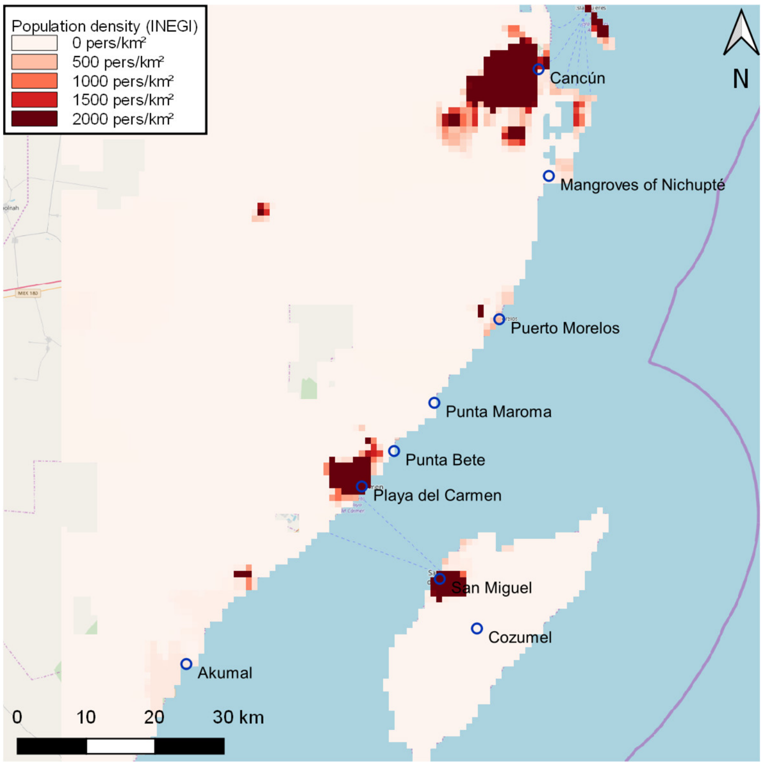

Figure 3.15. Population density for Quintana Roo study site (CIESIN, 2017).

Finally, the sea-level trend for Cabo San Antonio (Cuba) estimated by NOAA (2018a) is a rise of 4.12 mm/year, based on monthly mean sea-level data from 1971 to 2016. This value was adopted to characterize SLR value in Quintana Roo. The nearest location where there is SLR data in Mexico is Progreso, which has a sea-level increase trend of 3.69 mm/year between 1952 and 2013. However, this area is further away than Cabo San Antonio.

3.4. Data summary

This work considered three study areas that are similar in its geomorphologic composition (sandy coasts), as these types of coast are the most susceptible to coastal erosion, but different in terms of extension, wave climate (facing different oceans), and development levels. The type of information gathered allowed to represent the areas' characteristic ranges from global data to specific and local details, based on literature and local knowledge.

The information here presented was mainly collected from publicly available databases, which reinforce the aim to develop a methodology that does not require a great amount of resources to be applicable. It is expected that municipalities or national governments (potential end-users) would have even better access to local sources of information, which was allegedly produced by their staff for other projects, meaning that the effort required for applying coastal risk methodologies would be even lower.

The expertise required for gathering and manipulating this data is an intermediate knowledge of GIS applications. For an inexperienced user, GIS systems and related concepts would take some time to learn. However, most targeted stakeholders should have experience with this kind of software, as local municipalities require territory management, which is often done using these tools.

In the following chapters, this information will be used for development of GIS assessments across the three study sites. Some data is used in different forms for different methodologies, which requires a more intricate manipulation of GIS, but nonetheless achievable if the user has some knowledge of these systems.

4. GIS-based modified Coastal Vulnerability and Risk Assessment: CERA1.0

The development of a new proposal for coastal erosion risk assessment requires the acquisition of knowledge on several subjects. Thus, the application of existent methodologies contributes to the increase of experience on those subjects, such as GIS systems and risk analysis. The first step taken was the adoption of CVRA (see section 2.2.4), developed by Coelho (2005), as the base for a new methodology. The methodology got the name of CERA (Coastal Erosion Risk Assessment) and is presented in Narra *et al.* (2017). The method was renamed as CERA1.0 in this thesis, representing the first version of a methodology developed within the project. This chapter's content is featured in Narra *et al.* (2017), with the addition of the application of CERA1.0 to Quintana Roo study area, in Mexico.

The next sections of this chapter highlight the changes done to CVRA and the application of CERA1.0 to Aveiro, Macaneta and Quintana Roo. At the end, a discussion on the obtained results is presented.

4.1. Changes introduced from CVRA to CERA1.0

The changes introduced from CVRA to CERA1.0 were focused on 2 main parts. CVRA's algorithm was subject of adjustments in some key indicators and combinations, in order to better suit the methodology for application to a wider range of study areas. Additionally, the method was incorporated in a GIS environment for easier access and application by coastal managers.

4.1.1. Algorithm development

Regarding the vulnerability assessment, the classification criteria of distance to shoreline was changed to values presented in Table 4.1 (for comparison to the original values, refer to Table 2.2). In a preliminary assessment, the first 20 m classified as level 5 were considered underestimated and would not have any impact, namely on larger scale assessments. If a resolution larger than 20 m/px was considered in the inputs (common for areas with few data), class 5 would not be represented in those maps. In addition, four of the five classes were defined within the first 200 m of coastline. Therefore, the distance to shoreline limits that define the first three classes were increased. The goal was to fit the three most penalizing classes within the limit defined by the Portuguese coastal zone management plan, at 500 m distance to shoreline (MARN, 1993) as protected coastal zone. The geomorphology classification was also slightly changed, considering dune presence as class 3 instead of class 5. The presence of dunes represents a source of sediments for the beach in a deficit scenario and a natural protection for anthropogenic activities and infrastructures behind them. Therefore, it was considered that its presence should contribute for a lower level of vulnerability than it was firstly considered by Coelho (2005).

Table 4.1. Criteria changes from Coelho (2005) to CERA1.0 (Narra *et al.*, 2017).

Parameters	Very low 1	Low 2	Moderated 3	High 4	Very high 5
Distance to shoreline (m)	>1000	]500, 1000]	]300, 500]	]150, 300]	≤ 150
Geomorphology	Mountains	Rock cliffs	Erosive cliffs Sheltered beaches Dunes	Exposed beaches Coastal plains	River mouths Estuaries
Population density (inhabitant/km^2)	< 125	[125, 250[	[250, 500[	[500, 1000[	≥1000
Economy (employment/km^2)	0	]0, 120]	]120, 240]	]240, 480]	> 480
Ecology	No ecological relevance	Agricultural reserve Areas of community interest	Ecological protected area	Coastal protection zone	Natural reserve
Heritage	No heritage to preserve	Scattered houses Roads	Urban settlements	Regional historic buildings Critical facilities	National monuments

All indicators within the consequence assessment of the original method (Table 2.4) were slightly changed or rephrased to be more specific or to include other situations that were previously unmentioned. Classes regarding population density were pre-assessed and was concluded that values for each class were too broad, with most areas pre-assessed being classified in the lower three classes of consequences. Therefore, the population density thresholds for each class limit were reduced, allowing for a more even distribution of classes in the tested areas (Table 4.1). Coelho and Arede (2009) defined the economy classes by the (absolute) number of employments, as their work consisted in categorising several specific locations in the Aveiro district. This type of classification is incompatible with assessments of large areas due to the necessity of a unit area to measure employments. Therefore, this category was redefined, considering the number of employments per km^2. The definition of classes was performed by assessing the number of employments in several Portuguese parishes (INE, 2016). The classification of the ecology parameter remained essentially the same, only with slight changes in the definition of protected areas. Moreover, the methodology only considered historical infrastructures in the heritage classification (Table 2.4). Therefore, schools, hospitals, airports and housing were also added to the heritage indicator (Table 4.1).

Finally, during the development of CERA1.0, two different hypotheses were considered for the combination of vulnerability and consequence, namely, the summation and the product of individual class levels. For both, a distribution function was fitted and the cumulative distribution of that function was used to divide each level of risk, considering an equal percentage (20%) of the outcomes for each level. Of those two methods, the distribution function obtained by the sum of vulnerability and consequences levels was chosen because it presented a well-defined distribution function (linear and symmetric), allowing for a construction of a risk matrix with uniform variation, considering 5 possible combinations for each level. As a result, two values of the risk matrix (Table 4.2) were changed relatively to the original methodology (Table 2.5): the combination 2-2 (vulnerability - consequence), which corresponded to risk class I, was changed to class II, and the combination 4-4 was changed from risk class V to class IV. This change reduces some skewness in the final risk classification, which tended to extreme results.

Table 4.2. Risk matrix proposed for CERA1.0 (Narra *et al.*, 2017).

		Consequence				
		I	II	III	IV	V
Vulnerability	I	I	I	I Very low	II	III
	II	I	II	II Low	III	IV
	III	I	II	III Moderate	IV	V
	IV	II	III	IV High	IV	V
	V	III	IV	V Very high	V	V

4.1.2. Algorithm implementation

The integration of CERA1.0 in a GIS environment was considered essential for future uses, allowing for a quicker calibration of the method and for an easier acceptance by coastal managers. This integration was achieved by creating a plugin in QGIS (2018). This software is part of the Open Source Geospatial Foundation (OSGeo, 2018) and its popularity among the community leads to a great access to information on how to use it and how to develop for it. The creation of the plugin within a GIS software allows users to have access to features that this software provides while using the plugin, facilitating the utilization and editing of information that is already in GIS format. The development of plugins and scripts in QGIS was carried out using python as a programming language. Python was created in the early 1990s and is an interpreter, interactive, object-oriented programming language (Python, 2018), meaning that it requires fewer lines of code than C++ or Java to write the same application (Summerfiled, 2008). The connection between python and QGIS was developed through bindings, called PyQGIS (Sherman, 2014).

The choice of QGIS over proprietary software, such as ArcGIS (ESRI, 2016), was influence by its free and open-source nature. This characteristic could boost the adoption rate of the present plugin, since there are no fees required to use it and there is freedom to change the software to meet user needs. It was expected that a large number of users lead to a higher number of contributions and suggestions to improve the plugin, which can be implemented by the authors or even by other members of the QGIS community. For these reasons, the code for the plugin was made available on GitHub (2016) at www.github.com/NEFEC-UA.

Figure 4.1 presents the graphical user interface of the CERA1.0 plugin. The interface allows the selection of one raster layer for each indicator of vulnerability and consequence. These maps must be previously created to represent the classifications for each parameter from 1 to 5, as described in Tables 2.2 and 4.1.

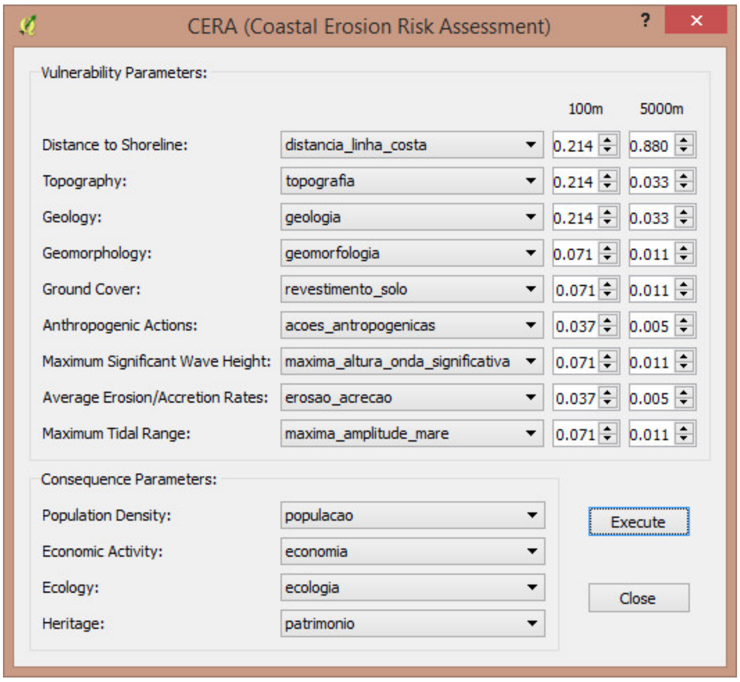

Figure 4.1. Graphical User Interface (GUI) of CERA1.0 (Narra *et al.*, 2017).

Buttons to change the weights of each vulnerability indicator were included to allow for testing of the methodology and quicker calibration for other study sites. The generated outputs are a vulnerability map, a consequence map and a risk map. The output resolution corresponds to the highest resolution of any input map. Adopting the highest resolution allows the final output to not lose information due to maps with lower detail. However, since no interpolation is performed, this does not increase the original information from the lower resolution maps. The user should have into account the effect that less detailed data can have in the final output. In addition, raster maps should all be in the same geodesic coordinate reference system (CRS), appropriate to the region of application.

4.2. APPLICATION TO AVEIRO CASE STUDY

The application of CERA1.0 to Aveiro requires the processing of data presented in section 3.1. This data was trimmed up to 2 km inland, as this was the area chosen for application of CERA1.0. The combination of GIS data also required the adoption of a single CRS. In the case of Aveiro, the most suitable CRS is the ETRS89-TM06 (EPSG:3035).

The development of indicator maps was mostly a straightforward transformation of the original data to get maps classified from 1 to 5, according to CERA1.0 criteria (Table 2.2, Table 2.4 and Table 4.1) for both vulnerability and consequence outputs.

Figure 4.2 shows the indicators of distance to the shoreline and topography. For the development of the distance to shoreline map, the vector shapefile of Lira *et al.* (2016), for 2010, was used to compute a raster distance map (Figure 4.2a), using the *Proximity* tool from QGIS.

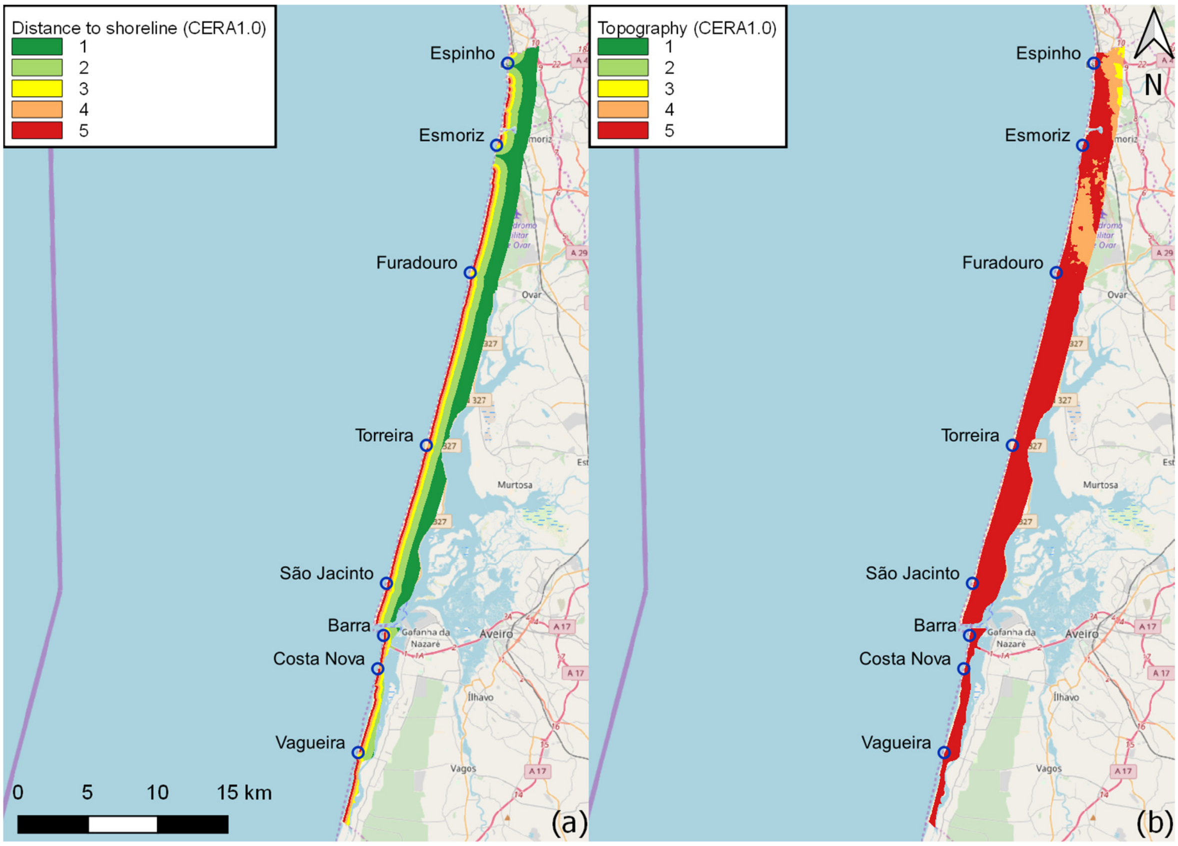

Figure 4.2. Classification of (a) distance to shoreline and (b) topography for Aveiro, using CERA1.0.

The *Proximity* tool produces a map with values of distance from a selected feature, in this case, the shoreline of Aveiro littoral. The output is then divided in classes from 1 to 5 according to Table 4.1, using the *Raster Calculator* in QGIS. After several computation efficiency tests and considering the remaining input data, the resolution chosen for this output map was 5 m/px. This resolution provided a reasonable quick computation time, while did not compromise data detail of any other indicator.

The topography maps used a DEM produced with elevation data from Google Earth. The DEM was produced by extracting numerous georeferenced points with elevation data and applying the *Interpolation* tool within QGIS. Next, the *Raster Calculator* was used to define the topography classes. The use of EU-DEM (EEA, 2016a) would have been more adequate, but at this early stage in the work, its existence have yet to be known. All area considered fall in classes 4 or 5, highlighting the low elevation of the region (Figure 4.2b).

The geology classification was based on GLiM dataset. A class was attributed for each nomenclature, based on the criteria of Table 2.2. As stated previously, the area is mainly composed by non-consolidated sediments, and that is shown in Figure 4.3a, where only a small percentage of territory is class 2 (metamorphic rocks). For geomorphology classes, the base dataset was the CLC2012 (EEA, 2016b), together with topographic, geologic and aerial imagery data. Since most area has a low elevation and is composed by unconsolidated sediments, only classes 3 and 4 are existent. The CLC2012 and aerial images were used to identify dune presence. Otherwise, the area was considered coastal plain or exposed beach, both classified as 4 (Figure 4.3b).

The CLC2012 was also the base data for ground cover classification. Each of the 44 land use/cover classes were classified from 1 to 5 as defined by Table 2.2 (Figure 4.4a). Impermeable areas, such as industrial facilities, urban areas or other infrastructures were fitted into classes 4 and 5. Beaches were considered non-vegetated areas (class 3) and vegetated natural areas were classified as 1 or 2, depending on the vegetation density.

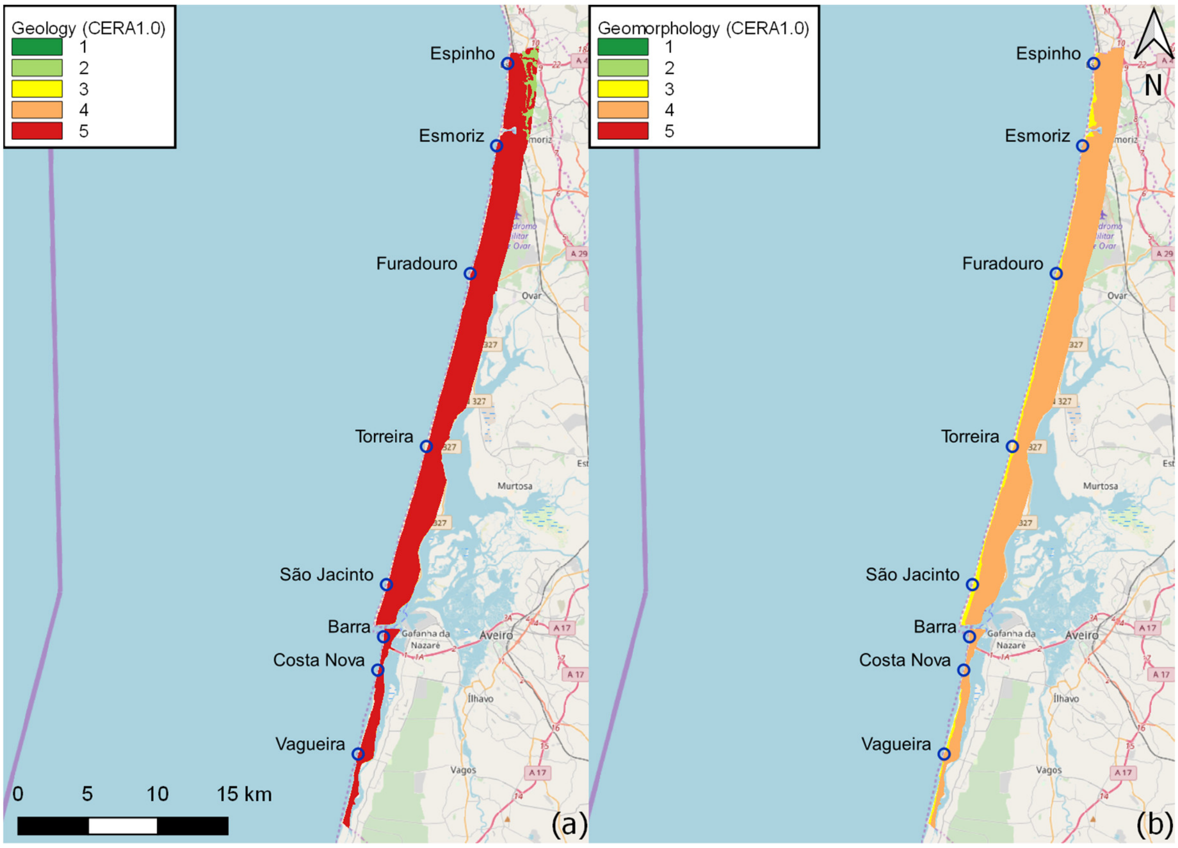

Figure 4.3. Classification of (a) geology and (b) geomorphology for Aveiro, using CERA1.0.

The classification of anthropogenic actions at Aveiro study area (Figure 4.4b) was set at very low vulnerability (class 1) for any location within 1 km length updrift (to the north) of any groyne, as the dominant incident wave climate is from northwest and the annual average sediment drift is towards the south. The coastline protected by longitudinal revetments was also considered as class 1. Areas with soft interventions, such as artificial nourishments, but where is identified a reduction of fluvial sources of sediment supply, were classified as class 3. Classes 4 and 5 were attributed to areas without any shoreline protection interventions. The difference between them lies on the reduction of natural sediment supplies verified on class 5, something that does not happen in class 4.

The shoreline change rates were classified by a straightforward application of the criteria presented in Table 2.2 (Figure 4.4c) using the dataset from Lira *et al.* (2016). For the latter indicator, the coastline that was stabilized by coastal structures was considered of class 1, corresponding to stabilized or accretion rates.

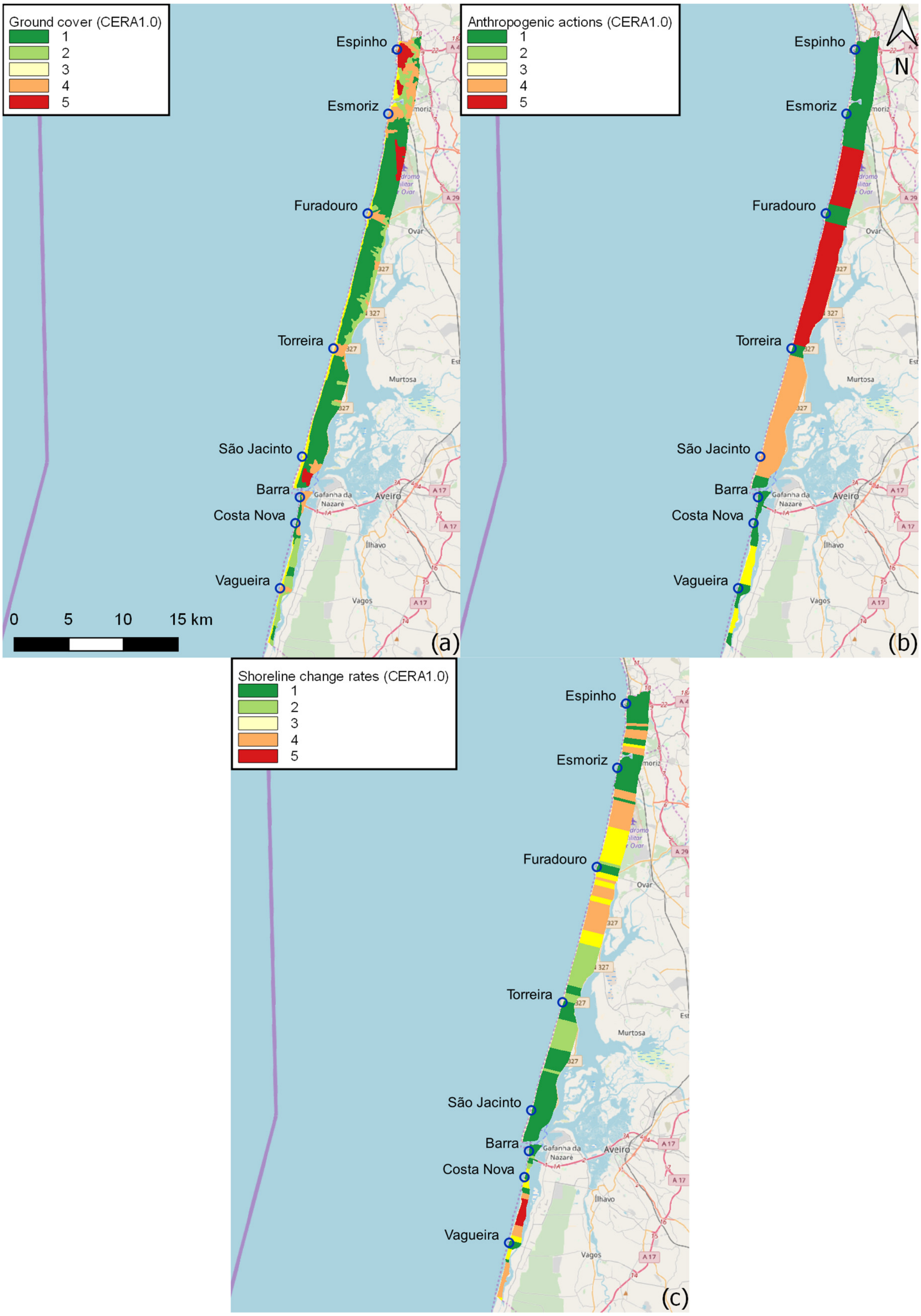

Figure 4.4. Classification of (a) ground cover, (b) anthropogenic actions and (c) shoreline change rates for Aveiro, using CERA1.0.

The indicators of maximum significant wave height and maximum tidal range were assessed based on local data collected by the Hydrographic Institute. During the period of 8 months analysed in Narra *et al.* (2015a), maximum significant wave height reached 9.48 m, corresponding to class 5 along the whole coastal stretch. As stated in the previous chapter, longer wave climate time series were used for later assessments. These datasets are in accordance with the data here used and do not affect the final output of this methodology. Tidal range varies between 2 m and 4 m, thus it is classified with class 3 along the entire coastline.

The classification for consequence indicators of population density and economy (Figure 4.5) were based on the criteria described in Table 4.1, and used information from Census 2011 (INE, 2016) and administrative areas from CAOP (DGT, 2017).

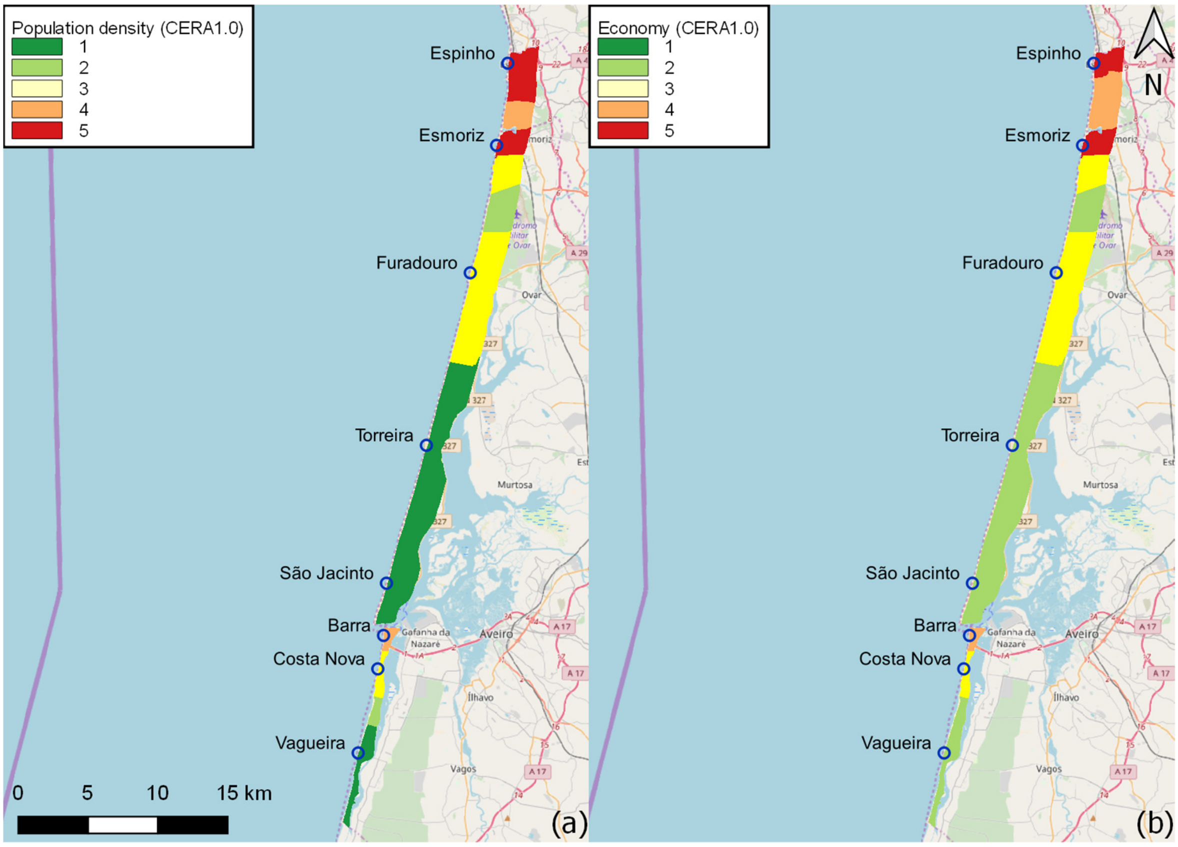

Figure 4.5. Classification of (a) population density and (b) economy for Aveiro, using CERA1.0.

The population density used in those classifications correspond to the complete area of the parish, and not only to the coastal area. Although the classifications attributed were probably below reality, this assumption corresponds to the highest level of accuracy possible to obtain at the execution time of the assessment and was considered representative of the area. This approach was revised in following assessments, namely on Quintana Roo study site. The classification of population density and economic activity is similar, since the amount of population is directly related with the amount of jobs available per parish. The parishes at north (*e.g.* Esmoriz, Espinho) were classified in classes 4 and 5 due to its higher population (around 10000 for each parish) and smaller area when compared with southern parishes (*e.g.* São Jacinto, Torreira).

The classification for ecology and heritage indicators (Figure 4.6) were also were based on the criteria described in Table 4.1.

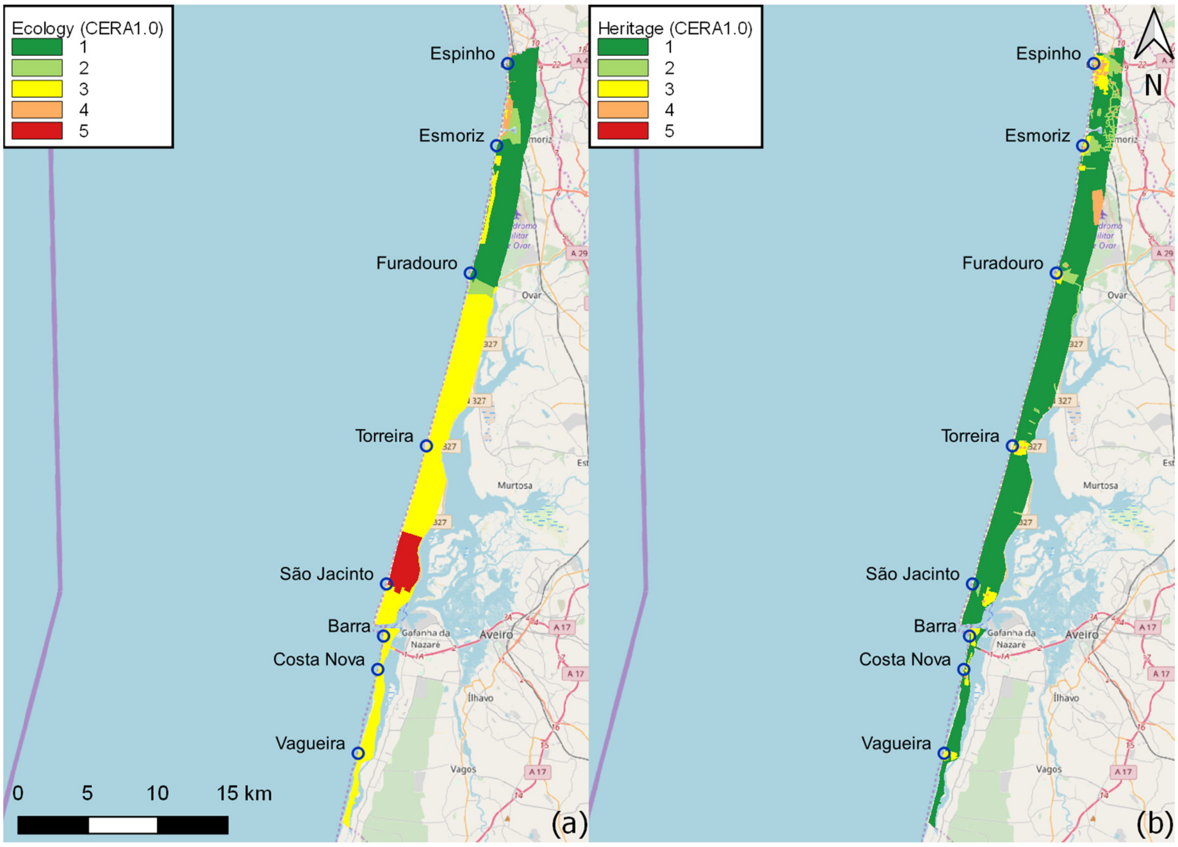

Figure 4.6. Classification of (a) ecology and (b) heritage for Aveiro, using CERA1.0.

The criteria for classifying the ecology indicator (Figure 4.6a) followed naming conventions for protected areas in Portugal. Therefore, each class in this map corresponds to a type of protected area in Portugal. For the heritage assessment (Figure 4.6b), all levels of urbanization were considered. Thus, scattered houses and roads are classified as level 2, urban settlements or urbanized areas are class 3 and a radius of 100 m around each location of non-protected heritage defined by SIPA (*Sistema de Informação para o Património Arquitetónico*; SNIG, 2018) was attributed class 4. Class 5 is reserved to national monuments, which are not present in the study area.

The resulting outputs from CERA1.0 processing is vulnerability (Figure 4.7), consequence (Figure 4.8) and risk (Figure 4.9) maps.

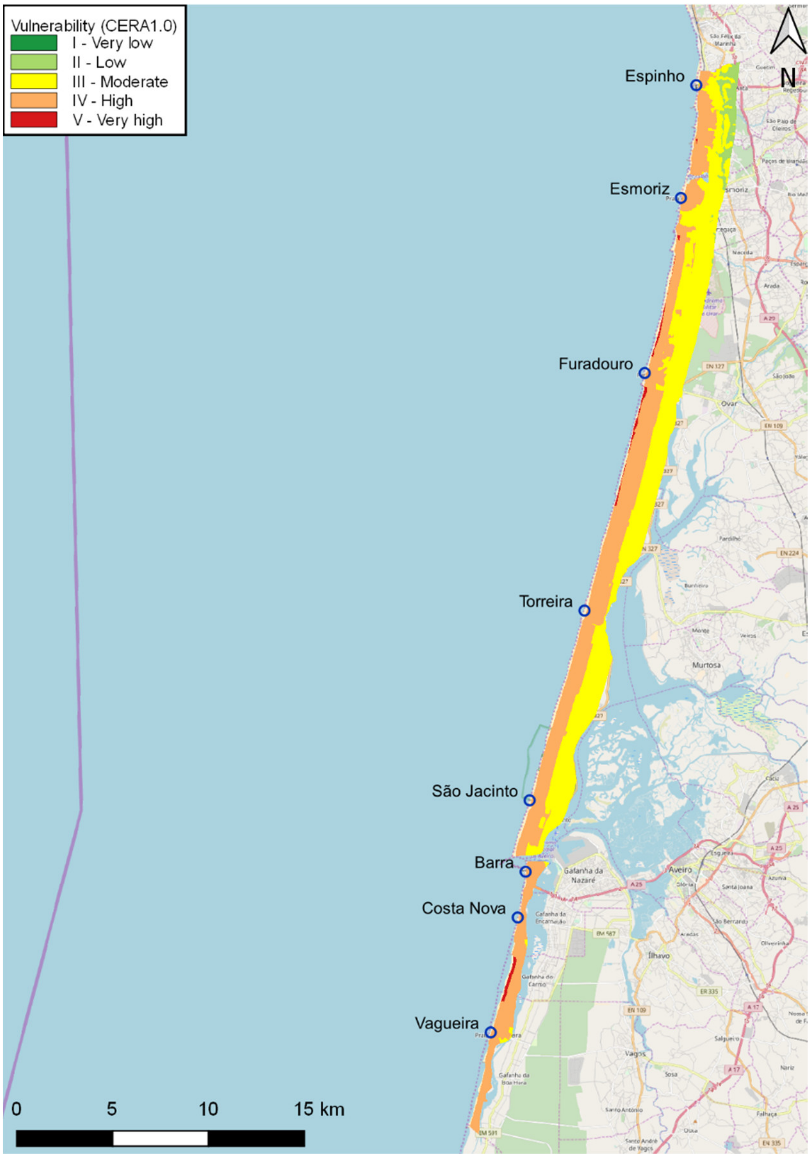

Figure 4.7. Vulnerability classification for Aveiro, using CERA1.0.

Like the individual indicator maps, the outputs assessed a land stripe with a maximum of 2 km parallel to the shoreline, classifying vulnerability, consequence and risk in a 5-level scale, from I to V (lowest to highest).

Figure 4.8. Consequence classification for Aveiro, using CERA1.0.

Aveiro vulnerability classification (Figure 4.7) shows that the study area is classified as highly vulnerable (class IV) along most of the shoreline, with just a few narrow stretches of very high vulnerability (class V). The classification of topography and geology, both mainly classified as very high, contribute the most for this classification. In addition, adverse hazard conditions, namely class 5 maximum significant wave height, contribute for a global high level of vulnerability. Inland, most area is classification III, as they are not as exposed to the hazard as the locations closer to shoreline. Class III of vulnerability is the most dominant in Aveiro study area (at non-water fronts), with around 49% of all territory, followed closely by class IV, with 47% (mainly waterfronts).

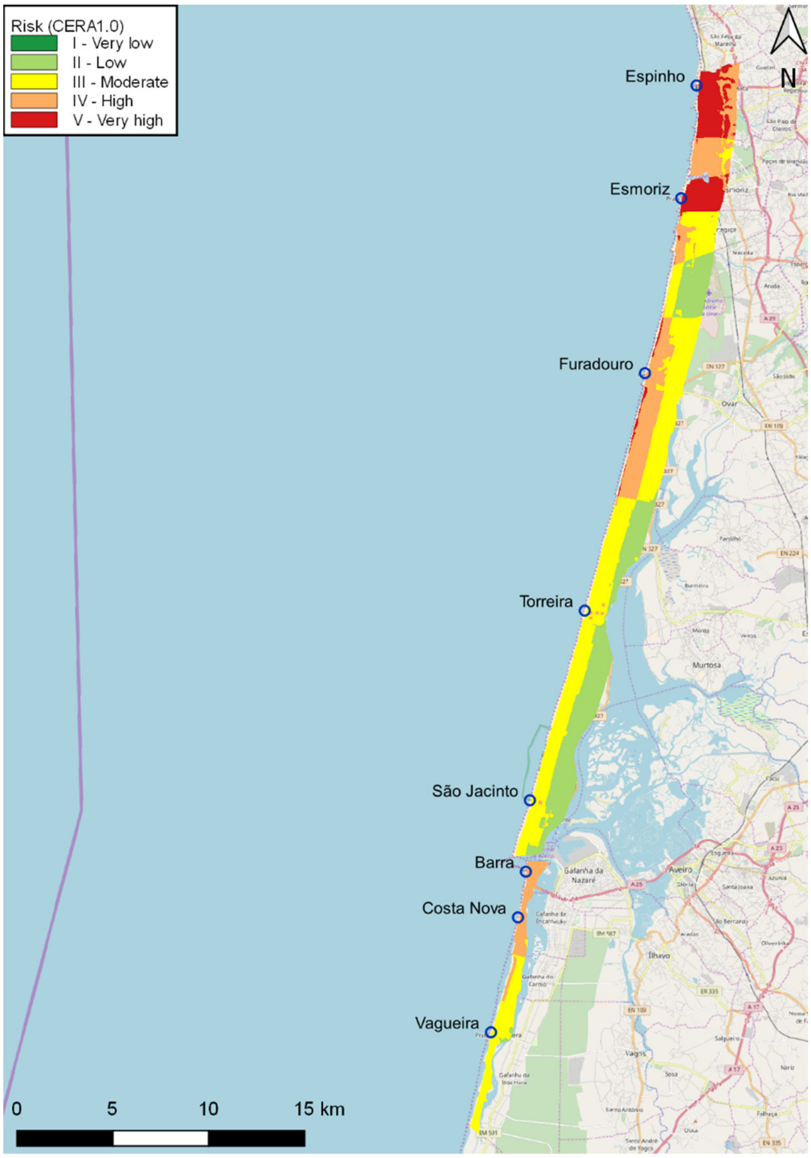

Figure 4.9. Risk classification for Aveiro, using CERA1.0.

On the other hand, the classification of consequences (Figure 4.8) presents a wide range of classes. In general, parishes at the north present higher consequence levels, with classifications between IV and V. This happens mostly due to a larger population density and employment density in those regions. Parishes located immediately south of Aveiro harbour also present larger population and employment densities, leading to a higher classification comparing with the others around them. Most area is classified as class II (51%), followed by class III (30%), regarding the consequences assessment.

Finally, the classification of risk (Figure 4.9) shows that most coastal zone is classified as III and IV, with only small exceptions at three parishes at the north, that present class V. These exceptions result on the very high level of consequences already mentioned in those parishes. Considering the entire study area, class III is the one with most area covered (mainly inland, for distance far from 500 m), with about 43%. Classes II and IV cover a similar amount of area (25% and 22%, respectively), followed by class V, which covers around 11% of the total area.

4.3. Application to Macaneta case study

As already mentioned, information from Macaneta is much less detailed than in other study areas and is based essentially on expert knowledge and aerial imagery. Much of the input data was produced by manual digitalization. The CRS used for all calculations and digitalization was the Tete/UTM zone 36S (EPSG: 2736).

For the vulnerability indicators, distance to shoreline and topography (Figure 4.10) were the only parameters that followed the same process as the Aveiro maps. The topography assessment for this methodology still used the DEM produced from the cross-shore profiles and Google Earth data. Like in Aveiro, this DEM was produced by using the *Interpolation* tool within QGIS.

For the remaining indicators, a unique value was attributed for the entire area, based on literature review or expert knowledge. Non-consolidated fine sediments were considered as the geologic composition of Macaneta spit (class 5), as it is a sandy beach. This sand spit morphology also led to rating 4 in the geomorphology indicator, considered as exposed beach. The ground cover was considered as non-covered soil and classified as 3, likewise sandy beaches of the Aveiro study area. The lack of coastal defence interventions, together with no evidences of shortage of natural sediments supplies, lead to the attribution of class 4 in the coastal anthropogenic actions.

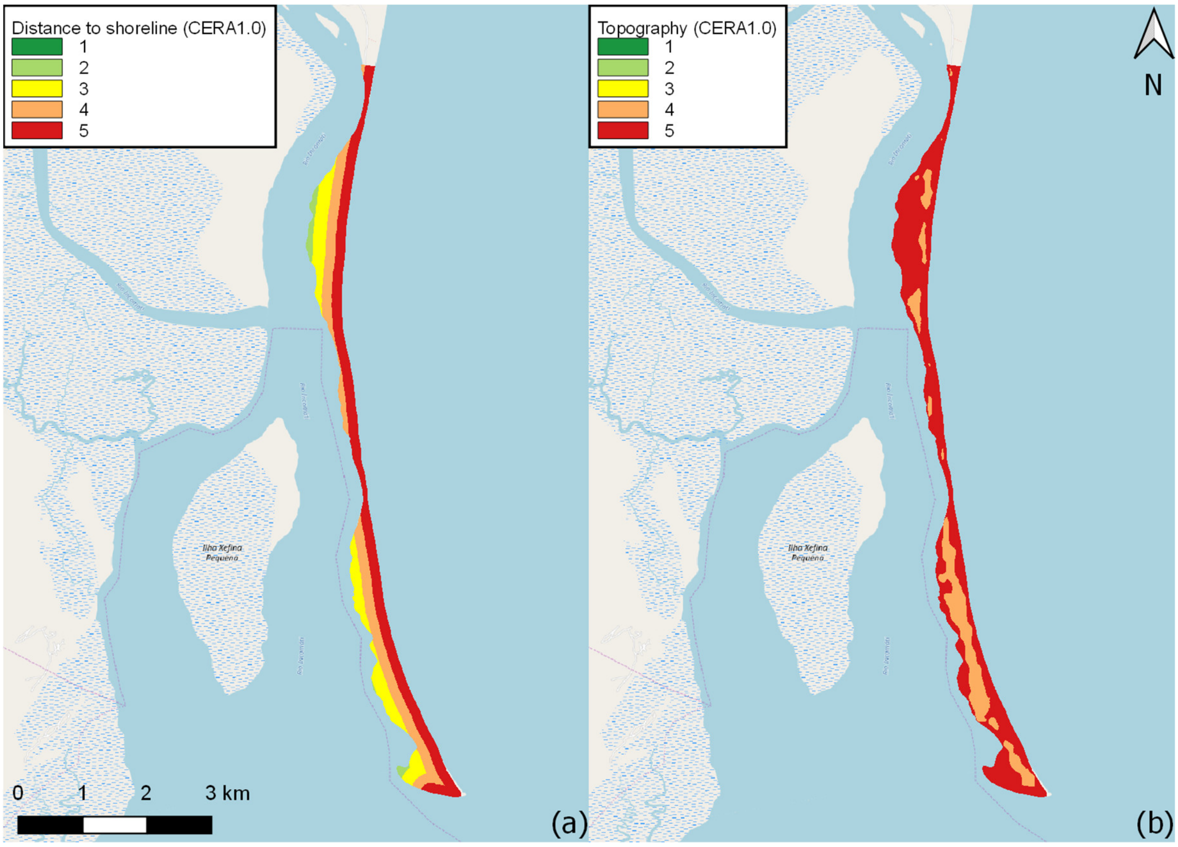

Figure 4.10. Classification of (a) distance to shoreline and (b) topography for Macaneta, using CERA1.0.

The maximum significant wave height was classified as 1, since waves rarely exceed 1.5 m (DHI, 2013). Tidal range varies between 2 m and 3 m, being classified as 3. Finally, Karlsson and Liljedahl (2015) concluded that the spit suffered accretion at its southern stretch, and Palalane *et al.* (2016) indicated that the gradient of the longshore transport is small. Therefore, the classification for the erosion/accretion parameter was considered 1.

From the consequence indicators, only the heritage classification (Figure 4.11) had more than one class along the area. Class 2 was set in a radius of 40 m of each visible house building, with the remaining area classified as 1.

The remaining consequence parameters were set mainly by contact with expert knowledge, which revealed that there is a very small amount of people living in the spit (class 1) and there are just a few economic activities (class 2). Despite not having an official ecologic nomenclature, Macaneta beach was considered important at an ecologic level, as it protects river Incomatí from breaching. The ecology was rated equal to that of sandy beach areas of Aveiro region (class 3).

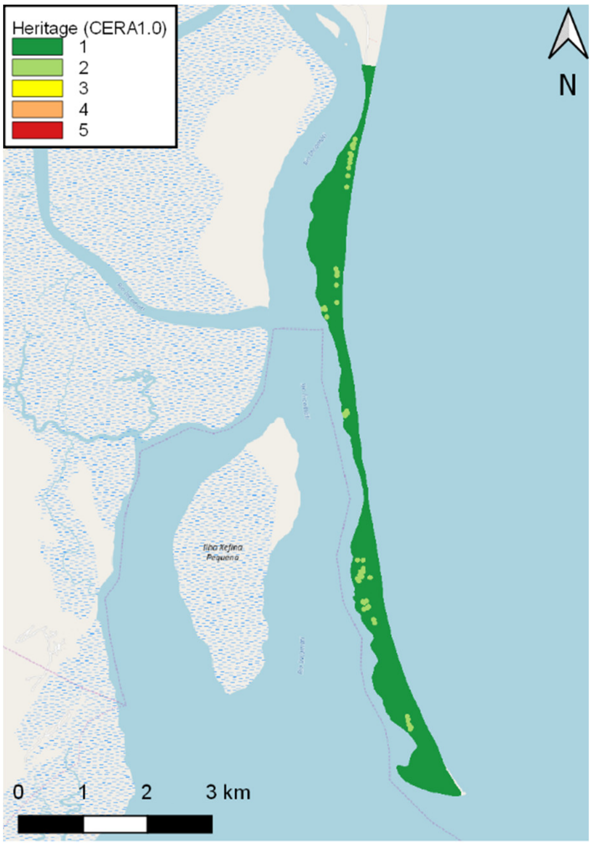

Figure 4.11. Heritage classification for Macaneta, using CERA1.0.

As expected, the less nuanced input data for Macaneta spit results in much less variable outputs for CERA1.0 classification (Figure 4.12). Macaneta spit presents a vulnerability level IV (high vulnerability) in most study area, with just a small amount of area classified as vulnerability level III, due to its greater distance to the shoreline.

The consequence level is homogeneous along all study area, with a classification of II. Despite some variation in the heritage indicator, this was not enough to provide a higher consequence level at infrastructures and its surrounding areas. This homogenous classification leads to a risk map very similar to the vulnerability map, only changing the severity of the results, which are attenuated by the low consequence level that could affect the study area. In conclusion, 97% of Macaneta study area is classified with risk level III, with the remaining 3% classified as level II.

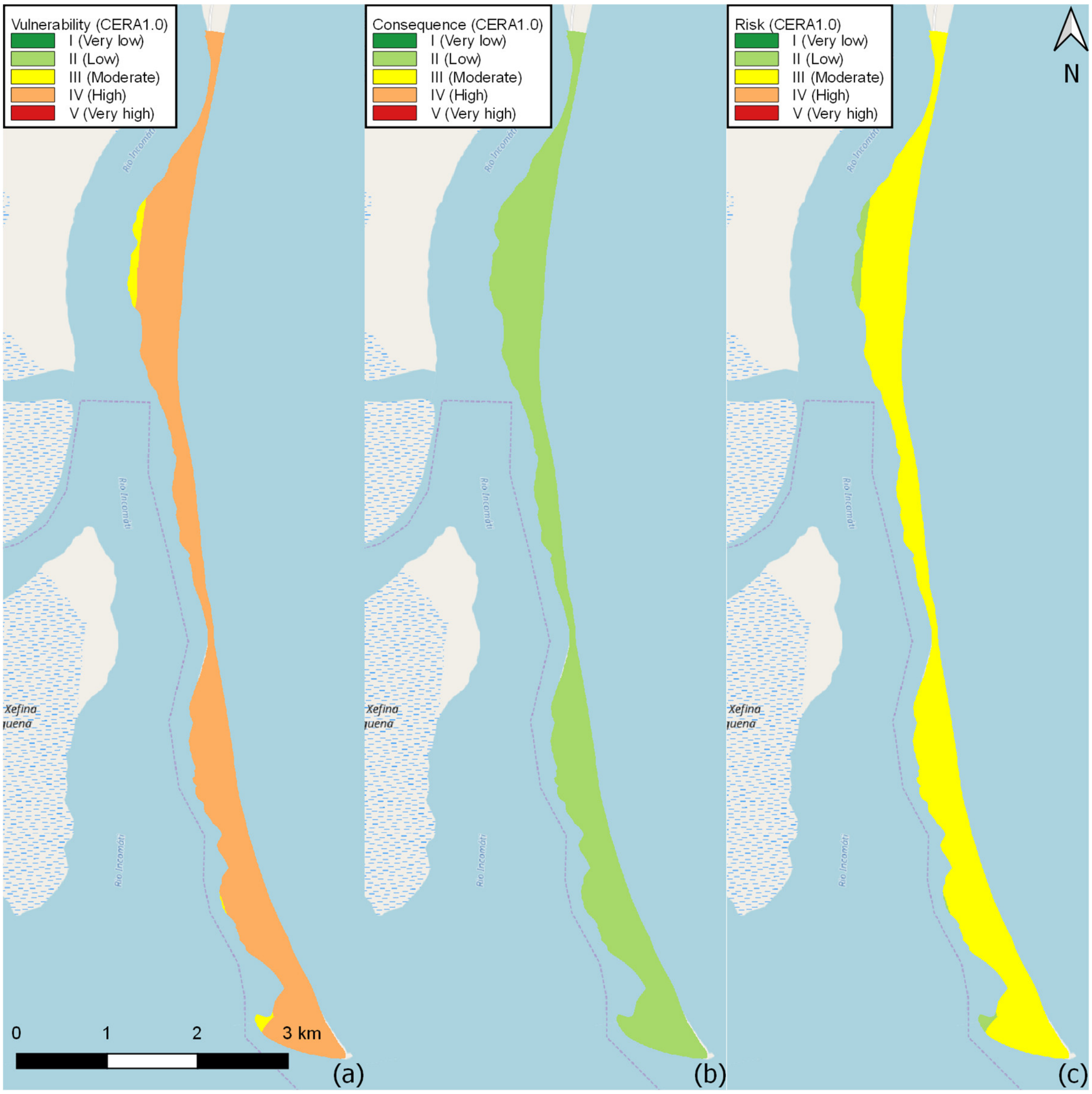

Figure 4.12. Classification of (a) vulnerability, (b) consequence and (c) risk for Macaneta, using CERA1.0.

4.4. APPLICATION TO QUINTANA ROO CASE STUDY

Like Aveiro, Quintana Roo has a considerable amount of georeferenced data that provides the opportunity for a similar approach to the one performed at that study area, in terms of data processing. The maps were developed on the CRS WGS89/UTM zone 16N (EPSG: 32616). Figure 4.13 shows four indicators for application of CERA1.0: distance to the shoreline, topography, geology and geomorphology.

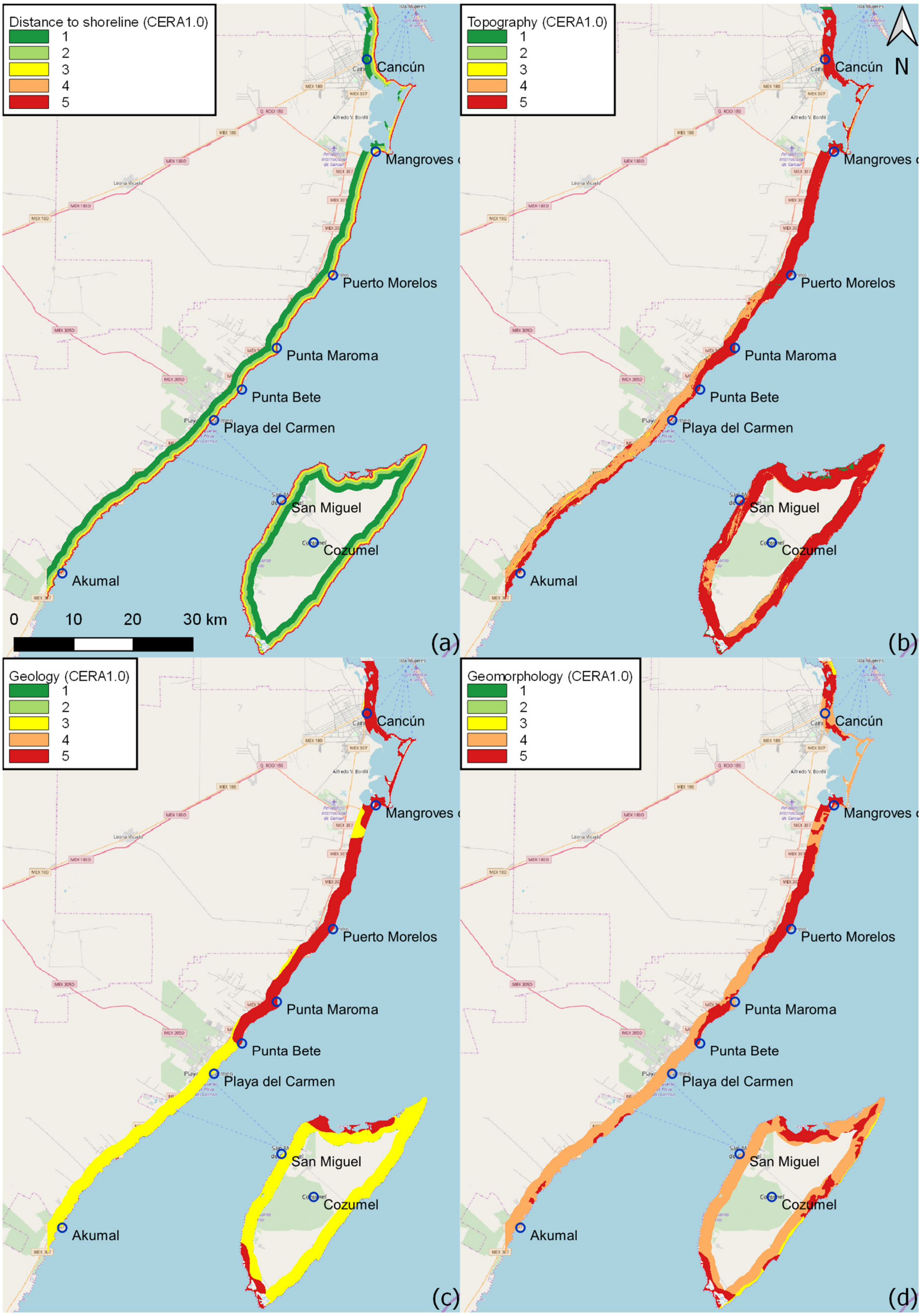

Figure 4.13. Classification of (a) distance to shoreline, (b) topography, (c) geology and (d) geomorphology for Quintana Roo, using CERA1.0.

The distance to shoreline map (Figure 4.13a) was created using the same method as in Aveiro. The drawn shoreline for 2016 was used as the base, and the proximity raster was created up to 2 km inland. Then, the threshold classes (Table 2.2) were computed using the *Raster Calculator*. As in Aveiro, water bodies were identified using the land use/cover data and not considered as assessment area. The topography classification map (Figure 4.13b) was produced using the *Raster Calculator* tool as well, based on the thresholds defined in Table 2.2. Overall, Quintana Roo is the study area with lower elevation, with all area represented by classes 4 and 5, meaning that all area is below 10 m elevation.

The geology classification map (Figure 4.13c) divides the region in class 5, for all area with non-consolidated sediments, and class 3, due to the carbonate and siliciclastic sedimentary rocks identified in GLiM. The geomorphology classification map (Figure 4.13d) assigned class 5 to swamp and mangrove areas showed in INEGI land use/cover map. The remaining area, composed by jungle or other vegetation, was considered a coastal plain (level 4), due to the low topography.

The ground cover classification map (Figure 4.14a) was also based on the land use/cover information from INEGI. The continuous urban areas were considered class 5 and discontinuous urban areas were classified as class 4. The remaining area is mostly forest. Thus, class 1 was attributed for most surface, with only some cultivated areas (class 2) and non-vegetated areas (class 3).

For the anthropogenic actions (Table 2.2; Figure 4.14b), aerial images were used for identification of coastal defence structures and shoreline change rates data was used to infer if there are sedimentary sources nearby. The areas where artificialized shorelines are present due to coastal protection structures were attributed class 1. Areas with presence of coastal defences and a stable shoreline position are class 2, while areas with coastal defence structures but presenting retreat of the shoreline are class 4. Lastly, where shoreline retreat was noticed but there is no presence of coastal defences, class 5 was considered.

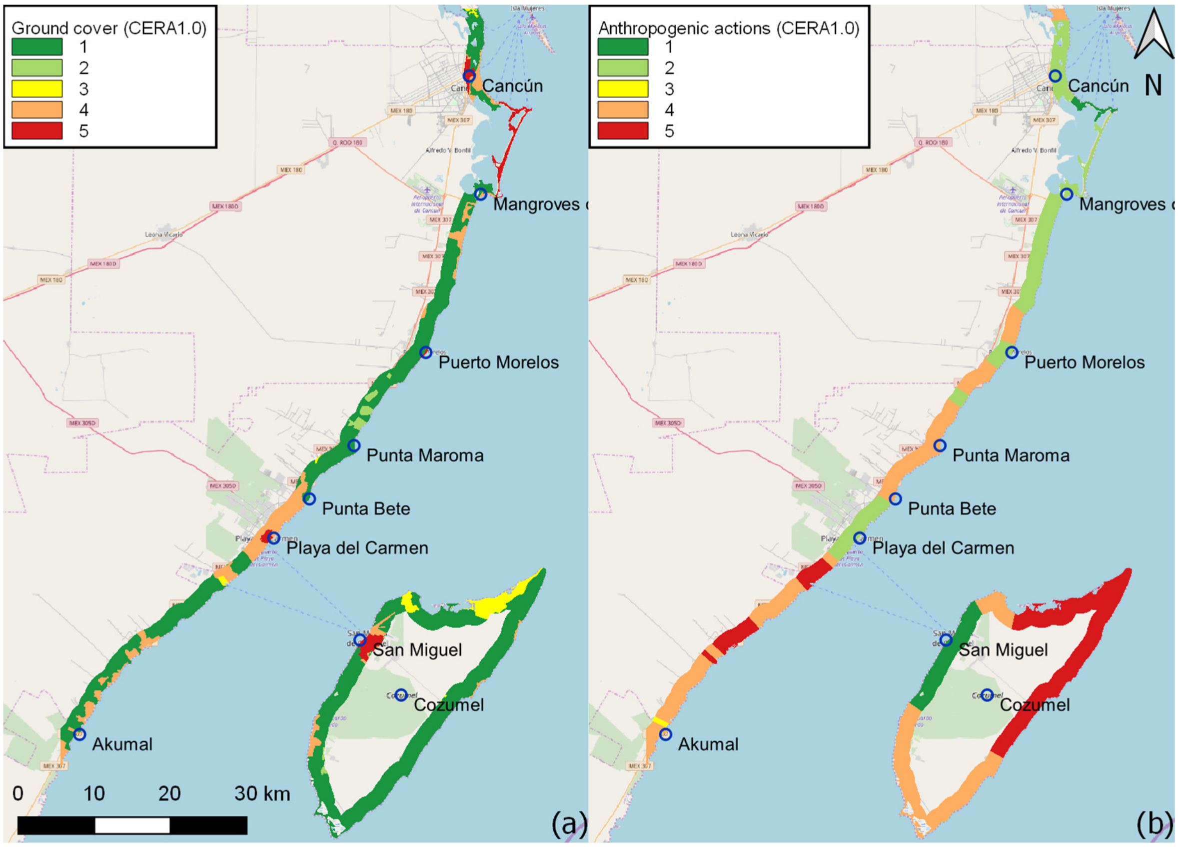

Figure 4.14. Classification of (a) ground cover and (b) anthropogenic actions for Quintana Roo, using CERA1.0.

The shoreline change rate classification map was produced using the shoreline positions of 2006 and 2016 that were digitized from Google Earth and applying the *Shoreline Analyst* (Lima *et al.*, 2016), followed by application of the thresholds using the *Raster Calculator*. Figure 4.15 shows that most area suffers from low retreat rates (class 2), with some areas even presenting accretion. Only a few transects of coastline suffer from higher erosion rates, such as the northern part of Cozumel island and the coastline surroundings of Playa del Carmen and Puerto Morelos.

The maximum significant wave height and maximum tidal range indicators were assessed as a unique value along all transect, considering the information presented in section 3.3. Regarding the significant wave height, despite having a low mean wave height, the presence of summer hurricanes leads to a registered maximum wave height of 13.1 m. Thus, the wave height classification was considered class 5. A variable wave height data along the transect would had been preferable, but it was not possible to obtain. Considering the maximum significant wave height registered (much higher than the class 5 threshold), it was considered adequate to classify all study area with the higher class. The maximum tidal range referenced in the literature is 0.6 m during spring tides. This value classifies Quintana Roo with a rating of 1 in the tidal classification.

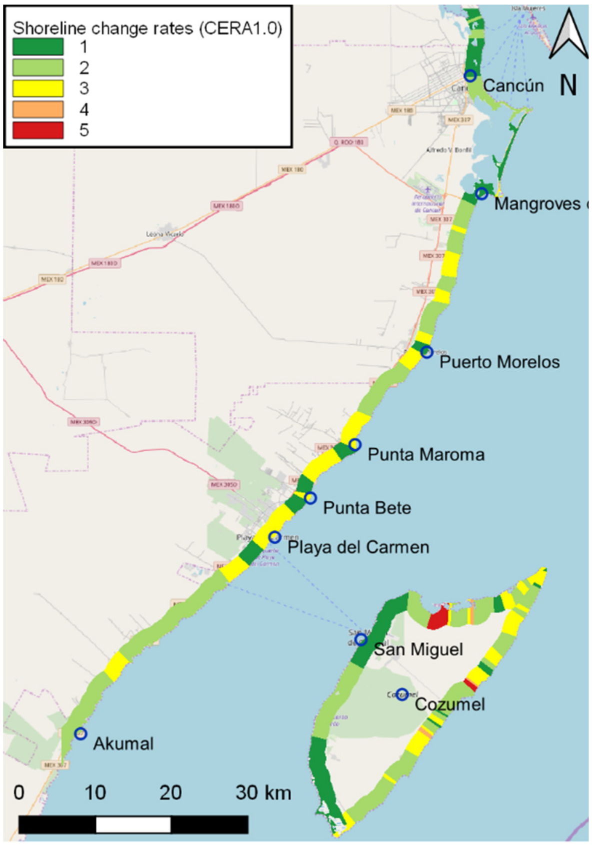

Figure 4.15. Classification of shoreline change rates for Quintana Roo, using CERA1.0.

The population density classification (Figure 4.16a) was produced using the Raster Calculator on the GPWv4 (CIESIN, 2017) dataset. This indicator was firstly produced using census data, like the evaluation performed at Aveiro study site. However, big discrepancies in the classification map (*e.g.* Playa del Carmen was classified as 1) lead to the necessity of reconstructing this indicator map. On the other hand, the economic classification (Figure 4.16b) map used the census data, as it was the best information available at the time. Due to the large areas representing each municipality, the assigned classifications are moderate to low (classes 2 and 3). The less accurate data relating economy is not expected to significantly influence the result, as the consequence output classification cannot be lower than the population.

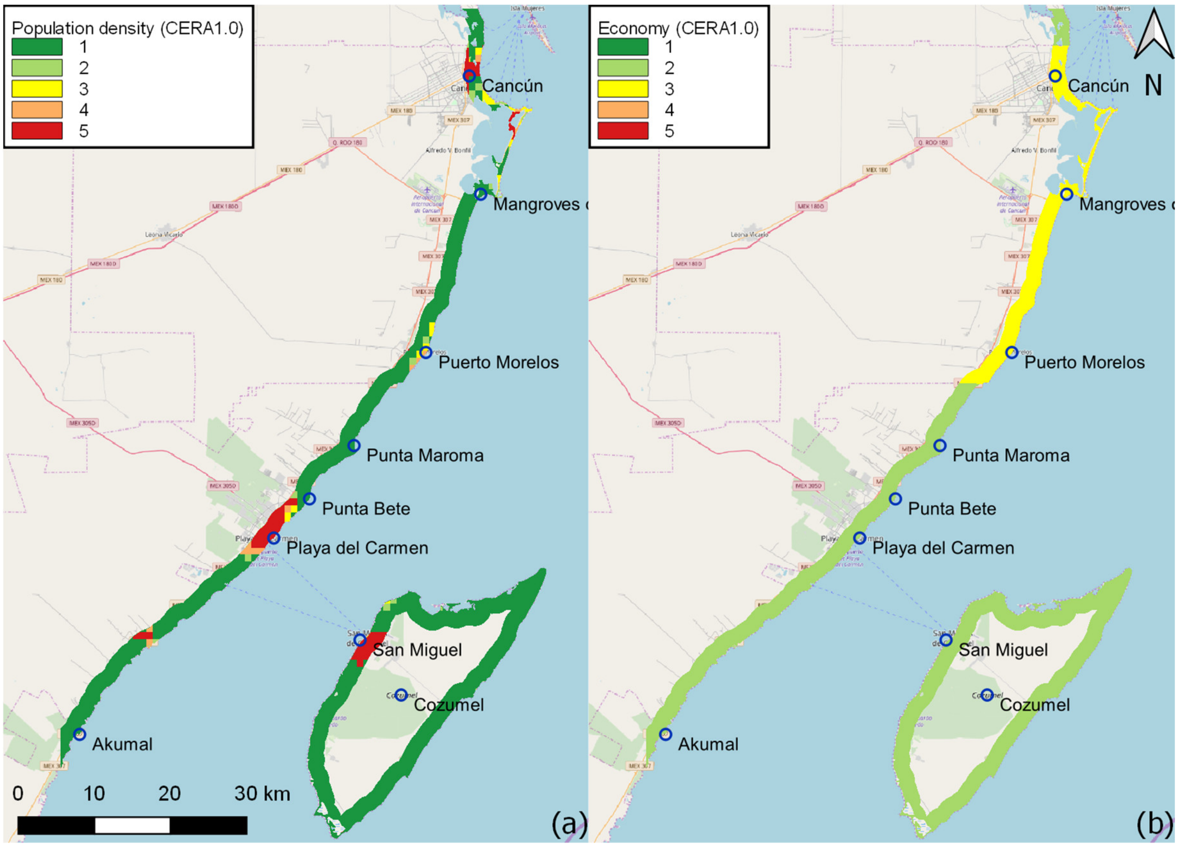

Figure 4.16. Classification of (a) population density and (b) economy for Quintana Roo, using CERA1.0.

The definition of ecologic classification at Quintana Roo (Figure 4.17a) was done considering the natural protected areas defined by CONANP (2017). Thus, protected areas of fauna and flora (APFyF) were considered class 4 and natural parks. Despite having other two ecologically classified areas, these are not located within the study area, consequently, they were not included in the ecologic classification. Some mangrove areas were not within a natural protected area. However, they were still attributed ecologic class 2, as they are usually important ecosystems from an ecologic perspective.

On the heritage classification (Figure 4.17b), the land use/cover was used for identification of continuous and discontinuous urban areas. These areas were considered class 3 for continuous urban areas and class 2 for discontinuous urban areas. Additionally, data on roads (class 2) and important historical landmarks (class 5) was collected. The urban waterfront near Cancun was considered a critical infrastructure (class 4), due to its touristic potential, the main attraction of the region.

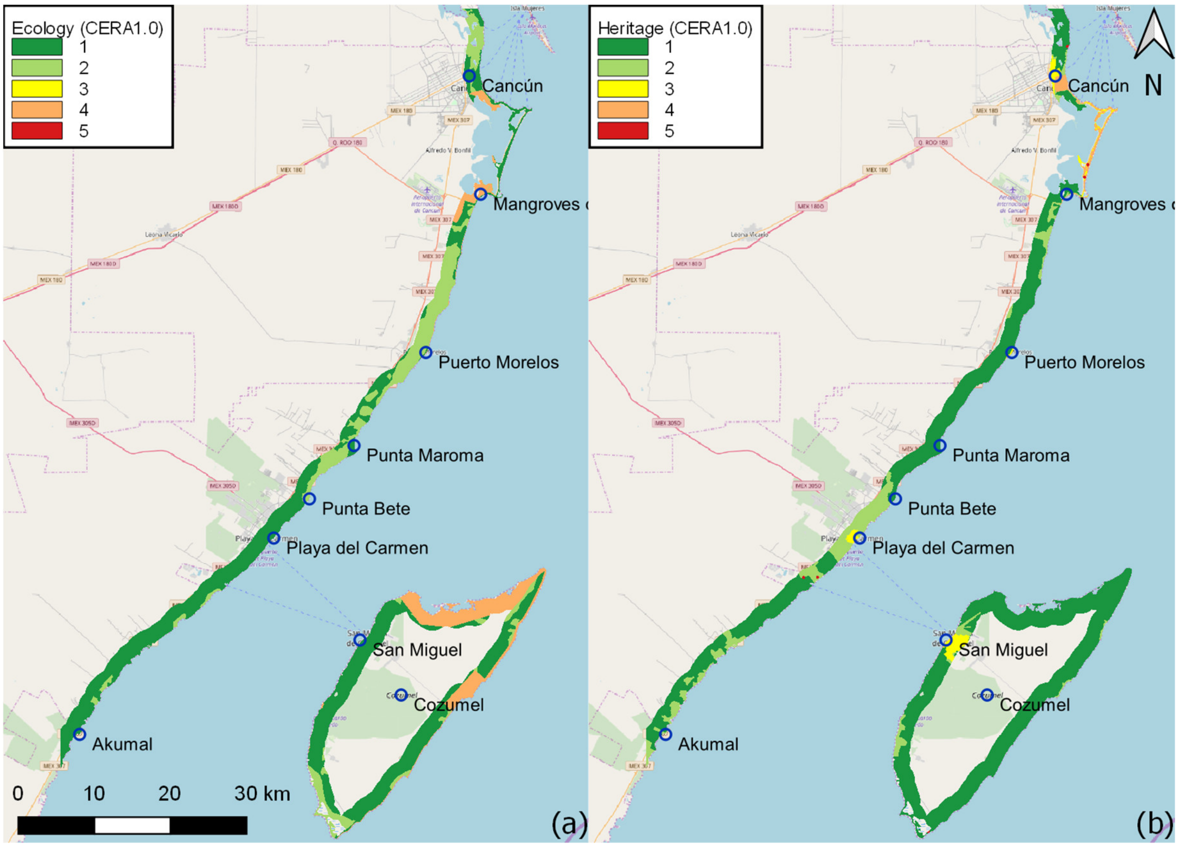

Figure 4.17. Classification of (a) ecology and (b) heritage for Quintana Roo, using CERA1.0.

The resulting outputs for CERA1.0 classification are presented in Figure 4.18 (vulnerability), Figure 4.19 (consequence) and Figure 4.20 (risk). The vulnerability classification (Figure 4.18) depicts most of the shoreline as a level 4 classification. The study area has some similarities to the Aveiro region, such as the low-lying topography and the non-cohesive sedimentary nature of its geological composition. The maximum significant wave height is also considered as level 5, despite its lower mean wave height. For the entire, 2 km wide, coastal strip, 23% of the territory was classified as highly vulnerable (IV), 53% as moderately vulnerable (III) and 24% as lowly vulnerable areas (II). Even though at the shoreline the classification is homogeneous, the area between Puerto Morelos and Cancun is considered the most susceptible, with a wider stripe of level 4 along the shoreline. On the other hand, the slightly higher topography and rocky geological formation give all the coastline south of Playa del Carmen greater resistance to coastal erosion. Cozumel island has a similar geological composition and thus, also appears to be less vulnerable than the Benito Juárez municipality (north of Puerto Morelos).

Figure 4.18. Vulnerability classification for Quintana Roo, using CERA1.0.

The consequence classification (Figure 4.19) has a higher variability in the assigned classifications for the study area. Areas with high population density resulted in the attribution of class 4 and 5. The natural environments were the main responsible for areas with class 2 and 3. The population is almost inexistent in those areas, but environmentally protected areas balanced that fact. In general, most area is classified with ratings 1 and 2, representing 41% and 47% of the total territory, respectively. The higher categories combine a total of 13%. From those, class 5 represents 8% of the total area.

Figure 4.19. Consequence classification for Quintana Roo, using CERA1.0.

Finally, the risk classification map (Figure 4.20) shows that most shoreline is classified with level 3, resulting from a high level of vulnerability along the shoreline and low level of consequences in most assessed area. Breaking this trend are the urbanized areas, which represent a great potential loss in case of a hazardous event. Playa del Carmen, San Miguel de Cozumel and Cancun are classified with maximum level of risk. Puerto Morelos was classified as level 4, mostly due to its smaller dimension when compared with the previous locations. The area located south of Playa del Carmen is the area with lower risk level. The combination of lower vulnerability (mainly due to geologic and geomorphologic indicators) and less urbanized area results in this outcome. Once again, the lower classes are the most represented (38% for class 1, 34% for class 2). However, these classes occupied areas more inland when compared with the higher classes. Class 3 represented 18% of the total area and the two highest classes covered 10% of the territory (5% each).

Figure 4.20. Risk classification for Quintana Roo, using CERA1.0.

4.5. Discussion about CERA1.0

The methodology and results presented in this chapter were subjected to discussion to improve future assessments and to take lessons for the expected new proposal. Narra *et al.* (2017) shows that the changes applied in CERA1.0 led to an overall higher risk classification for Aveiro district than with CVRA, mainly due to changes on the consequence assessment. The recalibration of population density categories led to a more even distribution along the 5 classes, in contrast with previous classes, where the majority would be classified as class 1 and 2, contributing for a final assessment where there was little to no consequences. The vulnerability assessment also had an increase in the overall level of classification, mostly due to the changes from the distance to shoreline thresholds. In general, these changes led to a more accurate assessment of the Aveiro coastline, recognised as one of the most endangered areas in Portugal regarding coastal erosion (Maia *et al.*, 2015).

Regarding the overall results, the study areas present similarities regarding the natural environment. All sites are low-lying areas with presence of exposed beaches. Quintana Roo presents some differences regarding geologic composition, as some transects are composed by sedimentary rocks, which also changes its geomorphologic landforms. Other parameters, such as the ones used in the consequence assessment, present very noticeable differences. As stated in the previous chapter, the amount of information available on each study area is also very different, with Aveiro and Quintana Roo having several sources of georeferenced information publicly available.

The three areas presented similar classifications regarding vulnerability. Most coastlines are class IV, reflecting similar characteristics regarding topographic, geologic and geomorphologic factors. However, the Aveiro coast also presents some transects of class V in narrow strips next to the shoreline. The difference between Aveiro and the other case studies is a higher classification of the shoreline change rate indicator, which presents much higher rates along the generality of the study area. Although areas with classification V are barely noticeable in Figure 4.7, they cover around 15 km of shoreline, corresponding to roughly 20% of the shoreline extension of Aveiro study site.

Despite the differences in coastal length, area and indicators, the overall similarity of vulnerability classification for the study areas raised the question whether the CERA1.0 was capturing the adequate parameters to correctly determine the vulnerability to coastal erosion. The general set of parameters used herein (Table 2.2 and Table 4.1) and in other methodologies (see chapter 2) suggested that these were adequate. However, in order to capture greater differences between study sites, in particular their globally different trends for shoreline evolution (erosion *versus* accretion), the shoreline change rate indicator weight could be increased, simultaneously reducing the corresponding weight for one or more of the other indicators.

In general, locations south of Aveiro harbour are the most vulnerable of the study site, presenting a large area of class IV and a small stripe of class V. The higher classification in topography, ground cover and anthropogenic actions are the factors that influence this classification. Several erosion problems encountered for this zone, accompanied by several soft interventions such as beach nourishments, support this classification. In addition, the parishes of Ovar municipality (*e.g.* Furadouro) have their shorelines classified as level V. The identification of these locations as highly vulnerable areas is corroborated by Pereira *et al.* (2013), which modelled the shoreline of Aveiro district using LTC (Coelho, 2005; Lima and Coelho, 2017) and GENESIS models (Hanson, 1989). The forecasted erosion rates for the Maceda-Furadouro and the Labrego-Areão coastal stretches presented two of the highest shoreline retreat rates in that assessment. These coastal stretches correspond to coastal areas in the Ovar municipality and south of Aveiro inlet (*e.g.* Vagueira), being identified by CERA as highly vulnerable areas. Generally, this assessment is in line with previous authors, who consider Aveiro a highly vulnerable location to coastal erosion. Pereira and Coelho (2011) identified damaging events along Aveiro study area. The identified events are majorly located in Ovar municipality (*e.g.* Furadouro, Cortegaça) and in Vagueira. Moreover, Veloso-Gomes *et al.* (2004) analysed 10 segments of the North-western Portuguese coast, in which 7 are from this study area. Those authors found erosion problems in all segments, except between Torreira and the northern jetty of Aveiro harbour, which corresponds to the greater transect of shoreline with a lower classification of risk (class III; Figure 4.9).

Pereira and Coelho (2013a) applied CVRA methodology to assess coastal erosion risk in Aveiro. Likewise, they assessed 2 km inland from the shoreline, although they also classified water bodies that are included in the area. The global coastal erosion vulnerability results were similar in both studies, although it is noticeable a decrease of class III in favour of class IV in this study. In addition, consequence results present significant differences, with the classification of Pereira and Coelho (2013a) dominated by classes II and III, while in this work, the other classes (mainly IV and V) have more significance than in Pereira and Coelho (2013a). The result of these differences is a skewed risk classification to higher classes in this work. These differences are explained by the changes made from CVRA to CERA1.0 and by the integration of the methodology in a GIS environment. Pereira and Coelho (2013a) produced the final map by computing individual points with a distance of 200 m between them, while this work computes the entire map with a resolution of 5 m/px.

Regarding the consequence map for Aveiro, the result shows that the northern part of the Aveiro district has more value at stake. The population density conditioned this classification, since the methodology states that the consequence classification cannot be lower than the individual classification of that indicator. Moreover, in this map, two indicators, population density and economy, have a maximum detail of classification by parish. This is noticeable in the result, where the administrative borders of each parish are delimitating the classifications. The area south of Aveiro harbour is also classified with consequence level IV, due to the population density and economic activity generated by the harbour. Contrary to vulnerability maps, the consequences in Pereira and Coelho (2013a) are much lower than those computed in this work, with almost all area classified within the 3 lower classes. The changes occurring in the consequence indicators caused a different classification in the consequence map and, consequently, in the risk map.

Lastly, the risk classification maps were produced by combining vulnerability and consequence maps. In Aveiro, the northern part of the study area is the most prone to a greater risk, influenced by a higher level in the consequence assessment. The southern area close to Aveiro harbour also presents a high risk, which is explained by having a high level of vulnerability and consequence.

Due to the measurements of population and employment densities being done at the parish scale, the sudden changes of classification along parish borders in the consequence maps were propagated to risk maps. These results should be looked with a critical view by experts and coastal managers, as they only provide an indication of coastal erosion risks in the area. THESEUS (Zanuttigh *et al.*, 2014) also uses these types of division regarding population density on their coastal risk assessment, with similar patterns also visible in the final output. As stated above, the approach taken in Quintana Roo assessment is more accurate and should be sought in the following assessments.

In general, the risk assessment of this work considers a higher risk for the Aveiro coastline than in Pereira and Coelho (2013a). The locations identified by this work as high-risk areas coincided in the vast majority with the areas that suffered damages in recent years, namely, in January 2014. In fact, during the storm events of 2013/2014, the coastal area of Ovar municipality suffered damages in coastal defence structures of the order of 1 million euros, and Ílhavo municipality (located at south of Aveiro) had damages of around 0.8 million euros due to coastal erosion (Pinto *et al.*, 2014).

In the Macaneta spit, the distance to shoreline and the topography are the only indicators that vary in the vulnerability assessment, leading to a more homogenous classification (only classes III and IV are present). These two indicators influence the boundaries of the area for each classification. Nevertheless, this classification can be important in the delimitation of areas allowed for future infrastructures. This map can be potentially improved with local field campaigns that result in a more accurate assessment of natural parameters, such as topography and geomorphology.

In Macaneta, despite the identification of the infrastructures present in the spit, the consequence map resulted in a homogenous class II due to the lack of other detailed information and since this area is mostly uninhabited and with small economic activity. However, the classification does not address external factors to the area itself. For instance, the consequence classification does not evidence the potential losses that could be caused by breaching of the two isthmuses, the narrowest sections of the spit.

The combination of vulnerability and consequence in Macaneta spit resulted in a medium level risk, with almost no variation in the classification. This classification is considered adequate, as the consequence level is attributed mainly due to ecologic factors. Therefore, the risk in this area is considered manageable. However, in a near future, anthropogenic pressure can lead to both increases on vulnerability and consequence assessments, leading to a higher risk.

Quintana Roo presents a vulnerability classification similar to Aveiro, albeit less critical, not presenting the maximum level of vulnerability in any transect on the entire area. The difference in shoreline change rate indicator, which is much lower, is the main responsible for that difference. The transect with a wider strip of vulnerability class IV is located between Punta Bete and Punta Maroma. This conclusion is in agreement with existent literature, that highlight this area as having erosion problems (Odériz *et al.*, 2014).

Regarding the consequence output in Quintana Roo, the use of a population density dataset in comparison with population density derived from censuses (as it was done in Aveiro) represents a major step forward a more detailed assessment. This change allowed the correct identification of areas with higher stakes, and it was especially important for this area, considering that each municipality in this study site occupied a large area. The consideration of census data would result in areas with actually very high population density to be classified as the opposite (*e.g.* Playa del Carmen). The outcome of this change was the accurate identification of urban areas as the main locations at stake, such as Playa del Carmen, San Miguel de Cozumel and Cancun. The remaining area is occupied by natural environments, and thus, ranked with a lower level of consequence.

The risk map for Quintana Roo identifies the urban areas with maximum level of risk, due to the potential consequences at stake, but also highlight areas where the vulnerability is higher, but the consequences are not as high. The location between Punta Bete and Punta Maroma have a large strip of risk level III when compared with the remaining area, and Puerto Morelos is ranked with class IV.

Lastly, the risk matrix (Table 4.2) was defined assuming that all class levels were equally represented by the combinations of the summation values of vulnerability and consequence classifications. This approach was favoured in relation to a similar one, arising from the product of the vulnerability and consequence levels. Other approaches are possible, for instance, based on the average and standard deviation values of the summation sample, and if a higher (/lower) class would correspond to the extremes of a Gaussian distribution (*e.g.*, one could attribute risk class V to all combinations whose summation values were above the mean plus one standard deviation, corresponding to the upper 84% frequency of occurrences). Results from this approach are not presented, but they homogenised the final risk classification for the Aveiro region towards the middle class (III), and reduced the total area classified by classes IV and V. Hence, despite reducing the high-risk areas, and thus probably leading to a less apprehensive attitude by the management authorities for that territory, the areas still classified by class IV or V would be indeed of high and very high risk, and would thus allow the management bodies to focus and prioritise their interventions into these high-risk areas.

In conclusion, the development and application of CERA1.0 provided a base for following applications of existent methodologies, giving the know-how on subjects such as GIS application and development, gathering and/or creation of georeferenced data. Moreover, the insights arisen by discussion of important coastal erosion indicators and socio-economic indicators, as well as the application of risk concepts, scale of application and targeted time frame were the base for the formulation of a new proposal, that accurately addresses the faults and aims to give coastal managers a viable assessment tool for evaluate coastal erosion risk.

5. Application of different hazard and risk assessment methodologies

The application of methodologies described in the literature was an important step in the development of the new proposal of coastal erosion assessment. The development of hazard, vulnerability and risk assessments provided insight and experience in gathering of data, use of GIS information and manipulation, GIS application development and, more importantly, the strengths and weaknesses of the methodologies, giving an opportunity to fill the gaps in the new proposed methodology. The next chapter presents the application of 4 methodologies (CVI; SL; CRAFI; and CHW) on the study sites presented previously. Then, the methodologies are subject of discussion, identifying the most suitable use cases for each one.

5.1. Coastal Vulnerability Index

The Coastal Vulnerability Index (CVI) was applied at Aveiro and Quintana Roo. Contrary to CERA1.0, this method is represented as a line along the shoreline. The CVI classifies relative vulnerability of the shoreline by defining thresholds of its formula, based on the results obtained. The thresholds for the 4 classes (1: Low, 2: Moderate, 3: High, 4: Very High) are defined based on the quartiles of those results. However, due to the homogeneity in some characteristics of the area, the area is not divided into exactly 25% for each class. This method was not applied to Macaneta due to its small size and homogeneity in the indicators, not having enough variety to establish the thresholds for each class.

5.1.1. Aveiro

The data used for application of CVI to Aveiro was similar to the data applied in CERA1.0. However, considering the assessment characteristics (only along the shoreline), some indicators are homogeneous along all extension, and therefore, were classified as a unique value along all study area. Coastal slope (Figure 5.1a) is one of the indicators that varied its classification along the shoreline. This classification was taken by extracting the slope value on the shoreline position. This was equivalent to the mean slope on a buffer area of 50 m, as described in section 3.1. Most shoreline has a slope classification level 5 (< 0.025%). The low topography of the area hints at this outcome. Only the northern part of the study area and some isolated locations present a lower classification (mainly classes 2 and 3).

The shoreline position change rate classification (Figure 5.1b) was produced by directly applying CVI criteria to the Lira *et al.* (2016) shoreline. This region exhibits large transects of the area with shoreline retreats superior to 2 m/year and only a few transects in accretion or balanced rates, confirming the idea that this transect is one of the most affected by shoreline retreat in Portugal. Thus, the classification to this indicator presents large extension of class 5.

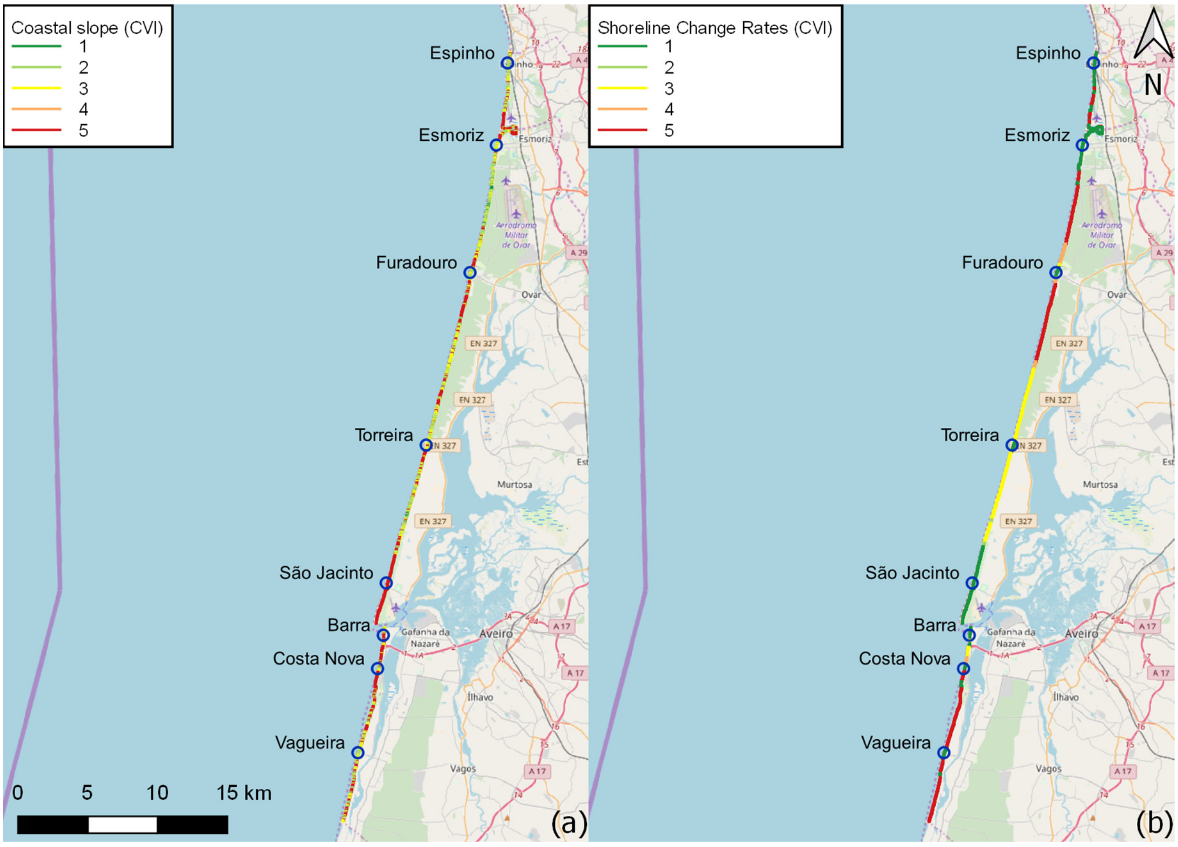

Figure 5.1. Indicators in CVI method that are not homogeneous along Aveiro: (a) shoreline coastal slope; (b) shoreline position change rates.

The remaining indicators were considered a single value along all the shoreline. For geomorphology, all area corresponds to exposed sandy beaches or barrier island, very dynamic systems, susceptible to changes when facing an energetic wave climate. Thus, the geomorphology was considered class 5. The sea-level trend considered by NOAA is 1.27 mm/year. Therefore, this puts the relative sea-level change classification at class 1. The mean tidal range falls in class 3, as it varies between 2 m and 4 m. The mean significant wave height is around 2 m, hence, class 5 was considered for all study area. The combination of indicators in the CVI formula lead to the relative vulnerability classification presented in Figure 5.2.

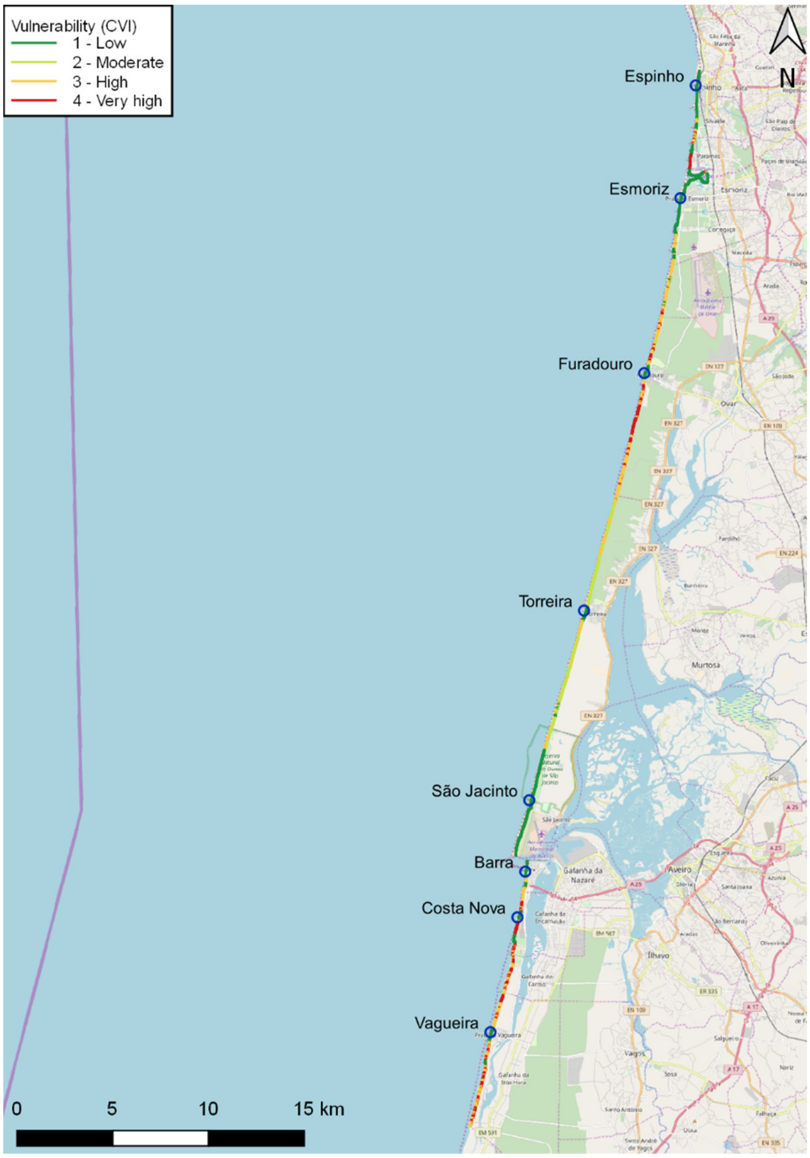

Figure 5.2. Relative vulnerability classification for Aveiro, using CVI.

Due to the homogeneity of some indicators, the defined thresholds do not divide the area classification in quartiles. Instead, 36% of the area is classified as having low vulnerability (class 1), 16% present moderate vulnerability (class 2), high vulnerability (class 3) occurs in 32% and the remaining 16% present the maximum classification (class 4). The most threatened transects are located around Furadouro, Costa Nova and Vagueira. On the other hand, the least vulnerable area is São Jacinto.

5.1.2. Quintana Roo

The CVI assessment was also applied to Quintana Roo study site. In this case, along with variable coastal slope (Figure 5.3a) and shoreline position change rates (Figure 5.3b), geomorphology (Figure 5.4) also varied, since it is a more extensive and varied coastline, already witnessed in the application of CERA1.0.

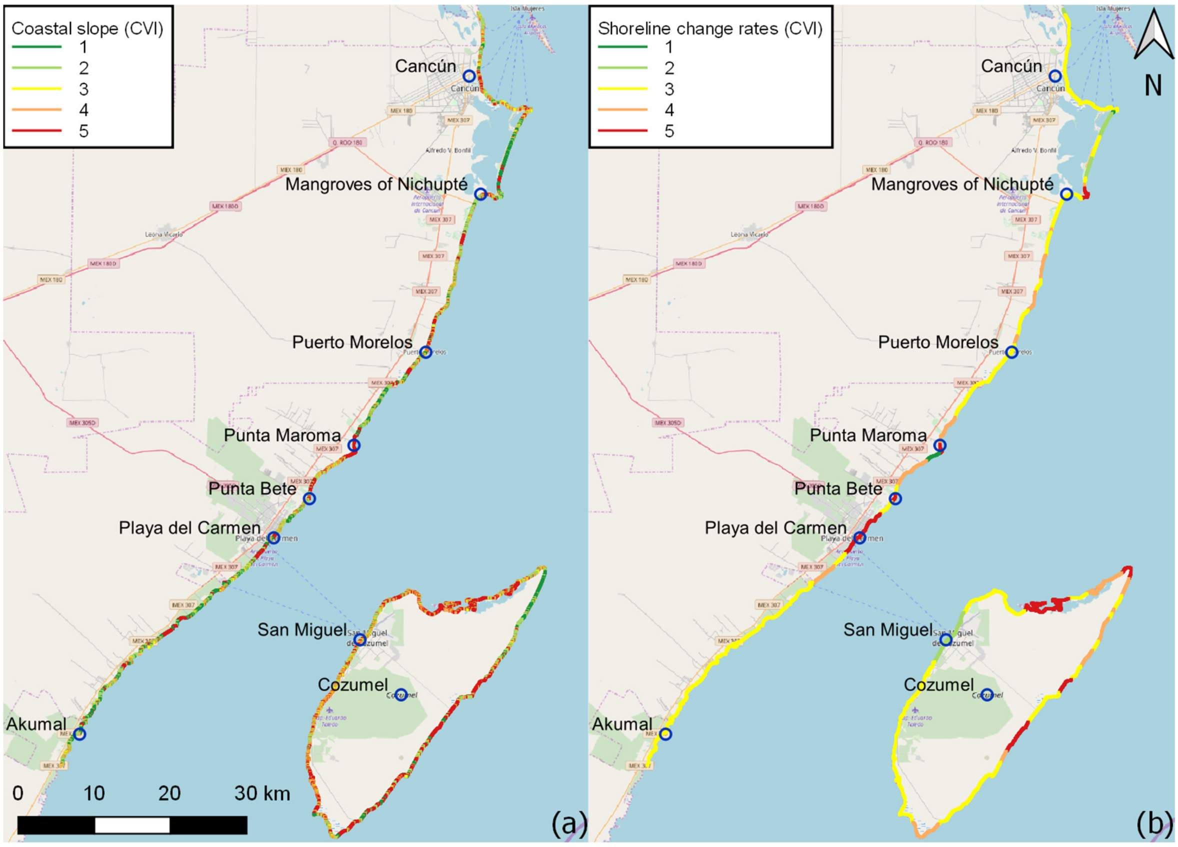

Figure 5.3. Indicators in CVI method that are not homogeneous along Quintana Roo: (a) shoreline coastal slope; (b) shoreline position change rates.

The coastal slope assessment (Figure 5.3a) was executed using the same process as in Aveiro, meaning that it is considered the mean slope of a 50 m buffer around the shoreline. Quintana Roo case study shows heterogeneous characteristics on this indicator. The higher extension of the study area and higher resolution of the original data is a possible factor for this result. While on Aveiro, the elevation of 2 cells was used for computing slope, here it is an average of 10 cells to cover the 50 m buffer. Overall, the slope seems to be steeper on the mainland than on Cozumel island, which presents a high classification on that indicator.

For shoreline position change rates (Figure 5.3b), it is possible to determine that the northern part of Cozumel and the coastline surroundings of Playa del Carmen are the most affected by erosion. Due to the smaller class thresholds, it is possible to distinguish those places from Puerto Morelos or the transect between Punta Bete and Maroma, which have high shoreline retreats, but smaller than the previous transects. Like in CERA1.0, geomorphology classification used data from INEGI (2016) land use/cover to classify the area. Thus, mangrove and swamp areas were classified with the maximum level, while urban areas and secondary vegetation was considered class 3 (Figure 5.4).

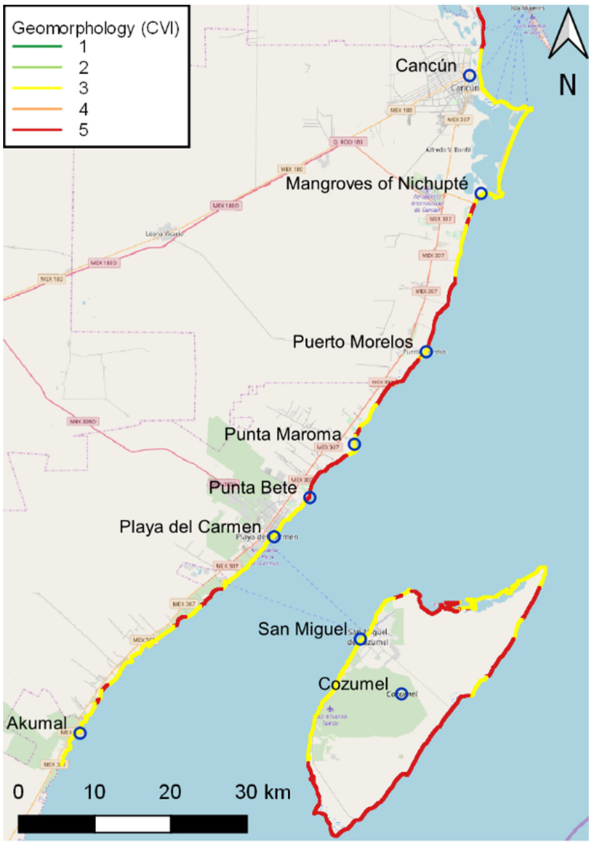

Figure 5.4. Geomorphology indicator in CVI method, for Quintana Roo.

The remaining indicators were considered a single value along the shoreline. The sea-level trend had an increase of 4.12 mm/year (NOAA, 2018a), and therefore, was attributed class 5. The considered wave time series has a mean significant wave height of 1.2 m and the literature review revealed this value to be accurate, meaning that CVI classification for this indicator is 4. The tidal range is very small in the region, with values between 0.2 m and 0.6 m. However, contrary to CERA1.0, these values correspond to the maximum class regarding tidal range. The results of the CVI assessment for Quintana Roo are shown in Figure 5.5.

Figure 5.5. Relative vulnerability classification for Quintana Roo, using CVI.

CVI clearly identifies the most vulnerable places, which are the east and north part of Cozumel island, the area around and at north of Puerto Morelos, and the shoreline between Punta Maroma and Playa del Carmen. On the other hand, the artificialized barrier island system at Cancun has a low vulnerability level, mostly due to the accretion rates in the area and the presence of coastal defences reflected on those rates. Also, the southern area of the study site is classified as of low vulnerability, due to its stable shoreline position. The shoreline erosion rates in the southern part are mostly null due to its geology and the protection from wave exposure given by Cozumel Island. Cozumel has a higher level of vulnerability at the east side of the island, mostly due to the greater shoreline erosion rates recorded there. In general, the CVI results were around 25% for each class: 29% low (class 1), 23% moderate (class 2), 26% high (class 3) and 21% with very high (class 4) vulnerability.

5.2. SMARTLINE

The Smartline (SL) approach was applied to all case studies (Aveiro, Macaneta and Quintana Roo). This method is also represented as a line along the shoreline, but allows to divide results into 6 classes, based on the correlation matrix presented by Lins-de-Barros (2010) and on the classification attributed by Lins-de-Barros and Muehe (2013) for the east coast of Rio de Janeiro State (Brazil). Thus, the first three categories (A, B, C) of the vulnerability classification represent stable shorelines, either due to accretion rates or due to coastal defences. Category C can also represent areas of low vulnerability, despite the historical erosion rates of the area. The three remaining categories (D, E, F) show increasing levels of vulnerability to coastal hazards with retreating shorelines.

5.2.1. AVEIRO

The Smartline procedure is divided in three main steps: the computation of erosion resistance; the computation of potential shoreline retreat; and the computation of physical vulnerability. The social vulnerability is also described in Lins-de-Barros

(2010), but considers social factors that are not relevant to erosion hazard, and therefore, it was not within the scope of this work.

For erosion resistance, indicators of grain size and dune presence are required. Both indicators are classified within 3 classes. The grain size is divided in fine, medium or coarse sand. For Aveiro, the median grain size of 0.36 mm corresponds to medium sand, and thus was attributed class 2 for the entire study site. Regarding dune presence (Figure 5.6a), the indicator considers the non-existence of dunes as the higher class, followed by the presence of dunes and presence of dunes with vegetation.

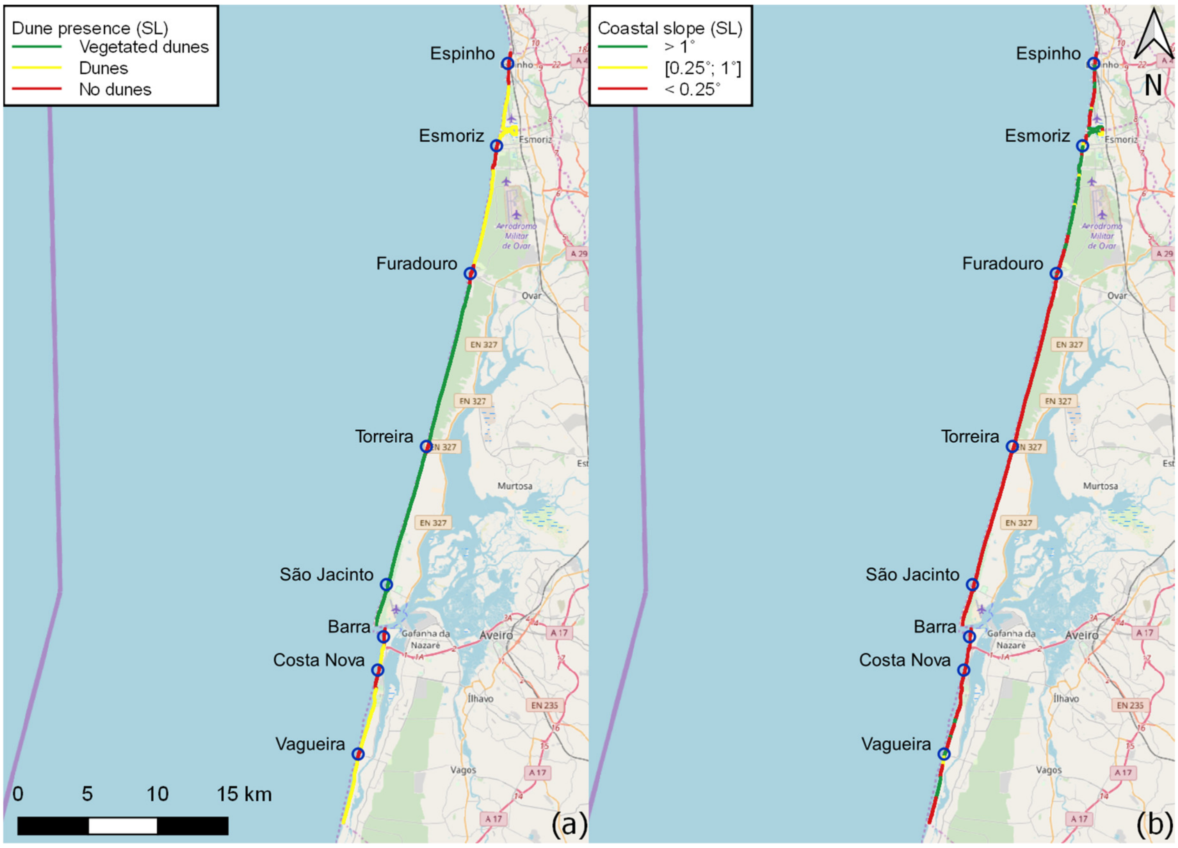

Figure 5.6. Indicators in the Smartline approach for Aveiro: (a) dune presence; (b) coastal slope.

In Aveiro, the dune identification was done through aerial images. The area surrounding São Jacinto has a considerable number of vegetated dunes, while the remaining area has dunes with few or no vegetation. In most urban areas near the coastline, dunes were not noticed. The assessment of these indicators resulted in resistance to erosion varying between moderate to high, considering the criteria of Table 2.6.

Next, the potential magnitude of shoreline retreat sub-index considers beach slope, in degrees (Figure 5.6b), and backshore features and elevation (Figure 5.7). The same method mentioned in the CVI methodology was used for the slope assessment (Figure 5.6b). The result here is that most area has a coastal slope inferior to 0.25°, with only a few areas with different results (namely in the northern area).

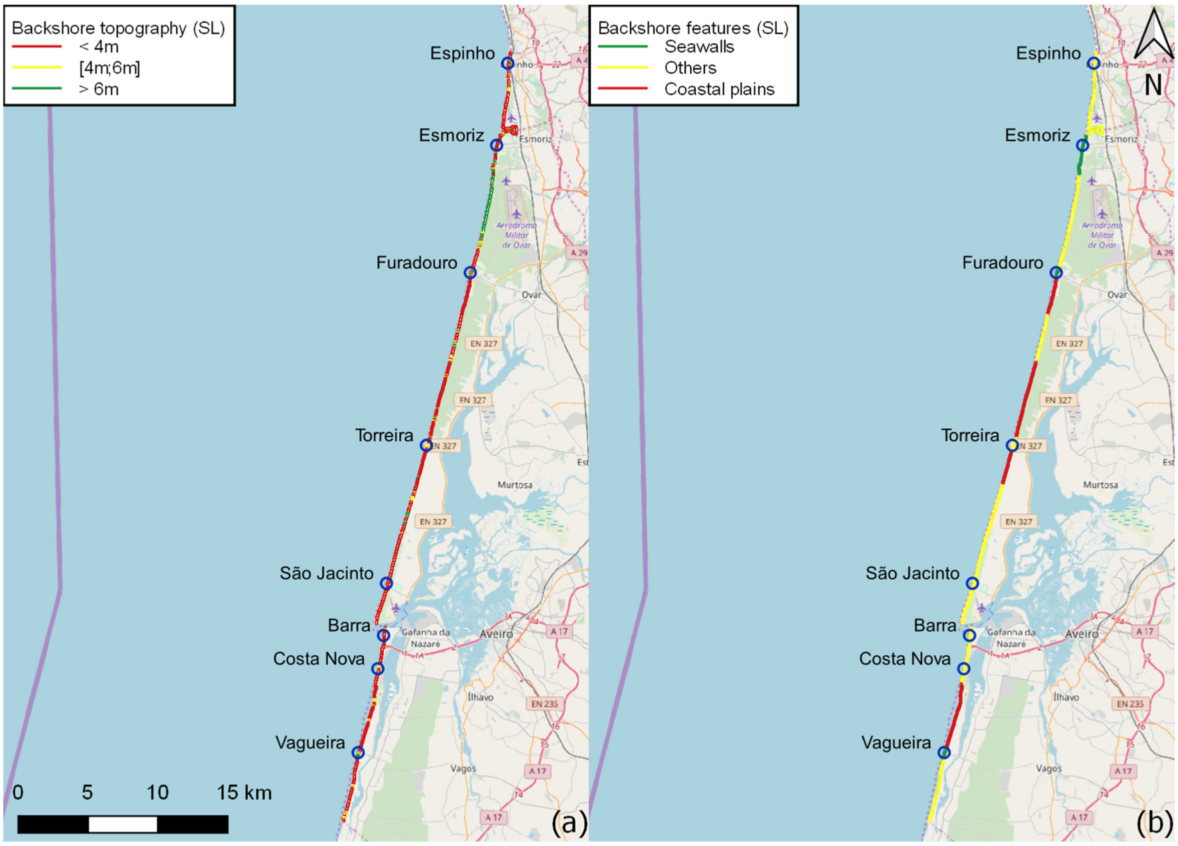

Figure 5.7. Indicators in the Smartline approach for Aveiro shoreline: (a) backshore topography; (b) backshore features.

Moreover, most backshore topography (Figure 5.7a) has an elevation inferior to 4 m. This assessment was done by identifying the backshore using satellite images and extracting the elevation in that location. The backshore features assessment (Figure 5.7b) was done using the CLC2012 dataset (EEA, 2016b). The inland areas were used to identify what corresponds to coastal plains (*e.g.* the category *moors and heathland* was considered coastal plain). On the other hand, the coastal defences considered in CERA1.0 were used for identification of seawalls and similar features. The combination of these features accordingly with Table 2.7 gives the results of the potential magnitude of shoreline retreat, which is divided into 5 classes. Most shoreline was considered with high erosion potential.

Theses sub-indexes together with information of wave exposure and shoreline position change rates are used to achieve the physical vulnerability classification (Figure 5.8).

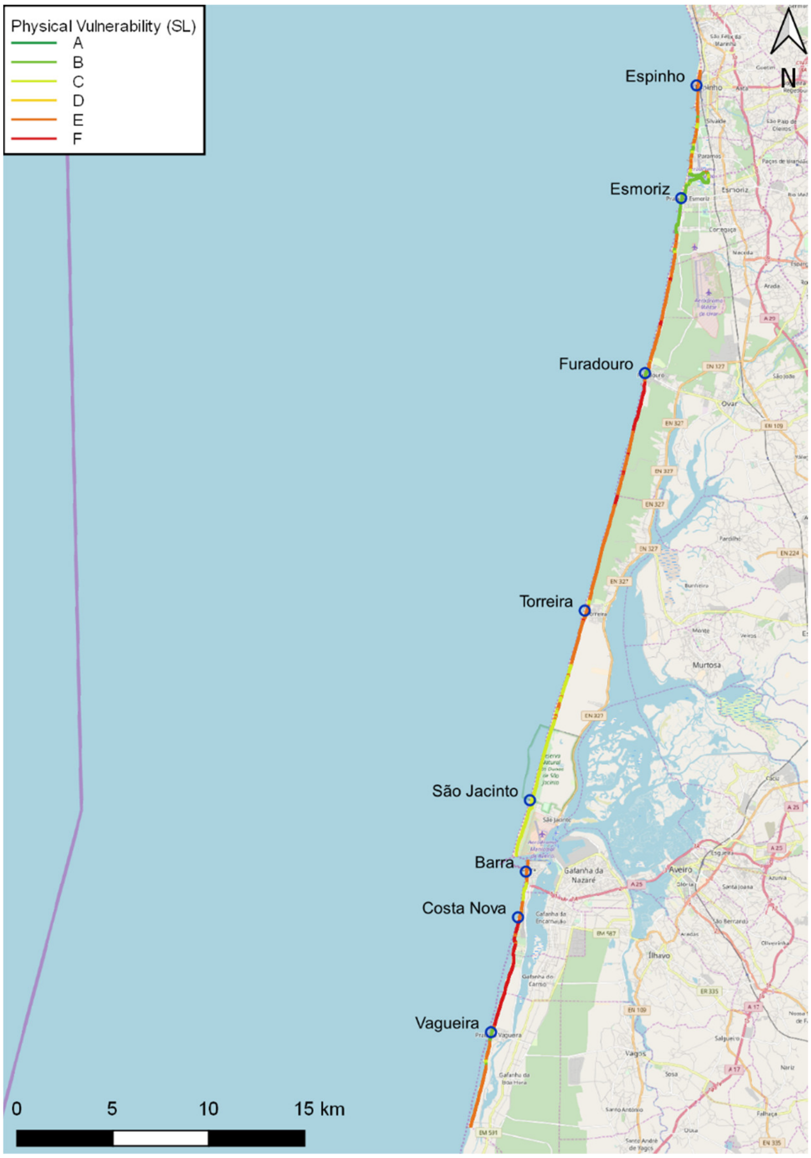

Figure 5.8. Physical vulnerability classification for Aveiro, using Smartline.

According to Lins-de-Barros (2010), the wave exposure is measured by its nearshore significant wave height. No further details are given on which wave height is to be considered by the method. Therefore, the classifications defined in CERA1.0 were adapted to the Smartline methodology. Wave propagation modelling would be recommended, but it is outside the scope of this work and it is not something to consider in the intended new proposal due to higher data requirements and increased complexity demanded. Consequently, for Aveiro, the highest class of wave height indicator was considered. For the shoreline position change rates, the method only distinguishes between stable or retreating shoreline. As showed in previous methods, Aveiro has mostly a retreating shoreline, only interrupted by attached coastal defences and by São Jacinto, which presents shoreline position accretion rates.

Despite the methodological difference of the Smartline approach compared with the previous methods, which do not rely on averaging all indicators but on a sequential qualitative assessment, the Smartline results have similarities with the other approaches, pointing out again the coastline of Furadouro, Costa Nova and Vagueira as the most likely locations to suffer coastal erosion. Overall, 32% of the shoreline was classified ranging between A to C classes, while the remaining areas have high (E) to very high (F) coastal hazard levels.

5.2.2. MACANETA

For Macaneta, the mean grain size estimated by Karlsson and Liljedahl (2015) corresponds to coarse sand. On the other hand, vegetated dunes are present along almost all spit formation, only interrupted in the narrower parts (Figure 5.9a). The result is a very high resistance to erosion according to the Smartline approach (Table 2.6). For the second sub-index, the coastal slope used (Figure 5.9b) was computed using the ASTER GDEM dataset. Most of the shoreline has a slope superior to 1°, which can be explained by the considerable size of the dunes that are present along the spit.

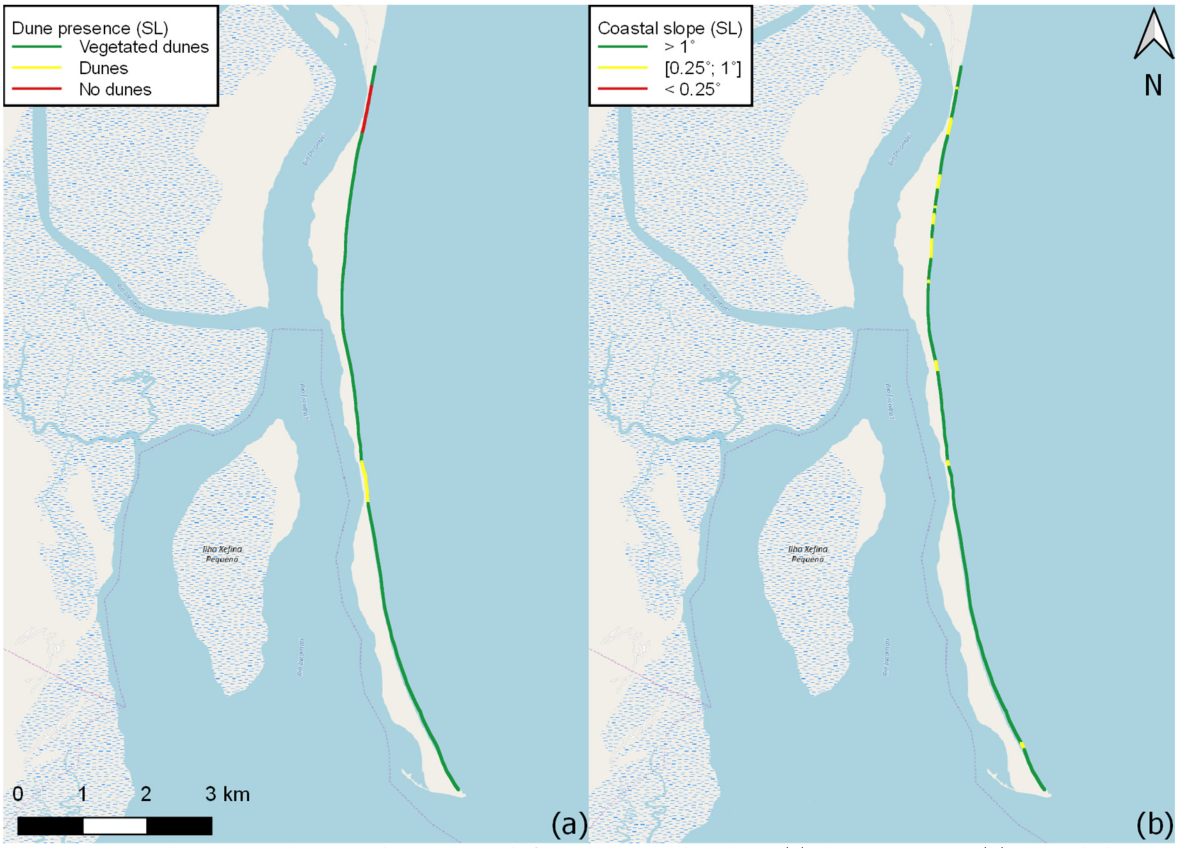

Figure 5.9. Indicators in the Smartline approach for Macaneta shoreline: (a) dune presence; (b) coastal slope.

Figure 5.10 shows the backshore features required for the potential magnitude of shoreline retreat. Regarding the backshore topography (Figure 5.10a), the southern part of the spit presents elevations superior to 6 m, while the northern area has generally lower elevations (inferior to 6 m). The backshore features (Figure 5.10b) were considered a coastal plain, as the geomorphology is equivalent to Aveiro. These indicators resulted into a potential shoreline retreat with a very high classification, considering the criteria showed on Table 2.7. In this case, the geomorphology considered was decisive in the classification, as all coastal plains are considered as having the highest potential magnitude of retreat.

As in CERA1.0, the wave exposure was considerate to be low/moderate and the shoreline is stable. The Smartline methodology applied to Macaneta returned an overall result corresponding to a stable shoreline with moderate vulnerability (level B; Figure 5.11), considering the Smartline vulnerability matrix, represented on Table 2.8. This shoreline has shown shoreline accretion/null rates over recent years, but its geomorphological nature (barrier system with non-cohesive sediments) and low-lying topography make the coastline susceptible to extreme hazardous events.

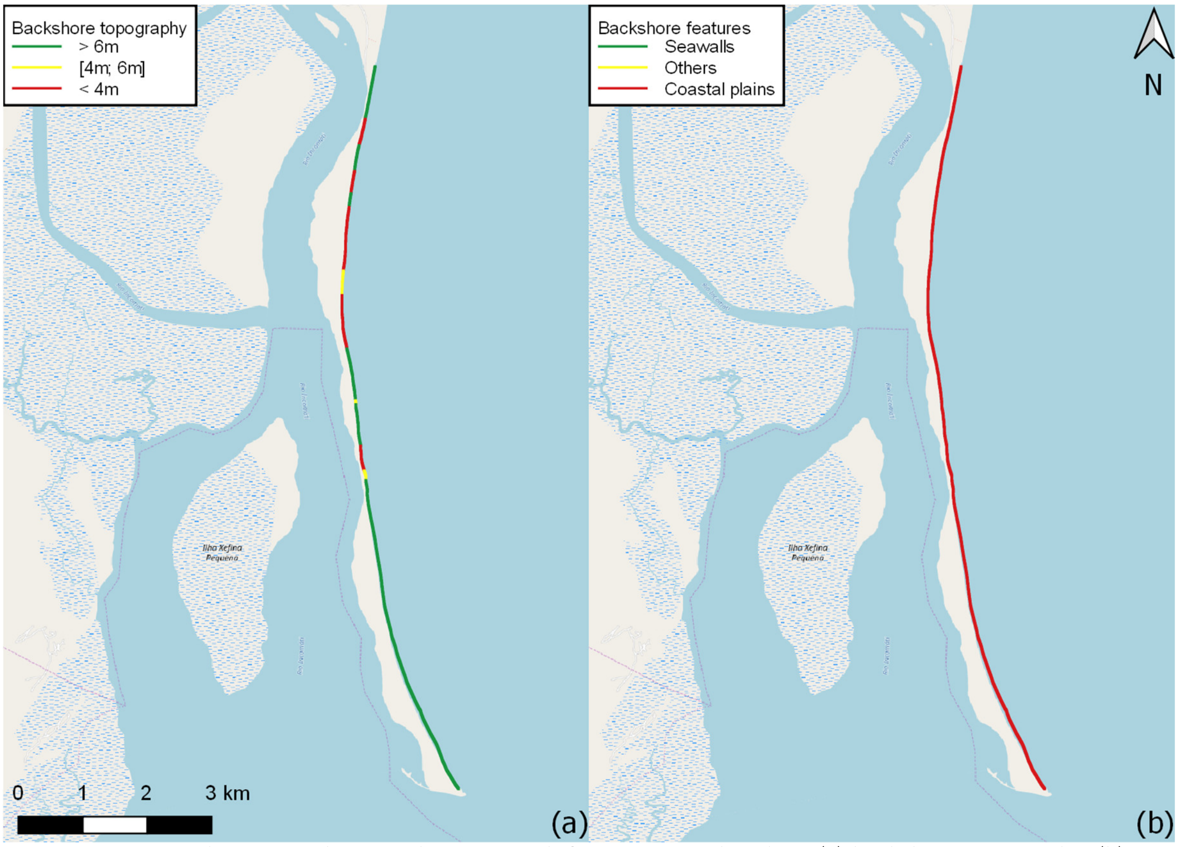

Figure 5.10. Indicators in the Smartline approach for Macaneta shoreline: (a) backshore topography; (b) backshore features.

5.2.3. Quintana Roo

The procedure taken for the application of the Smartline for Quintana Roo was as follows. The median grain size classification took in consideration the sediment samples described in section 3.3. Therefore, a medium grain size classification was considered representative for the entire study area, with exception of swamp areas, which are usually composed by silt and similar sediments. These were classified with the fine sediments class. The dune presence is almost inexistent (Figure 5.12a). These were identified using land use maps and satellite images. Only on the east coast of Cozumel is possible to identify some vegetated dunes, as well as at north of Cancun. The combination of dune presence and grain size resulted into a resistance to erosion that varied from very low on swamp areas to high where vegetated dunes are present. The remaining area has a moderate resistance to erosion.

Figure 5.11. Physical vulnerability classification for Macaneta, using Smartline.

Regarding coastal slope (Figure 5.12b), the data source map was the same as the one considered in CVI, being only required to convert the map from percent to degrees. Most study area felt into the medium category (between 0.25° and 1°), with only some minor hotspots being classified with the remaining classes, such as Puerto Morelos shoreline or the shoreline south of Playa del Carmen.

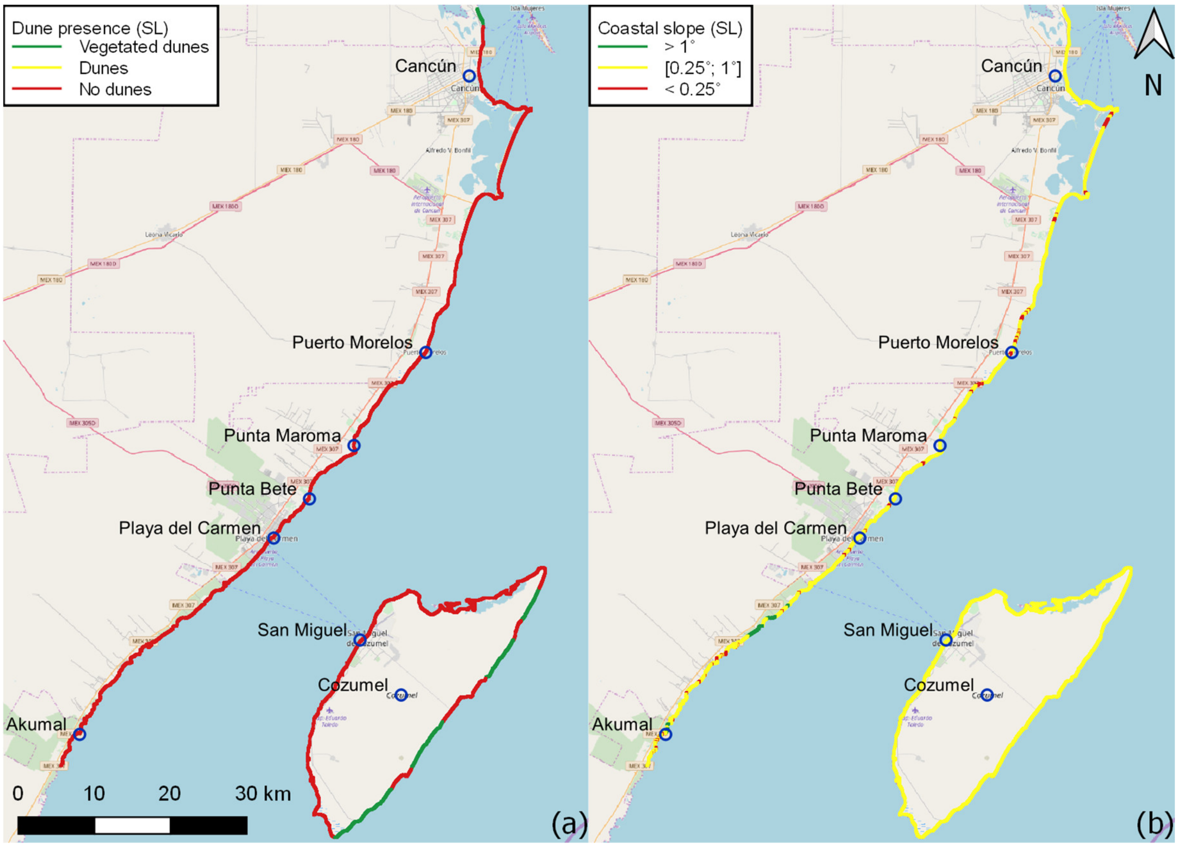

Figure 5.12. Indicators in the Smartline approach for Quintana Roo shoreline: (a) dune presence; (b) coastal slope.

Like the other study sites, the backshore topography was performed by drawing the backshore position and extracting its elevation from the DEM dataset. The output revealed that most area is in the higher classification level, with elevations below 4 m (Figure 5.13a). However, higher elevations were registered in Cancun barrier island. These registers could happen due to the infrastructures near the shoreline (in this case, a considerable number of hotels and resorts), which are captured by LiDAR. Some locations in Cozumel were also classified with the intermediate level of backshore topography. The backshore features assessment (Figure 5.13b) reveals a great variability when compared with the other study sites. For this map, artificialized shorelines were identified with satellite images and from previous maps, such as anthropogenic actions from CERA1.0. These locations were assigned the lower class, correspondent to seawalls and similar features. On the other hand, sand beaches were also identified using satellite images. These were classified as coastal plain. The low topography and slope resulted in a generally high to very high potential magnitude of shoreline retreat, with exception for the areas tagged as seawalls or similar features.

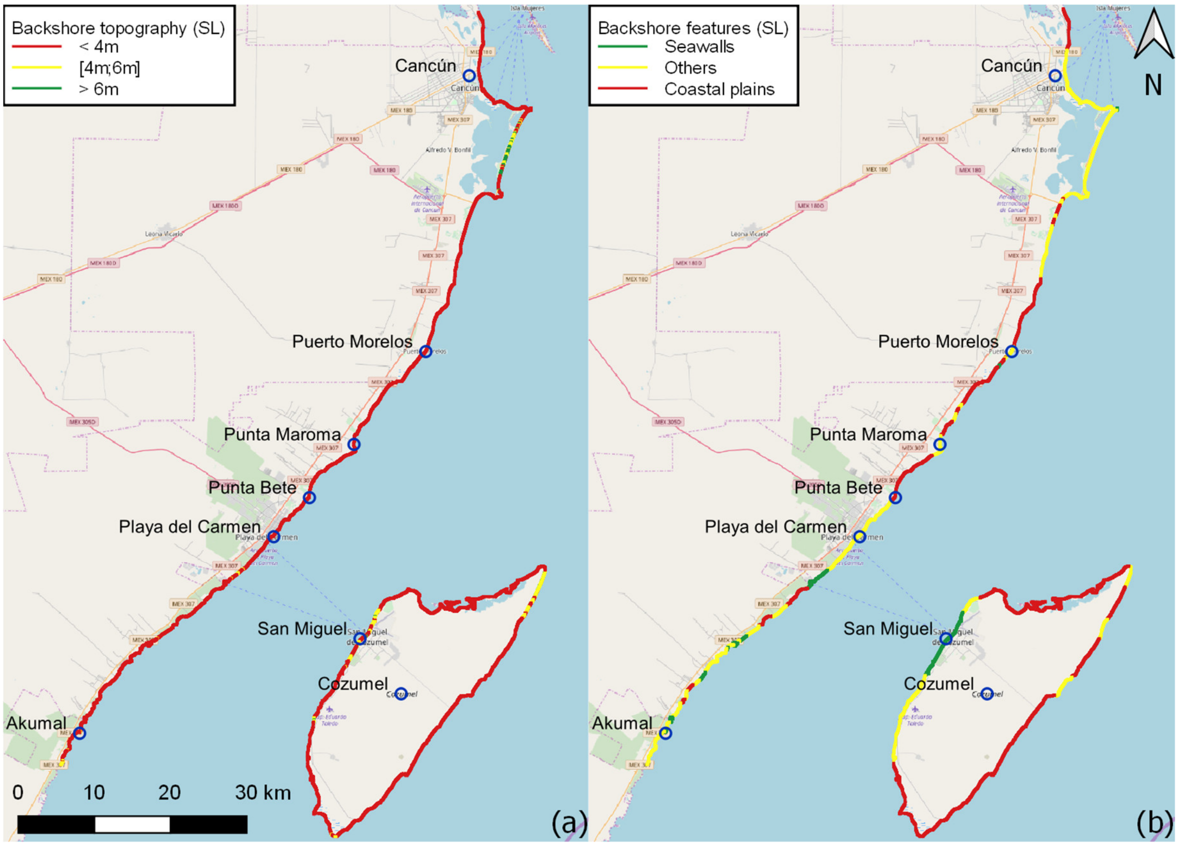

Figure 5.13. Indicators in the Smartline approach for Quintana Roo shoreline: (a) backshore topography; (b) backshore features.

Finally, considering the higher wave exposure class for the entire study site, and the shoreline position change rates, where most shoreline is stable, with only a few exceptions on Puerto Morelos, Playa del Carmen and the east side of Cozumel, the physical vulnerability map was produced (Figure 5.14). The result showed that the shoreline between Playa del Carmen and Puerto Morelos has a very high physical vulnerability (classes E and F). The northern and southern parts of Cozumel also presented high classifications. These areas were classified as having a low resistance to erosion, which was the main contributor for this outcome. The remaining area was classified as C. The stable shoreline and the higher resistance to erosion are the reasons for this result. San Miguel de Cozumel is the least vulnerable to erosion, as the majority of the indicators were favourable. Despite its location (protected from wave climate) not being directly reflected on any indicator, it certainly has influence, namely on shoreline change rates. As the largest study area in this work, Quintana Roo also presents the most variety in environments, combining natural with urban areas. This variety is reflected in the Smartline results, where most of the 6 classes were obtained on the overall classification along the shoreline.

Figure 5.14. Physical vulnerability classification for Quintana Roo, using Smartline.

5.3. RISC-KIT CRAF1 FOR AVEIRO

Due to its different assessment process and data required, the RISC-KIT Coastal Risk Assessment Framework phase 1 (CRAF1) was only applied to the Aveiro study area. Following the thesis aims, the methodology was applied to coastal erosion hazard, following the methodology proposed by Mendoza and Jimenez (Mendoza and Jiménez, 2006), as referenced earlier (section 2.2.12). The risk classification is achieved by combining hazard and exposure assessment (Eq. 2.5).

For the erosion hazard assessment, the eroded beach volume for a given storm was estimated through numerical modelling using XBeach (Roelvink *et al.*, 2010). For this, 12 cross-shore coastal profiles located between São Jacinto and Vagueira were used (Figure 5.15), which were considered representative of the entire study area. These profiles (Figure 5.16) were collected between 2009 and 2013 by APA (*Administração do Porto de Aveiro*), from the top of the dune to a 10 m depth (Palalane *et al.*, 2016).

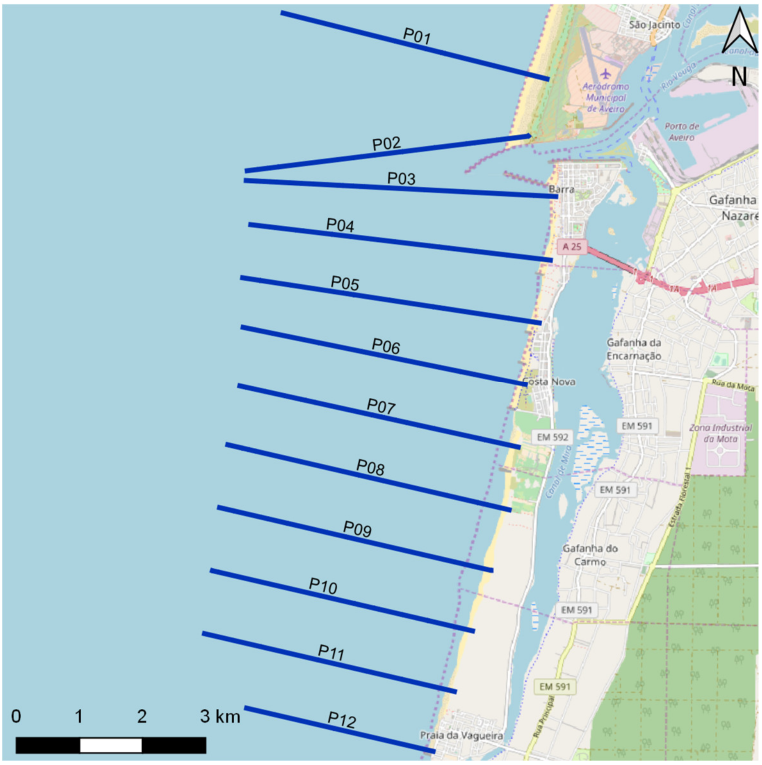

Figure 5.15. Cross-shore profiles location between São Jacinto and Vagueira, used in XBeach modelling.

For the wave climate, SWAN (Booij *et al.*, 1999) wave model results were obtained at the 15 m depth contour based on the work of Sancho *et al.* (2013), in front of Espinho, approximately 30 km north of the modelled area. The dataset includes records of significant wave height, wave peak period and wave direction every 6 hours, between 1953 and 2009, based on offshore hindcast time series provided by Dodet *et al.* (2010). This data was considered representative of the wave climate in the study area. A 5 m threshold for the significant wave height was used for the definition of a storm (Costa *et al.*, 2001). A total of 103 storms were taken from the dataset, with storms lasting up to 5 days, and maximum significant local wave heights of 7.3 m.

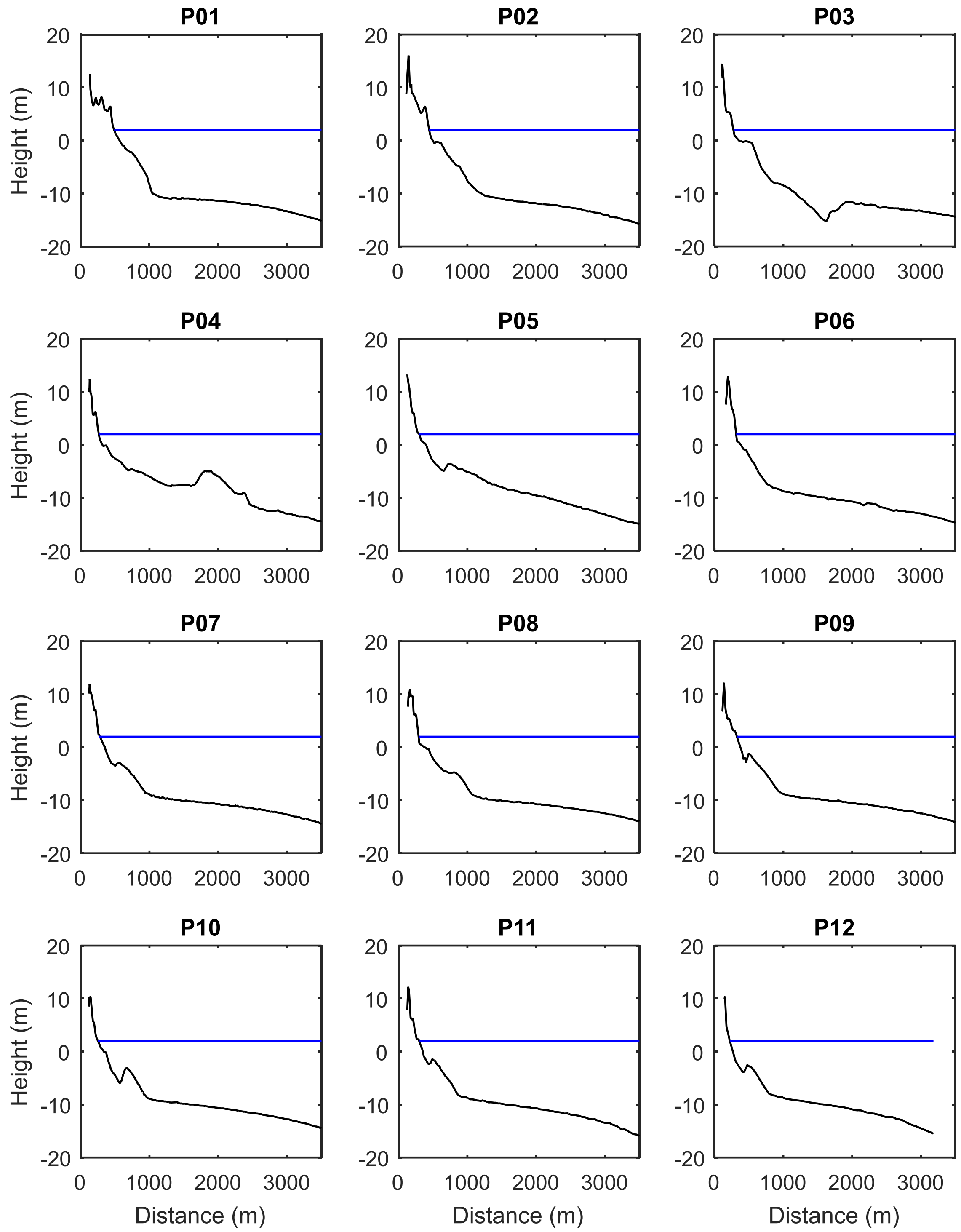

Figure 5.16. Cross-shore profiles between São Jacinto and Vagueira, used in XBeach modelling.

For each cross-shore beach profile, all 103 identified extreme conditions were modelled, allowing to characterize profile responses and consequent eroded volumes (Figure 5.17).

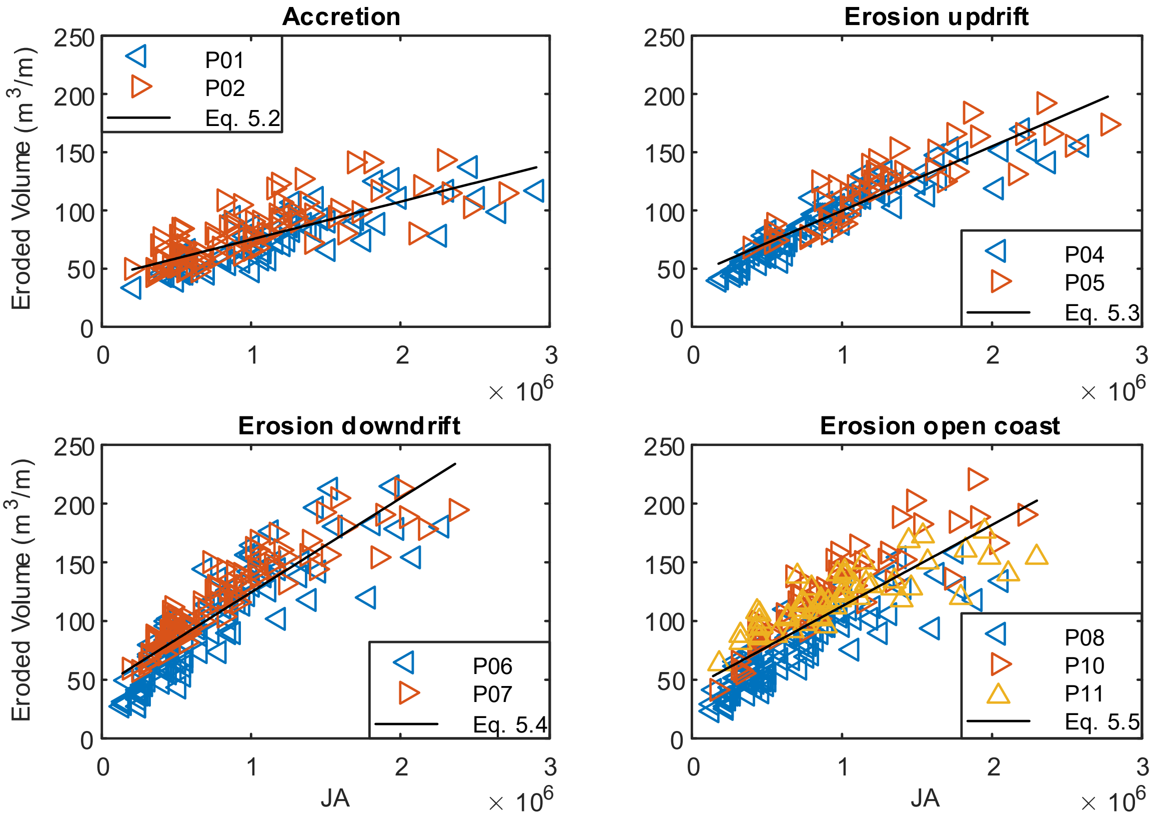

Figure 5.17. Eroded volume and linear correlation with JA parameter of 9 (out of 12) cross-shore profiles.

The results were correlated linearly to a coastal morphodynamic parameter (Figure 5.17), including the beach slope, the median sediment grain size and wave steepness, represented by the JA parameter in Equation 5.1 (Jiménez *et al.*, 1997):

$$\mathrm{JA} = \mathrm{m}\sqrt{\left|\mathrm{D}_{0,e} - \mathrm{D}_0\right|} \tag{5.1}$$

where D_0 is the offshore-related Dean parameter ($D_0 = H/T.w_f$), with w_f being the sediment fall velocity, H the offshore wave height and T the wave period. $D_{0,e}$ corresponds to offshore related Dean parameter value at equilibrium, which is considered 2.7 when using waves characteristics at deep-water. Given the similarity between wave characteristics at deep-water and at 15 m depth, the value of 2.7 was considered valid for this simulation. Finally, m is the profile mean slope (Jiménez *et al.*, 2015).

To obtain relationships to all environmental indicators, the profiles were clustered in to 4 different types: profiles mostly in accretion (P01 and P02; Eq. 5.2); profiles in erosion, located updrift of coastal defences (P04 and P05; Eq. 5.3); profiles in erosion, located downdrift of coastal defences (P06 and P07; Eq. 5.4); and open coast profiles in erosion (P08, P10 and P11; Eq. 5.5). The remaining profiles (P03, P09 and P12) presented results that did not allow clustering. Hence, they were not considered. Applying linear-regression and best-fit (Jiménez *et al.*, 1997), the following equations were obtained (represented in Figure 5.17), with the coefficients of determination (r^2) given in brackets:

$$\Delta V_{Accretion} = 3.25 \times 10^{-5}.\,JA + 42.61, (r^2 = 0.59) \quad (5.2)$$

$$\Delta V_{Erosion\ Updrift} = 5.53 \times 10^{-5}.\,JA + 44.43, (r^2 = 0.84) \quad (5.3)$$

$$\Delta V_{Erosion\ Downdrift} = 8.01 \times 10^{-5}.\,JA + 44.45, (r^2 = 0.77) \quad (5.4)$$

$$\Delta V_{Erosion\ Open\ Coast} = 6.93 \times 10^{-5}.\,JA + 43.36, (r^2 = 0.68) \quad (5.5)$$

Equations 5.2 to 5.5 were then applied for a storm with a 10-year return period (48-hour storm; H_s = 6.5 m; T_p = 15.7 s). The choice of a 10-year return period was considerate adequate for short to medium-term risk assessment, facilitating possible comparisons between CRAF1 approach and the other studied methods. The characteristics of a 10-year return period storm were defined by fitting the storm energy content, *E* (Eq. 5.6; Mendoza and Jiménez, 2006), of the 103 storms in a Weibull cumulative distribution function.

$$E = \int_{t1}^{t2} {H_s}^2 .\, dt \quad (5.6)$$

According to the computed distribution, a 10-year return period storm has around 2000 m^2.h of energy content. The storm with the closest energy content was used for the assessment. Additionally, the values of median sediment grain size (Figure 5.18a) gathered by Coelho (2005) were used to compute the fall velocity (Eq. 5.7; Soulsby, 1998), and consequently, the JA parameter along the study area.

$$\omega_s = \frac{\nu}{d_{50}}[(10.36^2 + 1.049D_*^3)^{0.5} - 10.36] \tag{5.7}$$

After computing the eroded volume along the study area, the shoreline retreat was obtained from the eroded volume through Equation 5.8:

$$R = \Delta V/(b + d^*) \tag{5.8}$$

where R is the retreat of the shoreline due to a storm event, ΔV is the eroded volume, b is the berm height (Figure 5.18b) and d^* is the representative depth at which erosion is null (Armaroli and Duo, 2018).

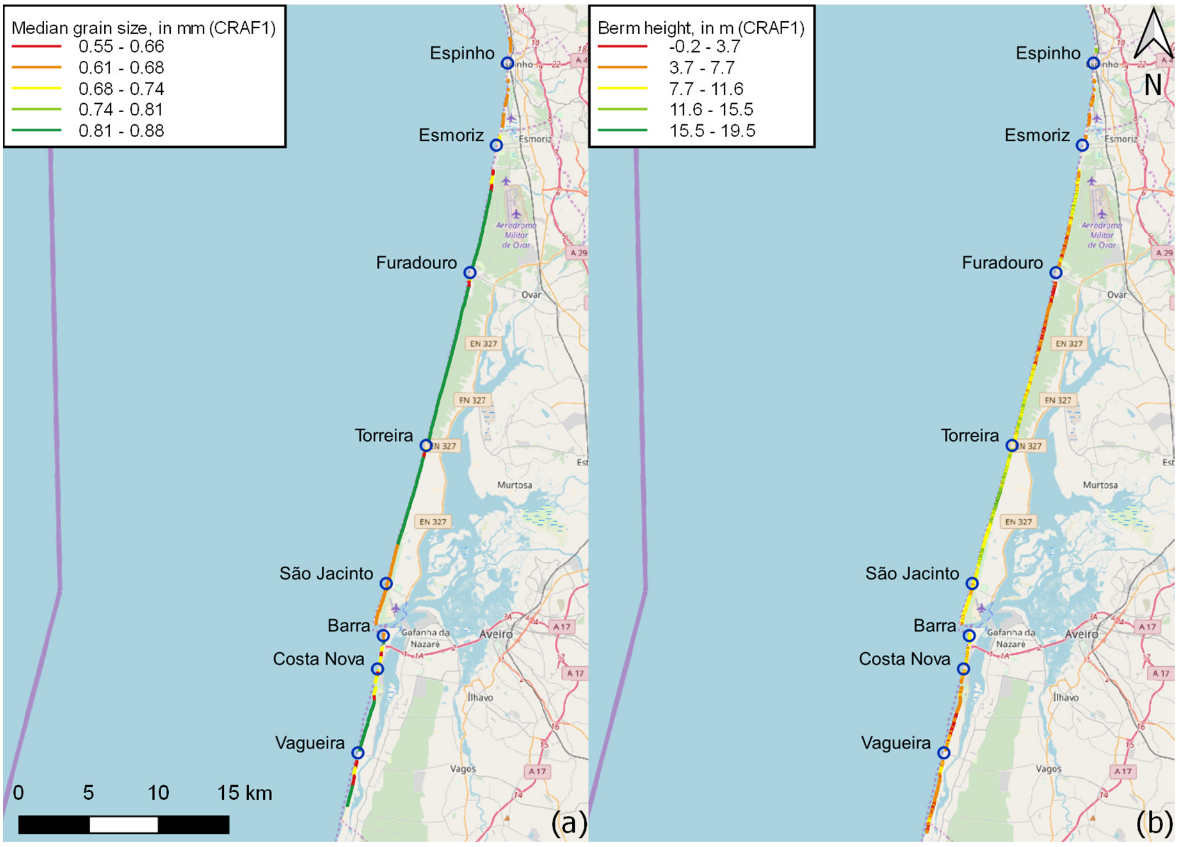

Figure 5.18. Data used in the hazard assessment of CRAF1 relative to (a) median grain size and (b) berm height for Aveiro.

The 3 m depth was adopted as d^*, since it was the maximum depth were erosion was registered during the XBeach numerical modelling. The berm height was estimated using the LiDAR DEM dataset (DGT, 2011) along the study area (Figure 5.18b). This dataset was used in favour of the EU-DEM dataset due to its much higher resolution (2 m/px against 20 m/px).

Based on values for the shoreline retreat, grouped into 5 different hazard classes, the storm-induced erosion hazard level obtained by this method is presented in Figure 5.19. The coastline that is covered by a coastal protection structure, such as a seawall, was not represented in Figure 5.19.

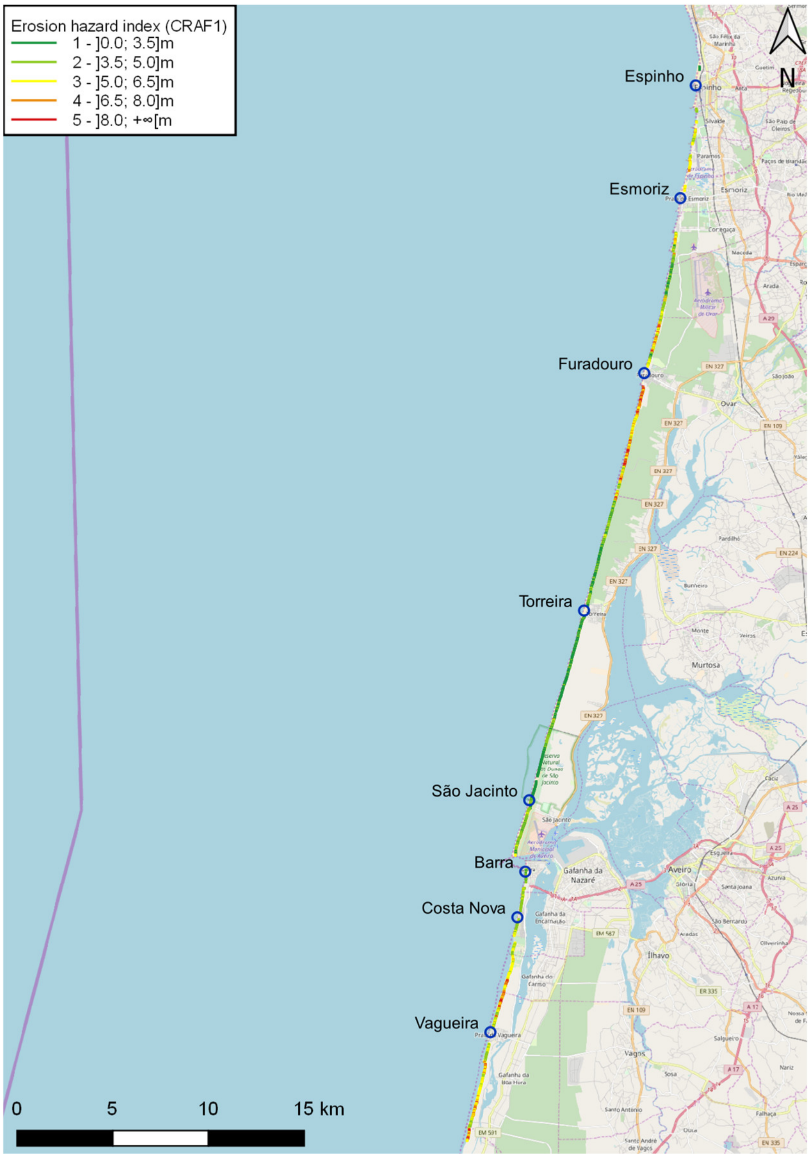

Figure 5.19. Erosion hazard classification for Aveiro, according to CRAF1.

The thresholds used for class definition in CRAF1 are established according to the user perception. In this case, the thresholds for each class were set at each 1.5 m (Figure 5.19), whereas the lower and upper limits were defined based on the minimum and maximum values obtained by the simulation (between 2 m and 10 m).

The CRAF1 erosion hazard results show that the area near Furadouro and between Costa Nova and Vagueira are, again, the most susceptible to coastal erosion for a 10-year return period storm, with expected storm induced shoreline retreats superior to 8 m. On the other hand, the area surrounding São Jacinto is, again, the least affected by the extreme event considered.

Furthermore, the exposure index is computed using Equation 2.6. For this assessment, the exposure variables established were population, heritage and economy (Figure 5.20). These indicators were also present in CERA1.0 and are considered adequate for the coastal exposure index proposed in CRAF1. Hence, the respective inputs in CERA1.0 were adapted for CRAF1.

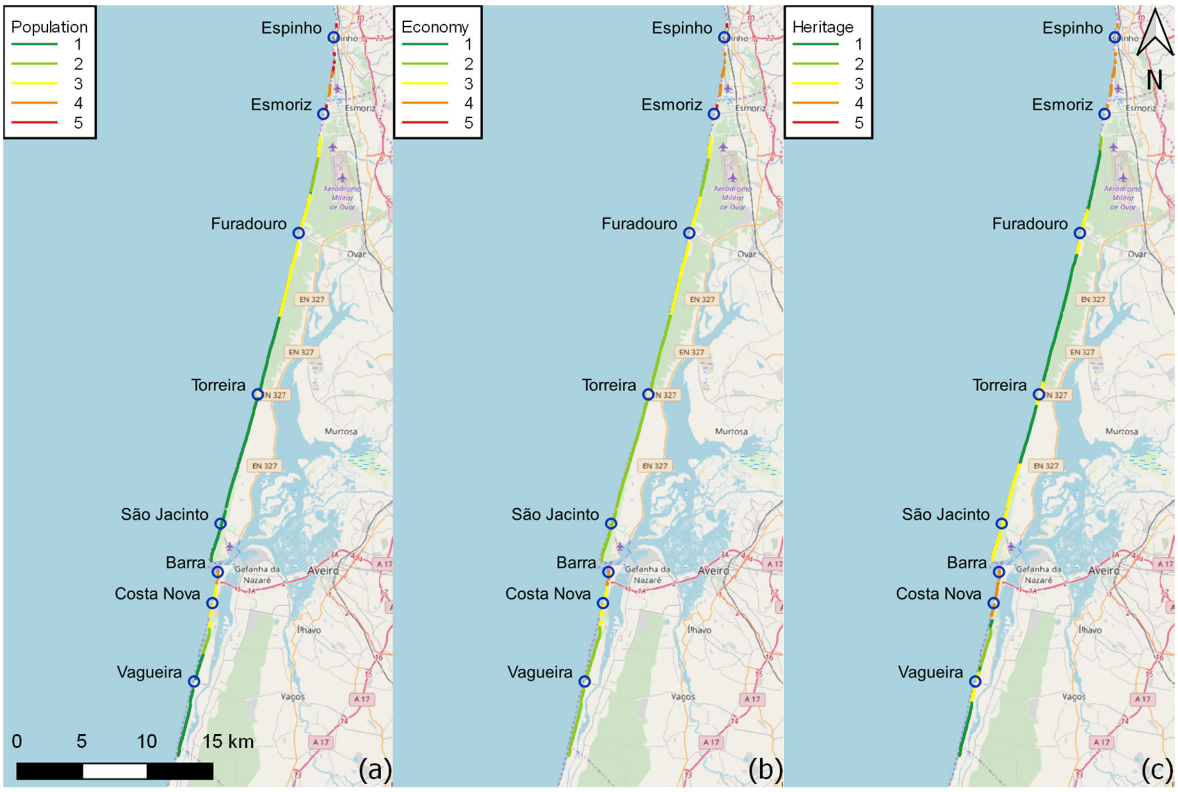

Figure 5.20. Data used in the exposure assessment of CRAF1 relative to (a) population; (b) economy; and (c) heritage for Aveiro.

Comparatively with the indicators commonly used in CRAF1 (Ferreira *et al.*, 2016; Viavattene *et al.*, 2018), critical infrastructures and transports were not included as a standalone exposure variable in this assessment. However, they were included within the heritage assessment of CERA1.0. Therefore, all exposure variables frequently used in CRAF1 were also considered in this assessment. The geometric mean of these inputs resulted in the exposure index, presented in Figure 5.21.

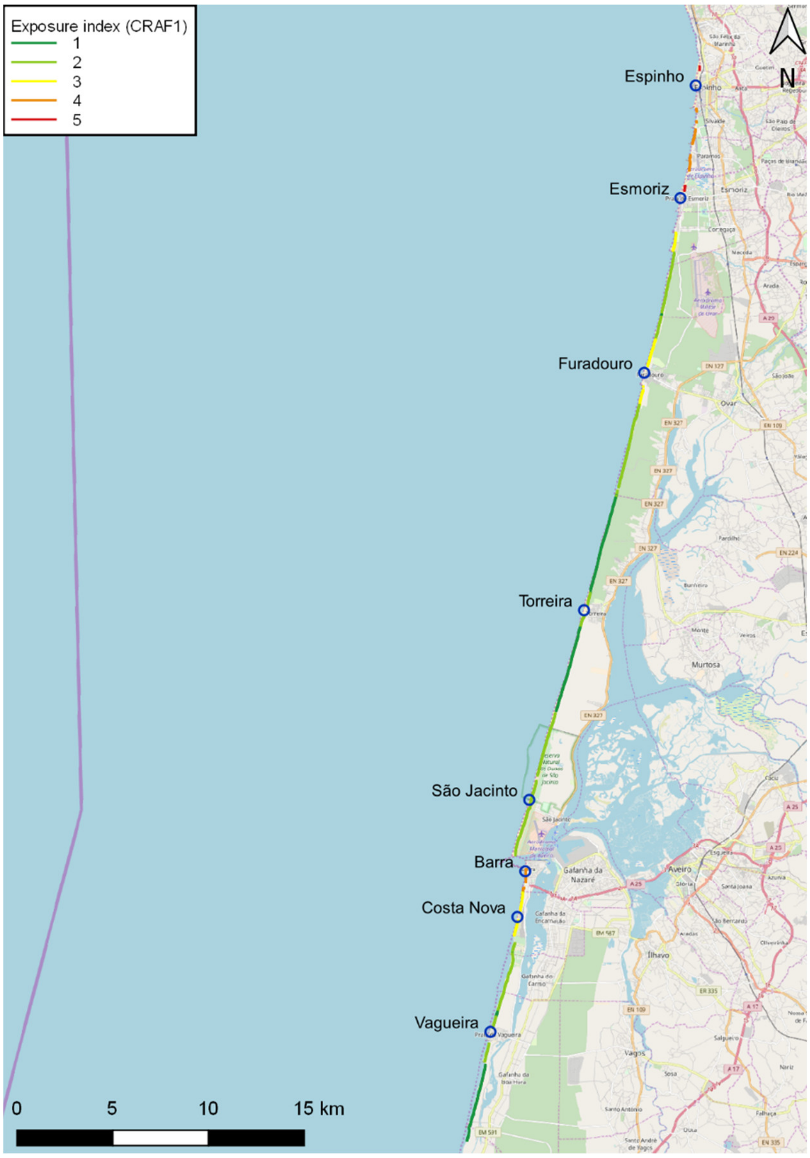

Figure 5.21. Exposure classification for Aveiro, according to CRAF1.

Naturally, the locations with the most exposed elements are the urban centres near the shoreline, which combine higher land value and population. Finally, the combination of hazard and exposure maps results in the risk classification, shown in Figure 5.22.

In general, the risk classification is low to moderate, despite the high hazard classification in some key locations. Urban areas are usually classified with level 3, except for Esmoriz and Furadouro, that reach risk class 4, mostly due to their high hazard classes (level 4 and 5). On the other hand, the area between São Jacinto and Torreira presents the lower risk level. The less populated area and the healthy backup of sediments provided by the dunes are the cause for the low risk level.

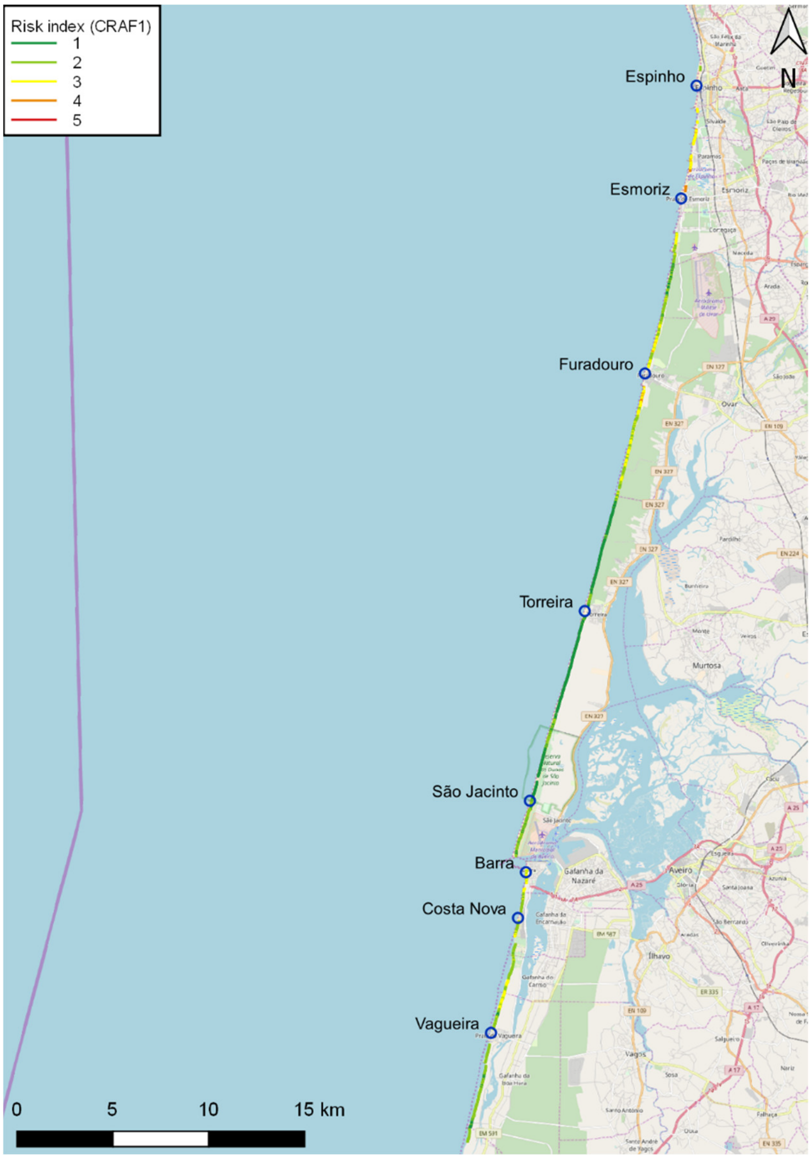

Figure 5.22. Risk classification for Aveiro, according to CRAFI.

5.4. Coastal Hazard Wheel

The application of the Coastal Hazard Wheel (CHW) to the study sites was performed through the use of its web application (Deltares *et al.*, 2017). As stated earlier, this application incorporates world databases and automatically applies CHW to provide a hazard classification with a low to moderate accuracy. The CHW classification attributed for each location is represented in Figure 5.23.

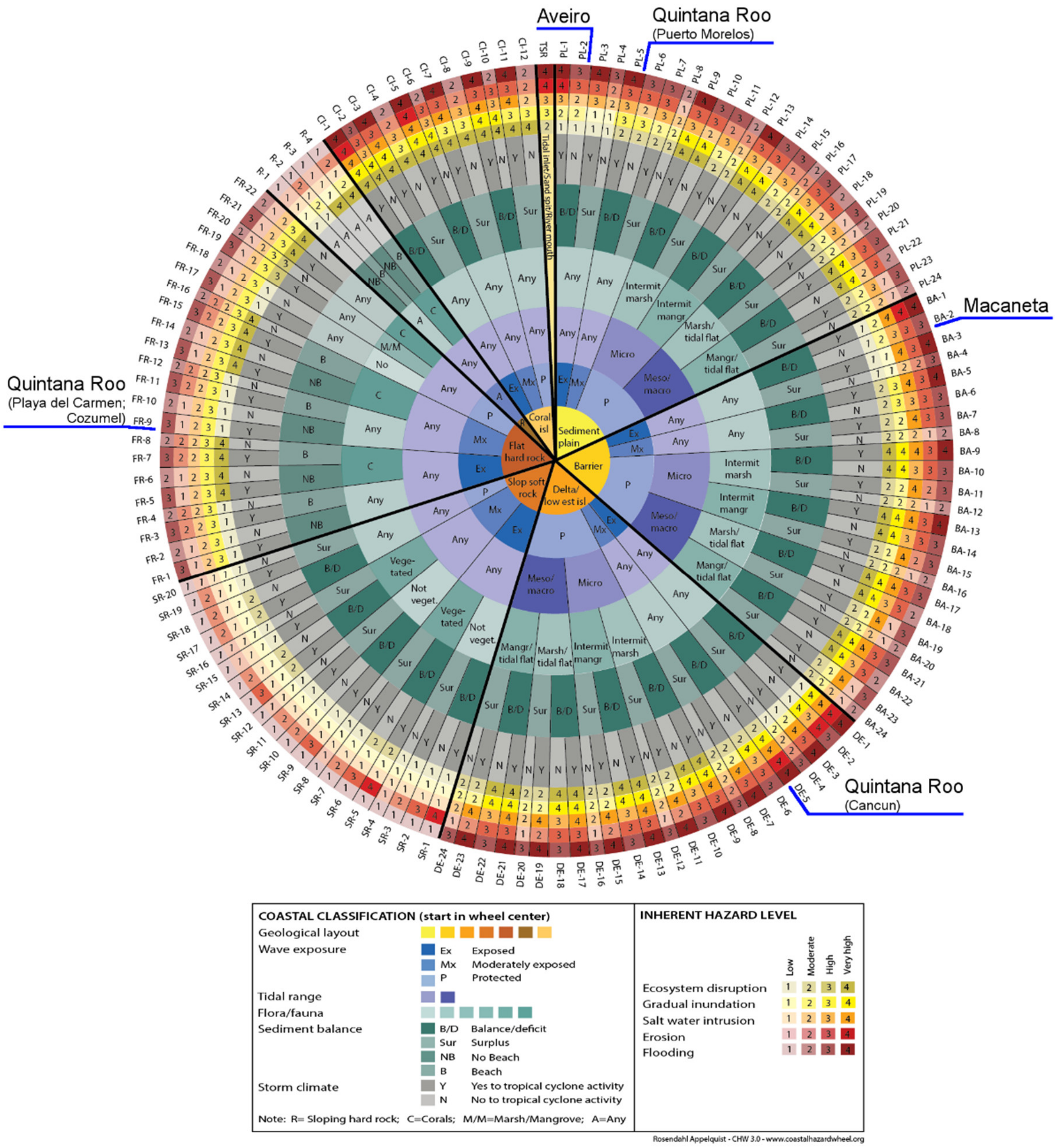

Figure 5.23. CHW classification for all study sites.

The CHW App allows to classify Aveiro as a sediment plain with high exposure to the wave climate and a meso-tidal range. The area is also identified as vegetated, salt marshes or tidal flats with no tropical cyclone activity. These classifications place Aveiro as an area highly threatened by erosion (level 3), corresponding to the combination PL-2 from the Coastal Hazard Wheel (Appelquist *et al.*, 2016).

On the other hand, Macaneta spit is considered as a barrier island with high wave exposure and a meso-tidal range. The application does not have data on the vegetation and considers the sediment balance as stable with no sign of cyclone activity. Therefore, the study area is considered as highly susceptible to coastal erosion (combination BA-2), mostly due to its classification as a barrier island, since the great majority of combinations with this geological environment are classified as level 3 in this methodology.

Finally, the CHW application results shows agreement with the previous methodologies, with an erosion hazard level 3 from south of Cancun to Punta Bete (PL-5), which is considered a sediment plain with moderately wave exposure, micro-tidal range and a deficit in sediment balance. In contrast, the CHW App results present a low erosion hazard level (FR-9) at south of Punta Bete and at Cozumel Island. This area has a different geologic composition, being classified as flat hard rock. The application also identifies in the vegetation assessment the intermittent existence of mangroves in those areas. Finally, the coastline of Cancun is identified as a delta or low estuarine island, with the other indicators being the same as the remaining areas. This change in geology increases the erosion hazard to level 4 (DE-5) in that area.

5.5. Results analysis

All methods applied above aim to assess coastal hazards, in general, or coastal erosion, in particular. Some also include assessment of socioeconomic and environmental features in order to assess risk. Considering that this work only assessed the socio-economic features on 2 methodologies (CERA1.0 and CRAF1), this discussion will primarily focus on the hazard assessments (*i.e.* not including socio-economic indicators).

A results summary of the hazard classification is presented in Table 5.1, where the percentage of total shoreline extension or total area (in CERA1.0) assigned to each hazard class is shown. The classes were normalized to fit every assessment in the qualitative thresholds of low, moderate and high. The categories included in the low class are 1 and 2 for CERA1.0 and Smartline, and 1 for CVI, CRAF1 and CHW. For the high class, the normalization included the highest two classes of all methods. The remaining classes were considered moderate. The normalized classes were chosen based on the descriptions of classes from source literature of each methodology.

Table 5.1. Percentage of regional extension/area classified as low, moderate and high hazard level, for each region.

		CERA1.0	CVI	SL	CRAF1	CHW
Aveiro	Low	3%	36%	12%	26%	---
	Moderate	49%	16%	20%	58%	---
	High	48%	48%	67%	16%	100%
Macaneta	Low	0%	---	100%	---	---
	Moderate	3%	---	0%	---	---
	High	97%	---	0%	---	100%
Quintana Roo	Low	24%	29%	9%	---	72%
	Moderate	53%	23%	42%	---	---
	High	23%	47%	48%	---	28%

The summary highlights most differences in the application of the different methodologies. That is, all methods yield dissimilar percentages of areas or shoreline extensions classified as low, moderate or high threatened to coastal erosion. For some classes, some methods and some case studies, similarities in percentage values can exist (*e.g.*, for the High class, in Quintana Roo, between CVI and Smartline), but there is no general agreement between them.

Despite the lack of agreement, the percentage of areas with high classification across most assessments should be highlighted (8 out of 12 assessments nearly reach, or surpass, the 50% coverage of high hazard level). In that regard, only the CRAF1 assessment does not present the same tendency, although the application to a single area discourage the conclusion that the method outputs present lower classification than the other methods. Moreover, the computation method is very different from the others and depends on user-defined thresholds. The thresholds in CRAF1 hazard index (Figure 5.19) were chosen to highlight the most susceptible areas and so, the percentage of areas classified as High is smaller than for the other methods.

Regardless of the differences highlighted in Table 5.1, when comparing the results of all methodologies for each study area, the hotspots identified generally coincide. In Aveiro, the municipalities of Ovar and Ílhavo (areas surrounding Furadouro, Costa Nova and Vagueira) are the coastlines with the highest hazard level for all methodologies. This result is in agreement with local experts and with recent events that produced damage in those areas (Pereira and Coelho, 2013b; Pinto *et al.*, 2014; Narra *et al.*, 2017).

In Macaneta, results contrast greatly between CERA1.0 and Smartline methodologies. Its stable shoreline, medium sediment grain size and low exposure to wave climate gives a class B for the Smartline assessment, while the low topography and non-cohesive sediment composition give high vulnerability for the CERA1.0 classification. The CHW App also classify this area with high hazard level, due to its geomorphological features. The difference in the classification exposes the diverse approaches that each method takes. CERA1.0 considers the historical shoreline change rates less important and the exposure to a potential hazard more important. On the other hand, the Smartline gives much more importance to the past events and therefore considers this a region of low vulnerability. This uncertainty in the hazard assessment of Macaneta is also noticeable in previous literature. On one hand, shoreline change rates are stable (DHI, 2013), on the other, the narrower sections of the spit are extremely vulnerable to extreme events (Palalane *et al.*, 2016), potentially causing breaching. For Macaneta, it is important to remember that the entire area was classified uniformly, and the application of CVI was impossible to achieve.

In Quintana Roo, similar hotspots were identified by the various methods, namely the area located between south of Cancun and Playa del Carmen, which has greater shoreline change rates and present non-cohesive sediments, as well as a uniformly low topography and great exposure to wave climate and extreme events. The existent literature is in agreement that this area, namely the stretch between Punta Bete and Punta Maroma have serious erosion problems (Odériz *et al.*, 2014) and suffer from coastal hazards in general, particularly extreme events (Silva *et al.*, 2007, 2012; Martell *et al.*, 2012). The east side of Cozumel island is also considered as highly susceptible to coastal hazards, although the agreement is not unanimous, with CERA1.0 presenting only a small strip of class 4 near the shoreline in its vulnerability output and class 3 in its risk output, contrasting with the others, which present high hazard levels in most coastal stretch. The smaller influence of shoreline change rate in the CERA1.0 method when compared with other methodologies, lead to this outcome for the vulnerability output.

5.6. Methodological procedure discussion

Despite having similar aims, the methodologies here presented differ in the procedures used to execute the assessment, the motivation behind the development of the method and the type of results. The nomenclature given by the assessments also differ, with some referencing the results as vulnerability. However, they include similar indicators. Thus, this work considers them possible to compare. In this section, for coherence, all methods are called hazard assessments. Table 5.2 shows an overview of the applied methods, comparing their key characteristics. CERA1.0, applied in the previous chapter, is also considered in this discussion.

CERA1.0 aims to tackle coastal erosion, although the result obtained can also indicate an increased vulnerability to other related coastal hazards, while CVI was developed to assess the relative vulnerability to sea-level rise. Although this work focused on the physical vulnerability to coastal erosion of the Smartline, this methodology is a multi-hazard assessment, including additional modules to assess other hazards and potential consequences. Lastly, the CHW and CRAF1 have a specific class for each hazard. Also, the CRAF1 addresses a specific extreme event, unlike the others.

The aims of each methodology justify the approach taken and the indicators required for the assessment. Regarding the number of indicators required for each methodology, CERA1.0 requires a total of 9 for the hazard assessment, the greatest number, requiring a good deal of georeferenced data. Topography, geological composition and ground cover are essential georeferenced data, since it would be very difficult and time consuming to classify these parameters only by inspection of satellite images and literature review. This method gives results for the shoreline and inland area, requiring characterization of inland areas for 5 out of 9 indicators.

Table 5.2. Overview of methodologies characteristics: CERA1.0 (Coastal Erosion Risk Assessment 1.0); CVI (Coastal Vulnerability Index); SL (Smartline); CHW (Coastal Hazard Wheel); CRAF1 (Coastal Risk Assessment Framework phase 1).

	Features	CERA1.0	CVI	SL	CHW	CRAF1
Indicators	Berm height					x
	Coastal defences	x		x		
	Coastal slope		x	x		x
	Cross-shore profile					x
	Distance to shoreline	x				
	Extreme events				x	x
	Geology	x			x	
	Geomorphology	x	x	x	x	
	Ground cover	x			x	
	Median sediment grain size			x		x
	Presence of dunes			x		
	Sea-level rise		x			
	Socio-economic/environmental	x		x		x
	Shoreline position change rate	x	x	x	x	
	Tidal range	x	x		x	
	Topography	x		x		
	Wave height	x	x	x		x
Approach: averaging indicators		x	x			
Approach: sequential combination				x	x	
Represented area: Inland and Shoreline		x				
Represented area: Shoreline only			x	x	x	x
Difficulty of access to data		Medium	Easy	Hard	Easy	Hardest
Aimed at extreme events		No	No	No	No	Yes
Estimation of shoreline retreat						x
Hazard specific		Yes	Yes	No	Yes	Yes
Assessment scale		Regional	National	Multi	Multi	Local
Number of classes for individual indicators		5	5	3	---	---
Number of classes in final classification		5	4	6	4	6
Number of hazard indicators		9	6	7	6	5
Requires modelling						x
Results: include risk assessment		x		x		x
Results: absolute		x		x	x	
Results: relative / user-defined			x			x

Smartline requires 7 indicators for its hazard assessment. Although this is fewer than for CERA1.0, they are more specific, requiring a more thorough review of the literature (*i.e.* grain size), manual mapping of certain features (*i.e.* dune presence) or a more complex manipulation of existing data (*i.e.* beach slope). Also requires inland data for backshore indicators, but not as extensive as CERA1.0.

CVI requires 6 indicators to assess coastal vulnerability, similar to CERA1.0 indicators, but adding coastal slope and sea-level rise and discarding 5 others. Despite some exceptions (*e.g.* beach slope), the processes involved in data processing and gathering are straightforward and, except for CHW, CVI is the easiest for which to get the data required. CHW also requires 6 indicators and the data is mostly easily gathered from publicly available databases. However, the author experience was limited to consulting the available outputs of CHW App for each study area.

Finally, the application of CRAF1 provides the estimation of the expected shoreline retreat. Only four classes of data are required for the hazard assessment (beach profile, median sediment grain size, berm height and a long-term time series of wave climate or data on extreme events). This data can be difficult to gather for a large study area, due to its specificity, and is often unavailable. Due to site specific characteristics, mainly of the cross-shore profiles, this method is more adequate for regional assessments.

Some indicators are used in many methods here reviewed. However, the thresholds or criteria used in their evaluation differs from method to method. The most used indicators are coastal slope, geomorphology, shoreline position change rates, wave height and tidal range. Geomorphology is a common characteristic to assess the susceptibility of the terrain to erosion or other hazards and is used in a similar way in all methods (*i.e.* rocky coasts have a lower susceptibility and open coasts have a higher susceptibility). Shoreline change rates have different approaches. While CERA1.0 considers accretion as the lowest classification and the others are rising levels of erosion, CVI divides the 5 classes into accretion for the first two and erosion for the last two, with class 3 being considered a stable shoreline. Smartline and CHW only show if the shoreline is or is not in erosion process. The wave height is considered for several methodologies but it differs in the type of wave (*e.g.* significant, maximum, offshore or local) and, consequently, in the thresholds considered for its assessment. CERA1.0 considers the maximum significant wave height, to account for extreme events, while Smartline and CRAF1 consider the average storm wave height. CVI considers the mean significant wave height. In the tide assessment, the thresholds considered are opposites for CERA1.0 and CVI. While CERA1.0 states that high tidal range is associated with a higher erosion potential, CVI states that lower tidal range leads to potentially more energetic storms over the same shoreline position (Coelho, 2005). CHW also considers tidal range in its assessment, but the analysis of the method does not reveal a clear trend of which tide type promotes erosion, although it appears that micro-tidal regimes favour lower erosion hazard classifications.

In terms of data processing required for application of each methodology, CERA1.0 is relatively straightforward. The most complex step is the classification of individual indicators. This requires some GIS knowledge, as it is necessary to use features such as the *Proximity tool* (in QGIS) to obtain the distance to shoreline and to use the *Raster calculator* or the *Rasterize* features to complete some inputs. After that, the indicators are combined according to the weighted average published in Narra *et al.* (2017), using the *Raster Calculator*. To facilitate this process, a QGIS (2018) plugin was developed.

The data processing of CERA1.0 differs from the other methodologies in that it covers a coastal strip, not just the shoreline. So, for CVI, the data processing is similar to CERA1.0, with the key difference that the CVI assessment only corresponds to the shoreline. Thus, in most cases, the data considered was that geographically coincident with the shoreline. The exception is the coastal slope, which requires more complex treatment. For Smartline and CRAF1, due to their specific methods, data gathering and treatment is more difficult. In these cases, the application of the methodologies along the shoreline reduces the amount of terrain that needs to be covered, facilitating manual digitizing. The Smartline approach includes sub-indexes to classify the area without the need to weight each parameter. CHW has a similar approach to Smartline, but yields a quantitative output from 1 to 4 for a variety of hazards, rather than a qualitative classification.

On the other hand, CRAF1 differs from the other methods in providing a concrete value for coastal retreat given a certain hazard (or storm). For that, a characteristic cross-shore profile of the area is required as well as a long-term time series to identify extreme events (or existing data on extreme events characteristics). The resulting output is the coastline retreat for each storm. Defining the appropriate thresholds, it is possible to identify the hotspots in the study area. However, despite its potential to give palpable results, the CRAF1 application requires the most time and effort, mainly due to the numerical modelling required in the preliminary approach.

5.7. SUMMARY AND TAKEAWAYS FOR THE NEW PROPOSAL

Chapters 4 and 5 presented the application of a multitude of methods to the study areas considered for this work. CERA1.0, SL and CHW were applied to all study sites, while CVI was applied to Aveiro and Quintana Roo. Finally, the CRAF1 was applied only to Aveiro study area.

One important difference between the results of each methodology is the area of land described in each classification, particularly with CERA1.0, or along the shoreline, as in the remaining methods. The results show that an area representation that relies on the distance to shoreline trends to homogenize the results along the shoreline. In CERA1.0, most shoreline in all study areas was classified as level 4, in contrast with the hinterland, which was classified mostly as moderate to low vulnerability. This is explained by the fairly similar geo-morphological conditions among all study sites, which present low-lying terrains of highly erodible soil. On the other hand, an inland classification can lead to better coastal management overall, by offering evidence for the restriction of construction in certain places. Therefore, the CERA1.0 methodology may be more appropriate for coastal stretches at a regional scale (50 km to 70 km), where it is possible to find high resolution data and to support coastal management at a municipal scale. Moreover, the representation type (area classification within the study site) is appropriate to delineate restricted areas for certain activities or constructions (*e.g.* municipal management plans).

The other methods present a classification along the shoreline and they differ in the hazard assessment process. The CVI, with less required data, is good for assessing large areas, such as the coasts of the USA and the Gulf of Mexico, where it was initially applied (Thieler and Hammar-Klose, 1999, 2000a, 2000b). The large area ensures enough variety in the results to provide an almost even distribution through its 4 levels of classification, making it possible to perform a relative assessment and easily identify hotspots along the coastlines. On the other hand, it is not suitable for small stretches with little data, such as Macaneta, since it relies on a variety of coastal characteristics to achieve its final output. Further, if the whole study area is similar, the CVI index has no great variation, meaning that a classification in the first quartile does not have a great difference in hazard level compared with a location in the fourth quartile. This can be observed in Quintana Roo when comparing Smartline and CVI. The area that extends from south of Cancun to Playa del Carmen is considered as highly threatened by Smartline, while in CVI there are sudden changes between levels. In Aveiro, these sudden changes in classification are also visible, mainly in the locations classified with high vulnerability levels. In addition, CVI registers more areas with a lower vulnerability, due to its relative nature. For this reason, the direct comparison of CVI results and others should be made qualitatively, such as the identification of seriously endangered hotspots, and not as a raw comparison. It should be noted that CVI assesses vulnerability to SLR-related hazard and not specifically coastal erosion, as most other methods do.

Like CVI, the Smartline approach is also suitable for large areas, although the results demonstrate that it also works well for local to regional scales, given that the available data is sufficiently complete to provide information for the required indicators. However, data on dune presence, median grain size and shoreline change rates are not usually available for large areas, so a detailed application of this methodology would require field surveys, which is difficult and expensive if the coastline is long. The results also show that areas designated as class A (stable shoreline with low vulnerability) are rarely found.

The Coastal Hazard Wheel works in a similar manner as Smartline, but with more well-known indicators, facilitating its application. The CHW App is suitable to get an idea of the general characteristics of any area, but its worldwide data yields less accurate results and thus, provide less differentiation between areas. For the CHW to perform as well as the other methods, a full GIS approach with local data should be developed, but it was not considered necessary within this work.

Finally, the CRAF1 presents an alternative approach on hazard assessment by directly extrapolating model results for a larger area. This method is appropriate to give an estimate of the shoreline retreat when facing an extreme event. The global results for Aveiro showed a much lower hazard classification with CRAF1 than with the other methods. This is due to the division of classes assumed, which may not translate to the thresholds considered by the other methods. However, the hotspots are the same (Vagueira and Furadouro). Moreover, this assessment refers to a single storm with a 10-year return period and does not consider long-term erosion that is not necessarily related to storms, which could lead to higher hazard levels, since there is a severe sediment deficiency in Aveiro, making long-term erosion very relevant. CRAF1 requires a significant amount of detailed data regarding topography (berm height), bathymetry (cross-shore profiles and coastal slope), sediment grain size and wave climate along the entire coastal stretch. The application of the model without detailed knowledge of these features could mean that the eroded volume given from the linear correlation would be uniform along the coast. The use of a single, representative cross-shore profile for modelling and development of the equation for the entire study site is possible, but the variation in results would be entirely dependent on the equation inputs, such as berm height, grain size or wave climate. The author considers that the use of different equations depending on hydrodynamic conditions would help capturing processes related to erosion that are not directly related to those inputs. In Aveiro, the 12 cross-shore profiles are all located south of Aveiro harbour, but the profiles are considered representative of the remaining shoreline when clustered, as it was shown in section 5.3. The necessity of modelling (using *e.g.*, XBeach or SBeach numerical models; Larson and Kraus, 1989; Roelvink *et al.*, 2010) to obtain a correlation between beach characteristics and the eroded volume can present a significant amount of work and demand the appropriate skills and resources. Hence, this method appears to be suitable only when applied to short coastal stretches up to tens of kilometres.

The obtained results and methodological processes executed in the application of these methodologies allowed for conclusions regarding the development of the new proposal, namely:

- The new proposal is intended to be focused on coastal erosion hazard. However, the increased exposure to other coastal hazards (*e.g.* flooding, overtopping) due to susceptibility to coastal erosion could also be considered in the assessment;
- Both long-term shoreline erosion and the effect of extreme events should be considered;
- The new proposal should be flexible enough to provide acceptable results at any scale, depending only of the input data;
- The combination of indicators should avoid weighted averaging, as the weights are difficult to estimate and justify;
- Despite the differences in classification and process, the results of the various methods identified similar hotspots on the case studies, validating the used indicators as adequate for coastal erosion assessments. The new proposal should focus on using similar indicators;
- Indicators that are easier to collect should be favoured. For example, geomorphology, land cover or elevation are data commonly available to the

public. On the other hand, indicators such as sediment grain size or dune presence require field surveys or extensive manual digitizing;

- Hazard and environmental features are easier to identify along the shoreline (*e.g.* geomorphologic landforms, wave exposure). However, exposure and value indicators should also consider inland characteristics to better assess potential consequences. The new proposal should seek a hybrid approach between area and shoreline classification, assessing each indicator on the best possible format;
- The new proposal should seek an absolute output result from its application. Despite the relative result allows for an easier identification of hotspots, their results are not comparable between different assessments. It is intended that the new proposal could work as an effective risk communication tool, and having relative outputs would confuse users and stakeholders. Moreover, a relative output does not work well with small scale case studies, which goes against the general target scale of the new proposal;
- Likewise, the thresholds for assessment of each indicator should be previously established whenever it is possible, to promote coherence and better risk communication;
- Modelling is a process that should be avoided in the new proposal, as it is intended to be a methodology able to respond adequately to stakeholder demands, which often include large region to be assessed within tight schedules.

6. NEW RISK ASSESSMENT METHODOLOGY: CERA2.0

The application of the methods described in chapters 4 and 5, and resulting takeaways, contributed for the development of a new coastal erosion risk assessment methodology. Following the first approach (CERA1.0), this methodology was called Coastal Erosion Risk Assessment version 2.0 (CERA2.0).

The CERA2.0 follows closely the risk concepts presented in section 2.1, namely the Source-Pathway-Receptors-Consequence (SPRC) model (Samuels and Gouldby, 2009), by dividing the risk assessment in components of the system. As stated in section 2.1, in the context of coastal erosion as the hazard, this work considers that: sources are the erosive agents, namely the wave climate; the pathway is the actual distance between the shoreline and the receptor; the receptor is any territory, which allegedly can be eroded; and the consequence is the loss of that territory and aggregated effects. Thus, the assessment process was divided into 4 different and independent modules. Each module produces a classification. Next, the modules' outputs are combined to produce classifications (vulnerability and consequence), based on concepts defined and presented in section 2.1, culminating in the risk classification. The 4 initial modules are: susceptibility assessment module; value assessment module; exposure assessment module; and coastal erosion assessment module. Although modules can be processed in any desired order, CERA2.0 framework performs the assessment in the inverted order of SPRC. Hence, the susceptibility module assesses how prone is the territory (*i.e.* receptor) to be affected by coastal erosion and the value module assesses the socio-economic relevance of that territory, the exposure module assesses the obstacles that coastal erosion must surpass (*i.e.* pathway) to reach the territory in evaluation, and the coastal erosion module assesses how likely and/or intense is coastal erosion (*i.e.* sources) in the study area. Figure 6.1 presents an overview of CERA2.0 framework. A total of 12 indicators within the 4 modules is considered (one less than CERA1.0). The following sections will detail each module, including the description of the considered indicators, how the recommended criteria were developed, and the suggested approach and data to perform the assessment.

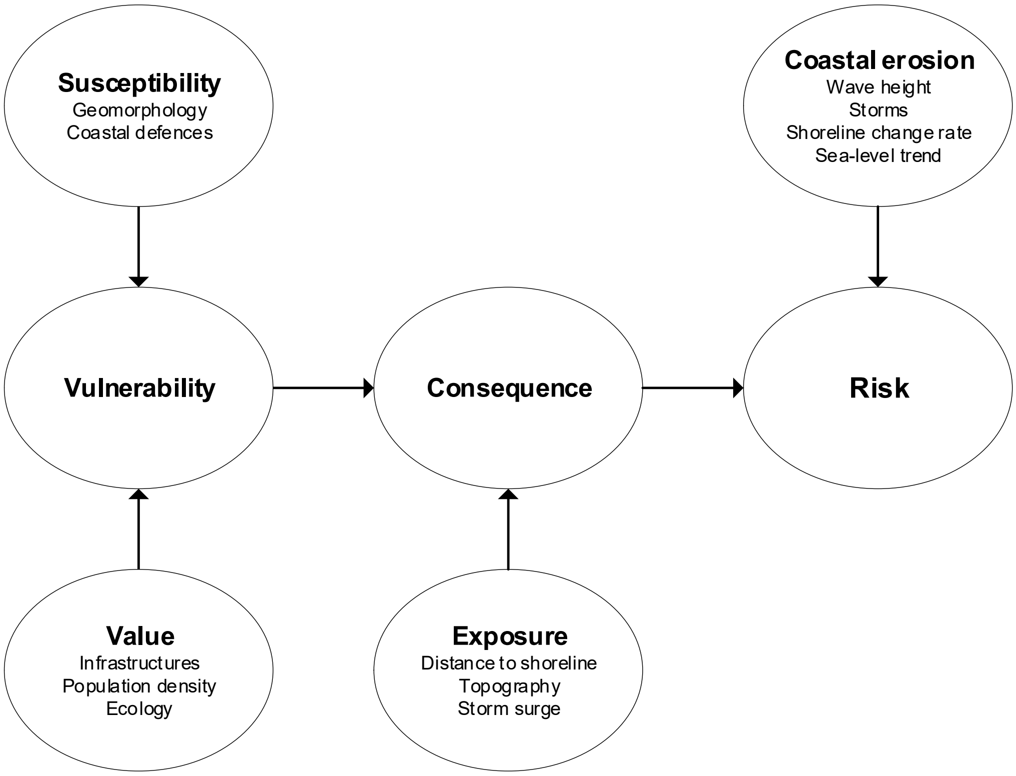

Figure 6.1. CERA2.0 framework structure.

6.1. SUSCEPTIBILITY ASSESSMENT MODULE

Considering coastal erosion as the hazard, the susceptibility assessment module intends to evaluate the propensity of soil to erode when facing erosive agents, in this case, wave climate and sea actions. Therefore, two main indicators are considered: geomorphology (Geo) and coastal defences (Cd).

Geomorphology is included as a qualitative classification based on how certain coastal landforms protect itself better, or worse, from the sea action, considering their characteristics and geologic composition. On the other hand, coastal defences, which can be seen as exposure indicators in another hazard (*e.g.* overtopping), as they represent obstacles in the pathway, are here better fitted as susceptibility indicator, as they are considered to enhance the resistance to coastal erosion. These two indicators are evaluated according to the following sections and combined by summing the results to get the susceptibility classification. The susceptibility classification is presented in CERA2.0 as a line along the coast, representing the overall landform characteristics of the coastline.

6.1.1. Geomorphology

The classification of geomorphologic coastal landforms considering its degree of erodibility is the first step in the application of CERA2.0. Contrary to CERA1.0, this new iteration does not consider geology and geomorphology as separate indicators, as they provided similar and complementary information. This new proposal of geomorphology classification (Table 6.1) is based on the publication of Gornitz (1991), which developed a coastal vulnerability index that includes coastal landforms as one of seven indicators. The criteria adopted by Gornitz (1991) for classification of indicators was also the base of several other methodologies, including the CVI (Thieler and Hammar-Klose, 1999) and CVRA (Coelho, 2005), previously applied.

As in the original classification, the proposal presented in Table 6.1 divides coastal landforms into 5 classes, with increasing susceptibility to erosive agents. Since CERA2.0 focus specifically on coastal erosion, instead of sea-level rise as studied in Gornitz (1991), some landforms considered in that work were removed (*e.g.* estuaries) to only consider landforms that are nearshore.

Table 6.1. Geomorphology susceptibility classification criteria for CERA2.0.

Very low 1	Low 2	Moderate 3	High 4	Very high 5
Rock coast Fiord Fiard	Consolidated sedimentary cliffed coast Indented coast	Saltmarsh Coral reef Mangroves	Pebble beach Protected beach Beach with significant dune presence	Barrier system Exposed sand beach Mudflat Deltas

Moreover, other coastal landforms were included, such as beaches with significant dune presence, as these have a higher recovery capacity from extreme events, and protected beaches, which take advantage of other natural landforms to mitigate the effect of erosive agents.

The coastal landforms presented above could not cover the entire variety of geomorphologies present in coastal areas. Thus, the user should fit its coastal area in the most similar environment. From the ones presented, each landform is defined as the following:

- Rock coast – coast composed by highly resistant geologic minerals. The resistance provided by these materials results in a much slower rate of erosion when compared with other environments (Arnott, 2009);
- Fiord – inlets at the mouths of valleys that were formerly glaciated. Fiord shores are steep sided, narrow and rocky (Bird, 2008);
- Fiard – inlets formed by Holocene marine submergence of formerly glaciated valleys and depressions in low-lying terrain (Bird, 2008);
- Consolidated sedimentary cliffed coast – steep slope coastal formations. Most cliffed coasts shoreline develop in material that possesses strength due to cohesion provided by the bonding of clay minerals, cementation by chemical precipitates or the crystal bonding of other rocks (Arnott, 2009);
- Indented coast – coastlines mostly formed by rocky material which present an intricate shape. Headlands are common in these types of coast, promoting the formation of pocket beaches, which are protected from wave energy;
- Saltmarsh – wetlands formed in the intertidal zone of sheltered coasts, notably in bays, lagoons and estuaries. Saltmarshes are dominated by grasses and herbs and are generally found in mid to high latitudes. Its vegetation attenuate wave action and speed of tidal currents, resulting in deposition of fine material (Arnott, 2009);
- Coral reef – coastal landforms in the fringe of the coastline, where they emerge to form limestone islands. Reefs are built by coral and associated organisms and thus, occurs extensively in tropical waters (Bird, 2008). When healthy and well-developed, coral reefs contribute to reduce wave energy, keeping shorelines stable and in equilibrium (Reguero *et al.*, 2018);

- Mangroves – similar to saltmarshes, but commonly found in the tropics and lower latitudes of subtropics (Arnott, 2009). Mangroves are a diverse group of trees and shrubs that develop in intertidal zones (Duke, 1992). Like saltmarshes, these ecosystems provide protection against coastal hazards, namely coastal erosion by promoting deposition of sediments (Alongi, 2002);
- Pebble beach – beach is an accumulation on the shore of generally loose, unconsolidated sediments, ranging in size from very fine sand up to pebbles, cobbles and occasionally boulders (Bird, 2008). The pebble beaches are made of sediments with significantly larger size, which makes sediment transport more difficult, and consequently, attenuate coastal erosion;
- Beach with significant dune presence – beaches that have dunes contain a large amount of stored sediments. Dunes are formed when sand is blown to the back beach and accumulate above high tide level (Bird, 2008). Dunes range from small forms with less than a metre high to 100 m or more, extending for tens of kilometres alongshore (Arnott, 2009). Dunes provide protection to coastal erosion, by nourishing the beach after high energy storms (Hanley *et al.*, 2014);
- Barrier system – depositional landforms closely related to beaches. These include spits, barrier built offshore or across inlets, embayment's to enclose lagoons and bars in the intertidal and nearshore zones (Bird, 2008). Its formation is associated with strong longshore sediment transport. Barrier beaches are the most dynamic of depositional coastal landforms. They react quickly to changes in littoral sediment supply and severe storms (Arnott, 2009);
- Exposed sand beach – beaches composed by finer sediments than the pebble beach and do not have protection from another natural landform, facing the open sea. Thus, this environment is very susceptible to energetic wave climate;
- Mudflat – areas formed in intertidal and nearshore zones, when strong currents and wave energy are less impactful. Here sediments of silt, clay and organic matter start deposition (Bird, 2008). Mudflats are generally not

vegetated and, although they are usually formed in sheltered areas, they are susceptible to change by wave climate action;

- Deltas – river mouths where the rate of sediment accumulation has exceeded the rate at which sediment is eroded and dispersed by wave currents (Bird, 2008). As barriers and mudflats, these are very susceptible to changes in the littoral sediment supply.

For assessment of this indicator using GIS data, it is recommended to get data for geologic composition, elevation data and aerial images. The lithologic map of GLiM (Hartmann and Moosdorf, 2012) offers a suitable source of information regarding geologic composition, which helps distinguish the lower susceptibility classes (1 and 2) from the others. After that, aerial photography can be used in the identification of coastal features. This requires a certain level of coastal landforms knowledge, but achievable for local managers who seek to assess their study area.

6.1.2. Coastal defences

The resistance to erosion of certain coastal landforms may be strengthened by introducing coastal defences in the area. Contrary to CERA1.0, which considered hard and soft interventions in its anthropogenic actions category, here soft interventions are not considered, as they are difficult to easily identify and quantify the benefits in a simplified assessment. For instance, artificial nourishments may be considered when assessing shoreline change rates (explained further), as they delay coastal erosion. Still comparing with CERA1.0, the presence of sedimentary sources is also not considered, as they are already reflected in shoreline change rates in the hazard assessment. Therefore, only hard coastal defences structures are introduced in this analysis step. Three main types of structures are identified: perpendicular coastal defences; longitudinal attached coastal defences (seawalls); and longitudinal detached coastal defences.

The perpendicular coastal defences, such as breakwaters or groynes, work by trapping sediments on the updrift side of structures and consequently, reducing the effects of wave action over the coastline. This behaviour is equivalent to confined beaches, where natural landforms work as coastal defences. Thus, a reduction by one level of classification was established to all shoreline influenced by a coastal defence, to match the classification of protected beaches.

Taking in consideration the analytical model of Pelnard-Considerè (1956) for estimation of the shoreline position updrift to perpendicular coastal defences, a simplified formula was developed to define the distance to which a perpendicular coastal defence has influence. The shoreline was considered under influence of a coastal defence when its presence promotes accretion and shoreline position variation up to 50% of the structure length, considering that the coastal defence reaches the full capacity to trap the sediments. Having established this criterion to define the coastal defence influence distance, the application of Pelnard-Considerè (1956) model only depends on the wave breaking angle and the coastal defence length. Therefore, a linear correlation between the coastal defence length and the shoreline extension influenced by the structure is verified by fixing the wave breaking angle. In Figure 6.2a, an example of this relation is presented for a wave breaking angle of 6°. Thus, by varying the wave breaking angle and correlating it with the obtained slope of the linear expression (*e.g.* a 5.9 value for the linear relation slope was found for 6° in wave breaking angle), a good correlation in terms of power function is found (Figure 6.2b).

Finally, considering the previous, the formula adopted to determine the updrift influence distance of a coastal defence is given by Equation 6.1, where d_p is the extension of protected shoreline, α_b is the wave breaking angle and y_s is the coastal structure length.

$$d_p = 43.8 \times \alpha_b^{-1.1} \times y_s \tag{6.1}$$

An increase of the susceptibility level due to aggravated predisposition to coastal erosion downdrift of perpendicular coastal defences was considered in this assessment. However, the susceptibility module classifies the shoreline according to its geomorphologic characteristics or considers an equivalent coastal environment as if the coastal defence is a natural feature. Locations downdrift of coastal defences do often change their characteristics, albeit the intensity of the hazard likely increases. Therefore, its susceptibility level is maintained, but the coastal erosion level is more severe.

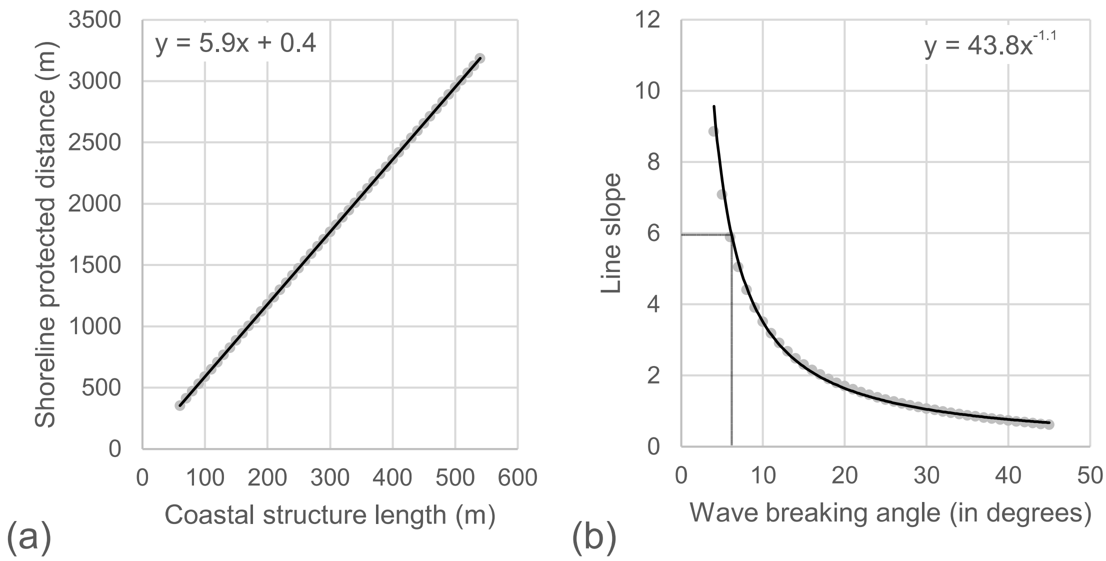

Figure 6.2. Correlation of: (a) coastal defence length and correspondent extension protected for 6° wave breaking angle; and (b) wave breaking angle and line slope of linear correlation between shoreline protected extension and coastal defence length.

Longitudinal attached coastal defences, such as seawalls and revetments, are the most adequate to hold the shoreline in place. Hence, these are the ones that reduce coastal erosion susceptibility the most. The quantification of how much an attached coastal defence would reduce the susceptibility was subject of reflection. The hypothesis of, given the theoretic effectiveness of those structures in hold the shoreline, assimilating these to a rock coast was considered. However, these structures do not change the core geologic composition of the territory, require periodic maintenance and have a measurable lifetime. Consequently, it was established that a longitudinal attached coastal defence would reduce the susceptibility attributed by the geomorphologic classification by 2 levels of classification, as they are not equivalent to rock coasts.

Finally, for the detached coastal defences, the consideration was similar to perpendicular coastal defences regarding the reduction of susceptibility to erosion. These structures reduce the wave energy and allow the deposition of sediments in sheltered regions of the structure. Thus, the shoreline protected by this type of structures was considered similar to protected beaches. Therefore, the reduction by 1 level of classification is considered.

For identification of coastal structures, a revision of literature is recommended, as well as the identification in satellite images. For each coastal defence, its required to get its length and georeferenced location. Additionally, for structures perpendicular to the coast, the average wave breaking angle is also required, which can be derived from offshore waves or estimated by satellite images, if the detail on them is sufficiently high. As a simpler alternative, the protected shoreline extension can be adjusted by taking in consideration the distance along the shore where sediment deposition is visible. The final classification of susceptibility is given by the sum of geomorphology and coastal defences classification, given that the values is between 1 and 5 (Eq. 6.2).

$$\text{Susceptibility index} = \begin{cases} 1, & \text{Geo} - \text{Cd} < 1 \\ \text{Geo} - \text{Cd}, & \text{Geo} - \text{Cd} \geq 1 \end{cases} \tag{6.2}$$

6.2. VALUE ASSESSMENT MODULE

Regarding the value assessment module, the approach adopted by CERA2.0 takes inspiration on both CERA1.0 and CRAF1 regarding indicators to assess, but also changes how these indicators are combined. For the value assessment module, CERA2.0 considers indicators of population density (Pop), infrastructures (Inf) and ecology (Eco).

Compared to CERA1.0, this new method proposal ditches the economy assessment by employment density, as the areas with high number of employments also present high value regarding both infrastructures and population density. This fact coupled with the difficulty regarding an accurate gathering of this data motivated the decision of not including the economy classification. Moreover, the heritage indicator featured in CERA1.0 was replaced by an infrastructure assessment. This allows the inclusion of other important infrastructures that do not have an important cultural significance (*e.g.* schools and hospitals). These infrastructures were already considered in the changes applied from CVRA to CERA1.0 (Table 4.1) and here takes another step in that direction.

The approach to the combination of indicators differs from both CERA1.0 and CRAF1. Instead of averaging all indicators like in those two methods, CERA2.0 considers the average of population density and infrastructures (with some exceptions detailed further) and then adds value depending on the ecologic level of the area. This approach was taken due to usual contrary values between ecology and the other value indicators (*i.e.* when the area has ecologic relevance, usually does not present value regarding infrastructures and has low population density, and vice-versa), which results in a low chance of reaching high value classifications.

Contrary to the susceptibility classification, the value assessment considers inland representation. The assessment of the included indicators is easier if performed in area instead of shoreline and the output corresponds directly to the unit area represented. A maximum distance is not established in CERA2.0, giving freedom to the user to apply the assessment to any desired area.

6.2.1. Infrastructures

As stated previously, the infrastructures indicator replaces the heritage indicator from CERA1.0. Consequently, the previous iteration of the indicator was the base for this new classification, but suffered significant changes in order to favour important structures from a socio-economic standpoint, instead of focusing on cultural attributes. The classification of infrastructures maintains the 5-level classification, with increasing precepted value from a social or economic standpoint. The nomenclature given to the classes are:

- No structures – no perceptible structures to preserve or protect;
- Rural agglomeration and municipal roads – small agglomerations of houses, houses outside of villages or small villages that may be relatively easy to relocate. These areas can be considered equivalent to rural areas in the degree of urbanization defined by Eurostat (2016). Additionally, regional or local roads that its disappearance may disrupt the regular functioning of small communities should also be considered in this level;
- Urban agglomerations – towns and suburbs of cities that present an intermediate population density (Eurostat, 2016) and have housing as main purpose. These urban clusters are often commuting zones for city centres, but already have a considerable amount of services and utilities that serve the inhabitants. These areas are often identified in land use maps as *discontinuous urban areas* (*e.g.* in CLC2012; EEA, 2016b);
- City centres, heritage landmarks, main highways – city centres are considered here, as they include a high density of inhabitants of the area, coupled with a significant number of services and utilities. These areas are often identified in land use maps as *continuous urban areas* (*e.g.* in CLC2012; EEA, 2016b). Moreover, heritage landmarks are also included in this category, which often have a high cultural significance and thus are important to protect. Main highways and roads, which are crucial for transportation in a regional or national scale, are also included here;
- Critical infrastructures – these are considered top level priority when it comes to value. Although there is no convention or consensus about what are critical infrastructures, there is a general agreement that they are systems that deliver goods and services fundamental to the functioning of society and economy

(Macaulay, 2009). The European Commission defines critical infrastructure as an asset, system or part thereof which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact because of the failure to maintain those functions (EU, 2008). Thus, education, healthcare, energy generation facilities, police and fire departments, critical transportation links (such as national railways or airports) and governmental buildings can be considered critical infrastructures. Regarding this class, the user is responsible to identify the critical infrastructures in his study area. The areas with class 5 should be considered as the highest level of value, regardless of the population classification. This rule was established to avoid a possible reduction of the overall value classification in these areas, as critical infrastructures are often located outside of highly populated areas (*e.g.* airports, hospitals).

The recommended approach for identification and classification of infrastructures is to use land cover maps (*e.g.* CLC2012 for Europe) and attribute a class for each category of the original land cover map. The result can then be tweaked based on the identification of critical infrastructures, which may require local knowledge and research, and identification of other features, such as roads, highways and heritage landmarks in a georeferenced dataset.

6.2.2. Population

For the population density assessment, the proposed method is similar to the approach of CERA1.0. The indicator is classified in 5 classes (1 to 5) based on the population density of the area. The thresholds defined for each class were changed comparatively to CERA1.0 to better reflect population densities worldwide. A complete statistical assessment of worldwide population density is difficult to execute. However, the analysis of a worldwide database, such as GPWv4 (Figure 6.3; CIESIN, 2017), allowed the identification of common thresholds for each type of urban area (*e.g.* village, town, suburbs or city). Therefore, the proposed thresholds are the following (Table 6.2):

Table 6.2. Population density classification, according to CERA2.0.

Population classification level	Population density (pers/km^2)
1	[0; 500[
2	[500; 1000[
3	[1000; 2000[
4	[2000; 4000[
5	[4000; +∞[

The thresholds were defined in order to fit with common population densities observed in the equivalent infrastructure class. Hence, population densities superior to 4000 habitants/km^2 are commonly verified in medium to high dimension city centres. Then, 2000 to 4000 habitants/km^2 are present in small cities, towns and suburbs near big cities. The remaining classes refer to smaller towns, villages and rural to uninhabited areas, respectively.

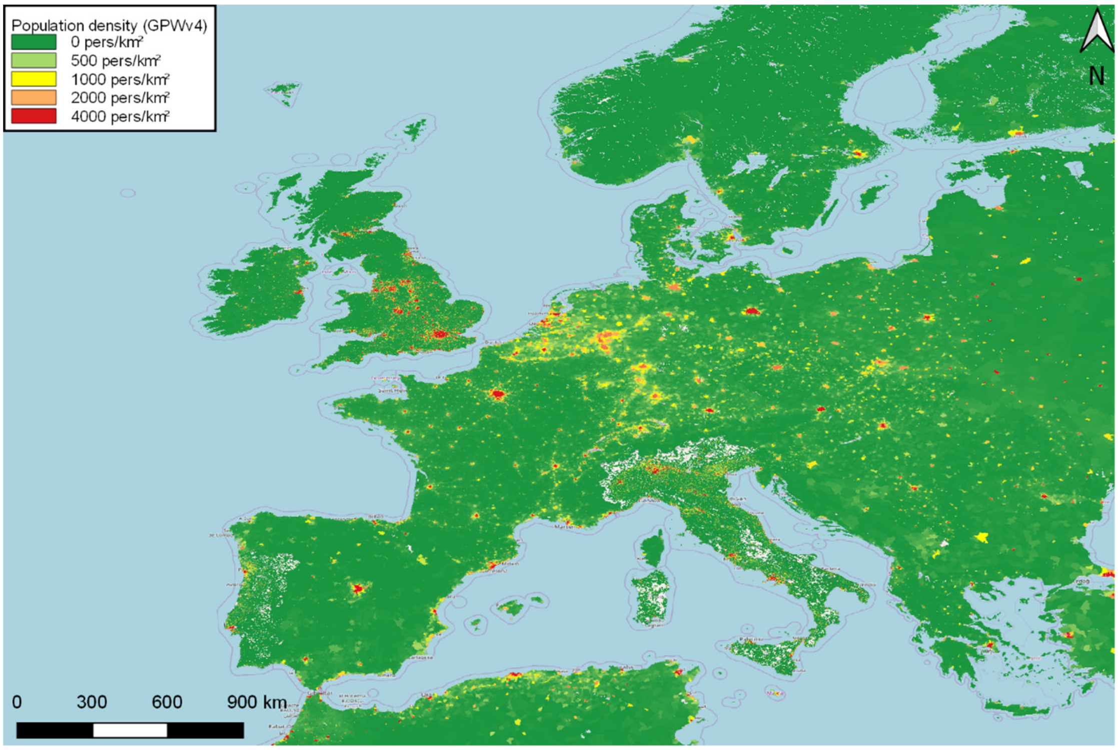

Figure 6.3. Representation of population density in Europe, by GPWv4 (CIESIN, 2017).

These classes were later applied to the study areas and considerate adequate. However, the user should have a critical judgement when applying these criteria, as the number of use cases is still reduced and could not register the most suitable results to all study areas. The use of population density maps is recommended for this assessment, with the highest possible resolution. However, as stated in earlier chapters, this information is not always available in high detail, as often the user only has access to information per municipality or parish.

The combination of population and infrastructures is done following Equation 6.3. When there are no critical infrastructures, Equation 6.3 is the geometric mean accompanied by a constant of 0.055, which was inserted in order to round up some combinations of results which are often close to the next classification, and ultimately better balance the possible outputs. This formula is used often in CERA2.0 method when is necessary to combine two indicators. The combination of population and infrastructures, using Equation 6.3, should compensate situations with less accurate data in any of the individual indicators. Urban areas can be differentiated by the population density attributed and areas with higher population density that are diluted in the municipality area should be highlighted by the identification of infrastructures and facilities.

$$\text{Population} + \text{Infrastruc. index (PopInf)} = \begin{cases} 5, & \text{Inf} = 5 \\ \sqrt{\text{Pop} \times \text{Inf}} + 0.055, & \text{Inf} \neq 5 \end{cases} \quad (6.3)$$

6.2.3. Ecology

The ecology classification aims primarily to highlight ecologic protected areas. A protected area is a geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values (Day *et al.*, 2012). Given the number and variety of local, national and international classification of ecologically protected areas, this indicator was divided in three categories that give the user freedom to adjust to his own study area: no ecologic relevance; moderate ecologic relevance; and high ecologic relevance. Relatively to CERA1.0, this represents a reduction from the usual 5 classes, which were considerate excessive and difficult to define, given the freedom allowed to the user.

The three ecology levels give the possibility of an ecologic protected area to reach value classification 3, considering that commonly does not present important infrastructures and corresponds to low population density. This classification is comparable to an urban agglomeration (*i.e.* village or town), which is considerate adequate. The use of 5 levels, as the remaining methods, was considered, but realistically there is a low probability of stakeholders to prioritize an ecologically relevant area in detriment of urban clusters. The reduction of classes aimed to reflect the stakeholder decisions as faithfully as possible. However, this indicator, as all evaluated in the value assessment, have an intrinsic subjective connotation. Hence, users should have a critical judgement of the results and, if needed, change the criteria used to better fit the study area in question.

The data required for this assessment is recommended to be georeferenced data which delimitates ecologically protected areas. These are often made available by entities responsible for these kinds of classification and therefore, relatively easy to gather and use. Other areas that are not officially classified as protected areas can also be included if the user considers that they are important for the region under study.

The output of the ecology indicator is to be summed with the classification of population and infrastructures, resulting in a susceptibility classification, from 1 to 5 (Eq. 6.4). If the result exceeds 5, the susceptibility value is equivalent to the maximum level, 5.

$$\text{Value index} = \begin{cases} 5, & \text{int}(\text{PopInf} + \text{Eco}) > 5 \\ \text{int}(\text{PopInf} + \text{Eco}), & \text{int}(\text{PopInf} + \text{Eco}) \leq 5 \end{cases} \qquad (6.4)$$

6.3. EXPOSURE ASSESSMENT MODULE

Taking in consideration the exposure assessment to coastal erosion of a certain location, the main obstacle that erosive agents must surpass to erode that location is the land that stands between the shoreline and that same location. In other words, the receptors nearest the shoreline work as protection to receptors further from the shoreline. Thus, the exposure assessment in CERA2.0 aims to quantify the exposed receptors (*i.e.* territory). Moreover, this assessment divides the exposed territory in classes from 1 to 5, with increasing proximity to the shoreline, and consequently, increasing exposure level. Thus, for the exposure assessment module, CERA2.0 considers indicators of distance to shoreline (Dsl) and topography (Top). An input regarding storm surge (Ss) is also considered in the exposure assessment. The inclusion of a storm surge indicator is less conventional and does not fit directly in the definition of exposure, but considering that this hazard can contribute greatly for increasing exposure to erosion, it was established that its inclusion here would benefit the correct assessment of areas where this phenomenon is common.

6.3.1. DISTANCE TO SHORELINE

Relatively to the distance to shoreline considered in CERA1.0, the thresholds for each class were largely reduced. Although not directly specified, the thresholds defined in CERA1.0 were developed with the intention of assessing a coastal strip of 2 km. This distance defines what is considered coastal zone in Portugal (MAMAOT, 2012), and therefore was the intention to classify all that area.

In this revision, and considering the focus on coastal erosion, 2 km was considerate excessive, taking in consideration the short to medium term target of the methodology. For example, a shoreline retreat rate of 7.5 m/year would be necessary to threaten all area included in the higher class in CERA1.0 for a period of 20 years. Thus, in order to highlight areas that can potentially be threatened by coastal erosion, CERA2.0 suggest classes presented in Table 6.3.

The thresholds were developed aiming to assess a coastal strip of 500 m inland. This area is equivalent to the land protection area defined in Portuguese law (MAMAOT, 2012), which contemplates that same distance, with the possibility of increasing to

1000 m, if justifiable. The not inclusion of a maximum distance for the assessment also has the intension of including more inland areas, or to better fit other countries, which may have different regulations.

Table 6.3. Distance to shoreline classification, according to CERA2.0.

Distance to shoreline level	Distance to shoreline (m)
1	]350; +∞]
2	]225; 350]
3	]125; 225]
4	]50; 125]
5	]0; 50]

The highest exposure class range (*i.e.* 0 to 50 m) intends to include the first urban waterfront, when there is no significant amount of natural protection (*e.g.* dunes). Defined the highest exposure class, the remaining class ranges were defined having a linear distance increase in mind, to reflect higher uncertainty regarding the effect of coastal erosion in inland areas, due to the longer time span required for these areas to be potentially affected by the hazard.

One important aspect in the distance to shoreline assessment is where to measure the shoreline position. In previous assessments in this work, the shoreline was measured in the foredune toe, whenever it was possible. This approach was taken by Lira *et al.* (2016) due to be recognized as being less influenced by tidal and seasonal changes, and adopted for the study sites presented in this work, with exception of Quintana Roo, which the absence of dunes difficulted that process. On the other hand, the consideration of other feature, such as the mean high tide, can be considerate acceptable. Although less precise, this consideration allows the inclusion of the actual beach in the assessment, which in many cases should be beneficial, given the touristic value of that area. In that case, the recommended thresholds could be adjusted to incorporate this scenario.

Regardless of the considered shoreline feature, a shapefile with data regarding the shoreline position is required for this assessment. Then, using QGIS features such as the *Proximity* tool and the *Raster Calculator*, the exposure classification is achieved.

6.3.2. TOPOGRAPHY (AND STORM SURGE)

Like the distance to shoreline, the topography was included in the exposure assessment of CERA2.0. This indicator was considerate essential in the exposure assessment, as higher elevations often translate in less exposure to coastal hazards. Contrary to all other indicators so far described, the thresholds considered originally by Gornitz (1991), and adopted in CVRA and CERA1.0, were also considerate adequate for CERA2.0.

Adding to the thresholds of topography, a variable regarding storm surge (Ss) was used to complement this assessment. Storm surge is an abnormal rise in seawater level during a storm, measured as the height of the water above the normal predicted astronomical tide. The surge is caused primarily by storm winds pushing water onshore (NOAA, 2018b)or by sea elevation due to a low pressure meteorology system. As stated in the beginning of the exposure assessment, the inclusion of storm surge here is less conventional and is not directly related with coastal erosion. However, adding this indicator promotes the inclusion of areas subjected to this hazard to be included in higher exposure levels, which leads to higher risk classifications and more awareness to those areas. Also, the inclusion of storm surge gives CERA2.0 flexibility to be applicable in areas where this phenomenon often occurs.

The inclusion of storm surge was not subject of profound scientific support, but rather an estimate resulting from debate and brainstorming. Thus, the maximum register of storm surge for the study site provided by measurements or in literature, should be included here. The recommended classes were based on worldwide registers. These registers were gathered from SURGEDAT (Needham and Keim, 2011), a worldwide database of storm surge events. Currently, SURGEDAT provides location and peak storm surge height of 702 events, since 1880.

The option of dividing per classes rather than use the exact value was done to provide the user with a window that would allow estimates rather than the requirement to have the exact information, facilitating its use. Therefore, Table 6.4 presents the classes considered for storm surge.

Table 6.4. Storm surge classification, according to CERA2.0.

Storm surge (m)	Adopted Ss (m)
[0.0; 0.5[	0.5
[0.5; 2.0[	2.0
[2.0; 3.5[	3.5
[3.5; 5.0[	5.0
[5.0; +∞[	6.5

Adding the storm surge classes to the topography classes (Table 6.5), the classes of this indicator are the following elevations, considering chart datum:

Table 6.5. Topography plus storm surge classification, according to CERA2.0.

Topography (and storm surge) classification level (TopSs)	Topography + storm surge (m)
1	[30 + Ss; +∞[
2	[20 + Ss; 30 + Ss[
3	[10 + Ss; 20 + Ss [
4	[5 + Ss; 10 + Ss[
5	[-∞; 5 + Ss[

To perform the assessment of this indicator, a digital elevation model (DEM) is the most vital data. A high resolution DEM can provide a better differentiation of areas, but if the user does not have access to that type of data, global DEM, such as the ASTER GDEM2 (NASA and METI, 2011) used in Macaneta, can be considerate. Then, a data transformation using the classes above (Table 6.5) and the *Raster Calculator* results in the respective exposure indicator assessment (Eq. 6.5).

$$\text{Exposure index} = \text{int}\left(\sqrt{\text{Dsl} \times (\text{TopSs})} + 0.055\right) \quad (6.5)$$

6.4. COASTAL EROSION ASSESSMENT MODULE

The coastal erosion assessment module presented in CERA2.0 aims to assess the driving sources of coastal erosion. Due to the difficulty in developing a simplified model that would translate wave climate conditions to actual coastal erosion, in the development of this module, the choice felt into a large-scale assessment of indicators that were considerate relevant for coastal erosion. Therefore, like the storm surge indicator, the thresholds here defined were not based on worldwide registers, to provide classes that could be meaningful regardless of where the methodology is being applied. The indicators considered by CERA2.0 are mean significant wave height, number of storms per year, past observed shoreline change rates and local sea-level rise. Comparatively with CERA1.0, tidal range is dropped, as there is no definitive conclusion on the effect to coastal erosion, and sea-level rise is added, while the criteria regarding wave height changes considerably. The following sections detail the criteria taken for each indicator.

6.4.1. WAVE CLIMATE

The incident wave climate is an indicator of the wave energy and potential sediment transport capacity. In CERA2.0, the wave climate assessment is divided in two indicators: mean significant wave height and number of storms per year. The change relative to CERA1.0, which only considered maximum significant wave height, intends to give a different indicator to long-term erosion and storm erosion. Each indicator was divided into 5 classes, as most other indicators, with increasing order of wave energy.

In order to define the thresholds for each class considering incident wave climate at a world scale, a considerable amount of data was required. Thus, the numerical wind-wave hindcast data developed by Bertin *et al.* (2013) was used. This dataset includes the significant wave height every 6 hours, for a period of 109 years (1900-2008). The dataset covers the North Atlantic Ocean and was based on the 20th century atmospheric reanalysis (20CR). From the hindcast data, 100 wave time series from random locations near the shore were extracted. The histogram representing the mean significant wave height for each location was developed (Figure 6.4). Bearing in mind the distribution of Figure 6.4, several sets of thresholds were tested, taking in consideration the number of cases that fall in each class, and comparing with previously applied methodologies. The thresholds chosen as recommended for CERA2.0 are presented in Table 6.6.

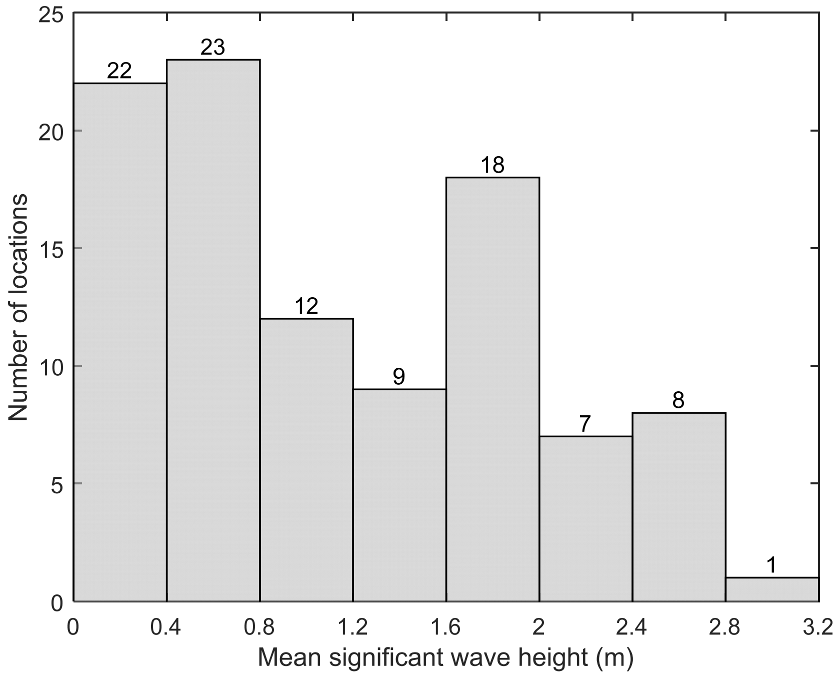

Figure 6.4. Histogram of mean significant wave height for 100 coastal locations.

Applying these thresholds to the random locations extracted from Bertin *et al.* (2013) database, a nearly uniform distribution is obtained, with all classes having around 20 locations in it (Figure 6.5). Comparatively with CVI, which is the only tested method that directly uses mean significant wave height, the thresholds here considered are much higher. This difference is justified by the intention of representing wave climate worldwide, and consequently, covering a larger amount of locations. The thresholds cover the usual mean significant wave heights registered in populated world locations, as represented in NC-GOW hindcast data (Reguero *et al.*, 2012), where only on polar locations the mean H_s show much higher values than the highest threshold.

Table 6.6. Mean significant wave height classification, according to CERA2.0.

Significant wave height classification level	H_s (m)
1	[0; 0.4]
2	]0.4; 0.8]
3	]0.8; 1.6]
4	]1.6; 2.0]
5	]2; +∞[

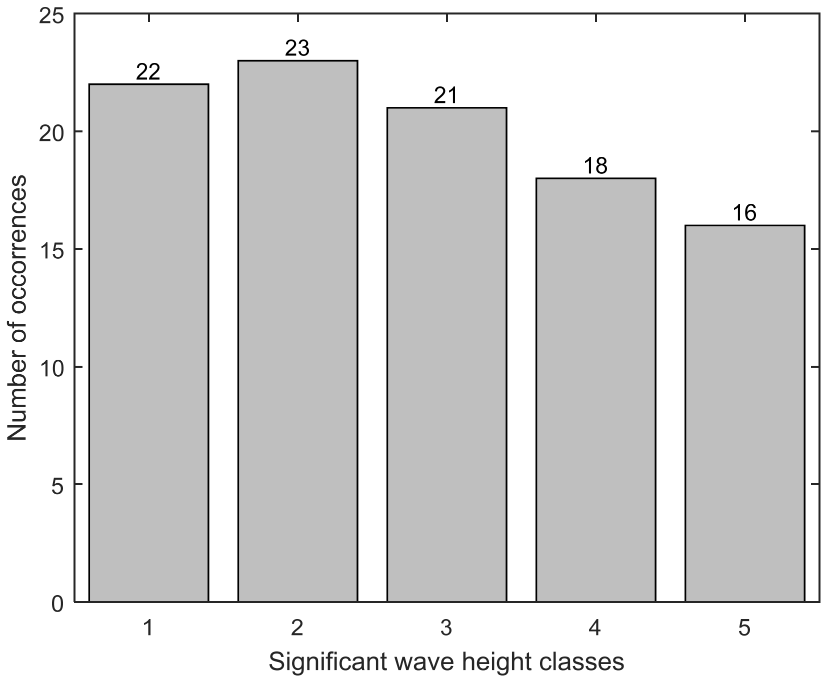

Figure 6.5. Histogram of mean significant wave height class distribution, for 100 coastal locations.

The definition of thresholds regarding the average number of storms per year followed the same principle as the mean significant wave climate. However, to do a statistical assessment on this indicator, it is first required to define what is to be considered a storm. Boccotti (2000) defines sea storms as a sequence of sea states in which H_s exceeds 1.5 times the mean H_s and does not fall below that height for a continuous time interval greater than 12 hours. More recently Archetti *et al.* (2016) also considers the same definition of sea storm. On the other hand, Mendoza *et al.* (2011) considers a H_s threshold of 2 m for a minimum period of 6 hours in order to be considered a storm event in the Catalan coast. Moreover, a minimum of 72 hours is required to consider two independent events. Armaroli *et al.* (2012) used the same H_s threshold, 2 m, to define critical storm thresholds for Emilia-Romagna coastline, Italy. After testing these criteria for the wave time series extracted from Bertin *et al.* (2013), it was considered that the definition of storm given by Bocotti (2000) is more accurate. However, additional criteria were also adopted. Thus, here it is considered that a storm event takes place when the H_s surpasses 1.5 times the mean H_s and is superior to 2 m for a period superior to 12 hours. Moreover, the H_s must drop below that threshold continuously for 12 hours to assume the end of the storm event. The consideration of two Hs thresholds is linked with the locations where the mean Hs is very low, which resulted in a high number of identified storms with a wave height that was not considerate threatening. The 2 m thresholds was adopted due to its previous application in the Mediterranean Sea, which has a calm wave environment and thus, appropriate for a minimum threshold. On the other hand, the use of a variable thresholds such as 1.5Hs gives flexibility to be more accurate, regardless of the location. Figure 6.6 shows the distribution obtained by applying the criteria to the previously mentioned locations.

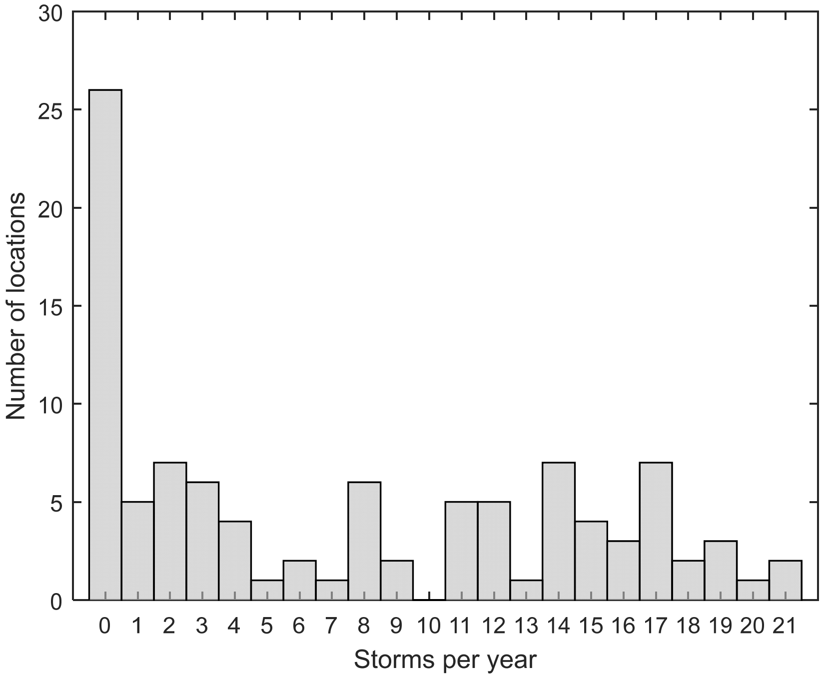

Figure 6.6. Histogram of average number of storm events per year for 100 coastal locations.

Taking in consideration Figure 6.6, the thresholds for definition of classes related with number of storms were established (Table 6.7).

Table 6.7. Number of storms per year classification, according to CERA2.0.

Storms per year classification level	Number of storms per year
1	0
2	[1; 5]
3	[6; 10]
4	[11; 15]
5	[16; +∞[

Since there is no clear trend visible on Figure 6.6, the defined thresholds aimed to cover the entire spectrum in equally spaced classes. The application of the thresholds to the random locations revealed an uneven distribution (Figure 6.7). Nonetheless, these were considered the most appropriate thresholds of all tested.

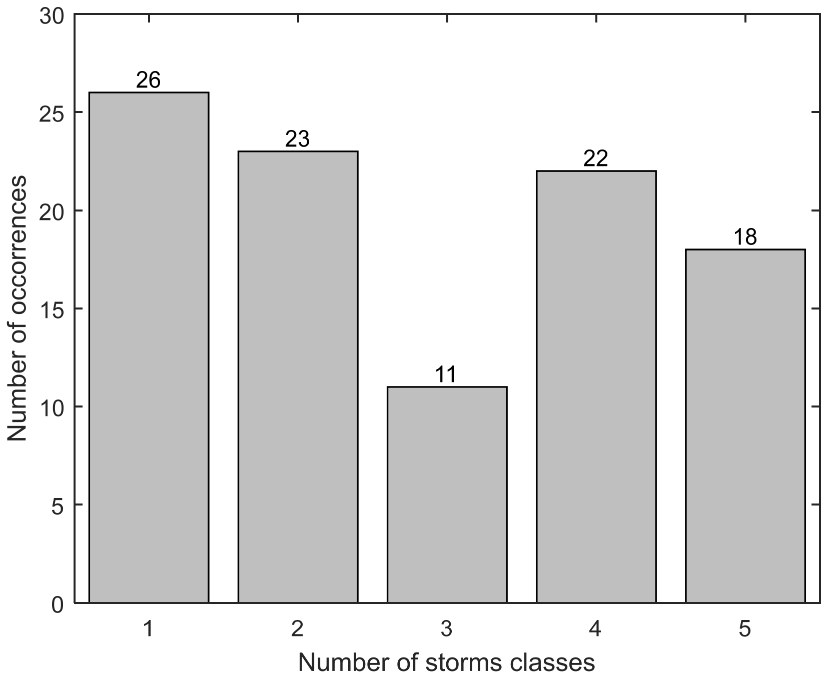

Figure 6.7. Histogram of storm class distribution for 100 coastal locations.

To define the mean significant wave height and the number of storms of a given location is recommended to have access to a long-term wave time series of that location. In case of not having access to this type of data, an estimation based on literature review can be sufficient to proceed with the assessment, given that the assessment does not require more than a value for a given study area, although the criteria for identification of storms should be considered when assuming values represented in the literature. The combination of mean significant wave height and average number of storms per year is done by application of Equation 6.6.

$$\text{Wave climate index (Wc)} = \sqrt{\text{Hs} \times \text{Storms}} + 0.055 \qquad (6.6)$$

6.4.2. Shoreline change rates

Like in CERA1.0 and all other methodologies tested in chapters 4 and 5, the shoreline change rates indicator was included in CERA2.0. This indicator represents the actual hazard that this methodology attempts to assess and reflects a cumulative summary of the processes which have impacted the coast through time (Dolan *et al.*, 1991), which the previous indicators seek to emulate.

The previously applied methodologies present different forms to assess and classify shoreline change rates. While the Smartline and CHW only distinguish between eroding or accreting shoreline, CERA1.0 and CVI define 5 classes with increasing level of erosion intensity. This approach was also taken in CERA2.0. However, as reviewed previously, the thresholds adopted by CERA1.0 and CVI are largely different. CERA1.0 considers the first class as accreting shoreline and all the following represent eroding shoreline. On the other hand, CVI considers 2 classes representing accretion, class 3 representing stable shorelines and the two highest classes representing retreating shorelines.

When reassessing this indicator for CERA2.0 proposal, it was considered that the highest class in CERA1.0, requiring retreat rates of 5 m/year, was difficult to achieve. In the dataset provided by Lira *et al.* (2016), which covers the entirety of Portuguese coast, only the location surrounding Vagueira, within Aveiro study area, achieved that classification. Furthermore, it is estimated that only 4% of the world sandy shoreline have retreat rates that exceed 5 m/year (Luijendijk *et al.*, 2018). Thus, the new thresholds were established aiming to reduce the shoreline retreat value required to be attributed maximum hazard level to 2.5 m/year. This still represents a serious shoreline retreat problem, corresponding to a retreat of 50 m in a 20-year period. This distance ties in with the higher exposure class in the distance to shoreline indicator. The remaining classes were inspired by the classification of Esteves *et al.* (1998) and extended by Luijendijk *et al.* (2018), and are showed in Table 6.8.

To assess the shoreline change rates indicator, georeferenced data, such as the ones presented in Lira *et al.* (2016) would be the easiest and most recommended information. Not having access to that information, the digitizing of the shoreline is possible using satellite images. Like previously mentioned in the distance to shoreline indicator, the feature considered to digitize the shoreline should be established. In this case, taking in consideration tide and seasonal variation and the long-term nature of this indicator, the use of a stable shoreline feature, such as the foredune toe used in Lira *et al.* (2016), is the most recommended. Also, a time span of at least 10 years between shoreline measurements is recommended to supress high-frequency effects (Eliot and Clarke, 1989).

Table 6.8. Shoreline change rates classification, according to CERA2.0.

Shoreline change rates classification level	Shoreline change rates (m/year)
1 – accretion shoreline	[+0.5; +∞[
2 – stable shoreline	[-0.5; +0.5[
3 – erosion shoreline	[-1.5; -0.5[
4 – intense erosion shoreline	[-2.5; -1.5[
5 – severe erosion shoreline	[-∞; -2.5[

After having the shoreline position data for a given time span, the change rates can be computed using GIS tools, such as the Digital Shoreline Analysis System (DSAS; Thieler *et al.*, 2009) for ArcGIS. These are then computed with the wave climate classification (Eq. 6.7).

$$\text{Shoreline change rates + wave climate index (ScrWc)} = \sqrt{\text{Scr} \times \text{Wc}} + 0.055 \quad (6.7)$$

6.4.3. Local sea-level trend

The sea-level trend represents a new addition to CERA2.0 proposal. In recent years, the phenomenon of sea-level rise is concern for low-lying coastal zones. The IPCC (2014) reported that the mean rate of global averaged sea level rise was around 1.7 mm/year in the last century, but increased to 3.2 mm/year between 1993 and 2010. In addition to the global rise of mean sea-level, local sea-level is also influenced by local factors. The variation of local sea-level has climate change (such as melting of land-based ice), thermal expansion of ocean waters and changing of ocean dynamics, non-climate uplift/subsidence processes and natural and anthropogenic-induced subsidence as main underlying drivers (Nicholls, 2010). From the previously applied methods, only the CVI directly considers a sea-level trend indicator. This option can be explained by the long-term nature of the indicator, which is not compatible with short to medium-term methodologies. Regardless, the inclusion of sea-level trends in CERA2.0 was considered appropriate due to its influence in related coastal hazards, including coastal erosion. The thresholds established for CERA2.0 were based on data from NOAA (2018a). At the time of the analysis, data from 234 stations around the world was collected, with a minimum year range of 28 years. The distribution of local sea-level trends is presented in Figure 6.8. From this data, it was concluded that local sea-level rise is within 0 mm/year and 3 mm/year for most locations. The mean of all samples is 1.06 mm/year.

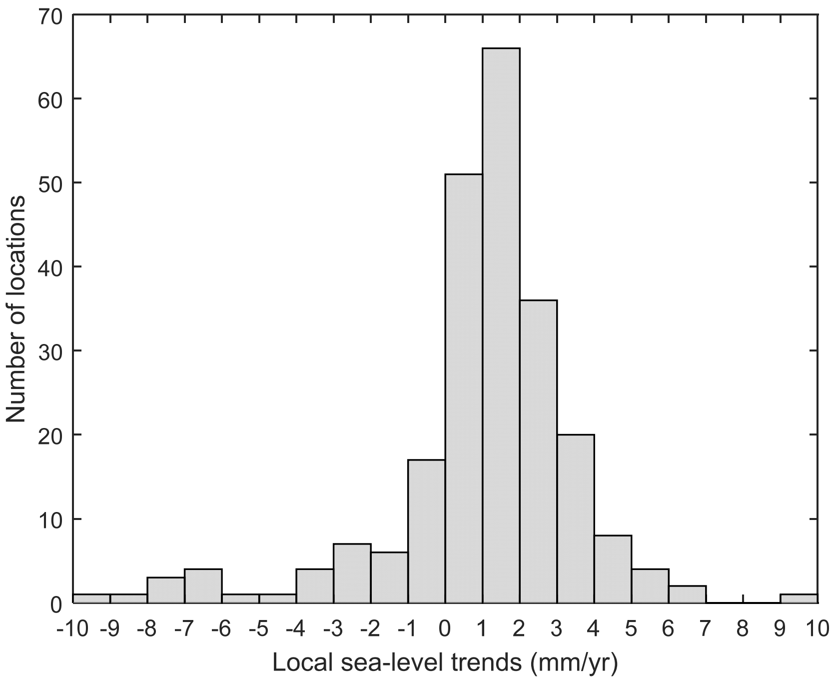

Figure 6.8. Distribution of worldwide sea-level trends (NOAA, 2018a).

Thus, 5 classes of sea-level trends were defined for CERA2.0, representing increased contribution for coastal erosion (Table 6.9). Like the ecology indicator in the value assessment, the first class here is defined as 0 because it does not contribute for the increase of hazard classification. The second level refers to areas with a reduced local sea-level rise (below the dataset mean). The 1.8 mm/year thresholds references the global sea level increase between 1971 and 2010 given by IPCC (Church *et al.*, 2013), which is the most fitting time span relative to the local sea-level trends dataset.

Table 6.9. Sea-level trend classification, according to CERA2.0.

Sea-level trend classification level	Sea-level trend (mm/year)
0	[-∞; 0.0[
1	[0.0; 1.0[
2	[1.0; 1.8[
3	[1.8; 3.0[
4	[3.0; +∞[

The distribution given by the classification of each location is given by Figure 6.9.

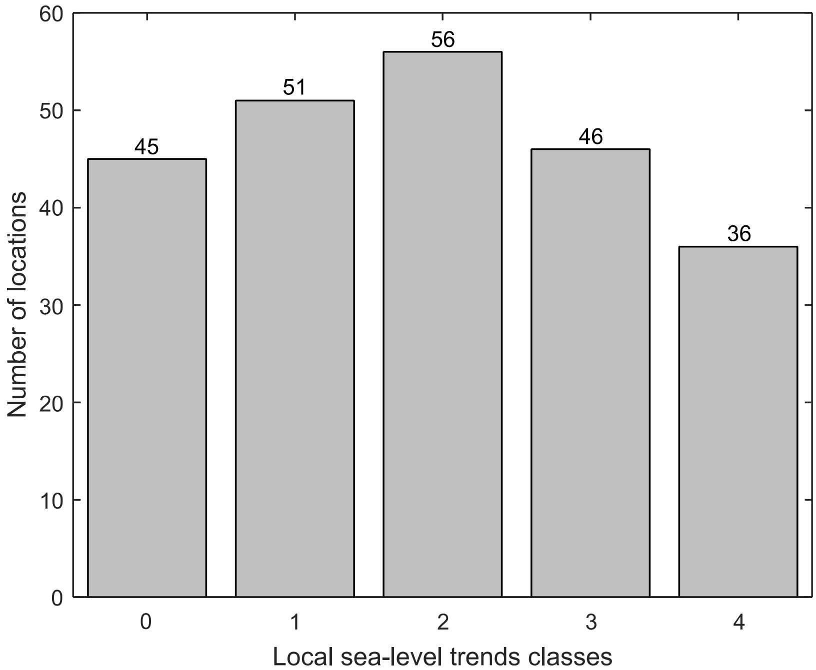

Figure 6.9. Histogram of sea-level trends class distribution, considering thresholds of CERA2.0.

The classification of this indicator is executed by finding the correspondent local sea-level trend for the study area. This value can often be found on literature review or databases, such as NOAA (2018a). This indicator only contributes to aggravate the hazard level, as showed in Equation 6.8. However, its contribution is minimal, reflecting the long-term nature of the indicator versus the short to medium-term aim of CERA2.0.

$$\text{Coastal erosion index} = \text{int}(\text{ScrWc} + 0.1 \times \text{Slt}) \tag{6.8}$$

6.5. VULNERABILITY, CONSEQUENCE AND RISK OUTPUTS

The results of the assessment modules (susceptibility, value, exposure and coastal erosion) are then combined in an established sequence, based on risk concepts explained in section 2.1. So, the susceptibility and value results are combined to produce the vulnerability classification, which assesses potential damages if driving sources of erosion reach the study area. Then, the consequences' output is the result of the combination of vulnerability and exposure. Here, the consequences show the potential harm, considering that receptors have different levels of exposure. Finally, risk combines those consequences with the likelihood of coastal erosion in the study area. This way, 2 different intermediate maps (vulnerability and consequence) are obtained though the assessment process, driving to the final map of coastal erosion risk assessment. As with several indicators, the approach taken to combine the module outputs was to execute the geometric mean accompanied by a constant of 0.055. Hence, Equations 6.9, 6.10 and 6.11 describe each index, respectively, keeping all results in a discrete range between 1 and 5.

$$\text{Vulnerability index} = \text{int}\left(\sqrt{\text{Susceptibility} \times \text{Value}} + 0.055\right) \tag{6.9}$$

$$\text{Consequence index} = \text{int}\left(\sqrt{\text{Exposure} \times \text{Vulnerability}} + 0.055\right) \tag{6.10}$$

$$\text{Risk index} = \text{int}\left(\sqrt{\text{Coastal erosion} \times \text{Consequence}} + 0.055\right) \tag{6.11}$$

This option was chosen instead of the risk matrix in CERA1.0, after executing preliminary results of CERA2.0. The continuous use of the matrix led to an increased amount of results to high classifications when compared with the geometric mean, which did not allow for an easy identification of higher risk hotspots. The geometric mean allows for a more selective attribution of the extreme classes, which leads to a potentially more helpful map for users and stakeholders.

To conclude, a complete overview of CERA2.0 framework is presented in Figure 6.10. The Figure includes all equations for each module, as well as all criteria used in each indicator.

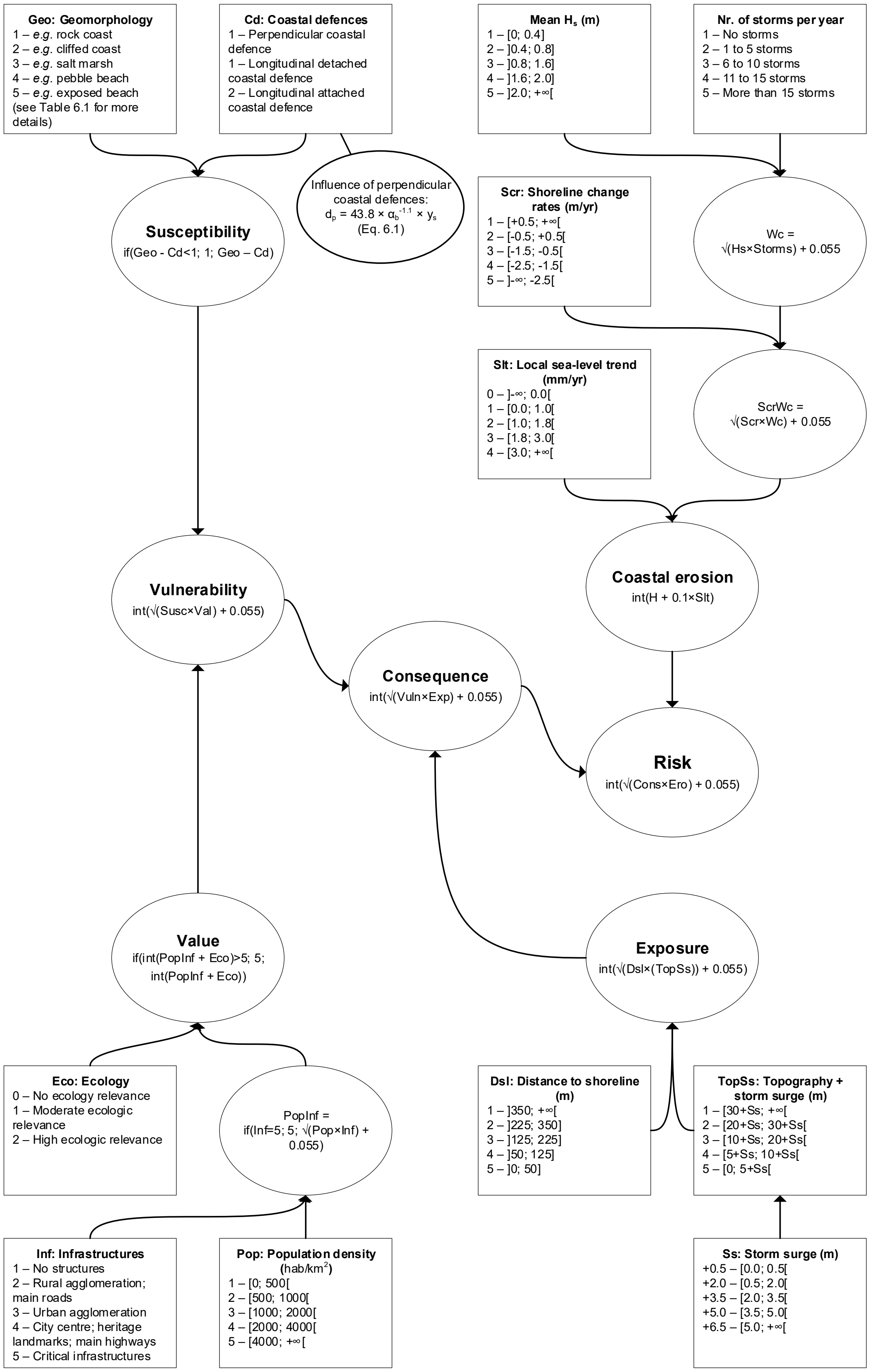

Figure 6.10. Complete framework of CERA2.0

6.6. MONTE CARLO SENSITIVITY ANALYSIS

Taking into account that CERA2.0 was proposed to be applied globally, which means every type of coastal environments worldwide, the execution of a general sensitivity analysis was considered a viable complement to evaluate the method's performance. Thus, a simulation recurring to Monte Carlo method was set-up. Monte Carlo simulation refers to the generation of random objects or processes by means of a computer (Kroese *et al.*, 2014). For each input, 1 million samples were randomly generated and used to perform all computation defined in CERA2.0. The result is showed on Figure 6.11, which demonstrate the probability of the result to fall in each class for all CERA2.0 process. In Figure 6.11 results, it should be noticed that some inputs had a conditioned random generation, as they relate to each other.

Ecology, which can fluctuate between 0 and 2, was limited to 0 or 1 if the combination between population and infrastructures resulted in a higher class than 3, since the higher ecology class is reserved for ecologically protected areas, which rarely include any type of urbanization. Also, the possibility to have coastal defences is only triggered if the geomorphology is 4 or 5, where beaches are featured.

The remaining indicators were not conditioned in the random generation and taken as independent. Although some of them are related (*e.g.* geomorphology is related to shoreline change rates), these are more difficult to quantify and restrict. Thus, all indicators were randomly generated with the respective class possibilities, with exception of the exposure indicators (*i.e.* distance to shoreline and topography), where a measurement was randomly generated and only then attributed the respective class. For distance to shoreline, values between 0 m and 500 m were randomly generated, while for elevation, the randomize values go from 0 m to 40 m.

The results of Figure 6.11 show that all outputs follow an approximately normal distribution, albeit skewed from the centre in a few outputs. The susceptibility output emphasizes the lower classes, as the outputs 4 and 5 from geomorphology have the possibility to be reduced due to coastal defences. On the other hand, the opposite occurs with the value output, as some lower classes derived by the combination of population and economy are subject to an increasing of value classification due to ecology. Exposure is slightly skewed to lower classes, as the range of each class increases exponentially in most classes of distance to shoreline and topography, resulting in a lower probability of occurring the higher classes. The hazard output distribution is the most approximate to a normal distribution, with only a slight skew to higher values due to the sea-level rise component.

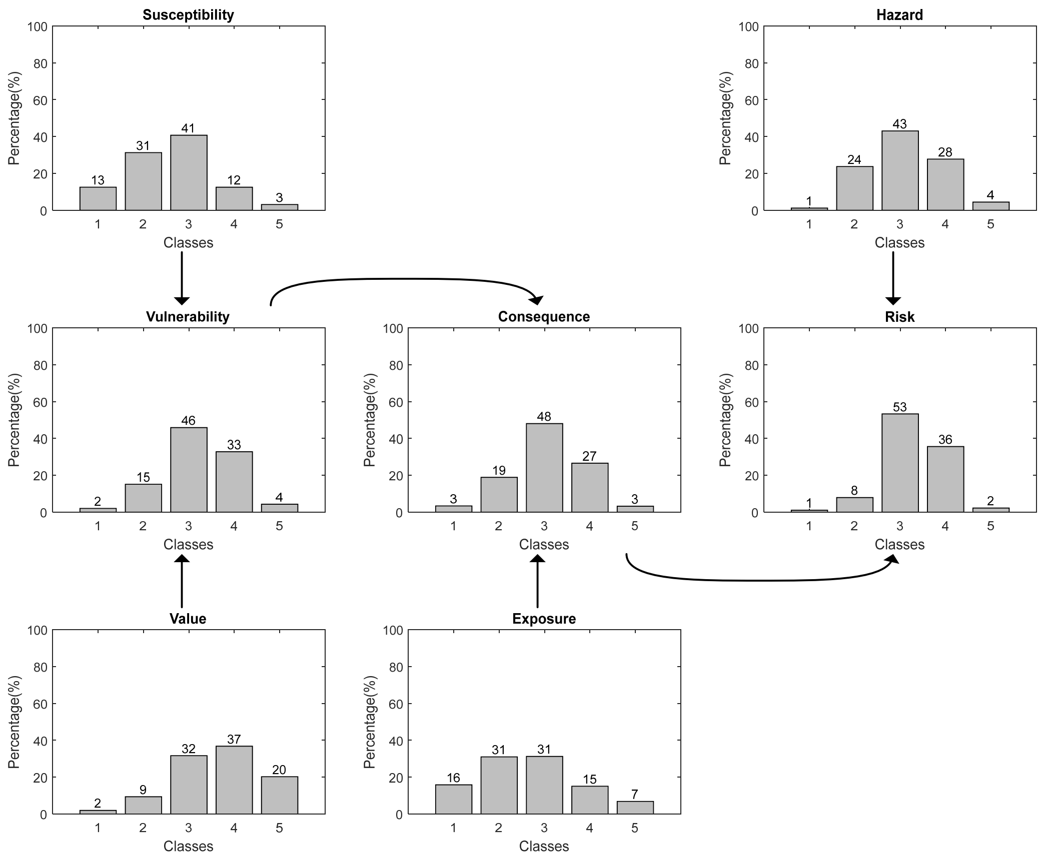

Figure 6.11. Distribution of probabilities through CERA2.0 method, given random selection of inputs for each indicator.

All following outputs (vulnerability, consequences and risk) present a skewness for higher classes. One possible reason behind this trend is the geometric mean and additional constant (0.055) used to combine the results. However, analysing the possible combinations given that function (25 combination of 5 levels of one indicator with the 5 levels of other indicator), it is concluded that there are three possibilities to result in class 1 and 5, seven to result in class 2 and 3, and five to result in class 4.

On the other hand, without the added constant, only combinations of indicators with both class 5 would result in the maximum class. The application of that hypothesis in the Monte Carlo simulation would result in 0% chance to achieve class 5 in consequence and risk outputs. The risk matrix from CERA1.0 was also considered, which resulted in higher probabilities in the extreme classes and overall more uniformly distributed results by the 5 classes. However, as stated in the previous section, the application to the study sites revealed that the amount of locations classified with the highest level was higher than intended, which did not allow for an accurate identification of the most problematic hotspots.

Together with literature support and accumulated experience from application of the previous methods, the Monte Carlo simulation was also used during the development of CERA2.0 to ensure that the defined combination of indicators would not result in null chances to get a determined result and to evaluate the potential impact of each indicator in the methodology.

In CERA1.0 the weighted average combination process made easy and intuitive to know which indicator had the most influence in risk assessment. On the other hand, CERA2.0 replaced that approach, making it more difficult to judge the order to which attribute have more impact. To assess the impact of each indicator, the data of Table 6.10 was developed. Table 6.10 shows twenty Monte Carlo simulation results where each indicator was maximized (left side of Table 6.10) and minimized (right side of Table 6.10). When more than one indicator is in the same headline row (at the left most column), the percentages showed refer to each individual indicator separately, as they have the same results in the simulation. Contrary to the previous simulation, these indicators were not conditioned in any form, as the objective was to measure the potential influence of the classification attributed to one indicator rather than try to approximate the test to real conditions. The shift to classes 4 and 5 in the outputs was observed to gauge the importance and impact of each indicator. This value was called potential impact (PI) in Table 6.10.

Table 6.10. Monte Carlo simulation of CERA2.0. Each indicator was fixed at its maximum and minimum class and probabilities for each output were estimated. Potential impact (PI) refers to the percentage of results shifting to classes 4 and 5.

		Minimum class					Maximum class					PI
		1	2	3	4	5	1	2	3	4	5	
Geomorphology	Susceptibility	100,0	0,0	0,0	0,0	0,0	0,0	0,0	25,0	50,0	25,0	75,0
	Value	2,0	9,4	22,2	30,5	36,0	1,9	9,4	22,3	30,5	35,9	---
	Exposure	15,8	31,0	31,2	15,1	6,9	15,8	31,0	31,2	15,1	6,8	---
	Hazard	1,2	23,7	43,0	27,8	4,4	1,2	23,8	43,0	27,7	4,4	---
	Vulnerability	11,3	88,7	0,0	0,0	0,0	0,0	1,9	14,9	48,5	34,6	83,1
	Consequence	19,3	33,5	47,1	0,0	0,0	0,3	16,1	36,1	36,6	10,9	47,5
	Risk	5,2	23,0	56,6	15,2	0,0	0,3	5,0	47,4	42,1	5,1	32,1
Coastal defences	Susceptibility	62,5	25,0	12,5	0,0	0,0	12,5	25,0	25,0	25,0	12,5	37,5
	Value	1,9	9,4	22,3	30,5	35,9	1,9	9,4	22,3	30,5	35,9	---
	Exposure	15,8	31,0	31,2	15,1	6,8	15,8	31,0	31,3	15,1	6,8	---
	Hazard	1,2	23,7	43,0	27,7	4,4	1,2	23,8	42,9	27,7	4,4	---
	Vulnerability	7,6	58,0	26,1	8,3	0,0	1,9	14,7	33,6	32,6	17,3	41,6
	Consequence	12,7	27,4	49,7	9,6	0,6	3,2	18,7	44,2	27,9	6,0	23,7
	Risk	3,5	16,8	56,2	23,0	0,6	1,0	7,8	51,6	36,5	3,2	16,0
Infrastructures or Population	Susceptibility	37,5	25,0	21,9	12,5	3,1	37,5	25,0	21,9	12,5	3,1	---
	Value	9,4	34,4	40,6	15,6	0,0	0,0	3,1	12,5	21,9	62,5	68,8
	Exposure	15,8	31,0	31,2	15,1	6,9	15,8	31,0	31,2	15,1	6,8	---
	Hazard	1,2	23,8	42,9	27,7	4,4	1,2	23,8	43,0	27,7	4,4	---
	Vulnerability	18,7	33,2	35,8	11,7	0,5	1,2	37,1	28,1	23,1	10,5	21,4
	Consequence	14,0	27,9	43,7	13,5	0,9	6,4	21,9	47,6	20,2	3,9	9,7
	Risk	3,8	17,8	53,5	24,0	0,9	1,9	10,9	53,9	31,2	2,1	8,5
Ecology	Susceptibility	37,5	25,0	21,9	12,5	3,1	37,5	25,0	21,9	12,5	3,1	---
	Value	7,8	21,9	37,5	25,0	7,8	0,0	0,0	7,8	21,9	70,3	59,4
	Exposure	15,8	31,0	31,2	15,1	6,8	15,8	31,1	31,2	15,1	6,8	---
	Hazard	1,2	23,7	43,0	27,7	4,4	1,2	23,7	43,0	27,7	4,4	---
	Vulnerability	13,1	34,8	34,0	16,1	2,0	0,0	37,5	26,7	24,1	11,7	17,7
	Consequence	11,6	26,0	45,3	15,6	1,5	5,9	21,5	47,7	20,7	4,2	7,8
	Risk	3,2	15,6	53,8	26,2	1,2	1,7	10,4	53,9	31,8	2,3	6,6
Distance to shoreline	Susceptibility	37,5	25,0	21,9	12,5	3,1	37,5	25,0	21,8	12,5	3,1	---
	Value	2,0	9,4	22,3	30,4	36,0	1,9	9,4	22,2	30,5	35,9	---
	Exposure	40,1	59,9	0,0	0,0	0,0	0,0	15,1	25,0	25,0	34,9	59,9
	Hazard	1,2	23,7	43,0	27,7	4,4	1,2	23,7	43,0	27,7	4,4	---
	Vulnerability	4,7	36,3	30,5	21,8	6,6	4,7	36,3	30,6	21,8	6,6	---
	Consequence	19,3	45,4	35,3	0,0	0,0	0,7	9,5	47,4	30,9	11,5	42,4
	Risk	5,3	25,7	57,6	11,3	0,0	0,3	3,8	48,8	42,0	5,1	35,7
Topography	Susceptibility	37,5	25,0	21,9	12,5	3,1	37,5	25,0	21,9	12,5	3,1	---
	Value	2,0	9,4	22,3	30,5	35,9	2,0	9,4	22,3	30,5	35,9	---
	Exposure	55,0	45,0	0,0	0,0	0,0	0,0	30,0	25,0	20,0	25,0	45,0
	Hazard	1,2	23,7	43,0	27,7	4,4	1,2	23,7	43,0	27,7	4,4	---
	Vulnerability	4,7	36,3	30,6	21,8	6,6	4,7	36,3	30,6	21,8	6,6	---
	Consequence	24,7	48,7	26,5	0,0	0,0	1,4	14,2	50,7	25,2	8,4	33,6
	Risk	6,7	30,4	54,3	8,5	0,0	0,5	5,4	52,5	37,8	3,8	33,0
Storm surge	Susceptibility	37,5	25,0	21,8	12,5	3,1	37,5	25,0	21,9	12,5	3,1	---
	Value	2,0	9,4	22,3	30,4	35,9	2,0	9,4	22,3	30,4	35,9	---
	Exposure	20,5	32,3	29,1	13,4	4,7	12,3	30,1	32,8	16,4	8,4	6,7
	Hazard	1,2	23,7	43,0	27,7	4,4	1,2	23,7	43,0	27,7	4,4	---
	Vulnerability	4,8	36,3	30,6	21,8	6,6	4,7	36,3	30,6	21,8	6,6	---
	Consequence	10,0	26,1	45,1	16,7	2,2	6,5	20,9	48,7	20,5	3,5	5,0
	Risk	2,8	14,4	54,1	27,3	1,4	1,9	10,7	53,8	31,6	2,0	4,9
Hs or Number of storms	Susceptibility	37,5	25,0	21,8	12,5	3,1	37,5	25,0	21,8	12,5	3,1	---
	Value	1,9	9,4	22,3	30,5	35,9	2,0	9,4	22,2	30,4	36,0	---
	Exposure	15,8	31,0	31,3	15,1	6,8	15,8	31,0	31,3	15,1	6,8	---
	Hazard	5,1	47,1	45,3	2,5	0,0	0,0	13,9	35,2	36,6	14,4	48,4
	Vulnerability	4,7	36,3	30,6	21,8	6,6	4,7	36,3	30,6	21,8	6,6	---
	Consequence	7,9	23,1	47,1	18,9	2,9	8,0	23,1	47,1	18,9	2,9	---
	Risk	5,3	18,2	64,9	11,6	0,1	1,1	10,1	46,0	38,6	4,2	31,2
Shoreline change rates	Susceptibility	37,5	25,0	21,9	12,5	3,1	37,4	25,0	21,9	12,5	3,1	---
	Value	2,0	9,4	22,3	30,5	35,9	1,9	9,4	22,3	30,5	35,9	---
	Exposure	15,8	31,0	31,2	15,1	6,8	15,8	31,0	31,2	15,1	6,8	---
	Hazard	9,4	88,9	1,7	0,0	0,0	0,0	0,6	21,7	53,5	24,2	77,7
	Vulnerability	4,7	36,3	30,6	21,8	6,6	4,7	36,3	30,6	21,8	6,6	---
	Consequence	8,0	23,1	47,1	18,9	2,9	8,0	23,1	47,1	18,9	2,9	---
	Risk	10,0	27,1	62,5	0,4	0,0	0,0	8,1	33,6	51,5	6,9	58,0
Sea-level trends	Susceptibility	37,5	25,0	21,9	12,5	3,1	37,5	25,0	21,9	12,5	3,1	---
	Value	2,0	9,4	22,3	30,5	35,9	1,9	9,4	22,3	30,4	35,9	---
	Exposure	15,8	31,0	31,2	15,1	6,8	15,8	31,0	31,2	15,1	6,8	---
	Hazard	3,3	28,6	44,5	21,5	2,2	0,2	18,4	43,0	32,4	6,1	14,8
	Vulnerability	4,7	36,3	30,5	21,8	6,6	4,7	36,3	30,6	21,8	6,5	---
	Consequence	7,9	23,1	47,1	18,9	2,9	8,0	23,1	47,1	18,9	2,9	---
	Risk	3,3	14,3	56,4	24,9	1,1	1,5	10,9	51,7	33,6	2,3	9,9

The shoreline change rates are the indicator with the most impact overall, causing 58% of the results to move to the higher risk classes. It also impacted 78% of the hazard results. Being the representation of the hazard that CERA2.0 intends to evaluate, it was considered acceptable that this indicator had this much emphasis in the hazard and risk assessment results.

Next, the exposure indicator of distance to shoreline and topography are the most influent, with near 36% and 33%, respectively. These indicators also present a potential impact of nearly 60% and 45% in the exposure result, respectively. Naturally, a receptor that is near the shoreline has a greater chance of being affected by coastal erosion, while receptors inland have reduced probabilities of being affected (simulation shows 0% results on class 5), even if the hazard likelihood is high, making these indicators essential in the risk assessment. The geomorphology has a similar potential impact to the previously mentioned indicators, with 32% on risk (and 75% on susceptibility). However, a low classification of this indicator is likely accompanied by low shoreline retreat rates, which would reduce drastically the risk level if this constrain was considered in the simulation.

The indicators related to wave climate also have a similar potential impact on risk (around 31% for each indicator). As driving sources of coastal erosion, these are important hazard indicators. Their influence of almost 50% on hazard output ensures that the hazard result could be executed with less detailed shoreline change rates information.

From the information of Table 6.10, the remaining indicators have much less impact on coastal erosion risk. With 16% of potential impact on risk and 38% on susceptibility, coastal defences are an effective measure to reduce risk, but cannot be compared to intrinsic characteristics of the study area, due to its necessity of maintenance and set lifetime, not being as effective as a rock coast, for instance. Sea-level trends have a potential impact of 10%, which is to be considerate suitable for its longer-term nature. Sea-level trends are followed by the value indicators of population and infrastructures, only estimated to have around 9% of influence.

However, in this case, the estimated potential impact does not correspond to real conditions, due to the influence of ecology in the value assessment. The ecology indicator, which has a potential impact of nearly 7% on risk, also has almost 60% on the value assessment. Due to its independence from the other indicators in CERA2.0, the simulation with minimum infrastructures still manage to have high value results. By executing an additional simulation where the ecology indicator is constrained and considered always class 0, the infrastructures and population indicators have a potential impact of around 19% each. Moreover, considering that population and infrastructures directly influence each other, the potential impact of both combined is 33%, which is in line with the other most influential indicators from each module. Finally, the storm surge indicator has a potential impact of nearly 5% on risk, which reflects the consideration that is not directly related with coastal erosion.

Overall, the sensibility analysis allows to conclude that the CERA2.0 structure appears to prioritize the indicators regarded as the most influential to classify coastal erosion risk. Compared with CERA1.0, the overall capacity of each indicator to impact the result seems to have increased, which potentially leads to more variate and realistic results. However, simulation of CERA2.0 performance was not considered sufficient for the development and conclusion of the methodology. Therefore, the following chapter tests the methodology on the study sites, to assess its performance on real assessments.

7. APPLICATION OF CERA2.0

The application of CERA2.0 to study sites was considered essential to test the new methodology. Extensive runs were made to test all parameters, alongside the sensitivity analysis described in the previous section. For an easier and faster application of CERA2.0, a plugin for QGIS was also developed.

In the following sections, CERA2.0 QGIS plugin is described and applications to each case study are presented in detail. The indicators are showed, the application process is detailed and results are displayed and discussed. The chapter ends with an overall discussion of CERA2.0, comparing its results to the outputs given by the methodologies presented in chapters 4 and 5, and concluding if CERA2.0 addresses the objectives identified in section 5.7.

7.1. DEVELOPMENT OF CERA2.0 PLUGIN IN QGIS

Like in CERA1.0, a QGIS application was developed to facilitate the execution of CERA2.0. The development of CERA2.0 plugin followed a different approach than CERA1.0 plugin. Rather than directly develop a plugin, CERA2.0 takes advantage of the QGIS built-in *Graphical Modeler*. This tool allows to chain several functions of QGIS. A model was produced for each module, which compute all processes described in chapter 6, taking advantage of built-in QGIS features or python functions developed during CERA1.0 plugin. Additional PyQGIS functions were developed to CERA2.0 to introduce automations in some indicators when the built-in tools of QGIS were not able to provide the required feature. Overall, the use of the *Graphical Modeler* allowed a much faster development time than in CERA1.0. Additionally, the division of the modules in independent models facilitates eventual changes and improvements in the tool, since it is only required to edit the respective model, rather than the whole plugin.

Figure 7.1 shows the main workflow of CERA2.0. This process combines all modules in one, which allows the execution of all CERA2.0 process in a single run. In Figure 7.1, the inputs are the purple boxes, the white boxes represent the secondary models/functions and the blue boxes are the results correspondent to each module and subsequent combinations.

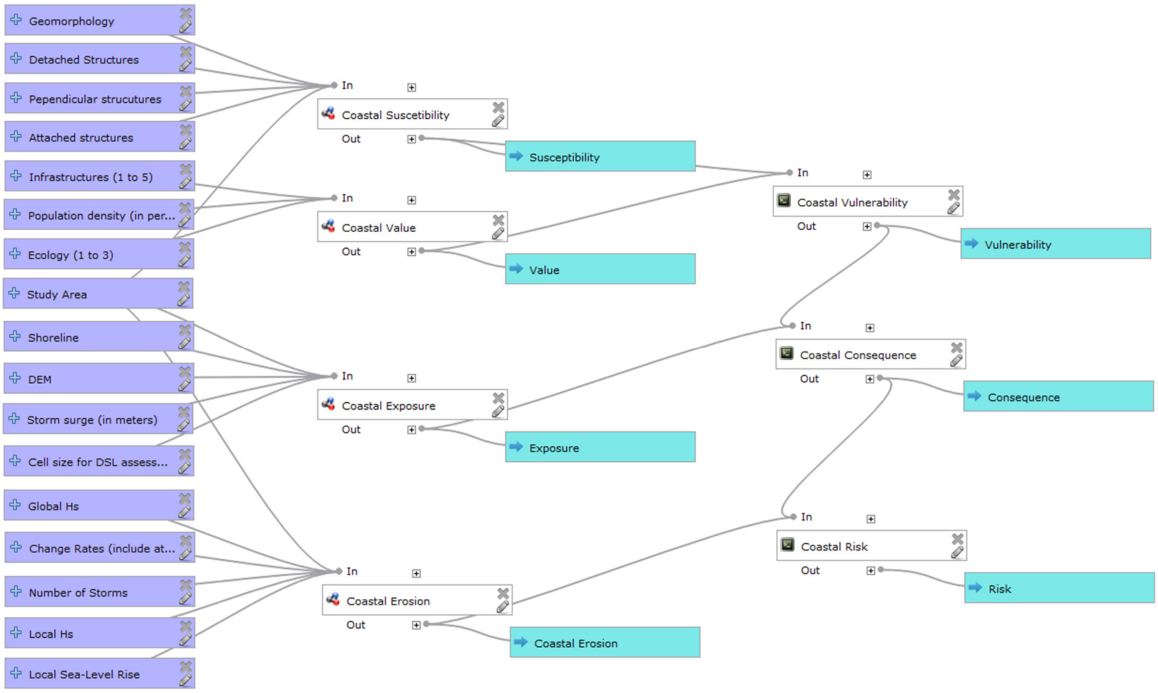

Figure 7.1. Graphical module built for QGIS2.0. The purple boxes are inputs and the blue boxes are outputs. The remaining boxes are independent modules or functions for each computation of CERA2.0.

The *Graphical Modeler* automatically provides a graphical user interface (GUI), including fields for all inputs, the possibility to choose the location where the outputs are to be stored and whether the outputs should be loaded in QGIS or not. The CERA2.0 interface is showed in Figure 7.2. The *Graphical Modeler* organizes the inputs by type. Hence, raster files are the first, followed by shapefiles (lines then polygons) and finishes with the indicators described by numbers.

As stated earlier, during the development of the application, the creation of automatisms whenever possible was an objective. This reduces the amount of work required in the manipulation of data, ultimately reducing the time to apply CERA2.0. On the other hand, some indicators, namely the most dependent of qualitative assessments (*e.g.* geomorphology, infrastructures, etc.) do not allow the introduction of automatic processes, being required to produce raster maps with set classifications, accordingly to CERA2.0 criteria.

Figure 7.2. Graphical User Interface (GUI) of CERA2.0 for QGIS.

For the susceptibility assessment module, two main indicators are required: geomorphology and coastal defences. Geomorphology requires a raster file with classifications from 1 to 5, according to CERA2.0 methodology. The classification is to be done along the shoreline to reflect the coastal landform closer to the hazard (*i.e.* coastal erosion). Although geomorphology is assessed along the shoreline, the raster file should cover all study area to be recognized by the plugin. The coastal defences are to be represented as line shapefiles and should be separated in different files depending on its type: longitudinal attached; longitudinal detached or perpendicular coastal defences. The application automates the process of coastal defences mapping using the shapefiles in addition to the study area shapefile. The lines representing the longitudinal attached structures decrease the susceptibility level of the parallel shoreline by two levels. The lines representing the perpendicular structures should cross the entire study area and have additional information in its attribute table, namely, a “Length” column with the length of the coastal structure, and a “Angle” column with the wave breaking angle. These are used to compute the influence distance for each coastal defence (Eq. 6.1). Within this distance, the susceptibility is decreased by one level. The result of the processes using the shapefiles representing the coastal defences is a raster map with values ranging from 0 to 2 that are combined with the geomorphology map, producing the susceptibility result.

For the value assessment module, three indicators are necessary: infrastructures, population density and ecology. These inputs are raster files, but vary in the processes required. For infrastructures, the user should use the capabilities of QGIS (or other GIS application) to produce a raster map from 1 to 5, according to CERA2.0 methodology. The same process should be done for the indicator of ecology, but with a range from 1 to 3. For the population density, the user should provide a raster map with data regarding this subject. The application will read the input data and automatically produce the respective map, with classifications from 1 to 5, according to CERA2.0 criteria. Then, all raster indicators are combined, resulting in the value output.

The exposure assessment module requires inputs for indicators of distance to the shoreline, topography and storm surge. The distance to the shoreline map is automatically produced given a line shapefile representing the shoreline position and the polygon shapefile of the study area. Additionally, an option to select the desired resolution (*i.e.* cell size for DSL assessment, in m/px) for that map is also available. For the topography indicator, the original DEM data (in the appropriate CRS) can be introduced as input. Once again, the application does all required computations to produce the topographic map. If storm surge affects the area, a value can be introduced in the application, which will be taken in account in the calculations. These indicators are then combined to produce the exposure map.

Finally, data regarding mean significant wave height, number of storms per year, shoreline position change rate and sea-level trends (in mm/year) is required for the coastal erosion assessment module. From those, only the shoreline position change rate indicator requires georeferenced data, namely, a polygon shapefile covering all study area with a "ChangeRate" attribute, describing the yearly shoreline change, in metres. The choice of a shapefile instead of a raster is related with the output of DSAS (Thieler *et al.*, 2009) being a shapefile as well. However, changes still must be done manually in order to convert the DSAS output to the input accepted by CERA2.0. The remaining inputs (*i.e.* mean significant wave height, number of storms per year and sea-level trends) are numerical values to be estimated and introduced by the user. CERA2.0 application contemplates the possibility of considering a variable significant wave height along the study area by introducing a polygon shapefile covering all area extent with a "Hs" attribute, describing the significant wave height, in metres.

After processing all individual module outputs, these are combined using a dedicated function to perform the geometric mean and to round the float values into integers, resulting in the classification of vulnerability, consequence and risk to coastal erosion, according to CERA2.0 methodology.

Although still in a beta stage regarding usability, a working version of CERA2.0 tool is available at https://github.com/NEFEC-UA. Continuous improvement of the tool is expected, mainly to improve the user interface and to address bugs. At the moment, the plugins are only compatible with version 2 of QGIS. QGIS3 (2018) was released recently and the applications of CERA methodologies (1.0 and 2.0) were not yet developed for the new software.

7.2. CERA2.0 FOR AVEIRO

The application of CERA2.0 to Aveiro covered the same shoreline as previous methodologies (chapter 5). Like CERA1.0, this new iteration covers inland locations, but aiming at a coastal strip of 500 m inland rather than 2 km. The coincident indicators were revised to contemplate this change and to update data sources that have been known in the meantime.

As described in the previous chapter, the susceptibility module requires two indicators: geomorphology and coastal defences. As referenced in section 6.1, the susceptibility indicators and output are assessed along the shoreline. Thus, regarding geomorphology (Figure 7.3a), most Aveiro shoreline was considered class 5 (exposed beach). Only the significant dune presence in São Jacinto reduced this indicator to class 4. Although geomorphology is assessed along shoreline, the raster file needs to cover all study area. Thus, Figure 7.3a presents the same classification at shoreline to the inland areas.

The coastal defences were identified in Google Earth satellite images and supported by reviewed literature (*e.g.* Presidência do Conselho de Ministros, 2000). Perpendicular structures and longitudinal attached structures were digitized in individual shapefiles (Figure 7.3b), which are inputs in CERA2.0 QGIS plugin. A total of 23 features regarding perpendicular structures and 7 features of longitudinal structures (which may include more than one coastal defence structure) were considered in the assessment.

The length of perpendicular coastal defence structures, required for the assessment of their influence distance was measured through the Google Earth satellite images.

The lengths varied between 100 m (groynes) and 1000 m (harbour breakwaters). On the other hand, the longitudinal attached structures vary their extension between 200 m and 1500 m. The wave breaking angle considered in the analysis of perpendicular coastal structures was admitted constant along all extension of the coast due to the regular shape of the shoreline. The angle was computed using Snell's law (USACE, 2002), considering the NW dominant wave direction (Coelho *et al.*, 2009c) and a N12°E orientation of the shoreline. The estimated result is a wave breaking angle of 11.8°.

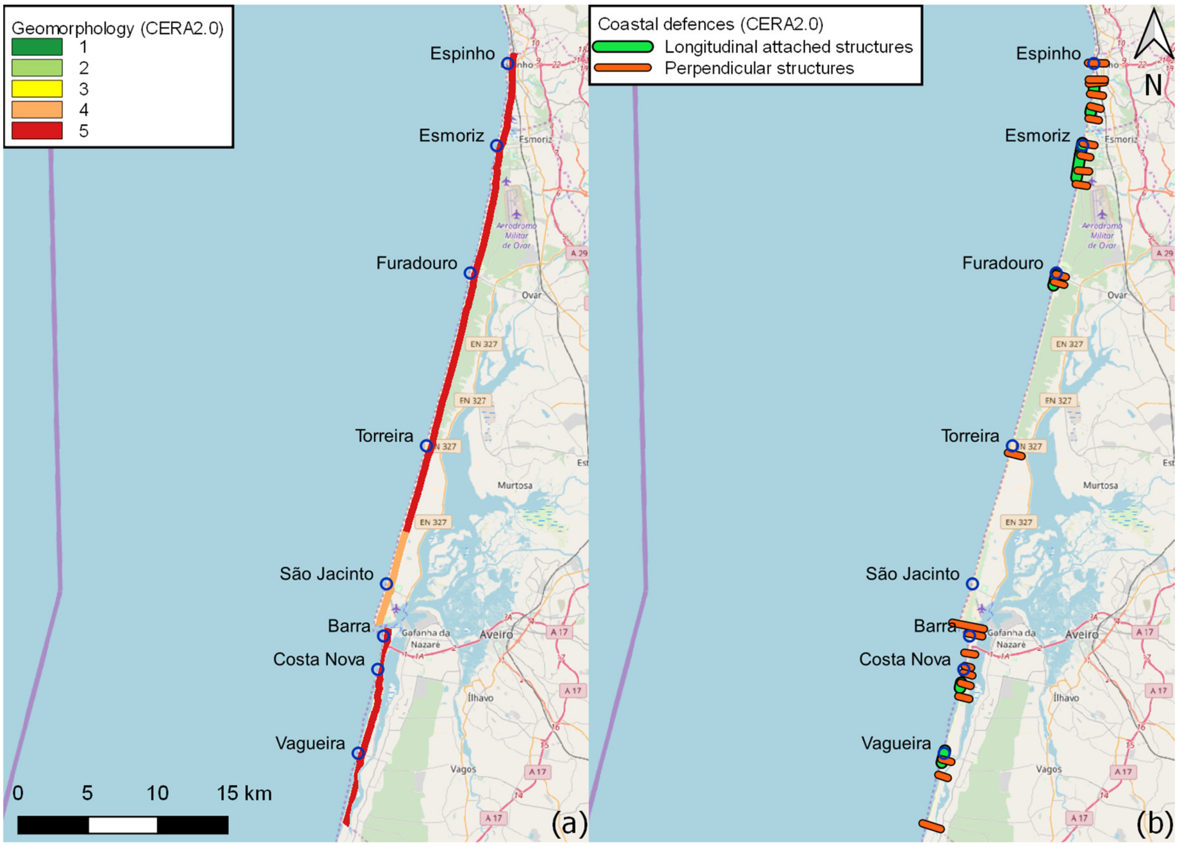

Figure 7.3. Indicators for susceptibility assessment module of CERA2.0 in Aveiro: (a) geomorphology; and (b) coastal defences.

The output of the susceptibility module is showed on Figure 7.4. Overall, the area is very susceptible to coastal erosion, with most shoreline classified with level 5. Most towns near the shoreline are protected by coastal structures, which reduces its susceptibility to coastal erosion, but the remaining area is composed by unconsolidated sediments in open coast, which is very susceptible to change. Furthermore, São Jacinto also has a moderate susceptibility (class 3), due to the significant dune presence in the area and the breakwater located immediately south of that site.

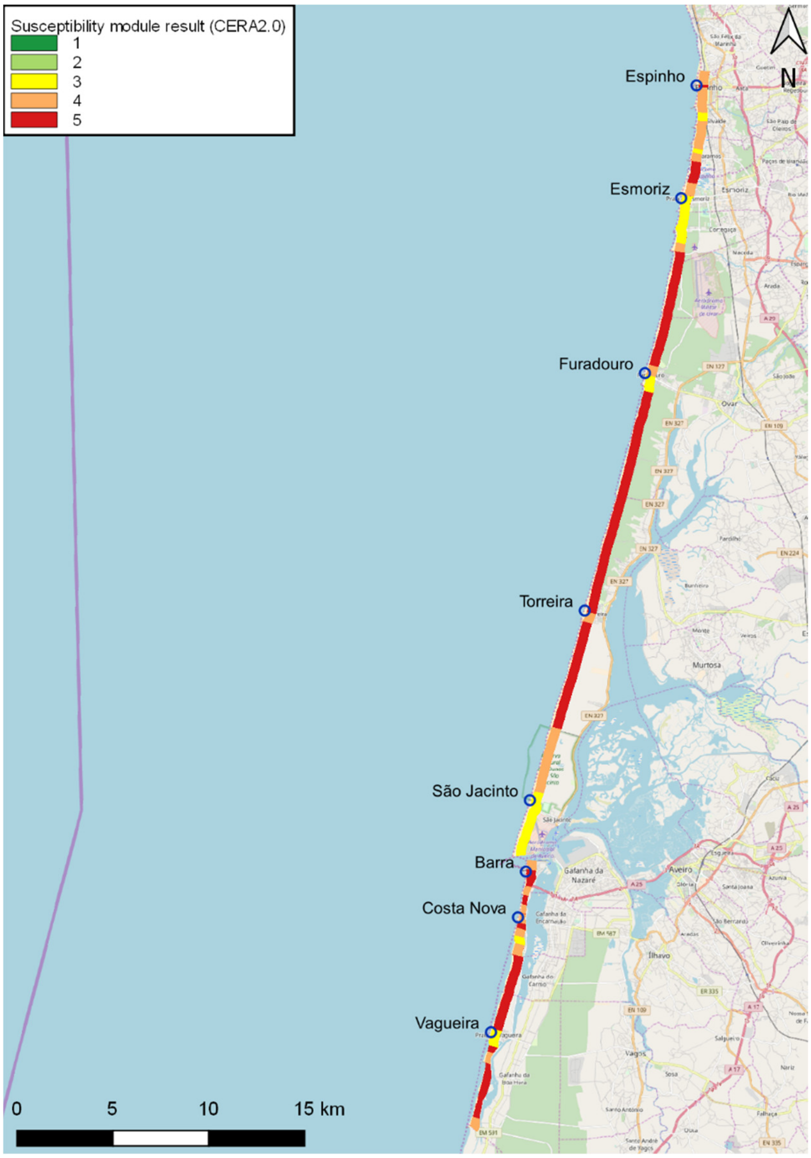

Figure 7.4. Susceptibility assessment module output for Aveiro, using CERA2.0.

Next, for the value assessment module, three indicators are necessary: infrastructures, population density and ecology (Figure 7.5). Like geomorphology, the respective inputs are raster maps covering the entire study area, containing data up to 500 m inland.

The infrastructures map (Figure 7.5a) was developed mainly based on Corine Land Cover 2012 (Figure 3.5; EEA, 2016b) and on data from OpenStreetMap (OSM, 2018).

Hence, from CLC2012, continuous urban areas were considered class 4 and discontinuous urban areas were classified as 3. Local roads identified in OSM® were defined as class 2. Finally, the national railway that intersects Espinho was considered of vital importance for transportation and thus, classified as critical infrastructure (level 5). As explained in the previous chapter, these are infrastructures which its failure represents a great disruption in the community. Thus, these are classified with level 5 in the value module output, regardless of the classification of remaining indicators.

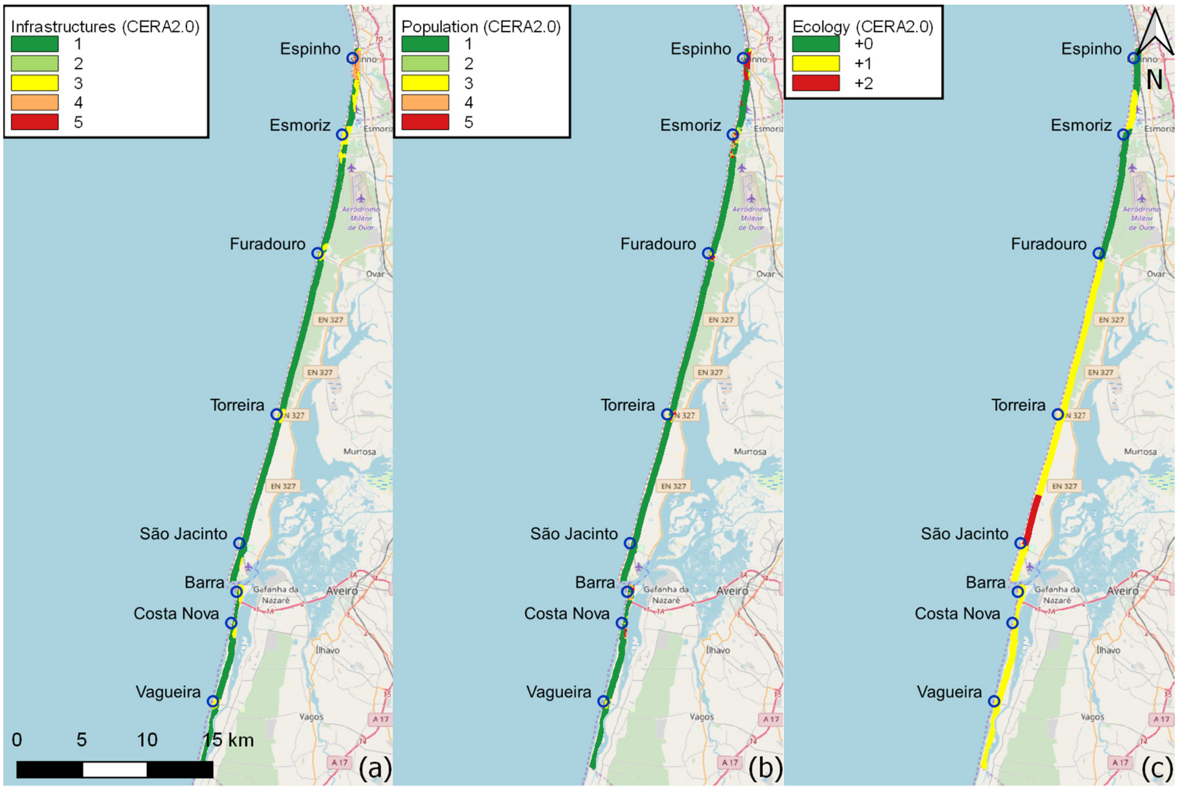

Figure 7.5. Indicators for value assessment module of CERA2.0 in Aveiro: (a) infrastructures; (b) population density; and (c) ecology.

For population density (Figure 7.5b), the data from Global Human Settlement (GHS; Freire *et al.*, 2016) was used. This approach represents an evolution when compared with CERA1.0 for Aveiro (Figure 4.5a) and is in line with the approach taken in CERA1.0 for Quintana Roo (Figure 4.16a). The classification shows that most villages have a population density superior to 4000 pers/km^2, but the remaining area is mostly uninhabited. Here, the input accepted by the plugin is the raw population density, as the process of classification is automated. Regarding ecologic relevant areas (Figure 7.5c), the base information are the classifications of Figure 3.6. The São Jacinto dunes were considered of high ecological relevance (*i.e.* +2 levels) due to its inclusion in RNAP (*Rede Nacional de Áreas Protegidas*). Most remaining area was considered of moderate ecological relevance (+1 level) due to its inclusion in the N2K network. The result of the value assessment module for Aveiro (Figure 7.6) presents a series of nearshore towns with high value classifications (4 and 5).

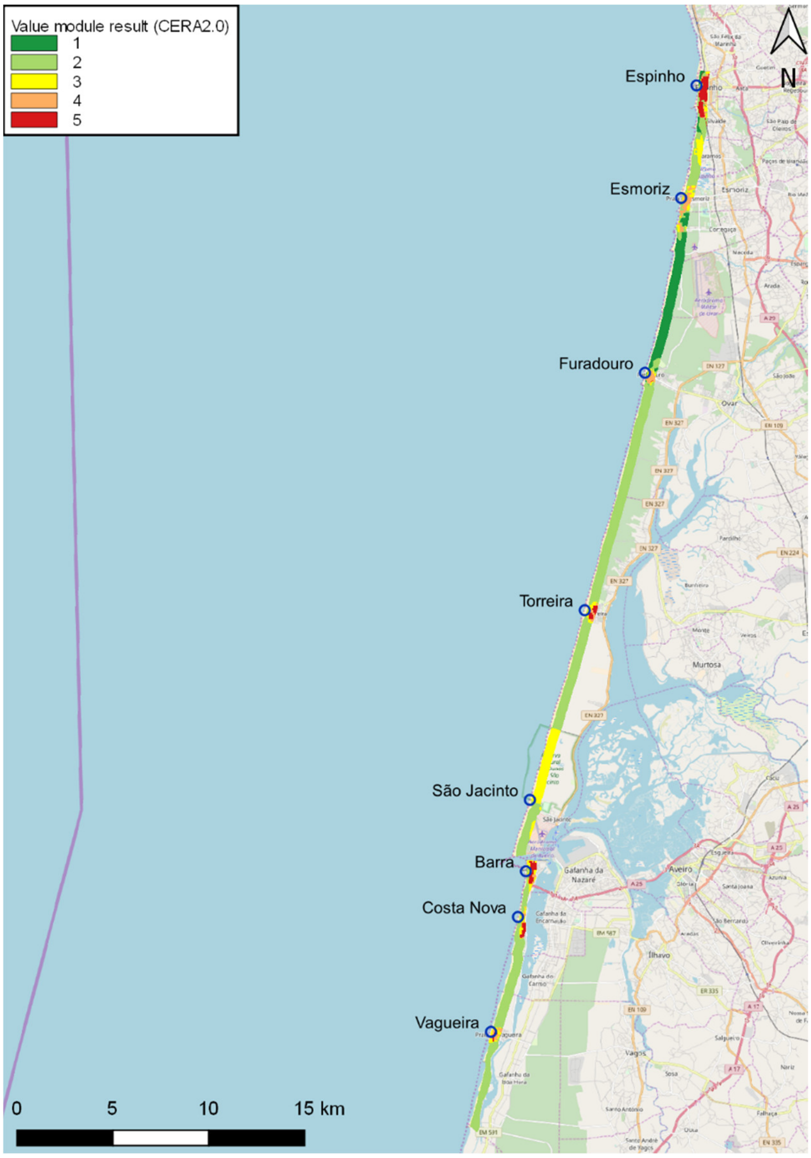

Figure 7.6. Value assessment module output for Aveiro, using CERA2.0.

Despite the relative low classifications regarding infrastructures, the high population density and the moderate ecological relevance contribute decisively to the high classifications in the nearshore villages. These are the cases of Torreira, Barra and

Costa Nova, which are within the Natura 2000 network, boosting its overall value by 1 level. On the other hand, Esmoriz and Furadouro have a lesser classification when compared with the others for the same reason.

Although not within an ecologically relevant area, Espinho is the most valuable location in Aveiro study area. The urban development and population density of this city makes it the most important location. Also, the railway passing through Espinho is noticeable in the value classification due to the nomination of critical infrastructure, resulting in a classification 5 in the value assessment. Finally, only the non-urbanized area between Esmoriz and Furadouro is level 1 regarding value classification.

Next, data regarding elevation, shoreline position and storm surge is required to apply the exposure assessment module. Figure 7.7 presents the classifications considered for the indicators of distance to shoreline and topography integrated with the storm surge factor, as described in the previous chapter. Despite CERA2.0 application automates the development of the maps presented in Figure 7.7. An original digital elevation model (DEM), a shapefile of the shoreline position and a value of recorded storm surge are the inputs required by the plugin.

For Aveiro, like in previous executed methodologies, the shoreline considered was produced by Lira *et al.* (2016) and the EU-DEM (EEA, 2016a) was used for elevation data. The dataset from DSGCIG (2011) was also considered for the topography assessment. Despite the shorter inland extent considered by CERA2.0, the DSGCIG (2011) dataset still does not cover the entirety of the study area. Thus, EU-DEM remained the dataset of preference. Regarding storm surge, Gama *et al.* (1994) present 78 cm as the maximum observed storm surge for Aveiro, putting this study area in class 2, according to CERA2.0 methodology (Table 6.4).

The distance to shoreline map (Figure 7.7a) represents the horizontal distance to the shoreline, and is mainly dependent on the shoreline position considered. In this case, the foredune toe was used as base, due to independence of short-term changes, as explained in section 6.3.1. The highest class of distance to shoreline often covers the first urban front in nearshore towns without a significant dune presence, which was the aim when developing the thresholds.

Regarding topography, as already shown in previous chapters, Aveiro is a low-lying area. Additionally, the class 2 of storm surge increases the thresholds of topography by 2 m. Consequently, most study area is within the highest classification of this indicator, with only a few exceptions in the northern part of the study area. Relatively to CERA1.0, the change to EU-DEM provides additional detail to the input. For instance, the high dunes of São Jacinto are noticeable in Figure 7.7b, contributing for a reduction of exposure classification in that area.

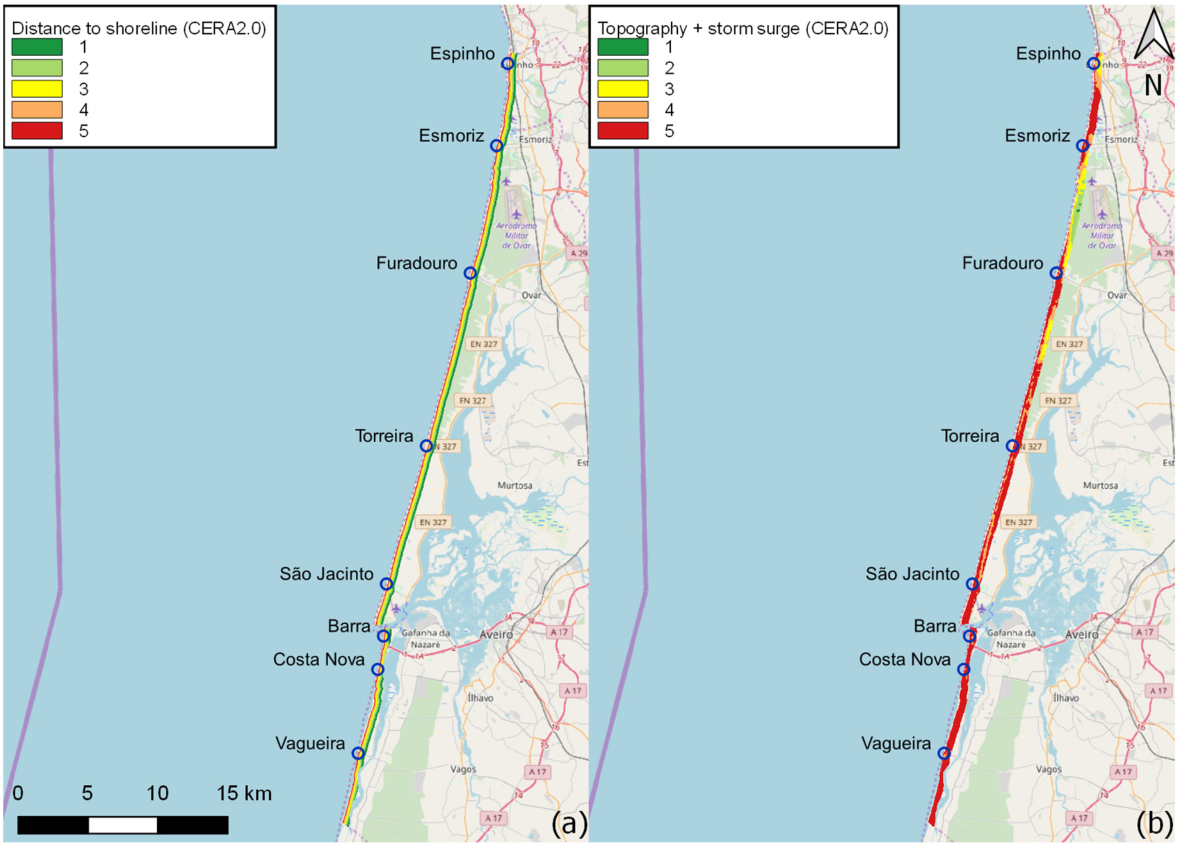

Figure 7.7. Indicators for exposure assessment module of CERA2.0 in Aveiro: (a) distance to shoreline; and (b) topography integrated with storm surge factor.

The combination of the inputs results in the exposure classification shown in Figure 7.8. Due to the relatively homogeneous topography classification, most nuances in exposure are due to the distance to the shoreline. Class 1 is almost non-existent, only with a small appearance between Esmoriz and Furadouro.

Looking at the highest class, it is noticeable a reduction of exposure in Vagueira, likely due to the seawall there built, which increases the elevation detected by EU-DEM (EEA, 2016a), and consequently, reducing the overall exposure of that town. Also, the height of São Jacinto dunes contributes for a reduction of exposure there. Considering the extension of the area, the data used in this assessment has enough quality for the exposure assessment, allowing for the identification of nuances in the level of exposure.

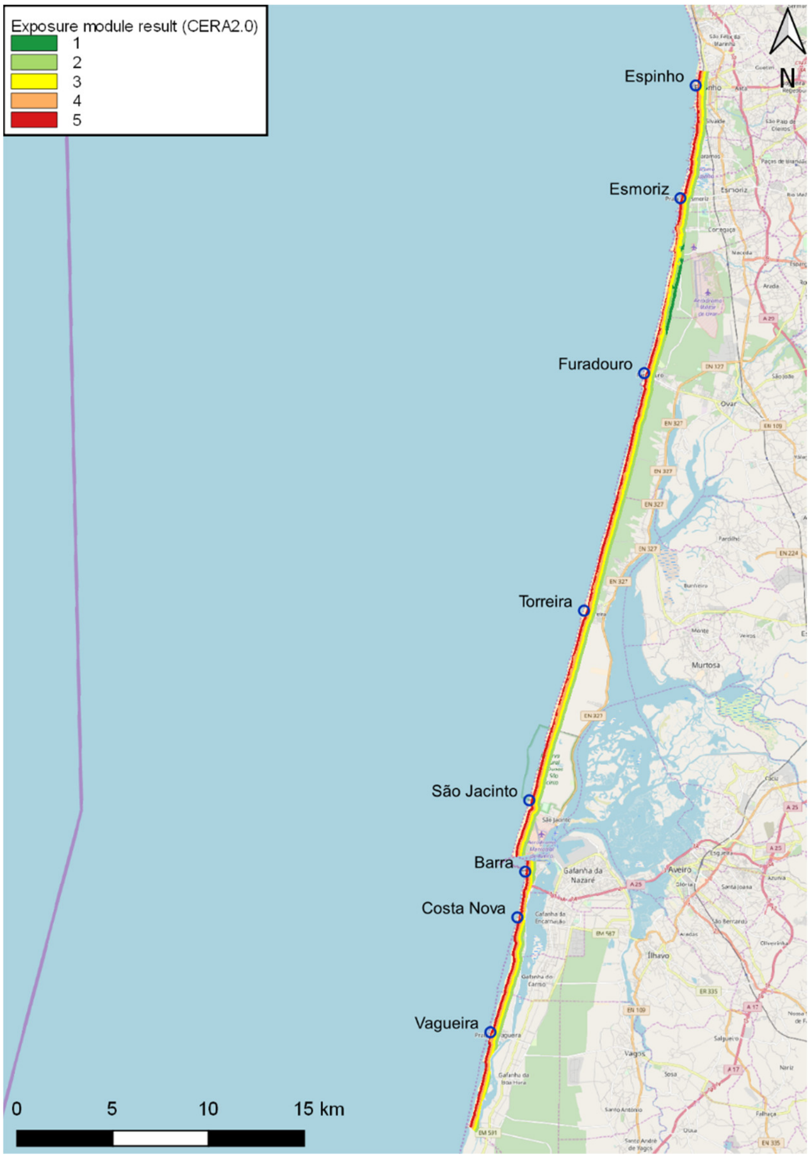

Figure 7.8. Exposure assessment module output for Aveiro, using CERA2.0.

The last module, the coastal erosion hazard assessment, requires data regarding wave climate (mean significant wave height and number of storms), shoreline change rates and local sea-level trends. From those, only the input of shoreline change rates requires georeferenced information. Like the shoreline position, the shoreline change rate classification used the data from Lira *et al.* (2016) as source. As already verified in previous assessments, the locations most affected by significant retreat rates are the coastal zones near Esmoriz, Furadouro, Costa Nova and Vagueira (Figure 7.9). On the other hand, São Jacinto presents shoreline accretion rates.

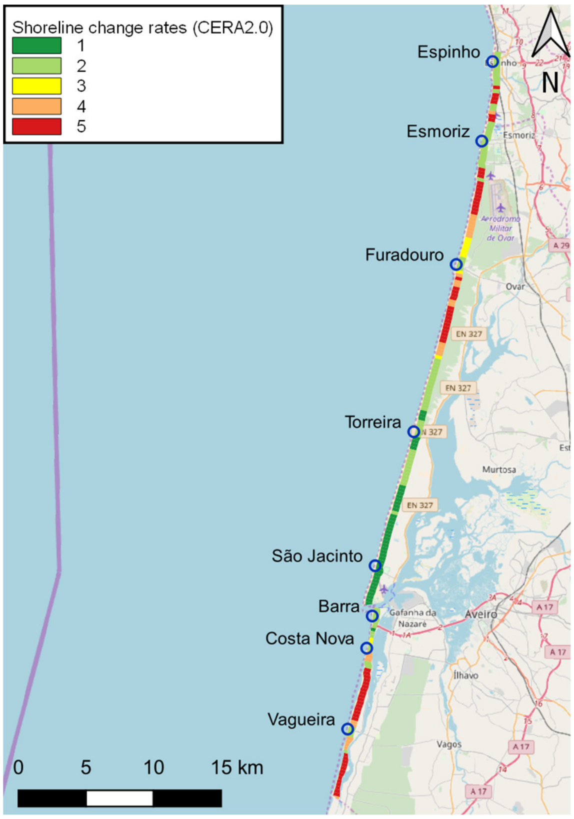

Figure 7.9. Indicator for coastal erosion assessment module of CERA2.0 in Aveiro: shoreline change rates.

The remaining inputs are values that should be estimated by the user. A wave climate time series for a significant time span is recommended for estimation of mean significant wave height and number of storms per year. Alternatively, these can be inferred based on literature review. A mean significant wave height of 2.16 m was considered for Aveiro assessment (Narra *et al.*, 2015a). This value is consistent with previous literature (Coelho *et al.*, 2009c) and results in a classification 5 regarding mean H_S. Furthermore, the hindcast simulation near Espinho (Heitor, 2014) was used to identify the number of storms, using the same procedure as in section 6.4.1. This hindcast data provides around 50 years of registers. It was concluded that Aveiro has around 10 storms per year, classifying it in class 3 regarding that indicator. Finally, 1.27 mm/year estimated by NOAA (2018a) were considered as sea-level rise. The resulting combination of these inputs is presented in Figure 7.10.

Figure 7.10. Coastal erosion assessment module output for Aveiro, using CERA2.0.

As concluded in the sensitivity analysis (section 6.6), the coastal erosion assessment module is mainly dependent on the shoreline change rates. This is visible in Figure 7.10, which is similar to the shoreline change rate input (Figure 7.9). The classifications are mostly aggravated, due to the highly energetic wave climate, but preserves the most impacted areas. The coastline transects around Furadouro and Vagueira are the most threatened. However, the towns have a reduced coastal erosion classification, as most of them have longitudinal coastal defences stabilizing the shoreline, which reduces that indicator to class 2 (stable shoreline).

Following the process of module outputs, the combination of those is achieved through Equations 6.9 to 6.11, showed in chapter 6, producing maps of vulnerability (Figure 7.11a), consequence (Figure 7.11b) and risk to coastal erosion (Figure 7.12).

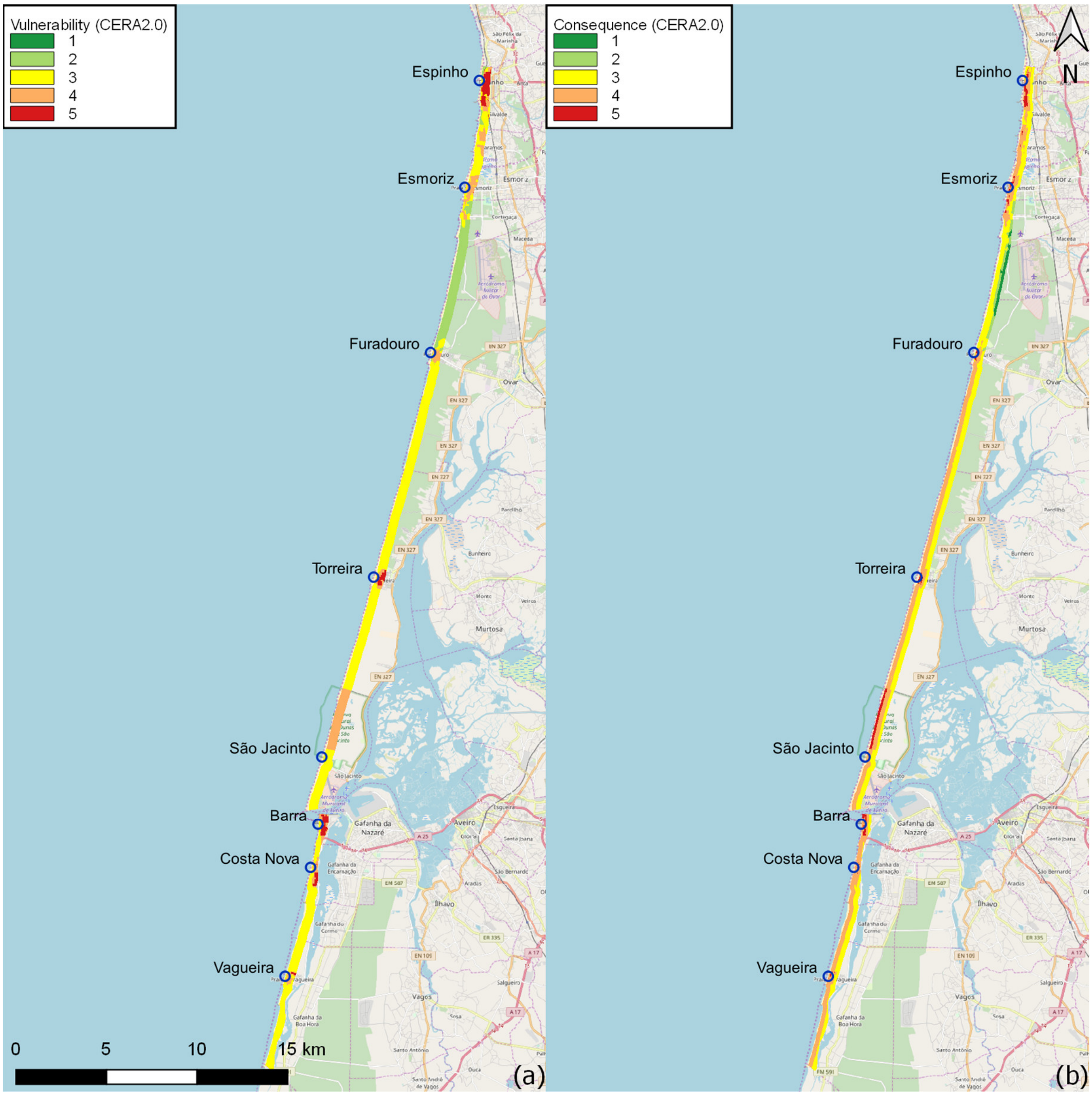

Figure 7.11. Outputs of (a) vulnerability and (b) consequence for Aveiro, using CERA2.0.

The vulnerability map results from the combination of susceptibility and value (Figure 7.11a). The vulnerability map intends to show the potential impact of the hazard, disregarding its likelihood or extension. Consequently, inland areas can be classified with higher vulnerability levels than nearshore areas, since they present the same susceptibility as these, but are regions where towns are often located within the 500 m stripe considered in the assessment, raising the value of these zones. In fact, the nearshore towns are the highlights of the vulnerability output, with almost all of them classified within levels 4 or 5. Likewise, the natural reserve of São Jacinto dunes also has a high vulnerability to coastal erosion, due to its high ecological value (Figure 7.5c).

Next, the consequence map results from the combination of vulnerability and exposure (Figure 7.11b). The consequence output adds to vulnerability the potential extension of the hazard by quantifying the most exposed receptors. Hence, the locations with the most potential consequences are places with high vulnerability that are nearer to the shoreline. These are the cases of Espinho, Esmoriz, Furadouro, Barra and Vagueira, and São Jacinto natural reserve, which are all classified with maximum consequence level. On the other hand, Torreira and Costa Nova, which are more inland within the study area, are classified with consequence level 4 due to less exposure, but that consequence level extends further inland in those areas. Overall, excluding the hotspots noted before, most shoreline has a consequence level 4, with inland areas being classified as 3.

Finally, the risk map is the result of combining consequence and coastal erosion outputs (Figure 7.12). The inclusion of hazard likelihood and intensity changes the aspect of the risk map when compared with the consequences map. Commonly, nearshore villages are protected from coastal erosion by attached structures that stabilize the shorelines. Thus, despite the common knowledge that those areas are endangered by coastal erosion, the measures implemented reduce the risk when compared with the surrounding areas. This is the case of Furadouro and Vagueira, which have risk level 5 in areas surrounding, but not on the village itself, albeit still have a risk level 4, due to all other indicators, which are not favourable to those locations. Hence, overall the risk level of Aveiro is moderate to high. The higher risk locations are shorelines surrounding Furadouro and all shoreline southern of Costa Nova, but all villages have at least risk level 4. The moderate risk is attributed to São Jacinto, as its area is mostly unaffected by coastal erosion.

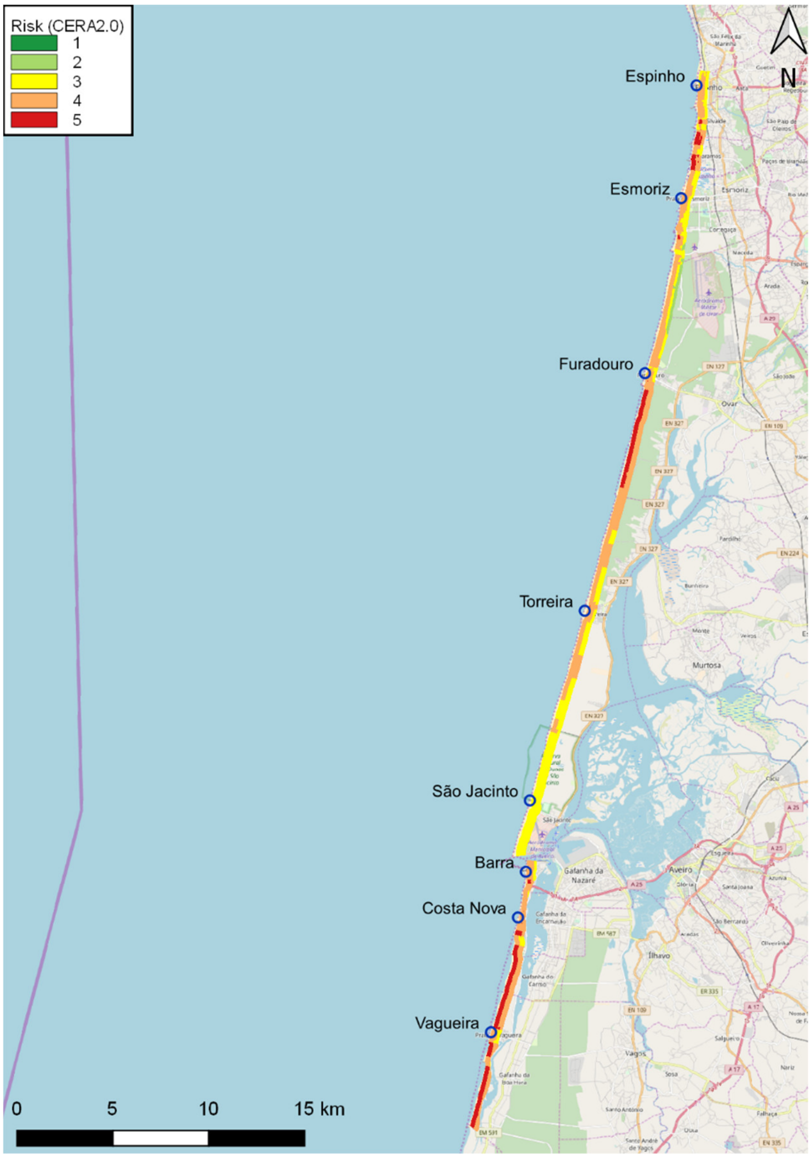

Figure 7.12. Risk output for Aveiro, using CERA2.0.

7.3. CERA2.0 FOR MACANETA

Like with other methodologies, the application of CERA2.0 in Macaneta is simpler than the other study sites due to its characteristics, resulting in simplified data.

Regardless, the application was executed to assess the performance of CERA2.0 when considering smaller study areas.

Macaneta spit is a barrier system made of unconsolidated sediments. Therefore, the geomorphology indicator was classified with level 5, due to its susceptibility to change with varying wave climate conditions or sediment sources. Moreover, there are no coastal defence structures in the area. This results in a susceptibility level 5 in all study area, as represented in Figure 7.13.

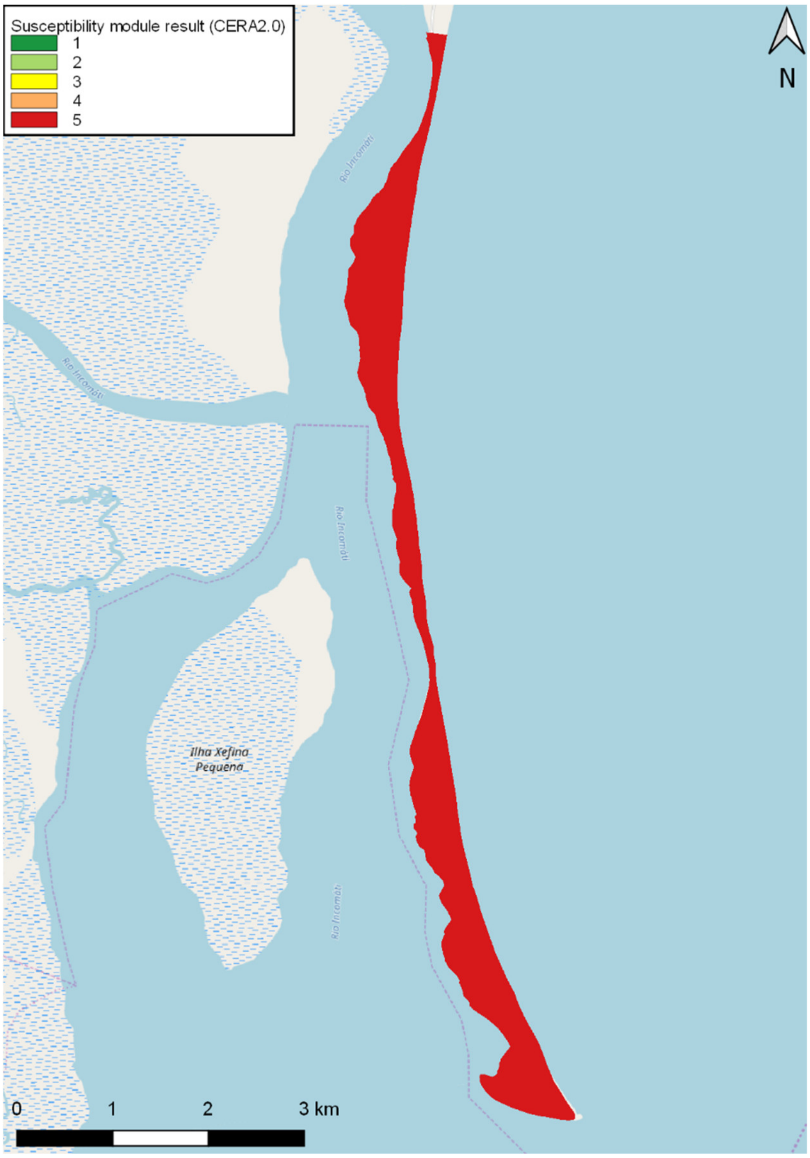

Figure 7.13. Susceptibility assessment module output for Macaneta, using CERA2.0.

For the value assessment, the indicators are based on the assessment of CERA1.0, but were reviewed to take advantage of newer satellite images in Google Earth. As with CERA1.0, the scattered summer houses along the spit were identified and attributed class 2 regarding infrastructures, while the remaining territory was considered class 1 (Figure 7.14a). For population (Figure 7.14b), the lower class was considered, as only a very small amount of people lives in the spit (Narra *et al.*, 2017). The ecology (Figure 7.14c) was set as moderate (class +1) due to its role in Incomatí river protection from breaching.

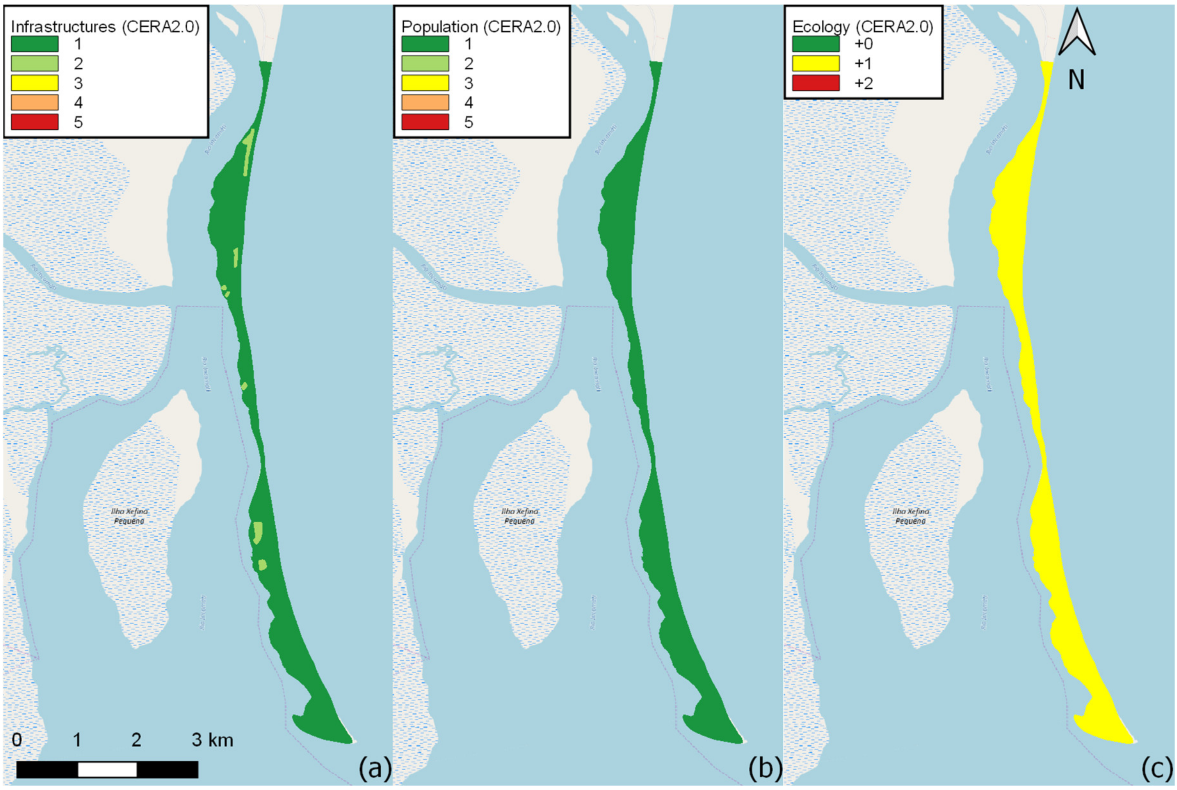

Figure 7.14. Indicators for value assessment module of CERA2.0 in Macaneta: (a) infrastructures; (b) population density; and (c) ecology.

Despite the different classifications in the infrastructures indicator, the result of the value assessment module is class 2 for the entire Macaneta spit (Figure 7.15). This level is considered adequate given the lack of infrastructures or population. On the other hand, the ecologic classification contributes decisively to the value classification of the spit. As stated in Narra *et al.* (2017), there is social pressure to explore Macaneta spit, making it an attractive area for tourism. This can lead to a significant increase in the value classification in the future.

Figure 7.15. Value assessment module output for Macaneta, using CERA2.0.

The exposure assessment module considered the same shoreline position as used for the previous assessments, presented in chapters 4 and 5. However, the change in criteria for CERA2.0 results in a more varied distance to shoreline classification than on CERA1.0, with presence of all classes along the study area (Figure 7.16a).

On the other hand, like in Aveiro assessment, the elevation data was updated when comparing with CERA1.0. In case of Macaneta, the ASTER GDEM (NASA and METI, 2011), presented in chapter 3, was used to compute the topography classes. Moreover, according to Karlsson and Liljedahl (2015), there are no significant registers of storm surge events in the areas. Thus, that indicator was not considered for Macaneta.

Consequently, Figure 7.16b only presents the classification considering the topography indicator. In opposition to CERA1.0, this new dataset highlights the considerable amount of dune presence in the spit, with moderate classifications of topography in dune areas, namely in the southern area, where the highest class of topography is almost non-existent along the shoreline.

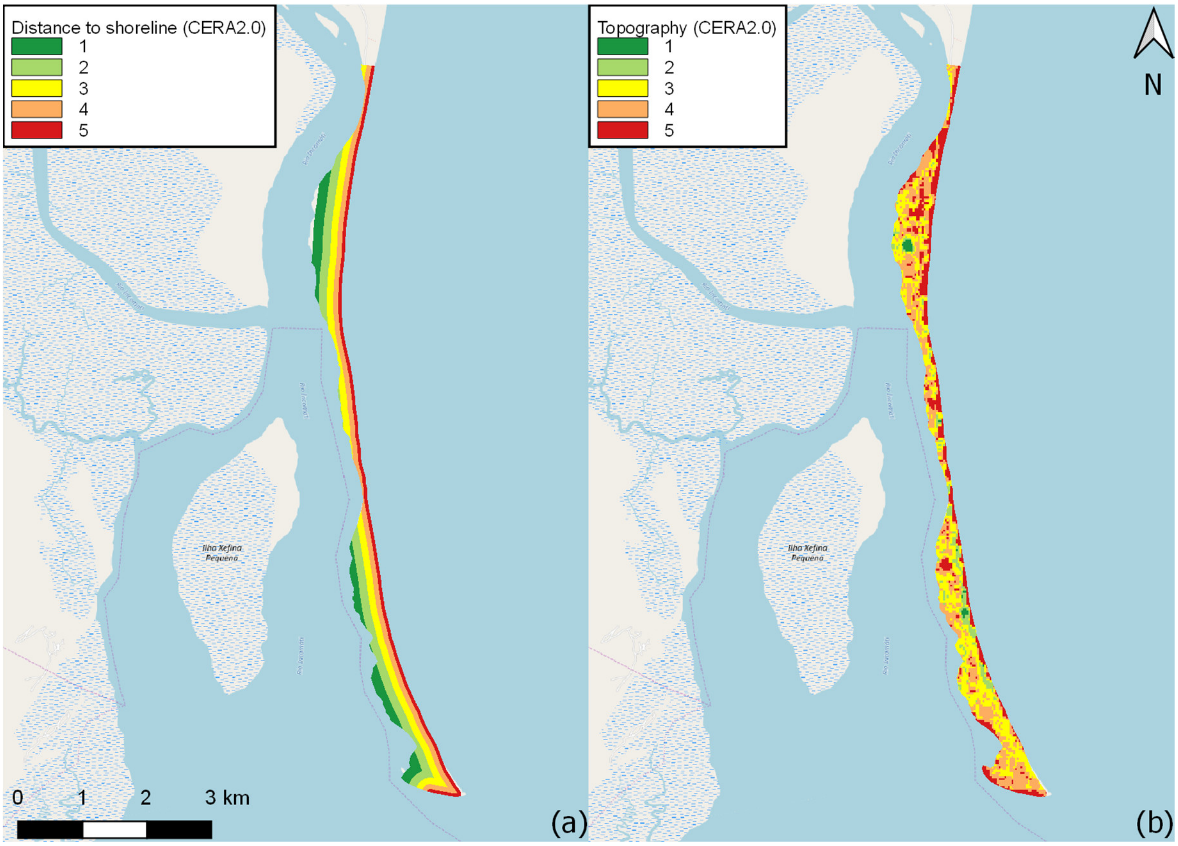

Figure 7.16. Indicators for exposure assessment module of CERA2.0 in Macaneta: (a) distance to shoreline; and (b) topography.

The new topography classification contributes decisively for a varied result regarding the exposure assessment module output (Figure 7.17). Naturally, the slimmer parts of the spit are the most exposed locations, as both indicators present high classifications there. On the other hand, aside from a specific location in the northern part that presents exposure level 1, the southern part of the spit is the least exposed to coastal erosion, with most area being classified with an exposure level 3.

Regarding the coastal erosion assessment module, all indicators were considered homogeneous along the study area. For the wave climate indicators, offshore wave data was collected from reanalysis data provided by the Wavewatch III model (Tolman, 2009) and nearshore conditions were calculated by DHI (2013), using MIKE 21 SW. This dataset covers a 10-year period (2005 to 2014). In this case, the nearshore wave conditions were used in favour of offshore conditions due to the presence of Danae shoal, a sandbank located a few kilometres off the coast that attenuate the wave heights significantly (Karlsson and Liljedahl, 2015).

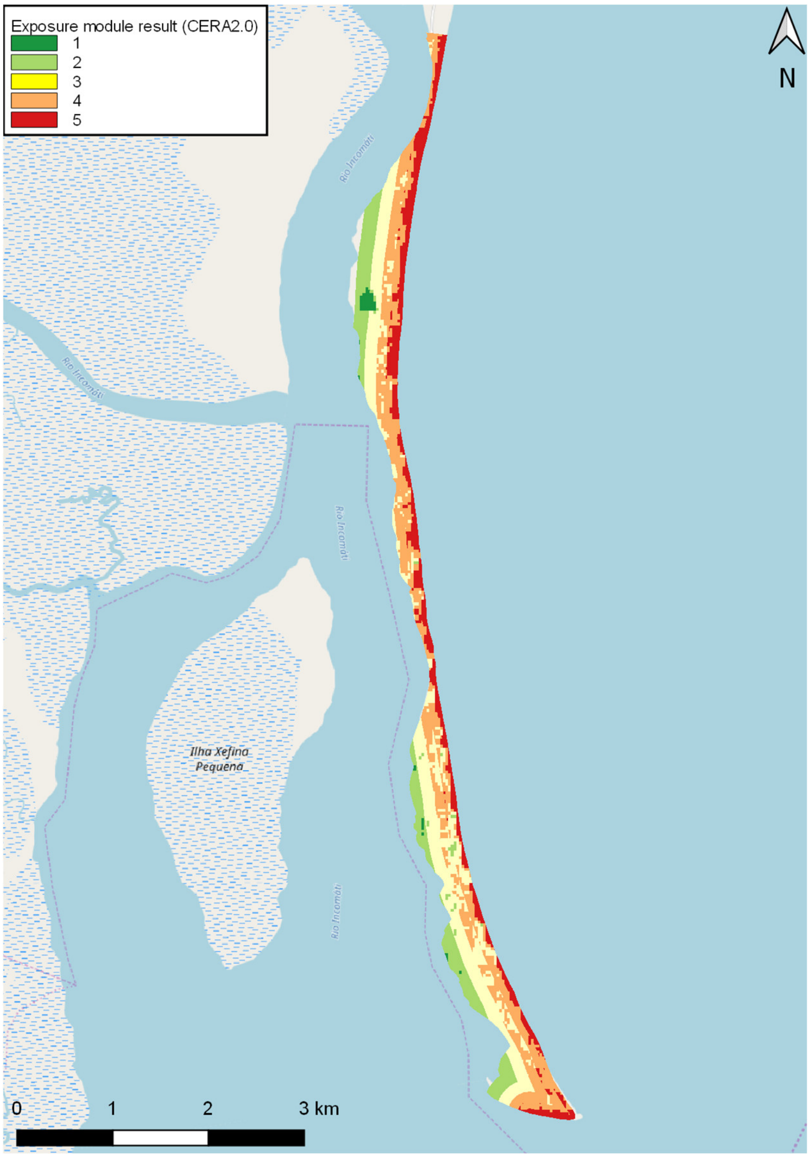

Figure 7.17. Exposure assessment module output for Macaneta, using CERA2.0.

The data reveals a mean significant wave height of 1.14 m and only one storm was registered during the 10 years. These inputs lead to a mean H_s class 3 and a classification 1 regarding the number of storms. Concerning shoreline change rates, as referenced before, Karlsson and Liljedahl (2015) observed accretion in the southern stretch, but overall, Macaneta spit is at an equilibrium state regarding shoreline position, and therefore, classified with level 2 in that indicator. Finally, for sea-level trend indicator, the 1.4 mm/year estimated by NOAA (2018a) for Durban was taken as representative of Macaneta spit. The result from these indicators is a uniform class 2 regarding the coastal erosion assessment (Figure 7.18), which is considerate adequate, given the history of the study area regarding coastal erosion problems.

Figure 7.18. Coastal erosion assessment module output for Macaneta, using CERA2.0.

Following the production of module outputs, the results for vulnerability and consequence are computed. Given the high susceptibility of the study area, but the low classification regarding value, the vulnerability of Macaneta spit is classified with level 3 in all study area (Figure 7.19a). Then, the consequence output (Figure 7.19b), which combines vulnerability with exposure, highlights a large stripe with consequence level 4 until the southern part of the spit, which is mostly level 3. The only exception in these two classes is the spot with class 2, which is attributed due to the high elevation (high dunes) when compared with the remaining area.

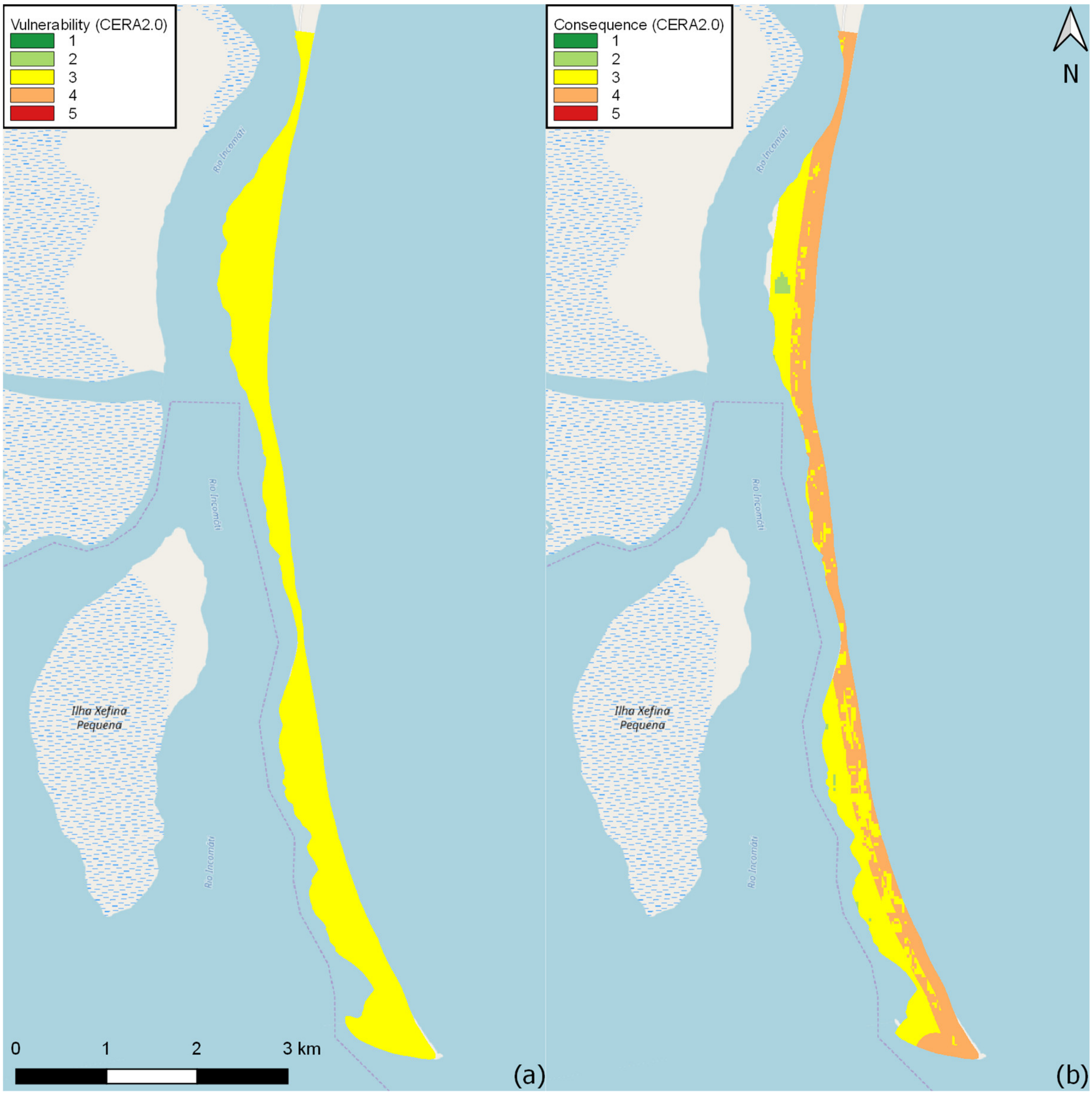

Figure 7.19. Outputs of (a) vulnerability and (b) consequence for Macaneta, using CERA2.0.

Finally, the risk output (combination of consequence and coastal erosion results; Figure 7.20) presents a moderate risk (class 3) to nearly the entirety of the study area.

The lower level locations in the consequence result is reflected in the risk result and represents an exception to the overall risk level 3.

Figure 7.20. Risk output for Macaneta, using CERA2.0.

7.4. CERA2.0 FOR QUINTANA ROO

Lastly, CERA2.0 was applied to Quintana Roo. Like the other study sites, Quintana Roo was subjected to a data revision and consequent inputs for this last application. The assessment was also done up to 500 m inland.

Starting with the susceptibility module assessment, the geomorphology indicator (Figure 7.21a) was developed based on a conjunction of several databases. The GLiM (Hartmann and Moosdorf, 2012) allowed the identification of lithology, which helped distinguish the geomorphology classification north and south of Playa del Carmen. The southern part is made of sedimentary rocks and the satellite images reveal an indented coast (geomorphology evaluated as class 2). On the other hand, the northern part and Cozumel island present unconsolidated sediments. Thus, class 5 was attributed where exposed beaches were visible, except when the land use map from INEGI (2016) identified mangroves or dune presence, which occurs mostly in Cozumel. In that case, class 3 and 4 was considered, respectively.

The coastal defences indicator was developed in a different form, when compared to Aveiro (Figure 7.21b). Due to the irregular shape of Quintana Roo coastline, the automation process developed in CERA2.0 QGIS application is not effective in delineating the coastal structures influence distances. Thus, in this case, the raster file of coastal defences was produced manually with QGIS built-in features, with classifications 1 (no structures) to 3 (longitudinal attached structures).

The coastal defences were identified in Google Earth and their protection influence were digitized in the indicator map. The influence of perpendicular coastal defences was computed using Equation 6.1. The length was estimated through the satellite images and the wave breaking angle was computed using Snell's law (USACE, 2002) and considering offshore waves coming from East, the main direction according to Silva *et al.* (2008) hindcast dataset. This direction is consistent with other literature, such as Odériz *et al.* (2014). The perpendicular coastal defences vary their length from 30 m (groynes near Cancun) to 300 m (terminal groyne in the northern end of Cancun barrier island) and the measured offshore wave angles varied between 6° and 77°, which results in wave breaking angles varying from 4° to 38°. Moreover, detached parallel coastal structures can be found between Puerto Morelos and Punta Maroma, with varying lengths from around 50 m to 200 m. Artificialized shorelines can be found sparsely in all study area.

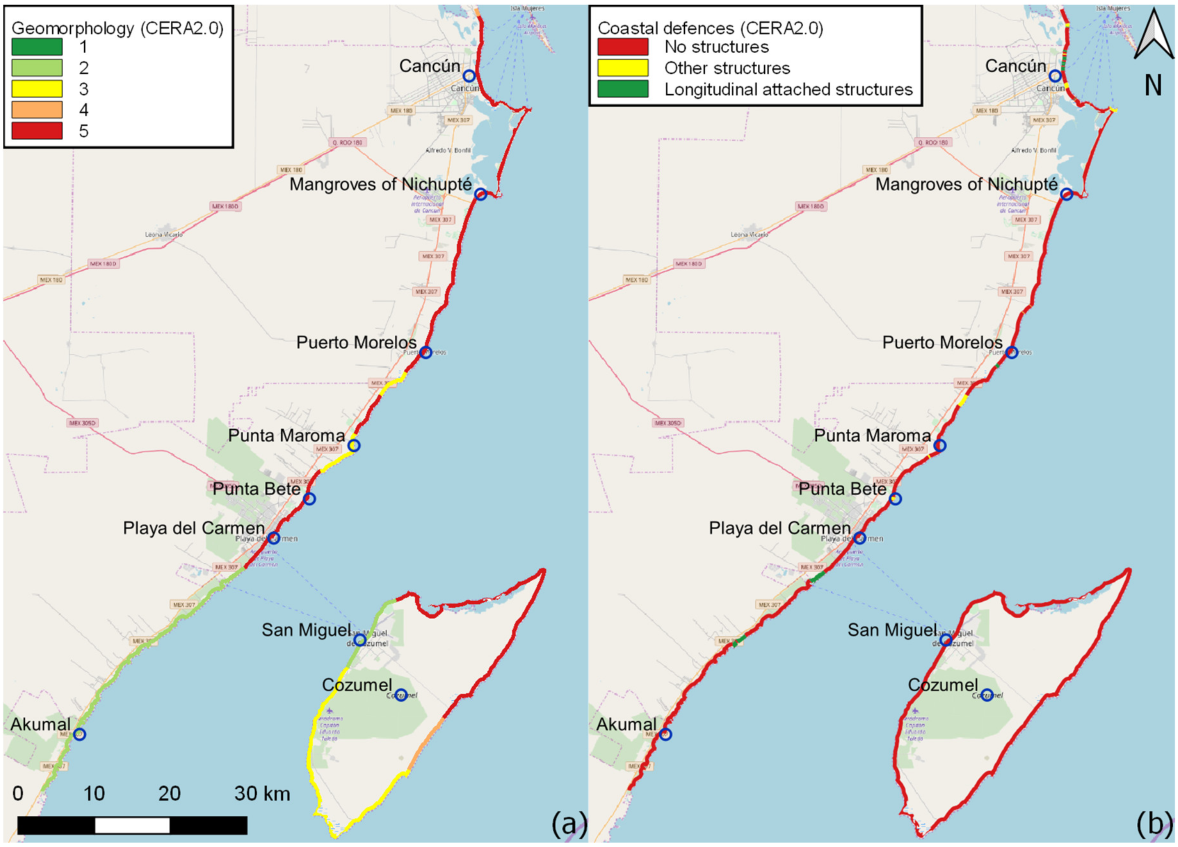

Figure 7.21. Indicators for susceptibility assessment module of CERA2.0 in Quintana Roo: (a) geomorphology; and (b) coastal defences.

These indicators resulted in a susceptibility module result as presented in Figure 7.22. The susceptibility to coastal erosion in Quintana Roo covers the entire range of classifications. The southern part of the study area is the least susceptible, mostly due to its geomorphology. Some cases of class 1 are also visible, where it was possible to clearly identify coastal protection structures.

On the other hand, the northern area is highly susceptible to coastal erosion. Despite the noticeable anthropogenic presence, this part of the shoreline does not present clearly visible coastal defence structures in Google Earth images and literature to confirm the presence of coastal defence structures was not available. The ones that are visible, have a small length and are targeted to protect only a specific location in the shoreline. The areas with susceptibility class 3 rely on the presence of mangroves to decrease its susceptibility. Moreover, dune presence is identified in the East part of Cozumel island (INEGI, 2016), justifying class 4 attributed to that location.

Figure 7.22. Susceptibility assessment module output for Quintana Roo, using CERA2.0.

The indicators required for the value assessment were produced based on the land use (INEGI, 2016), population density (CIESIN, 2017) and ecologically protected areas (CONANP, 2017) presented in chapter 3.

Relatively to infrastructures (Figure 7.23a), the delimitation of urban areas was used as a starting point for definition of classes 3 and 4, like in Aveiro study area. From those areas, Playa del Carmen and San Miguel de Cozumel were considered class 4, due to its size and importance in the respective municipalities. The remaining urban areas were classified with level 3. Also, the hotel zone in Cancun was considered as critical infrastructure (class 5), due to the economic importance that tourism has in the area (Silva *et al.*, 2007). Finally, the roads identified by INEGI (2014) within the study area, but outside urban areas, were classified with infrastructure level 2.

The population density map was produced by directly applying CERA2.0 thresholds to CIESIN (2017) dataset. The result (Figure 7.23b) shows that most area is uninhabited, only revealing population in the nearshore urban areas. Therefore, the urbanization presented in the infrastructures assessment is mainly targeted to touristic activities. On the other hand, the low resolution of CIESIN (2017), a worldwide database, opens the possibility of population not being accurately represented.

The protected areas identified by CONANP (2017) were divided in terms of relevance to the study area, based on their descriptions, extent and frequency in Mexico. Hence, the APFyF (*Áreas de Protección de Flora y Fauna*) and PN (*Parques Nacionales*), referring to coral reefs, mangroves and special habitats, were considered of high ecologic relevance (+2). The coastal areas that overlap with RB (*Reservas de la Biosfera*) delimitation, corresponding to the Caribbean Sea, were classified with moderate ecologic relevance (+1). The remaining area was considerate of no ecologic relevance, as shown in Figure 7.23c.

The combination of the referred inputs, accordingly with CERA2.0 methodology, resulted in value output presented in Figure 7.24. The hotel zone in Cancun is the most valuable location, given its critical infrastructure status. Also, the city centres of Playa del Carmen and San Miguel de Cozumel were attributed value level 5. The remaining areas are mainly influenced by the ecologic value, given that most shoreline was given class +1 or +2. This is the case of Cozumel island and the mangroves of Nichupté, which are located south of the hotel zone. Overall, the full range of value classification is present in Quintana Roo, which is to be expected given the much larger size of this study area when compared with the other study sites.

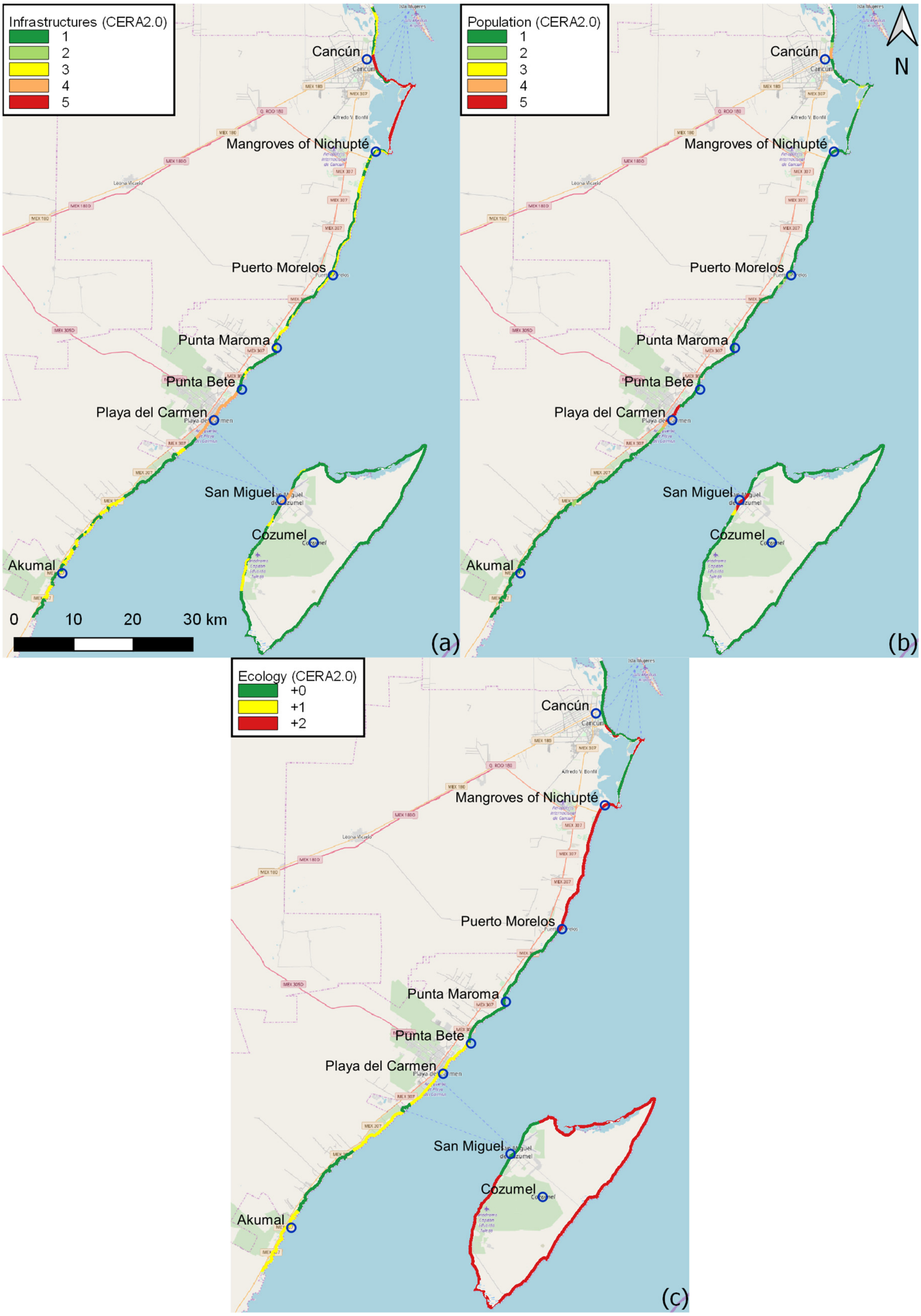

Figure 7.23. Indicators for value assessment module of CERA2.0 in Quintana Roo: (a) infrastructures; (b) population density; and (c) ecology.

Figure 7.24. Value assessment module output for Quintana Roo, using CERA2.0.

The indicators of the exposure assessment module require information relative to the shoreline position, topography and a historical record of storm surge. As stated previously (section 3.3), the shoreline position was estimated using the Google Earth satellite images. The shapefile was introduced in the CERA2.0 plugin and the output is presented in Figure 7.25a. Furthermore, the DEM produced by INEGI (2012) was used to apply the topography thresholds with the added storm surge factor. According to SURGEDAT (Needham and Keim, 2011), the storm surge registers in the study area vary between 4.57 m (storm Emily) and 5.25 m (storm Gilbert). These are higher registers than the usual storm surges described by Villatoro *et al.* (2015), which state up to 2 m of storm surge in summer hurricanes. However, to preserve safety, the higher registers were considered, which corresponds to the least favourable class regarding storm surge. Consequently, the topography integrated with storm surge indicator is almost completely classified with level 5 (Figure 7.25b).

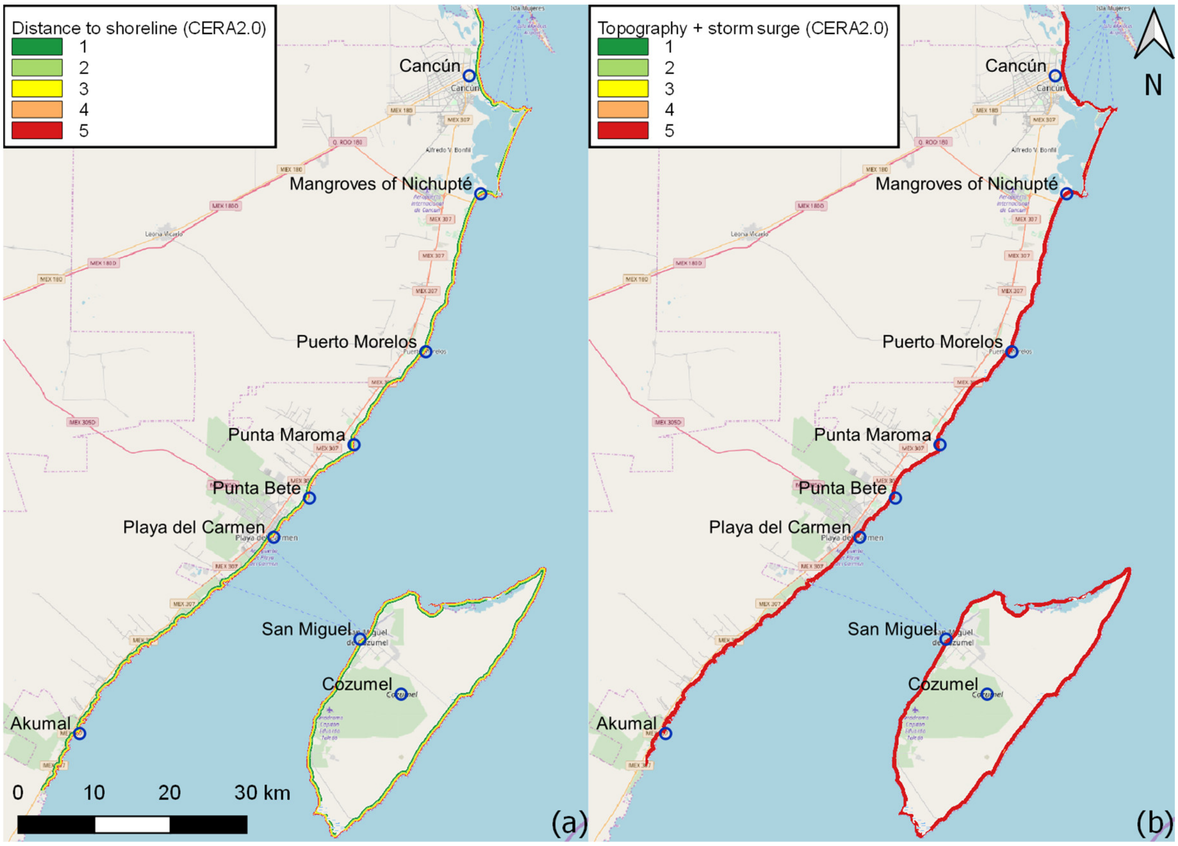

Figure 7.25. Indicators for exposure assessment module of CERA2.0 in Quintana Roo: (a) distance to shoreline; and (b) topography integrated with storm surge factor.

The exposure module result is directly based from the distance to shoreline indicator, given the constant nature of the topography plus storm surge classification. Hence, the distance to shoreline levels 4 and 5 results in a level 5 exposure, while the remaining exposure classification correspond to one level higher than the respective distance to shoreline classification input (Figure 7.26).

The hindcast wave data of Silva *et al.* (2008) was used in the assessment of mean significant wave height and number of storms indicators. The dataset contains information regarding significant wave height from 1948 to 2010 in an offshore location north of Cozumel island. From that data, a mean significant wave height of

1.2 m (class 3) was calculated and 8 storms are the yearly average in Quintana Roo (class 3). CERA2.0 QGIS plugin allows the input of a shapefile describing various states of wave climate along the study area. This option would be preferable, as the mean wave height is certainly not uniform along the whole coast, given its size and configuration of the shoreline (*e.g.* the west side of Cozumel island should be less affected by highly energetic wave climate). However, data for this type of assessment was not accessible at the time, so a unique value was adopted, despite being less accurate. Hence, this assessment could be improved using wave modelling or more detailed spatial data.

Figure 7.26. Exposure assessment module output for Aveiro, using CERA2.0.

Next, as stated in section 3.3, given the lack of georeferenced data regarding shoreline position, the shoreline change rates were estimated using the shoreline position between 2006 and 2016, from Google Earth satellite images. In this case, due to the absence of dunes, the wet/dry line was used as reference for digitizing. Since the area has a microtidal regime (maximum amplitudes of 0.3 m), tides were not considered to influence the upper foreshore limit. Next, the shoreline rates were computed using the Shoreline Analyst for QGIS and DSAS for ArcGIS. This shapefile was the input for CERA2.0 plugin, which resulted in the classification showed on Figure 7.27.

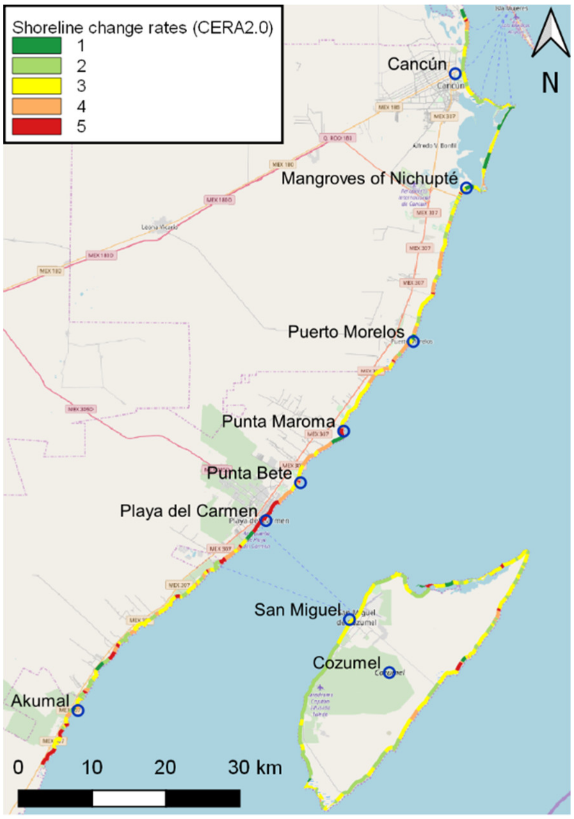

Figure 7.27. Indicator for coastal erosion assessment module of CERA2.0 in Quintana Roo: shoreline change rates.

The highest shoreline retreat registered is in Punta Maroma, with losses around 10 m/year. Playa del Carmen also has the highest classification, but much lower shoreline retreats, with 2.5 to 3 m/year. Most shoreline is classified between stable and under erosion (class 2 and 3, respectively). Eventually, the uncertainty associated to the process used to estimate shoreline changes could have had an impact on these two classes.

Finally, the sea-level trend adopted for Quintana Roo is 4.12 mm/year, as referenced in section 3.3. The adopted SLR rate corresponds to the maximum class regarding this indicator and is representative of all study site extension.

The result of the coastal erosion module assessment is presented in Figure 7.28.

Figure 7.28. Coastal erosion assessment module output for Quintana Roo, using CERA2.0.

According to CERA2.0 assessment, Quintana Roo is subject of moderate coastal erosion, given its relatively low significant wave height and slow erosion rates (with some exceptions). The shoreline in Playa del Carmen, between Punta Maroma and Bete, and in Puerto Morelos appear to be the most affected areas. On the other hand, the shoreline at the hotel zone in Cancun seems to be stable, which could be the result of maintenance efforts, such as beach nourishments and coastal defence structures (Villatoro *et al.*, 2015), to preserve such a valuable location. With all assessment module outputs executed, the combination process takes place. The vulnerability assessment, resulting from combination of susceptibility and value, is shown in Figure 7.29.

Figure 7.29. Vulnerability output for Quintana Roo, using CERA2.0.

Given the value of the hotel zone and the urban centre of Playa del Carmen, these are the most vulnerable locations in Quintana Roo. San Miguel de Cozumel also has a high classification, but its susceptibility level is lower, reducing its vulnerability to coastal erosion. On the other hand, the rest of Cozumel island is more vulnerable than its respective city, due to its ecological value and sandy beaches, visible from Google Earth satellite images. The southern area of Quintana Roo coast is the least vulnerable, mostly due to the indented shoreline that provide shelter and reduce sediment transport. The consequence, which adds the exposure indicator to vulnerability, is presented on Figure 7.30.

Figure 7.30. Consequence output for Quintana Roo, using CERA2.0.

Considering the uniform classification obtained in the exposure map output for Quintana Roo, the locations with the most consequences are similar to the most vulnerable. Hence, the northern part of Quintana Roo, from Cancun to Puerto

Morelos, and Playa del Carmen are the most impacted location by potential coastal erosion. On the other hand, the proximity to the shoreline contributes for the increase of potential impacts in some areas, namely for the southern part of Quintana Roo, which has a consequence level 3. Finally, the risk output, where the consequences are combined with the coastal erosion assessment, is shown in Figure 7.31.

Figure 7.31. Risk output for Quintana Roo, using CERA2.0.

In this final output, Playa del Carmen is the main identified hotspot. The biggest city within the study area and the noticeable shoreline retreat in the last years are the main reasons for this classification. Other locations reach the highest class of risk, namely Puerto Morelos and its coral reefs, located north of the town. Despite its value, San Miguel de Cozumel is one of the locations with lower risk. Its low susceptibility is verified by the low shoreline change rates affecting the area. On the other hand, the northern part of Cozumel island also presents a high-risk level, much due to high consequences resulting from the ecological value of the island and overall considerable shoreline retreat rates. As expected, the southern part of the study area has the least risk level. However, some specific locations present high retreat rates, leading to some hotspots with risk level 4.

7.5. Discussion of CERA2.0

The application of CERA2.0 to the study sites allows for a series of takeaways regarding how results are representative of the situation in the study areas and how they compare with previously applied methodologies, what are the best features regarding an application of CERA2.0 and where processes can be improved.

7.5.1. Study areas results

Table 7.1 shows the area percentages with each classification for the study sites regarding vulnerability, consequence and risk. Generally, these percentages are consistent with the distribution of probabilities showed in Figure 6.11, albeit slightly shifted to the higher classes. This shift is related with the choice of study sites. Although the study sites vary in terms of value and hazard levels, these are similar locations regarding geomorphologic composition (all are majorly sandy and low-lying coastlines). As stated earlier, these locations were chosen based on partners feedback and willingness to participate.

Naturally, partners with interest in coastal erosion are likely to have coastal erosion problems in the area, and these areas are often sandy and low-lying locations. This contributes for a certain degree of similarity in the results for the study sites. Despite these results, the Monte Carlo simulations (Table 6.10) show that a region with a geomorphology resistant to erosive agents drastically reduces the probability of having high risk hotspots. The effect of geomorphology is even more extensive than portrait on Table 6.10, where interconnection between indicators is not considered. For instance, in case of applying CERA2.0 to a rocky coast, the shoreline position change rates are likely to be stable. In that case, a Monte Carlo simulation reveals that there is no possibility of an area to be classified with levels 4 or 5 regarding risk, proving that CERA2.0 is sensitive to changes in geomorphology, and consequently, applicable to environments other than sandy coastlines.

Table 7.1. Summary of CERA2.0 results.

		Aveiro	Macaneta	Quintana Roo
Vulnerability	1	---	---	5,9%
	2	14,1%	---	23,8%
	3	64,7%	100,0%	21,5%
	4	15,1%	---	35,0%
	5	5,1%	---	13,8%
Consequence	1	2,4%	---	2,0%
	2	3,5%	1,1%	11,3%
	3	47,8%	47,5%	39,8%
	4	42,4%	51,4%	30,0%
	5	3,9%	---	16,9%
Risk	1	---	---	0,2%
	2	2,4%	1,1%	2,4%
	3	32,2%	98,9%	45,3%
	4	51,8%	---	49,0%
	5	13,6%	---	3,1%

7.5.1.1. AVEIRO

Regardless of the similarities in geomorphologic characteristics, the study sites present differences in terms of the other indicators, as well as application scale. Looking at results for Aveiro, it can be concluded that this study area is relatively vulnerable to coastal erosion, but the intense wave climate reflected in very high shoreline retreat rates is what in fact raises the risk, which otherwise would be manageable. Coelho *et al.* (2009a) states that the decrease of the updrift river sediment supplies towards Aveiro study area, allied with the great sediment transport capacity of the wave climate, is the main cause for such high shoreline retreats. This is shown by Lira *et al.* (2016) and clearly translated to CERA2.0 result. Given the dominance of class 3 in the vulnerability result, the higher risk locations are directly related with the shoreline change rates. Hence, the coastal transects located south of Costa Nova, south of Furadouro and surrounding Espinho are the most affected in the risk classification. Comparatively with CERA1.0, although the hotspots are similar, CERA1.0 trends to give a higher importance to value indicators, leading to a risk classification that highlights the vulnerable areas and gives less importance on where coastal erosion is occurring. This is evident in the surrounding coastline of Vagueira, where CERA1.0 attributes a moderate risk level, while CERA2.0 considers all that area with maximum risk. The exception is the town itself due to the protection given by the coastal structure there implemented, albeit classifies Vagueira as high risk (class 4). Despite some methodologies applied in chapter 5 not aiming at risk classification (*i.e.* CVI, SL and CHW), their outputs are here qualitatively compared with the outputs obtained in CERA2.0. Looking at the indicators for these methodologies, the main omission is the lack of socio-economic indicators. In Aveiro study site, the CERA2.0 vulnerability output, which depends majorly on value indicators, covers most area (65%; Table 7.1) with moderate classification. Thus, the comparison of these results was considered valid and valuable to get insight on CERA2.0 performance.

In general, the methodologies are in accordance with the CERA2.0 results. CVI clearly distinguishes the southern coastline and Furadouro as the most threatened hotspots, as well as identify São Jacinto as the least threatened, which is also true in CERA2.0. It should be remembered that CVI considers a relative output, thus, the lowest level only represents a lower vulnerability than the rest of the study area. Moreover, the CVI aims to assess coastal vulnerability tied to sea-level rise and consequently, its results are not directly comparable with CERA2.0, albeit related to each other. The Smartline physical vulnerability also highlights the same hotspots, although in this case the extension of high classes is much bigger. The result of RISC-KIT CRAF1 presents a general lower risk classification than CERA2.0, albeit it coincides with the higher risk locations. CHW considers Aveiro as highly endangered by coastal erosion, which is of general agreement, including CERA2.0. As detailed in previous discussions (see section 4.5), the locations identified with high risk by CERA2.0 are also widely recognized as having coastal erosion problems, including considerable damages in recent years (Pinto *et al.*, 2014).

7.5.1.2. Macaneta

For Macaneta, the results of CERA2.0 show an overall moderate risk level (class 3; Table 7.1). This result is the same as in CERA1.0, despite the different procedure. The result reflects the duality represented in this study site. The high susceptibility due to a widely dynamic ecosystem (*i.e.* barrier system) contrasts with the shoreline stability registered in recent years. Given the low likelihood of coastal erosion processes to affect the area and the low value currently existent, the risk should be lower than CERA2.0 estimates. However, the high susceptibility associated with the consequences caused by breaching to Incomatí river raise the stakes for the area. In this case, the result provided by CERA2.0 can work as communication tool for stakeholder who intend to urbanize Macaneta spit. A scenario simulation with urbanized areas certainly largely increases vulnerability, given the already high susceptibility level. Like this case study, CERA2.0 can work as a low-cost simulation and communication tool, since it is capable to provide moderately accurate results even with small amounts of information. In addition to CERA1.0, Smartline and CHW were also applied to Macaneta. These methodologies presented contradictory results. As already discussed here and in section 5.5, these results reflect the duality of characteristics and the relevance given to each characteristic by the methodology. In this case, Smartline values recent past events the most, thus, outputs a low classification and CHW outputs a high classification due to be a barrier system. CERA2.0 ends up classifying Macaneta in between, showing no particular tendency to favour any type of indicators.

7.5.1.3. Quintana Roo

Finally, Quintana Roo is the location with most variety in the classifications of vulnerability, consequence and risk, being the most approximate to the standard simulation (Figure 6.11). CERA2.0 identifies Playa del Carmen, Puerto Morelos and its coral reefs with the highest risk level, followed by most of Cozumel island and the coastline between Punta Bete and Punta Maroma. As verified in previous discussions (section 5.5), the coastline transect between Punta Bete and Maroma is recognized as having coastal erosion problems (Odériz *et al.*, 2014). Silva *et al.* (2007) also identifies Cancun beach as having serious erosion problems, mostly due to extreme events and poor planning tourist development. However, according to the data in this work, the measured shoreline position is stable to moderately eroded, which is likely the result of measures implemented by local authorities, such as beach nourishments and construction of coastal defences structures (Villatoro *et al.*, 2015). The stable shoreline position reduces the CERA2.0 risk level in Cancun, albeit is still high. Other literature (Silva *et al.*, 2007, 2012; Martell *et al.*, 2012) highlights all study area as affected by coastal hazards in general, due to frequent extreme events (*i.e.* hurricanes).

Compared with CERA1.0, the high-risk locations are similar. The main difference is once again due to the higher importance of socio-economic features in CERA1.0, when compared with the second version. For example, San Miguel de Cozumel is considered of high risk, despite the small retreat rates and low susceptibility to coastal erosion. Contrary to CERA2.0, CVI and Smartline clearly identify the coastline transect between Punta Bete and Maroma with high classifications, and Cancun and San Miguel with low classifications. However, in opposition to Aveiro, Quintana Roo has great variability in the value indicators, and consequently in the vulnerability output, which justifies the differences between CERA2.0 results and these methodologies. In this case, the direct comparison of results should not be performed and does not validate the accuracy of CERA2.0.

7.5.2. CERA2.0 FEATURES AND SHORTCOMINGS

It should be noted that any methodology applied throughout this work requires user judgement, which is accompanied with a certain degree of subjectivity, namely when assessing indicators through satellite images or inferring classifications on socio-economic value. Also, these methods are highly dependent of the quality and reliability of the input data, which has been improving since the first applications, as more insight on georeferenced data was acquired. Although it is not probable that changes in the data used for some indicators would affect in meaningful way the final outputs produced throughout this thesis, it is nonetheless worth to look at these results and comparisons with critical judgement.

Nevertheless, considering the comparisons carried out in this discussion, it is possible to indicate the positive and negative aspects of CERA2.0 relatively to the other applied methodologies. Relatively to the original methodology, CERA2.0 results show a greater variety in the outputs, presenting more nuanced results. This is the outcome from the greater impact that each indicator has. On the other hand, CERA2.0 is built to have redundancies in its process. For instance, while CERA1.0 considered only the maximum significant wave height, CERA2.0 includes the mean wave height and an indicator of storm activity. These are included in conjunction with shoreline position change rates, that by themselves could indicate the presence of coastal erosion. However, by including both, the redundancy created helps to validate both inputs. Contributing for the results there is also the change of procedure regarding the averaging and weighting of indicators. CERA2.0 interconnection of indicators follows the SPRC model (see section 2.1), which bases itself on how risk is propagated. This process eliminates the need for directly judging the impact that each indicator has in coastal erosion risk, which is often subjective given the uncertainty of coastal processes. The built framework for CERA2.0 also brings advantages regarding future developments, allowing for modular improvements that can be carried out in parallel by several researchers or teams. For instance, although outside the scope of this work due to the objective of doing large scale assessments, a shoreline simulation model, such as LTC (Coelho, 2005; Lima, 2018), can be integrated in the hazard assessment module, maintaining the remaining modules as they are.

CERA2.0 maintained the inland classification, but reduced the aimed distance in its design. The approach aiming at 2 km inland assessment was considered excessive, looking at the long-term nature of coastal erosion and the short to medium-term objective of CERA2.0. The excessive area assessed is also reflected in CERA1.0 results, where a high percentage of the area is classified with low values, despite all regions have moderate to high susceptibility to coastal erosion.

The inland classification was still considered as the most appropriate approach due to being more suitable for stakeholder communication and compatible with area delimitation asked by government programs, such as POC *(Programa da Orla Costeira*; Santos *et al.*, 2017). Despite the outputs considering inland classification, inputs related with susceptibility and coastal erosion are classified along the shoreline, with their classification extrapolated inland, attributing to these the same classification as that of the closest point at the shoreline.

CERA2.0 also presents an absolute result, in opposition to the relative outcome computed by CVI. As stated in section 5.7, although the relative output is ideal to identify the most endangered locations on an overall affected area, these results are not comparable with results obtained for other study areas, since a high classification does not necessarily represent high vulnerability to coastal hazards. The absolute output is considered an advantage for CERA2.0, which promotes more palpable results and comparisons of case studies, which can lead to validation and further improvements of the method. On the other hand, CVI has less inputs required and ensures that hotspots will be identified. Thus, it is better suited than CERA2.0 for national scale assessments, where a high level of detail is often not necessary.

The Smartline results show a trend of the output classes to be located within the extreme classes of the methodology. The high number of available outcomes may provide a more granular result, but the results show large stretches of coastline classified with the maximum class. In this case, it is considered that CERA2.0 does a better job identifying the hotspots of the area. CERA2.0 also requires more indicators than Smartline, but relies for the most part on easier to collect indicators. However, the objective stated in section 5.7 of using accessible indicators was not fully realized, as CERA2.0 recommends the use of a medium-term wave climate time series, with wave height, period and wave direction. Also, the shoreline position change rates included in CERA2.0 are not always available, requiring manual digitizing. This process introduces uncertainty in the result due to often unreliable source data, tide variations and misinterpretation of satellite images.

Comparatively with RISC-KIT CRAF1, the main difference is the requirement of modelling for application of this method, in opposition to CERA2.0. The absence of modelling was a main requirement set for CERA2.0, in order to facilitate the procedures and processes for large scale assessments. The requirements of CRAF1 are specific, such as cross-shore profiles and sediment grain size. Therefore, CERA2.0 is considered easier to apply than CRAF1. However, the lack of information regarding shoreline position rates difficult the application of CERA2.0, but does not represent a problem for CRAF1.

Relatively to the assessment of socio-economic indicators, these are similar in CRAF1 and CERA2.0. However, thresholds are set in CERA2.0 in order to promote coherence between different assessments whenever possible, while CRAF1 gives guidelines, but ultimately trusts the user to identify the most valuable locations. Despite not being the approach taken by CERA2.0, if local experts are conducting the assessment, CRAF1 method has the potential to output more accurate results.

Overall, CERA2.0 showed to be a flexible approach, with enough detail to be applicable on a local scale, but also possible to apply to large scales, given the fitting data is provided. The number of indicators used is equivalent to CERA1.0, but some are more specific (*e.g.* wave breaking angle). This was an approach not desired during the development, but the complexity associated with coastal environments requires it. It should also be noted that the methodology is clearly aimed at coastal erosion, which is not often represented, in favour of other hazards, such as floods, overtopping or others directly related with extreme events. However, the existence of other hazards is acknowledged by CERA2.0, as coastal erosion often exposes the shoreline to other hazards.

8. Final remarks

Considering the confrontation between the importance of coastal areas through human development and the potential natural hazards that can arise in those areas, the execution of a thoughtful coastal management is considered of great importance. To help in decision making and support coastal management, several tools and methodologies to assess risk to coastal hazards have been developed over the years (*e.g.*, IPCC CZMS, 1992; Thieler and Hammar-Klose, 1999; Hinkel and Klein, 2009; Zanuttigh *et al.*, 2014; van Dongeren *et al.*, 2018).

This work intended to contribute for further development on this subject, by proposing a new methodology that fill gaps of existing methods. CERA was developed with the objective to provide an accessible coastal erosion risk methodology, capable to assess that hazard in a medium-term perspective. The methodology specifically targets coastal erosion, a hazard that lacks dedicated risk assessment methodologies, and is applicable to a wide range of coastal environments and scales. CERA was designed to perform the risk assessment without the need for numerical modelling and built on tools that are freely available to the public, contributing to its accessibility, both in terms of application and required resources. In the next section of this chapter, the main conclusions of the developed work are highlighted and possible future developments to continue this research are suggested.

8.1. Conclusions

CERA was developed through a series of tasks that aimed to gain a deeper knowledge on coastal erosion, in particular, and coastal risk evaluation, in general. These tasks allowed to draw conclusions on various subjects regarding coastal risk assessment. Hence, the first task was to establish the definition of risk and all related concepts. Following the literature review, the work considers risk as a combination between potential damage of coastal erosion (consequences) and the likelihood/intensity of that hazard. To assess the consequences, the vulnerability and exposure should be evaluated. Vulnerability stands as the amount of potential damage that coastal erosion could cause. This is independent if coastal erosion often affects the given area. Vulnerability can be considered as a combination of the susceptibility of the terrain to erode and the value contained in that terrain. Finally, exposure quantifies the elements that are within range of coastal erosion.

Next, a literature review of the existent coastal risk assessment methodologies was performed. A total of 12 methods were identified and detailed. These methods present a wide range of processes, indicators and scope that could be applied, both in different time and spatial scales. They also vary in objectives and hazards to assess. The literature was not limited to coastal erosion risk assessment methods, but coastal erosion was acknowledged in all of them.

When characterizing the methods, an increase in the complexity of processes is noticeable along time. The oldest methods provide guidelines that heavily rely on expert knowledge for the assessment, the following are based on ranking of indicators, and the latter are software-based methods that use GIS technology or numerical simulation to achieve the desired result. Moreover, the most common data used in coastal erosion assessments are the wave conditions and geomorphologic features in the area, followed by socio-economic data. These classes of indicators tie with the Source – Pathway – Receptor - Consequence conceptual model presented in section 2.1. Most methodologies adopt a regional scale for their assessments, balancing detail and extent. The aimed time frame majorly depends on the type of process. The methodologies that rely on scenario generation have a long-term assessment in mind. On the other hand, the indicator-based assessments look at current conditions. Thus, its assessment results in a short to medium-term perspective.

Regarding study areas, three locations were selected and characterized for application of coastal risk assessment methodologies: Aveiro, in Portugal; Macaneta spit, in Mozambique; and Quintana Roo, in Mexico. These study areas were chosen throughout CERA development process, as opportunities with willing partners appeared. The partners were essential to give the required support for development of the assessments in their areas. The areas present similarities regarding geomorphology, being all mostly low-lying sandy coasts, but also have differences in terms of spatial scale, anthropogenic occupation and wave climate conditions.

A total of five methodologies were applied to the selected study areas prior to the final method development: CERA1.0, which resulted from an improvement of CVRA method (Coelho, 2005), adding a GIS component and readjusting input indicators; CVI (Thieler and Hammar-Klose, 1999), an assessment of relative vulnerability to the coast due to hazards related with sea-level rise; the Smartline (Lins-de-Barros and Muehe, 2013), a multi-hazard physical and social vulnerability assessment; the RISC-KIT CRAF1 (Viavattene *et al.*, 2018), an assessment of coastal zones for identification of high-risk segments; and CHW (Appelquist *et al.*, 2016), a multi-hazard assessment tool.

The methodologies were applied within QGIS (2018), using georeferenced data and dedicated software developed for each of them. The results varied depending on the methodology, reflecting the differences in assessment processes and slightly differentiated objectives, albeit most agreed in the identification of high-risk hotspots on the study sites. In general, all study areas have moderate to high susceptibility to coastal erosion due to its geomorphologic characteristics (low-lying, mostly sandy areas), but vary in wave conditions, and, most importantly, urbanization level. Therefore, the methodologies that include socio-economic factors (*i.e.* CERA1.0 and CRAF1) highlight urbanized areas in its final classification, while methodologies that only consider environmental and hazard-inducing characteristics (*i.e.* Smartline, CVI and CHW) trend to reflect areas where the actual hazard is more prominent.

In Aveiro, the shorelines surrounding Furadouro, Costa Nova and Vagueira are the ones with highest-risk classifications, regardless of the methodology (Figures 4.9, 5.2, 5.8, 5.22 and 5.23). This result is also in agreement with local experts and are coincident with recent damaging events in those hotspots (Pereira and Coelho, 2013b; Pinto *et al.*, 2014; Narra *et al.*, 2017).

In Macaneta, the results were divisive (Figures 4.12, 5.11 and 5.23). While the Smartline gives a low vulnerability classification, due to its low exposure to wave climate and stable shoreline, CERA1.0 and CHW consider that this area has a high vulnerability, mainly connected to the barrier system characteristics, very susceptible to changes of wave climate or sediment supply.

In Quintana Roo, the shoreline between Puerto Morelos and Playa del Carmen was generally pointed as having highest classifications (Figures 4.20, 5.5, 5.14 and 5.23). On the other hand, the East side of Cozumel island was indicated as having high vulnerability in CVI and Smartline, while CERA1.0 only outputs moderate risk in a small stripe along the shoreline. However, these outputs should be compared with caution, as CERA heavily weights socio-economic factors in its assessment, while CVI and Smartline do not.

The application of these methodologies to the study sites allowed to draw conclusions relative to their assessment processes, general results and applicability. Besides the aforementioned difference in specific objectives for each methodology, these also consider slightly different definitions of risk related concepts, namely, in the vulnerability concept. CVRA (and CERA1.0 by extension), CVI and Smartline consider hazard-inducing indicators and disregard socio-economic indicators in their vulnerability assessments, which contradicts the definition of vulnerability established by this work. This fact highlights the necessity to clearly establish the core definitions of these concepts in any work on the subject, which hopefully will lead to an agreement in the scientific community.

The application of the selected methodologies also contributed to outline guidelines that a new CERA proposal would follow. As the objectives state, CERA2.0 (Figure 6.1) is mainly focused on coastal erosion, considering a process that closely follows the established definitions of risk concepts. The methodology contemplates 12 indicators that result in outputs of 4 distinct modules: susceptibility, value, exposure and coastal erosion hazard. These are then combined to produce outputs of vulnerability, consequence and risk. The 12 indicators are geomorphology, coastal defences, infrastructures, population, ecology, distance to shoreline, topography, storm surge, mean significant wave height, number of storms per year, local sea-level trends and shoreline change rates. The results are classified from 1 to 5 and consider inland classification, with recommended distance of 500 m.

Alongside CERA2.0 development, a GIS-based application was created to facilitate the manipulation and combination of inputs. The application was developed within QGIS built-in *Graphical Modeler* and is publicly available to install in QGIS at https://github.com/NEFEC-UA. A version of CERA1.0 is also available in the same website.

Like the previous methods, CERA2.0 was applied to the study sites. In general, the results agree with previous assessments. For Aveiro, the results present a general moderate vulnerability (Figure 7.11a), with higher classification in urbanized areas, where value is higher. The consequence output highlights urbanized areas nearer to the shoreline (Figure 7.11b), such as Barra or Espinho, as suffering the highest impact in case of erosion hazard occurs. Finally, the risk map agrees with the previous methodologies (Figure 7.12), highlighting the surrounding coastlines of Furadouro, Costa Nova and Vagueira as having the higher risk in this study area.

For Macaneta, the results of CERA2.0 show an overall moderate risk level (Figure 7.20), due to a high susceptibility, but low value and coastal erosion level. Given the general disagreement in the results obtained by the other methods regarding this study area, CERA2.0 ends up taking a moderate approach. This application also proves that CERA2.0 is possible to execute without detailed information, being flexible enough to provide an accurate result if the inputs are detailed, or a rough estimate if there is only indicative data.

For Quintana Roo, CERA2.0 identifies Playa del Carmen, Puerto Morelos and its coral reefs with the highest risk level (Figure 7.31), resulting mainly from high vulnerability levels in these locations (Figure 7.29). Punta Bete to Punta Maroma, and the East side of Cozumel also present high-risk classifications. For these, high shoreline retreat rates and ecological significance are the main contributors. The CERA2.0 identification of high-risk locations agree with the previous assessments.

CERA2.0 presents several improvements over the first version. The most noticeable difference is the reduced influence in the result of certain indicators from CERA1.0 to 2.0, such as the socio-economic indicators (*e.g.* population density) and exposure indicators (*e.g.* distance to shoreline), albeit still present in CERA2.0. The influence of these was noticeable in the vulnerability output of CERA1.0, which registered very few nuances across all study areas, leaving the differentiation of risk output mostly to the socio-economic characteristics. In CERA2.0, due to the change in the adopted approach from fixed weights to the flowchart featured in Figure 6.1, one single indicator does not have an excessive influence in the result. Consequently, broader results are obtained, and the high-risk hotspots are more easily identified.

Regarding the indicators chosen, these were all featured in previous methodologies, which validates its influence in coastal erosion risk. The number of indicators is equivalent to CERA1.0, but some are more specific (*e.g.* number of storms per year, storm surge height). The classes for each indicator are defined whenever possible, to contribute for more coherence across different assessments. This is also the main reason for using absolute results, instead of relative, like in CVI assessment.

Overall, CERA2.0 corresponded to the initial expectations of creating a coastal erosion risk assessment methodology for short to medium-term, based on current indicators. As intended, the methodology is flexible enough to be applicable to a wide range of coastal environments and scales, with variable accuracy, depending on the input data. Moreover, the methodology has an accessible process that avoids numerical modelling and can be replicated by interested users and stakeholders without major resources required. A GIS-based application was developed and can be used freely within QGIS, a free and open-source software, boosting the accessibility of the methodology.

8.2. FUTURE DEVELOPMENTS

It is considered that CERA2.0 methodology already represents a capable risk assessment tool, but it is still in early stages of its development. This work intends to open the methodology to the public, giving users the possibility to execute their own coastal erosion risk assessments. The tool was developed aiming to not require extensive amounts of data, to promote its application by entities who not have a great amount of resources or to governmental institutions that require a quick assessment of its coastal area, not compatible with complex and data demanding studies. For instance, the availability of this tool can be beneficial to entities like APA (*Agência Portuguesa do Ambiente*) for support in the elaboration of POC's (*Programas da Orla Costeira*). With the experience and resources held by APA, a complete assessment of the Portuguese coast using CERA2.0 is possible in a relatively short period, which could provide the basis for delimitation of construction areas and development of protection strategies for high-risk hotspots. The effects of coastal protection schemes in a large scale can also be estimated using CERA2.0.

In a short-term, CERA2.0 should be applied to locations with coastal environments other than low-lying sandy shorelines. This would provide real world cases to check CERA2.0 performance and attest its applicability to other areas. Moreover, the further development of CERA plugins to QGIS should be carried out. At the current stage, although completely applicable, a considerable amount of data manipulation is still required to produce the inputs. Also, a wider number of tests should be performed to check the presence of eventual software bugs. The current versions of the plugins were designed for QGIS2, which are not compatible with the recently released QGIS3. These plugin versions should be updated to work with the most recent software.

In medium to long-term, the framework of CERA2.0 can be further improved to target a larger variety of use cases. Like DIVA's case (Hinkel and Klein, 2009), its modular composition can provide the base for several users to work in parallel to further development of separate modules. For instance, a variation of the coastal erosion module can be developed based on LTC outputs (Coelho, 2005; Lima, 2018), evaluating shoreline evolution scenarios. This variation of CERA2.0 would be less capable of providing large scale assessments, due to the difficulty associated with modelling a large area. Yet, it could work as a second phase of assessment, focused on the hotspots identified in phase 1. Likewise, a more robust value assessment module could be developed, based on scenario simulation, higher detail of value perception, consideration of indirect impacts on the system, or use of resilience indicators, such as average income, employment rates or insurance data. Also, the seasonal increase of population density in touristic areas should be included. Currently, only the resident population is considered. This leads to eventual inaccuracies regarding the value assessment of a location. For instance, the hotel front of Cancun has a low resident population density, which results in a low classification regarding that indicator, but certainly has significant increase of population density due to seasonality. In future developments, this impact should be integrated in CERA.

The integration in other coastal management software, as a first-order assessment, is also a possible future application for CERA2.0. This was already explored with the presentation of COMASO (Coastal Management Solutions; Farias, 2017), where CERA1.0 works as a tool for identification of high-risk hotspots, LTC (Coelho, 2005) previews in detail the shoreline evolution under different intervention scenarios and tests solutions for the areas, and XD-COAST (Lima *et al.*, 2013) is used to design the coastal structures selected for intervention. More recently, a cost-benefit assessment of coastal structures (Lima, 2018) was also added to the portfolio, contributing to make COMASO a fully-featured coastal management tool.

As CERA2.0 increases its user base, it is expected that the amount of contributions for its improvement will increase as well, due to its free and open-source nature. Following the partnership with the National Autonomous University of Mexico to assess Quintana Roo study site, several south-american countries express their willingness to participate in the project. The contributes can vary from application to additional study sites, to further development of the process within each module, passing through improvements in the QGIS, or in GIS technology in general. Most importantly, it is expected that CERA will contribute to increase awareness of the risk that coastal hazards represent to society, boosting a thoughtful coastal management around the world.

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