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Development of a Regional Risk Assessment methodology for climate change impact assessment and management in coastal zones.

Sviluppo di una metodologia di Analisi di Rischio Regionale per l'analisi e la gestione degli impatti dei cambiamenti climatici nelle aree costiere.

SETTORE SCIENTIFICO DISCIPLINARE DI AFFERENZA: CHIM/12
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TABLE OF CONTENTS

Index.

A mia mamma…

…e a mio figlio Gianmarco.

Summary

Today there is new and stronger evidence that global warming is likely to have profound impacts on coastal communities and ecosystems. Accelerated sea-level rise, increased storminess, changes in water quality and coastal erosion as a consequence of global warming, are projected to pose increasing threats to coastal population, infrastructure, beaches, wetlands, and ecosystems. Coastal zones represent an irreplaceable and fragile ecological, economic and social resource that need to be preserved from the increasing coastal resources depletion, conflicts between uses, and natural ecosystems degradation. Accordingly, there is a growing importance of innovative integrated and multidisciplinary approaches to support the preservation, planning and sustainable management of coastal zones, considering the envisaged effects of global climate change.

Climate change impacts in coastal zones are very dependent on regional geographical and environmental features, climate, and socio-economic conditions. Impact studies should therefore be performed at the local or at most at the regional level. In order to provide effective information that can assist coastal communities in planning sustainable adaptation measures to the effects of climate change, the main aim of this thesis is to develop a GIS-based Regional Risk Assessment (RRA) methodology for the integrated assessment of climate change impacts in coastal zones at the regional scale. The main aim of the RRA is to evaluate and rank the potential impacts, vulnerabilities and risks of climatic changes on coastal systems. Moreover the methodology allows the identification of key vulnerable receptors in the considered region and of homogeneous vulnerable and risk areas, that can be considered as homogeneous geographic sites for the definition of adaptation and management strategies. The present thesis complies with the research activities of the Euro-Mediterranean Centre for Climate Change (CMCC) and was implemented in a Decision support System for Coastal climate change impact assessment (DESYCO).

In order to characterize climate related hazards and vulnerable receptors the RRA approach integrates downscaled climate, circulation and wave models output for the construction of future climate change scenarios and includes the analysis of site-specific physical, ecological and socio-economic characteristics of the territory (e.g. coastal topography, geomorphology, presence and distribution of vegetation cover, location of artificial protection).

The RRA methodology was applied to the coastal area of the North Adriatic sea, in order to analyze the potential consequences of sea-level rise, relative sea-level rise inundation and coastal erosion impacts on multiple coastal receptors (i.e. beaches, river mouths, wetlands, terrestrial biological systems, protected areas, urban areas and agricultural areas) and compare the results based on multiple climate change scenarios.

The main output of the analysis include exposure, susceptibility, risk and damage maps that could be used to support coastal authorities in the implementation of sustainable planning and management processes.

Exposure maps obtained for the permanent inundation impacts (i.e. sea-level rise and relative sea-level rise) in 2100 allowing identification of coastal areas where the territory would be more submerged by projected water levels (i.e. areas surrounding the Po River Delta and the hinterland region between the Northern Venice lagoon and the Grado-Marano lagoons). Future exposure scenarios of coastal erosion depict a worse situation in winter and autumn for the future period 2070-2100 and highlight hot-spot exposure areas surrounding the Po River Delta.

Susceptibility maps highlighted that the receptors more susceptible to coastal erosion are the beaches with about 94% of the territory identified by the very high and high susceptibility class.

Risk maps showed that receptors with very high risk scores for the sea-level rise impact are wetlands, agricultural areas, protected areas and river mouths. The municipalities more interested by potential loss of beaches due to relative sea-level rise inundation are Ariano nel Polesine, Porto Viro, Porto Tolle, and Caorle. The receptors at higher risk for coastal erosion are the beaches where the percentage of the territory with higher risk scores is about 72% in the winter, 21% in the spring, 14% in the summer and 41% in autumn.

Finally, the damage assessment phase showed that the receptors with by higher percentages of the territory in the medium and high damage classes are wetlands, agricultural areas, protected areas and river mouths for the sea-level rise inundation; beaches, wetlands and river mouths for the coastal erosion impact.

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1. INTRODUCTION.

1.1. Motivations and objectives.

Coastal zones are considered key climate change hotspots worldwide (IPCC a, 2007; Voice et al., 2006; EEA, 2010). The major expected impacts are associated with permanent inundation of low-lying areas, increased flooding due to extreme weather events (e.g. storm surges), greater erosion rates affecting beaches and cliffs (Nicholls and Cazenave, 2010; EC, 2005; EEA, 2006; Klein et al., 2003). Furthermore, it is widely recognized that climate change can have far reaching consequences on coastal surface and groundwater (e.g. saltwater intrusion), coastal ecosystems (e.g. wetlands and biodiversity loss) marine biological communities and commercial species (Abuhoda and Woodroffe, 2006; Wachenfeld et al, 2007; Nicholls, 2004; IPCC, 2008).

At the international level two main research communities are involved in the analysis of climate change and climate variability impacts on coastal zones: the natural hazard and the climate change communities.

According to the framework proposed by the natural hazard community (UN-ISDR, 2009), the analysis of the likely impacts or risks related to coastal hazards involves the evaluation of two main components: hazard (i.e. an event or phenomenon with the potential to cause harm such as loss of life, social and economic damage or environmental degradation) and the system vulnerability (i.e. the characteristics of a system that increase its susceptibility to the impact of climate induced hazards). In this context, vulnerability is often expressed in a number of quantitative indices and is a key step toward risk assessment and management (Romieu et al., 2010).

Within the climate change community, vulnerability is mainly defined as a function of three components: exposure (i.e. the magnitude and rate of climate variations to which a system is exposed); sensitivity (i.e. the degree to which a system could be affected by climate related stimuli), and adaptive capacity (i.e. the ability of a system to adjust or to cope with climate-change consequences) (IPCC a, 2007). Climate change vulnerability is also defined as a combination of physical, environmental, social and economical factors whose assessment implies the integration of multiple quantitative and qualitative data (Füssel and Klein, 2006). Moreover, it is considered as a descriptor of the status of a system or community with respect to an imposed hazard (Kienberger et al., 2009) and is related to a given location, sector or group (Hinkel and Klein, 2007).

The potential consequences of climate change on natural and human systems can be quantified in terms of potential or residual impacts and risks, depending on the consideration of the adaptive capacity component in the final assessment (Füssel and Klein, 2002).

Considering that climate change impacts and risks on coastal zones are very dependent on regional geographical features, climate and socio-economic conditions, impact studies should be performed at the local or at most at the regional/sub-national level (Torresan et al., 2009).

A relevant challenge is therefore to develop suitable approaches for the assessment of climate-induced impacts at the regional scale, taking into account the best available geographical information for the case study area, in order to highlight most critical regions and support the definition of operational adaptation strategies.

The main aim of this thesis is therefore to develop a Regional Risk Assessment (RRA, Landis, 2005) methodology for the integrated assessment of potential climate change impacts on multiple natural and human ecosystems (i.e. beaches, wetlands, protected areas, river mouths, urban and agricultural areas and terrestrial biological systems). The methodology was developed in order to support regional/sub-national assessments and provide suitable information to plan preventive adaptation measures (e.g. construction of coastal defences, beach nourishment, planning and zoning of coastal territory).

The RRA integrates numerical models output for the construction of future climate change scenarios and considers bio-physical and socio-economic vulnerability indicators/ indices. In order to analyse impacts at the regional spatial scale, the RRA employs downscaled climate, circulation and morphodynamic models for the analysis of inundation and coastal erosion processes and includes the analysis of site-specific physical, ecological and socio-economic characteristics of the territory (e.g. coastal topography, geomorphology, presence and distribution of vegetation cover, location of artificial protection). The method is based on Multi Criteria Decision Analysis (MCDA) that includes a wide variety of methods for the evaluation and ranking of different alternatives, considering all relevant aspects of a decision problem and involving many actors (Decision makers as well as Experts) (Giove et al., 2009). It integrates expert judgments and stakeholder preferences in order to aggregate quantitative and qualitative environmental and socio-economic indicators representing the vulnerability of each coastal target to different climate induced hazards. The final outcome of the analysis include the identification and ranking of homogeneous risk units for each target of interest allowing the establishment of hotspot risk areas and defining priorities for intervention.

The methodology was developed within the Euro-Mediterranean Centre for Climate Change (CMCC, www.cmcc.it) in the frame of the CMCC-FISR project (2005-2010) funded by the Italian Special Integrative Fund for Research (FISR). The North Adriatic coastal area was selected as case study to test the RRA methodology and the main results of the analysis are presented and discussed in this thesis. The structure of the thesis is outlined in the next paragraph.

1.2. Thesis structure.

This thesis is structured in three main sections: the first one (section A) illustrates the theoretical background of this work; the second (section B) delineates the conceptual framework and the methodology developed in the thesis; finally, the third section (section C) describes the application of the methodology to the case study area of the North Adriatic coast.

Section A, focuses on the review of the state of the art concerning the main tools and methods developed at the international level for the assessment of impacts, vulnerability and risks related to climate change in coastal areas. Indicators and indices are also reviewed as useful tools to support impact, vulnerability and risk assessment studies. Finally, an evaluation of the importance of scenarios in climate change risk assessment and management is performed.

Section B is divided in two main chapters presenting the Regional Risk Assessment (RRA) methodology developed in the thesis. Chapter 3 presents the risk conceptual framework and Chapter 4 describes the main steps for the application of the methodology (i.e. Hazard scenarios assessment; Exposure assessment; Susceptibility assessment; Risk and Damage assessment).

Finally, Section C regards the application of proposed methodology to the coasts of the North Adriatic Sea (Italy). It is composed of Chapter 7 presenting the results of the application of the RRA to study sea-level rise and coastal erosion impacts and of Chapter 8 delineating the conclusions of the work, where a summary of main findings and possible further investigations and recommendations are presented.

Section A

THEORETICAL BACKGROUND

2. METHODS AND TOOLS FOR IMPACT AND VULNERABILITY ASSESSMENT.

In the context of increasing concern about measured and envisaged impacts of climate change, the development and the application of specific methods and tools for the assessment of vulnerability, impacts and risks related to climate change is an increasing task. As far as coastal systems are concerned, impact, risk and vulnerability assessment methodologies can support decision-makers in a sustainable management of resources and in the implementation of appropriate adaptation measures. Moreover, essential tools for the implementation of these methodologies are indicators and indices used for monitoring climate variations, characterising spatial and temporal distributions of stressors and drivers, identifying key vulnerable sectors and systems (IPPC a, 2007). Finally, scenario analysis is widely considered as a key tool for impact and risk assessment (UKCIP, 2003) and it is especially important where global changes are likely to occur and where there is high uncertainty about the future.

As will be described in the following Paragraphs, the main aims of this Chapter are: 1) to review current approaches developed at the international level for the assessment of impacts, vulnerability and risks related to climate change in coastal areas; 2) to identify and compare potential indicators and indices useful to support impact, vulnerability and risk assessments; 3) to explore the role of scenarios analysis as a fundamental component of risk management and decision-making processes.

2.1. Climate change impact, risk, and vulnerability assessment methods.

This literature review analyses several relevant approaches developed by the scientific community for the assessment of impacts, vulnerability and risk connected to climate change.

Starting from climate impact assessment methodologies, a first interesting approach is given by Füssel (2002), who defines impact assessment as the practice of identifying and evaluating the detrimental and beneficial consequences of climate change on natural and human systems. Particularly, impact assessments evaluate the potential effects of several climate change scenarios, including a (hypothetical) constant climate scenario, on one or more impact domains.

As depicted in Figure 2.1, climate impacts are a function of the exposure of a system to climatic stimuli and of its sensitivity to these stimuli.

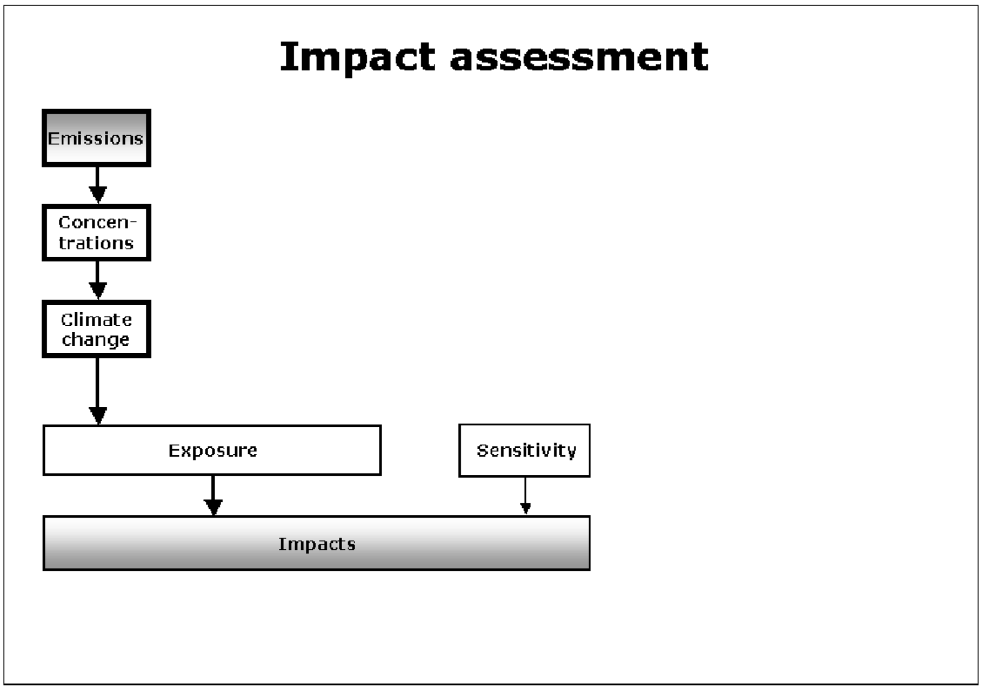

Figure 2.1. Conceptual framework for a (climate) impact assessment (Füssel, 2002).

Exposure is defined as the nature and degree to which a system is exposed to significant climatic variations and depends on its location and on the level of global climate change. Sensitivity represents the degree to which a system is affected, either adversely or beneficially, by climate–related stimuli. This characteristic denotes the (multi–dimensional) dose–response relationship between the exposure of a system to climatic stimuli and the resulting effects. According to Füssel (2002), climate change is a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Figure 2.1 seems to imply that climate change is purely an anthropogenic phenomena. However, it is important to consider that climate change may be due both to natural forcing (e.g. solar activity and volcanoes) and to persistent anthropogenic changes that would cause further warming and changes in the global climate system (e.g. continued greenhouse gas emissions or land use changes) (IPCC, 2007b).

A similar approach for impact assessment is offered by the Handbook of United Nations Environment Programme (UNEP; Feenstra et al., 1998), that emphasizes that climate change impact studies are necessarily conjectural. In fact, impact studies, cannot usually be experimentally confirmed or verified and it is not possible to conduct a controlled experiment by changing the global atmosphere to test the effects of changes on human and natural systems. Accordingly, this approach suggests investigative techniques to support the analysis of potential impacts of future climate change, such as: palaeological, archaeological, or historical studies of how climate changes and climate variations have affected human and/or natural systems in the past; studies of short term climatic events (i.e. droughts and floods); studies of the impact of present day climate and climate variability.

In addition to impact studies, vulnerability assessments are useful methodologies to investigate climate change issues on ecological and human systems. In fact, they constitutes an extension of an impact assessment and are aimed to: 1) produce information that helps to understand how a system is potentially affected by and responds to a change in climatic conditions; 2) contribute to policymaking by presenting this information to stakeholders; 3) recommend adaptation measures and facilitate sustainable development Füssel (2002).

A key approach for vulnerability assessment is given by the IPCC in the third assessment report (IPCC, 2001). According to this report, vulnerability is defined as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Specifically, vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity. The combination of climate exposure and system sensitivity determine the potential impacts that would be experienced in the absence of an adaptive response. Adaptive capacity is therefore a key component of vulnerability assessments and can be planned or autonomous (IPCC, 2001).

A planned adaptation is a strategic change in anticipation of a variation in climate to increase the capacity of a system to cope with (or avoid) the consequences of climate change. An autonomous adaptation is the capacity of systems to improve their ability to cope over time as a reaction to climate pressure.

In addition to the aforementioned components of a vulnerability assessment (i.e. exposure, sensitivity and adaptive capacity), the Australian Government (2005) include two additional aspects: adverse implications and potential to benefit. Adverse implications are an estimate of the loss that could occur due to climate change impacts; potential to benefit is an estimate of the potential benefit introduced by alternative adaptation options for sectors and/or regions.

As far as vulnerability assessment is concerned, Füssel (2006) presents a general framework with two different generations.

The first generation is characterized by model and scenario-based analyses of potential impacts and includes the following factors contributing to vulnerability: climate variability, non-climatic determinants, evaluation of potential impacts in terms of their relevance to goods and services, mitigation and adaptation measures to reduce adverse effects.

In this framework, mitigation refers to limiting global climate change through reducing the emissions of greenhouse gases (GHGs) and enhancing their sinks, adaptation aims at moderating its adverse effects through a wide range of system–specific actions.

The requirements for, and limitations to, implementing adaptation measures are more thoroughly assessed in second–generation vulnerability assessments. A second-generation assessment requires the involvement of social scientists in a multidisciplinary research group, a stronger participation of stakeholders and, focuses more on adaptive capacity to reduce the adverse impacts of climate variability and change.

In addition to impact and vulnerability assessment methods, risk assessment methodologies are widely employed to evaluate the consequences of climate change on different natural and human systems.

Jones and Boer (2005) describe two different major approaches to assess climate risk, a natural hazards-based approach and a vulnerability-based approach. These two approaches are complementary and can be developed separately or together.

The natural hazards-based approach to assess climate risk begins by characterising the climate hazards and can be written as the product between the probability of climate hazard and vulnerability. A hazard is an event with the potential to cause harm. Hazard is generally fixed at a given level and used to estimate changing vulnerability over space and/or time. For example, a flood of a given height or a storm with a given wind speed may increase in frequency of occurrence over time, increasing the risk faced (assuming that vulnerability remains constant).

The vulnerability-based approach applies the conceptual framework of the coping range that represent a climate range in which the outcomes of climate hazard are tolerable. Within the coping range, a system or an activity is able to withstand stress without undergoing significant change. Beyond this range the damages or losses are no longer tolerable and an identifiable group is said to be vulnerable. The coping range provides a template that is particularly suitable for understanding the relationship between climate hazards and society. The climatic stimuli and their responses for a particular local activity or social grouping can be used to construct a coping range if sufficient information is available. Risk can be assessed by calculating how often the coping range is exceeded under given conditions. The method of assessing risk can range from qualitative to quantitative. Qualitative methods can be carried out by building or using an existing conceptual model of a specific coping range; quantitative methods will begin to assess the likelihood of exceeding given criteria, such as critical threshold.

UKCIP (2003) gives a general definition of risk as the product of the probability or likelihood of occurrence of hazard and the magnitude of a consequence. The consequence (or set of consequences or impacts) is usually associated with exposure to a defined hazard, which is often detrimental or harmful. Risk assessment is the structured analysis of hazards and impacts to provide information for decisions; it usually relates to a particular exposure unit (i.e. individual, population, infrastructure, building or environmental asset). The process usually proceeds by identifying hazards, assessing the likelihoods and severities of impacts. Specifically, climate change risk assessments attempt to define the consequences (or impact) of future climate on vulnerable or climate-sensitive exposure units and receptors UKCIP (2003).

UN-ISDR (2009) provides another widely used approach in which risk is defined as the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions. Hazard is considered as a potentially damaging physical event (e.g. tropical cyclones, droughts, floods, storm surges); vulnerability is the combination of the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards.

Regional Risk Assessment (RRA) is another important approach for the assessment of impact and environmental risk related to climate change.

RRA aims at providing a quantitative and systematic way to estimate and compare the impacts of environmental problems that affect large geographic areas (Hunsaker et al., 1990). Moreover, according to Landis and Wiegers (1997) and Landis (2005), RRA allow to consider many environmental hazards which impact on large geographical areas (e.g. increased global CO_2, ozone depletion, global climate change, biodiversity loss) and take into account a wide range of sources releasing a variety of stressors which can impact a multiplicity of assessment endpoints.

The main characteristic of the regional risk assessment is the complexity of the analysis caused by the presence of multiple sources releasing multiple stressors which impact diverse receptors and the regional scale of the analysis which requires the assessment and integration of a huge amount of input data.

Accordingly, RRA becomes important when policymakers are called to face problems caused by a multiplicity of sources of hazards, widely spread over a large area, which impact a multiplicity of endpoint of regional interest. In fact, the limited economical resources don’t allow to plan remediation strategies to reduce all the identified risk and it is necessary to classify risks and prioritize the remediation actions.

Two different approaches are identified for the RRA: the first approach uses the traditional concepts of ecological risk assessment but analyses exposure and response over a large area (Hunsaker et al., 1990); the second approach uses ranking models to estimate the relative probability that some environmental negative effects, caused by anthropological activity, can occur (Landis and Wiegers, 1997).

The first approach combines regional assessment methods and landscape ecology theory and concerns the evaluation of the impacts which occur on population, species or ecosystem that are widely dispersed over a region to estimate a regional hazard; uses regional models for exposure and effect assessment, and probabilistic spatial models to support the risk quantification.

The RRA of the first approach includes 5 key steps: qualitative and quantitative description of the source terms of the hazard; identification and description of the reference environment within which effects are expected; selection of endpoints; estimation of spatiotemporal patterns of exposure by using appropriate environmental transport models or available data and quantification of the relationship between exposure in the modified environment (reference environment) and effects on biota.

In the second approach proposed by Landis and Weigers (1997) the phases for the RRA are: identification of the different sources, habitats and impacts; ranking the importance of the different components of the risk assessment; spatial visualisation of the different components of the risk assessment to verify if they overlap; relative risk estimation.

The main objectives of regional scale assessment are the evaluation of broader scale problems, their contribution and influence on local scale problems as well as the cumulative effects of local scale issues on regional endpoints in order to prioritize the risks present in the region of interest (Smith et al., 2000) in order to prioritise and evaluate intervention and mitigation measures.

Impact, risk and vulnerability assessment concepts are essential to understand and compare national and international case studies aimed at evaluate climate change impacts on coastal areas.

In fact, case studies often show differences not only associated with the type of coastal systems analyzed, the aim of the study, and the spatial and temporal scale; but also concerning methods, techniques, tools and scenarios employed in the analysis.

In accordance with Klein and Nicholls (1999) there are studies where natural-system vulnerability is primary evaluated, and studies where socio-economic vulnerability related to climate change is assessed. However, as defined by the authors natural-system and socioeconomic vulnerability are related and interdependent, and proper analysis of socioeconomic vulnerability requires a prior understanding of how the natural system would be affected.

An assessment of natural-system vulnerability at national level was performed by Silenzi et al. (2002) and Gambolati and Teatini (2002). The aim of Silenzi et al. (2002) is to develop a preliminary methodological guideline for the evaluation of the integrated hazard and risk of coastal areas to relative sea-level changes. The method adopt a multidisciplinary approach for the territorial analysis including geological, topographical, geomorphological, hydrological, geohydrological and land use surveys, and use forecasts of ground level changes and accelerated beach erosion with respect to sea-level rise. All data are processed through a Geographic Information System (GIS) that performs the development of a provisional Digital Terrain Model (DTM), and allow the construction of susceptibility, hazard and land use maps.

The aim of Gambolati and Teatini (2002) is to evaluate the morphodynamical evolution of the Northern Adriatic coastal profile due to sea-level rise, storm surge and wave set-up, littoral sediment transport and land subsidence. The predictions of each individual process is obtained using IPCC global sea-level rise scenarios (Wigley and Raper, 1992), land subsidence, and hydrodynamic and wave models. The outcome of numerical simulations are managed with a GIS and then are interpolated with a Digital Elevation Model (DEM) in order to find out those lowlands which are most likely to be flooded both permanently and occasionally, and to assess the expected coastline regression during the decades to come. Moreover, in accordance with the methodology developed by the United Nation Disaster Relief Office (UNDRO, 1995) an inundation risk factor is defined. It depends on flooding hazard equal to the probability that a selected storm event occurs at least once during a time interval; the economic value of the flooded area, and the relative damage equal to the water elevation over the flooded area. The result is maps of the normalized risk factor at present and in 2100 at regional and local scale.

Silenzi et al. (2002) and Gambolati and Teatini (2002) use GIS technologies in front of archiving, organizing, and managing the data and for develop thematic map, but also to combine three-dimensional terrain elevation models (DTM and DEM) with different sea-level rise scenarios. Both studies attempt to assess the socioeconomic vulnerability using land use maps and risk analysis. Additionally, there is a need to regionalize the scenarios to compare them with local data given by the case study area. Natural climate variability on a regional basis comes out from a document of the National Committee on Coastal and Ocean Engineering (NCCOE, 2004) that present a methodology that considers the relative changes of climate change scenario modeling to key environmental variables (i.e. mean sea-level, ocean currents and temperature, wind climate, wave climate, rainfall/runoff, air temperature). Then possible effects on secondary variables of relevance to local coastal and ocean engineering (i.e. local sea-level, currents, winds, waves, groundwater level and quality, coastal flooding, foreshore stability, sediment transport, hydraulics of estuaries, quality of coastal waters, ecology) are also considered. The likely interactions between the primary and secondary variables are explored by means of an Impact Assessment Interaction Matrix.

Another interesting method is proposed by the National Oceanic and Atmospheric Administration (NOAA, www.csc.noaa.gov/products/nchaz/startup.htm) that gives a step-by-step guideline for assessing community vulnerability to environmental hazards. The aim is to develop and implement a vulnerability assessment methodology that result in a foundation for identifying and prioritizing community-based hazard mitigation activities. The initial steps focus on identifying hazard and establishing relative priorities, identifying high potential impact areas for each hazard and assign scores within risk consideration areas. After intersecting critical facilities categories (i.e. schools, hospitals, police, utilities, communication, transportation) with high-risk areas, a societal and economic analysis is performed. The societal analysis is made considering the categories of more sensitive population (i.e. % households below poverty, % single parent with child families, % housing units with no vehicle available); while economic analysis considers the major economic sectors (i.e. agriculture, mining, construction, manufacturing, transportation and public utilities). An environmental analysis identifies secondary hazard risk consideration sites (i.e. toxic release inventory sites, solid waste facilities, oil facilities) and the last step is the mitigation opportunities analysis. GIS technologies are used, primary to manage the large amount of data needed for the analysis, and to conduct vulnerability assessment analysis and to visualize results. This approach is not finalized on climate change, but it permits the analysis of multiple natural hazards such as earthquakes and bushfire and flooding. Moreover, the methodology focuses on the analysis of socioeconomic aspects and the environmental characteristics related to vulnerability of natural resources (i.e. wetlands, significant habitat areas and fisheries nursery areas) are considered only in the phase of the identification of secondary impacts.

Considering the socioeconomic vulnerability assessment, an innovative approach is proposed by the Joint Research Centre (JRC) in Sagris et al. (2005). This method considers the actual state of the socioeconomic system, and future demographic and economic trends using land use scenarios. Moreover, this method demonstrate how integrated assessments of climate change effects can be conducted at the local spatial scale, using sea-level rise scenarios regulated with regional climate dynamics. Moreover, local DEM and GIS technologies are the basis to transform sea-level and surge values into impact maps useful for a quantitative assessment in terms of territory affected. The impact maps represent one of the main input to risk and vulnerability assessment.

Recent international vulnerability studies focus on conceptual frameworks related both on natural and on socioeconomic system. For instance, a vulnerability assessment report of the Australian coasts made by the Australian Greenhouse Office (Voice et al., 2006) primary identifies drivers and stressors of climate change (i.e. sea-level rise, coastal erosion, frequency of extreme events), then the preliminary impacts on natural and socioeconomic systems and, finally, the probable responses to the negative effects. The report remarks that a full assessment of vulnerability requires consideration of economic and social value of goods and services, infrastructure or ecosystems at risk, combined with an assessment of resilience of the communities or ecosystems.

The last and most recent methodology for the assessment of vulnerability, impacts and risks is proposed by the Sydney Coastal Councils Group (SCCG), partnered with CSIRO and working in collaboration with University of the Sunshine Coast entitled Mapping Climate Change Vulnerability in the Sydney Coastal Councils Groups (Preston, 2008). The aim of the project is to assess and manage climate vulnerability in the Sydney region. The future climate of the SCCG region is projected to be both warmer and drier. Meanwhile, sea-level rise is projected to increase the risk of inundation and erosion of the SCCG coastline. Five areas of potential climate impacts were selected for vulnerability assessment: extreme heat and human health effects, sea-level rise and coastal hazards, extreme rainfall and urban storm water management, bushfire, and natural ecosystems and assets. In conducting this vulnerability assessment, simple conceptual models identifying the key processes and assumptions were developed for each of the above impact areas. These models were subsequently utilised to select a broad range of indicators reflecting the three components of vulnerability (exposure, sensitivity and adaptive capacity). These indicators were integrated within GIS technologies to facilitate mapping of relative vulnerability. The resulting regional vulnerability maps provide an indication of the relative vulnerability of different areas within the SCCG to different climate change impacts.

From the studies proposed in this paragraph, it is clear that there is no a unique response for the assessment of impacts, vulnerability and risks related to climate change in coastal zones. Accordingly, there is the need to identify time by time an adequate method consistent with project and research aims, and compatible with available technologies, tools, and dataset.

In the following paragraph, after a general introduction, a comparative analysis of indicators and index useful to support the implementation of vulnerability, impact and risk methodologies will be presented.

2.2. Indicators and indices.

In general terms, an indicator is a value that represents a phenomenon that cannot be directly measured and may aggregate different types of data (Agostini et al. 2009). Indicators usually have three relevant functions: they may reduce the number of parameters that normally would be required to represent a situation; they may simplify the process of results communication to the users; and they may quantify abstract concepts such as ecosystem health or biotic integrity that are not measurable. In the field of environmental sciences, indicators are physical, chemical, biological or socio-economic measures that best represent key elements of a complex ecosystem or environmental issue (http://www.ozcoasts.org.au/glossary/def_i-l.jsp).

The Organisation for Economic Cooperation and Development (OECD, 1993), define an index as a set of aggregated or weighted parameters or indicators. Moreover, the OECD (1993) proposed a framework linking different indicators called the “Pressure-State-Response” (PSR) model, re-elaborated later by the European Environmental Agency (EEA, 1995) in the “Driving-forces-Pressure-State-Impact-Responses” (DPSIR) framework. Each of the five components of the DPSIR framework can be analysed through the use of suitable indicators, in such a way that the complexity of the environmental dynamics, without loosing its own flexibility, is well described (Agostini et al., 2009).

Particularly, considering the effects related to climate change, indicators and indices are used for monitoring climate variations, characterising spatial and temporal distributions of stressors and drivers, identifying strategic vulnerability (IPCC, 2007a).

Generally, environmental indicators are divided in different categories concerning several sectors and/or environmental problems. While the European Environmental Agency (EEA, 2004) identified eight main categories of environmental indicators (i.e. atmosphere and climate, snow and ice, marine ecosystems, terrestrial ecosystems and biodiversity, water, agriculture, economy and human health), the Australian site for coastal assessment (http://www.ozcoasts.org.au/indicators/index.jsp) proposes four main categories of indicators (i.e. coastal issues, biophysical indicators, pressure indicators and coastal management indicators), which are then divided in further sub-groups (e.g. declining water quality, climate change, habitat/species alterations). Accordingly, climate change is not always considered as a main category for environmental indicators, rather it is a cross-cutting theme of relevance for all the categories of environmental indicators.

Jones and Boer (2004), defined sustainability indicators that are related to thresholds indicating reference values over which irreversible changes would happen, and use these indicators in order to measure the risk for systems exposed to climate change.

In relation to the conceptual framework adopted, vulnerability indicators could reflect the outcome of a defined climate hazard (e.g., monetary costs, human mortality, ecosystem damage, etc.) or the state of a system prior to the occurrence of the hazard event (e.g., geomorphological, biological and ecological features, population distribution, land use, economic condition, etc.) (Brooks 2003). Moreover, according to Klein and Nicholls (1998) vulnerability is a multi-dimensional concept that should be represented by an heterogeneous subset of biogeophysical, economical, institutional and socio-cultural indicators.

The main aim of this paragraph is to identify and review indicators and indices that may be useful for the analysis of impacts and risks related to climate change on coastal areas. Indicators and indices will be classified based on their geophysical, biochemical, socio-economical characteristics and will be compared and discussed considering their principal characteristics (e.g. objective, scale of analysis) and based on the information reported in

Table 2.1.

Table 2.1 allows an easy visualisation of reviewed indicators/indices and facilitate their comparison based on the following criteria:

- name given by the author;
- objective of indicator or index;
- types of factors considered in the indicator/indices (geophysical, biochemical, socio-economical);
- description of indicators or parameters considered in the indices;
- spatial scale (local, regional, national and supranational);
- reference.

Starting from the analysis of the "name" column of
Table 2.1, there are various examples of indicators/indices of vulnerability and sensitivity (i.e. Adger et al., 2004; AIACC, 2006; Branko et al., 2008; Hinkel and Klein, 2007). However some indicators are sustainability indicators (Breton, 2004) or environmental state indicators (EEA, 2005), and some others are referred to the DPSIR framework (i.e. Casazza et al., 2002; Marotta and Vicinanza, 2001) or to physical and geophysical characteristics of coastal systems (i.e. Bryan et al., 2001, Berger and Iams, 1996).

Considering the "Type of factors" column, while some authors propose indicators that consider heterogeneous factors (i.e. geophysical and biochemical or geophysical and socio-economical), others are focused on the analysis of a single type of factors (e.g. geophysical, biochemical or socio-economic).

Among the broad category of geophysical indicators, Bryan et al. (2001) consider various physical aspects of the coasts (e.g. elevation, exposure, aspect and slope) calculated at the regional scale using GIS technologies in order to assess coastal vulnerability to sea-level rise in tide-dominated, sedimentary coastal regions.

Berger and Iams (1996) use geoindicators to measure the magnitudes, frequencies, rates, or trends of geological processes and phenomena that occur at or near Earth's surface and that are significant for assessing environmental change over periods of 100 years or less. Specifically, the following geoindicators are identified for coastal zones: relative sea level, coastal subsidence and uplift, shoreline position, coastal erosion, sediment transport and deposition, wind erosion, wetland extent, structure and hydrology and can be used for the assessment of coastal vulnerability to climate change.

In addition to geophysical indicators considering geological characteristics of the coast (i.e. coastal height, rock typology, morphology and position of the shoreline), the report to Agency for the Assessment of Impacts and Adaptations to Climate Change (AIACC, 2006) suggest to use indicators regarding the main driving forces that affect coastal systems (e.g. sea level, tidal variation, height of wave etc.). These indicators are used in order to orient scientific efforts toward effective management or policy decisions at the regional or national level.

Within the category of vulnerability indicators, the U.S. Geological Survey (USGS, 2004) uses a Coastal Vulnerability Index (CVI) to map the relative vulnerability of the coast to future sea-level rise. The CVI scores different variables in terms of their physical contribution to sea-level rise related coastal change. Considered variables are divided in geological variables (i.e. geomorphology, historical shoreline change rate, regional coastal slope) and physical process variables (i.e. relative sea-level rise, mean significant wave height, mean tidal range). In particular, the geological variables take into account the shoreline's relative resistance to erosion, long-term erosion/accretion trend, and its susceptibility to flooding. The physical process variables contribute to the inundation hazards of a particular section of coastline over time scales from hours to centuries.

Another index-based approach is proposed by Schleupner (2005) with the Coastal Sensitivity Index (CSI) that is aimed at the assessment of the sensitivity of the coast to flooding and erosion caused by climate change and sea-level rise. To evaluate the probability of flooding and coastal erosion, four categories that influence vulnerability are chosen: elevation and morphology of the coast, erodibility, coastal exposition to the wind regime, and natural shelter of the coast. Relative elevation, coastal morphology and erodibility represent geological/geomorphological characteristics of coastal zones. Coastal exposition to the wind regime may affect coastal erosion and the withdrawal of the coast. Natural shelter of the coastal segment have the function of natural breakwaters along the coastline (i.e. coral reef, small islands, bays). Relative local subsidence and elevation movements are added to these four categories.

As far as biochemical factors are concerned, the Australian society for the assessment and monitoring of coastal areas (www.ozcoast.org.au) suggests the following indicators: algal blooms, anoxic an hypoxic events, euthrophication, vector borne diseases, variation of terrestrial flora and fauna, marine fauna, alloctone species presence. These indicators are used to explore coastal ecosystem evolution, processes complexity, and information about ecosystem health.

Further biological indicators are proposed by Carlton and Battelle (2004) in order to assess the economic impacts of climate change analysing the fish stock and its main characteristics (e.g. species composition and habitat). Moreover, Branko et al. (2008) study the life cycles of new species in the Eastern Adriatic coast in order to economically protect marine biomass to climate change.

For the analysis of climate change impacts on plankton communities, Temnykh et al. (2008) provide indicators regarding the variation of species composition of marine zooplankton in relation to changes in water temperature; Gameiro and Brotas (2008) evaluate the variability of the phytoplankton in the estuary in relation to multiple climatic drivers (i.e. temperature, wind, rainfall, river flow, salinity).

Some indicators referred to biogeochemical factors are also provided by the European Environmental Agency (EEA), in the State of Environment reports (EEA, 2005a,b). These indicators concern the quality of bathing water, nutrient concentration in coastal, transition and marine areas, and are important to evaluate the state of the environment.

Some authors, Casazza et al. (2002) and Marotta and Vicinanza (2001), analyse socio-economic factors and apply the DPSIR framework in order to evaluate the environmental quality of Italian coasts. The main driving-forces of this approach include population density, increase in population, GDP distribution (agriculture, industry, services), tourism and coastal occupation but do not explicitly include climate change forcings.

Adger et al. (2004) propose specific sub-set of indicators that enable a comparison of the vulnerability and adaptive capacity of different systems, groups or regions to climate change. These indicators are mostly related to socio-economic aspects and include the percentage of the national population living in flood plains or in low-lying coastal areas, the assessment of population immediately dependent on agriculture, the conditions of economic welfare, health, nutrition and education, and finally the analysis of infrastructures and institutions.

Finally, several authors (Sorensen, 1997; Coastal Resources Center, 1996 and 1999; Hertin et al., 2001; EEA, 2000) proposed some indicators in order to evaluate the effectiveness of Integrated Coastal Zone Management (ICZM) policies and to monitor the results of this process (e.g. number of ICZM activated, number of plan or strategies, stakeholder participation).

A specific set of indicators to study impacts of climate change in coastal zones is proposed by the IPCC-Coastal Zone Management Subgroup (IPCC CZMS, 1992). These indicators are referred both to socio-economic and to biochemical factors and include people potentially affected by climate change impacts, people at risk, loss of capital, land loss, costs for prevention and adaptation measures and wetland loss.

Breton (2004) defines sustainability indicators in order to promote the sustainability of coastal zones and the development of ICZM strategies. These indicators concern both socio-economic factors (i.e. demand for property on the coast, area of built-up land, human and economic assets at risk) and geophysical/biochemical ones (e.g. amount of semi-natural habitat, change to significant coastal and marine habitats and species, quality of bathing water, sea-level rise and extreme weather conditions).

Voice et al. (2006) explain that a full assessment of vulnerability to climate change requires consideration of the economic and social value of goods and services, infrastructure or ecosystems at risk, combined with an assessment of vulnerable receptors to impacts such as sea-level rise, and extreme weather events. Receptors to be considered in the analysis are both natural and human ecosystems (i.e. beaches and dunes, estuaries, tidal wetlands, coral reefs, sea grasses, coastal infrastructure, fisheries and aquaculture, tourism and health).

In order to support vulnerability studies related to climate change impacts in coastal zones, Hinkel and Klein (2007) provide an integrated set of geophysical and socio-economical indicators at the global scale, such as soil or sand loss, dune height, number of people in flooding risk areas, saline intrusion areas, costs for adaptation and mitigation measures.

Also Travisi (2007) gives an heterogeneous set of indicators to define the costs for different climate risk scenarios. These indicators include meteo-climate factors (i.e. temperature, precipitation), environmental factors (i.e. natural areas, water resources, biodiversity), social factors (i.e. growth rate and composition of the population, employment/unemployment rate, health), economic factors (i.e. GDP, economic and technologic growth) and administrative factors (i.e. land planning, resource management, prevention plans).

In order to assess the relative vulnerability of coastal zones within a region, Ashbindu Singh (2005) considers the following indicators: population density in coastal areas, probability of natural disaster incidents, percentage of vegetation cover, geographic exposure as the percentage of flat land and the proportion of the length of the coastline to the country’s total boundary. Since the original data are represented in non-comparable units, a formula is proposed to convert the data into a set of equivalent indices. All the indicators are scaled between 0 and 1 using a scaling formula. Once scaled, all the indicators are combined to produce a Coastal Vulnerability Index (CVI) applied to assess the relative status (i.e. level of vulnerability) of coastal areas within each country worldwide.

Finally, Torresan et al. (2008) adopt specific indicators to address climate-change related issues in coastal zones and to identify vulnerable areas at the regional level. They include a heterogeneous subset of indicators (i.e. coastal topography and slope, geomorphological characteristics, presence and distribution of wetlands and vegetation cover, density of coastal population and number of coastal inhabitants) that are referred to biophysical, ecological and socio-economical features of coastal systems.

This literature review identified several environmental indicators that may be useful for the assessment of vulnerability, impact and risks related to climate change in coastal zones. However, as shown in

Table 2.1, reviewed indicators are targeted to multiple environmental and management objectives (e.g. assess marine water quality, evaluate the sustainable development of coastal areas, or support a deeper understanding about coastal system complexity) but not always related to the specific assessment of climate change issues (e.g. identify vulnerability and adaptive capacity to climate change, assess coastal vulnerability to sea-level rise, assess economic impacts of climate change).

Considering the indicators that are specifically developed to study climate change impacts, while some approaches are more focused on the evaluation of the physical and geological susceptibility related to climate change (e.g.. elevation above sea-level, coastal morphology), other parameters are focused on potential adverse effects of climate change on biological and ecological resources (e.g. vegetation cover, fish stock) or on human communities (e.g. population density, land use, fishing).

Concerning the type of factors considered in the analyzed literature, the most common geophysical parameters include elevation above sea-level, coastal slope, coastal geomorphology and the erosion rate of the coastline; the main biochemical indicators describe species composition of marine and terrestrial fauna, and vegetation communities on the coastal zones; finally, the socio-economic indicators include impacted population, quantity and quality of economical activities on risk areas.

From the analysis of

Table 2.1,it seems that most authors are mainly focused on the analysis of a limited set of indicators. This could result inadequate for the integrated assessment of the manifold environmental and socio-economical aspects that should be considered in the assessment of climate change impacts and risks on the coastal zones.

Moreover the use index-based methods are prevalent such as the Coastal Vulnerability Index (CVI) and the Coastal Sensitivity Index (CSI) for the assessment of vulnerability related to climate change in coastal zones. These approaches are generally simple to implement and express coastal vulnerability by a one-dimensional, and generally unitless, risk/vulnerability index. Moreover they can be easily modified and adapted for particular research purposes and for the specific characteristics of the study area. In fact, it is possible to identify and select different types of variables and specific vulnerability/susceptibility classes according to the main features of the analyzed system and to the scale of analysis. The use of index-based methods gives the possibility to define coastal areas most vulnerable/sensitive to climate change and can be the starting point to assess vulnerability and socio-economical impacts of climate change on the studied area. However it is important to consider that index-based approaches are not immediately transparent, since the final computed indices do not allow the user to understand the assumptions and evaluation that led to its calculation. A clear explanation of the adopted methodology is therefore essential to support the proper use of these methods (Ramieri et al., 2011).

Finally, as regards the scale of analysis, reviewed indicators/indices are defined at municipal, basin, regional, national level or supranational/global scale. The definition of the scale analysis is a key step for the application of indictors and is very dependent on the objective of the study and on data availability.

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Name	**Objective**	**Types of factors**	**Description**	**Aggregation formula**	**Scale/area of study**	**Reference**
Predictive indicators of vulnerability	Identify vulnerability and adaptive capacity to climate change of a country	Socio-economical	Percentage of population living in coastal areas Population dependent on agriculture Economic welfare Health and nutrition Education Infrastructures and institutions.		National, small islands	Adger et al., 2004.
Vulnerability indicators	Support effective management or policy decisions at regional or national level.	Geophysical	Coastal height Rock typology Morphology Sea level Position of the shoreline Tidal variation Height of wave		National, regional, Rio de la Plata basin	AIACC, 2006.
Coastal Vulnerability Index	Assess the relative vulnerability of coastal zones within the region	Socio-economical, Geophysical, Biochemical	population density on coastal areas (PD) Probability of natural disaster incidents (ND) Low forest cover (1-FC) Proportion of the length of the coastline to the country's total boundary (GE) Elevation above sea-level (GE) Human development (HD)	CVI= (PD+ND+(1-FC)+GE)-HD	National	Ashbindu Singh, 2005.
Geoindicators	Give information for the assessment of environmental impacts	Geophysical	Relative sea level Shoreline position Dune formation and reactivation Stream sediment storage and load Mass movement Wetland extent, structure and hydrology Wind erosion		Regional	Berger and Iams, 1996.
Vulnerability indicator	Quantify the effects of climate change on marine biomass	Biochemical, Socio-economical	Variation of fish species		Neretva estuary, Croatia	Branko et al., 2008.
Sustainability indicators	Promote the sustainability of coastal zones and the integrated coastal zone management	Socio-economical, Biochemical	Property on the coast Area of built-up land Natural, human and economic resources Amount of semi-natural habitat Change to significant habitats and species Quality of bathing water			Breton, 2004.

Name	**Objective**	**Types of factors**	**Description**	**Aggregation formula**	**Scale/area of study**	**Reference**
			Sea-level rise Extreme weather conditions Coastal erosion and accretion			
Physical environmental parameters	Assess coastal vulnerability to sea-level rise	Geophysical	Elevation land Slope land Exposure and orientation	Statistical analysis, rank-correlation test, linear regression	Regional, Northern Spencer Gulf	Bryan et al., 2001.
Fishing indicators	Assess economic impacts of climate change	Biochemical, Socio-economical	Fish stock		Regional	Carlton and Battelle, 2004.
DPSIR indicators	Define environmental quality of the coastal area	Socio-economical	Population density Increase in population GDP distribution (agriculture, industry, services) Tourism Coastal occupation		National, Italy	Casazza et al., 2002 Marotta and Vicinanza, 2001.
Indicators of the state of the environment	Evaluate the state of marine water	Biochemical	Quality of bathing water Nutrient concentration in coastal, transition and marine areas		Europe	EEA, 2005.
Vulnerability indicator	Measure human influence on water ecosystems	Biochemical	Variability of phytoplankton		Tagus estuary, Portugal	Gameiro and Brotas, 2008.
Vulnerability indicators	Support vulnerability studies related to impacts of climate change on coastal zones	Geophysical, Socio-economical	Soil or sand loss Dune height Saline intrusion areas Number of people in flooding risk areas Costs for adaptation and mitigation measures			Hinkel and Klein, 2007.
Vulnerability indicators	Analyse the vulnerability of coastal zones related to climate change	Socio-economical, Biochemical	People affected by impacts People at risk Loss of capital Land loss Costs for prevention and adaptation measures Wetland loss	Common methodology	National, regional, Holland, Poland and Germany	IPPC CZMS, 1992.
Evaluation measures of climate risk	Measure the risk for systems exposed to impacts of climate change	Biochemical, Socio-economical, Geophysical	Salinity Mangroves Planning for disasters/hazards Infrastructure/economics		National	Jones and Boer, 2004.

Name	**Objective**	**Types of factors**	**Description**	**Aggregation formula**	**Scale/area of study**	**Reference**
			Regional assessment planning			
			Critical thresholds for atolls			
			Coastal dynamics			
			Flooding and wetlands			
Coastal Sensitivity Index (CSI)	Assess the sensitivity of the coast to flooding and erosion caused by climate change and sea-level rise	Geophysical	Relative height of the coast	$CSI=(X1^2+X2^2+X3^2+X4^2+Xn^2)/n$	Caribbean region	Schleupner, 2005
			Morphology of the coast			
			Erodibility			
			Coastal exposition to the wind regime			
			Natural shelter of the coast			
			Subsidence			
			Elevation of the area			
			Sediment processes			
Indicators for the integrated coastal zone management	Evaluate the effectiveness of ICZM policies and to monitor the results	Socio-economical	Number of ICZM activated			Sorensen, 1997 Coastal Resources Center, 1996 and 1999 Hertin et al. 2001.
			Number of plan or strategies			
			Stakeholder participation			
Vulnerability indicator	Analyse the effects of temperature change on water ecosystem	Biochemical	Species composition of zooplankton		North-East zone of The Black Sea	Temnykh et al., 2008.
Regional indicators of coastal vulnerability	Identify vulnerable areas at the regional level	Geophysical, Biochemical, Socio-economical	Land of a particular elevation value		Regional, Veneto	Torresan et al., 2008.
			Slope			
			Geomorphological characteristics of the coast			
			Potential migration of wetlands			
			Vegetation cover			
			Density of coastal population			
			Number of coastal inhabitants			
System dimension	Define the costs for different climate risk scenarios. Estimate the cost of areas exposed to a possible flooding risk	Biochemical, Geophysical, Socio-economical	Natural area		Local, Piana di Fondi (Lazio), Piana di Sangro (Abruzzo), Grado and Marano (FVG)	Travisi, 2007.
			Biodiversity			
			Water resource			
			Rate of population growth			
			Composition of the population			
			Employment/unemployment rates			

Name	**Objective**	**Types of factors**	**Description**	**Aggregation formula**	**Scale/area of study**	**Reference**
			Sanitary resources			
			GDP			
			Economical and technological growth			
			Land assessment planning			
			Methodologies for resources assessment			
			Existing prevention planning			
Coastal Vulnerability Index (CVI)	Assess the rate of coastal erosion/accretion and the response of a coastline to sea-level rise	Geophysical	Geomorphology (a)	$CVI= \sqrt{[(a*b*c*d*e*f)/6]}$	Regional	USGS, 2004.
			Historical shoreline change rate (b)			
			Regional coastal slope (c)			
			Relative sea-level rise (d)			
			Mean significant wave height (e)			
			Mean tidal range (f)			
Coastal vulnerability factors	Quantify the vulnerability of analysed systems to the impacts related to climate change	Geophysical, Biochemical, Socio-economical	Beaches and dune coasts		National, Australia	Voice et al., 2006.
			Estuaries			
			Tidal wetlands			
			Water resources			
			Sea grasses			
			Coastal infrastructures			
			Fish and aquaculture			
			Tourism			
			Health			
Coastal indicators	Explore coastal ecosystem evolution, processes complexity, and information about ecosystem health	Biochemical	Algal blooms		National, Australia	www.ozcoasts.org.au
			Anoxic an hypoxic events			
			Euthrophication			
			Vector borne diseases			
			Variation of terrestrial flora and fauna			
			Marine fauna			
			Alloctone species presence			

Table 2.1. Comparative analysis of indicators and indices found in literature for climate change impact, risk and vulnerability assessment.

2.3. Scenario analysis.

At the international level, scenarios are widely considered as a key tool for climate change risk assessment. They are used to identify various sources and types of uncertainty associated with our knowledge of the future, and as a tool to help analyzing the consequences of this uncertainty (UKCIP, 2003).

In general terms, scenarios describe plausible futures as a function of changes in major driving forces (i.e., the main determinants of change in a scenario), such as population growth, economic development or technological change (DINAS-COAST, 2006). Accordingly, a scenario is a coherent, internally consistent, and plausible description of a possible future state of the world (IPCC, 2007b). This kind of scenarios are not predictions or forecasts (which indicate outcomes considered most likely), but are alternative images without ascribed likelihoods of how the future might unfold. However they are widely used to assess future developments in uncertain and complex conditions, to illustrate future conditions relative to main environmental driving forces (e.g., in technology, agriculture or ecology) and to devise effective responses by modifying current policies and decision making.

Scenarios can also be divided into exploratory (or descriptive) and normative (or prescriptive). The former class includes scenarios describing the future according to known processes of change, or as extrapolations of past trends (Carter et al., 2001); the latter considers scenarios describing a pre-specified future, either optimistic, pessimistic, or neutral (Alcamo, 2001), and a set of actions that might be required to achieve (or avoid) it. Such scenarios are often developed using an inverse modelling approach, by defining constraints and then diagnosing plausible combinations of the underlying conditions that satisfy those constraints (IPCC, 2007b).

As regards climate change inherent literature, in the Special Report on Emission Scenarios (SRES) (Nakićenovićet al., 2000), the Intergovernmental Panel on Climate Change (IPCC) defined a set of Emissions Scenarios that describe future and present-day global and regional emissions of Green House Gases (GHG) and other pollutants (for example sulphur dioxide and carbon monoxide) which can influence climate. The so called SRES scenarios are also based on storylines showing a set of possible conditions relative to the main driving forces of environmental change (e.g., demography, economy, technology, energy and agriculture). Specifically, the SRES storylines are structured in four major “families”, labeled A1, A2, B1 and B2, each of which emphasizes a largely different set of social and economic ideals and they are used to provide quantitative estimates of GHG and aerosol emissions from energy use, industrial activities and land use.

For climate change risk assessment, two main types of scenarios are very useful: climate change and socio-economic scenarios.

Scenarios of climate change represent uncertainty in future climate and are simply the predictions from Global Climate Models (GCMs) or Regional Climate Models (RCMs). These models provide information on future climate for a range of climate variables (e.g. air and water temperature, rainfall, wind circulation) at a spatial resolution determined by the climate model (generally hundreds of kilometers a side for GCMs and tens of kilometers a side for RCMs). The starting point for developing climate change scenarios is the definition of scenarios of future emissions of the greenhouse gases and other pollutants that could affect climate (e.g. SRES scenarios).

Socio-economic scenarios describe uncertainty in the future socioeconomic environment and provide contextual socioeconomic descriptions allowing climate change risk to be judged against other sources of risk (UKCIP, 2003). Each description of future world in the socio-economic scenario represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways and result in different levels of (GHG) emissions.

Accordingly, each socio-economic scenario leads to a specific emissions scenario from which climate scenarios can be generated.

Climate change scenarios provided by GCMs and RCMs are widely used to assess climate change at the global and supra-national scale. However, the GCMs and RCMs outputs alone cannot assess the detailed changes that may happen at the regional/local levels. Recently, there has been a lot of effort from the climate community on the development of dynamical and statistical downscaling techniques to represent climate change at local and regional scale, respectively. However, bridging the gap between the resolution of global climate models and the local scale weather and microclimatic processes still represents a considerable technical problem (STARDEX, 2005 http://www.cru.uea.ac.uk/projects/stardex/).

Moreover, most impact studies are done for spatial resolutions of the order of a few square kilometres. This is much less than the horizontal areas of the GCMs and RCMs (i.e. from hundreds to tens of kilometres a side), especially for regions of complex topography, coastal or island locations, and in regions of highly heterogeneous land-cover (Wilby, 2004).

Consequently, climate scenarios usually investigate processes that happen at a geographical scale not useful for coastal planners to study impacts regionally or locally. Therefore, methods are needed to bridge the gap between the large scale of climate scenarios and the fine scale where local impacts happen as a consequence of changed climate conditions.

In climate impact and risk assessment studies, a set of several significantly different scenarios can help in bounding the uncertainty of the future. A good set of scenarios should include at least one or more negative images of the future as well as a optimistic scenario assuming a successful future world.

Section B

METHODOLOGICAL DEVELOPMENT

3. REGIONAL RISK ASSESSMENT FRAMEWORK.

Traditionally, Regional Risk Assessment (RRA) aims at providing a quantitative and systematic way to estimate and compare the impacts of environmental problems that affect large geographic areas (Hunsaker et al., 1990). In more detail, 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). Accordingly, the RRA approach concerns the use of Multi Criteria Decision Analysis (MCDA) in order to estimate the relative risks in the considered region, compare different impacts and stressors, rank targets and exposure units at risk, and select those risks that need to be investigated more thoroughly.

In order to provide a RRA methodology for the integrated assessment of climate change impacts on coastal systems, this Chapter includes an introduction to the general objectives and functionalities of the RRA and of the potential stakeholders of the methodology (Paragraph 3.1); a description of the risk conceptual framework (Paragraph 3.2); and finally an overview about the climate change impacts considered by the RRA (Paragraph 3.2).

3.1 Objectives, functionalities and potential stakeholders.

The main objectives of the Regional Risk Assessment methodology could be resumed as follows:

1. Identification and prioritization of targets and areas at risk from climate change in the considered region;
2. Identification of homogeneous areas (i.e. homogeneous geographic sites for the definition of adaptation and management strategies) resulting from the aggregation of multiple climate change stressors and vulnerable exposure units;
3. Definition of the consequences (or impacts) of future climate on vulnerable or climate-sensitive exposure units and receptors;
4. Help decision-makers in examining the possible risks and damages associated with uncertain future climate and in identifying where adaptation to climate change may be required.

Moreover, the RRA methodology offers a wide range of functionalities to support the analysis of different issues that affect coastal zones in relation to climate change. The main functionalities are the following:

- Provide Source-Pathway-Receptor-Consequence risk frameworks;
- Provide regional climate change hazard scenarios using the output of numerical models simulations, downscaling techniques and time series analysis;
- Transfer information about climate change impacts and risks for responding to stakeholders needs and challenges;
- Enable various stakeholders, governmental and non-governmental bodies and communities the implementation of appropriate adaptation actions;

- Use GIS tools to facilitate the visualization and the identification of coastal areas and receptors exposed to the risk of climate change;
- Provide a base for coastal zoning and land use planning considering long-term scenarios in an Integrated Coastal Zone Management (ICZM) perspective.

The functionalities offered by the methodology can support different stakeholders (e.g. municipalities, regions, policy makers, citizens) involved in the management of coastal zones in accordance with the Integrated Coastal Zone Management (ICZM) Protocol (COM, 2007). Specifically, stakeholders are potential end-users of information provided by climate change risk assessments and are representative of those public institutions which have a mandate for ICZM (Table 3.1).

RRA Stakeholders
Municipal, Province and Regional administrators;
Policy-makers;
Protected areas responsible;
Port authorities;
Coastal town citizens, owners of coastal properties or employee in coastal zones;
River basin authorities;
Ministry of Public Works and Transport;
Ministry of Environment.

Table 3.1.List of stakeholders involved in the coastal management and representing potential end-users of the RRA products (source: author of the thesis).

3.2 Risk conceptual framework.

The RRA approach proposed for the integrated assessment of climate change impacts on coastal communities and ecosystems is based on the conceptual risk framework shown in Figure 3.1.

In order to rank potential impacts, targets and areas at risk to climate change at the regional scale, the RRA methodology integrates two main components in the final risk estimate: climate change hazard and the vulnerability of the system.

Climate change hazard represent the physical manifestation of climatic variability or change that may cause the loss of life or social and economic disruption or environmental degradation (e.g. droughts, floods, storms, episodes of heavy rainfall ,sea-level rise inundation). Basic data supporting hazard analysis include numerical climate simulations running at the global and the sub-continental scale and simulations of cascading physical processes performed by high resolution numerical models for the region of concern (e.g. hydrodynamic, biogeochemical and hydrological models). Numerical models simulations used for the characterization of hazards are related to different scenarios of greenhouse gas emissions and aerosol (e.g. IPCC scenarios A1 or A1B) that reflect changes in major driving forces of environmental change (e.g., demography, economy, technology, energy and agriculture) (Nakicenovic et al., 2000). Moreover, numerical models' simulations are associated with specific time periods (e.g. short or long-term scenarios) reflecting the temporal interval analyzed during the simulation. Finally, useful information in constructing hazard scenarios include the analysis of observations and time series of climate parameters and extreme events. Based on the output provided by numerical models and/or time series analysis, it is possible to identify hazard metrics ($h_{k,s}$) that are the parameters used for the characterization of climate change hazard and therefore for the construction of exposure scenarios.

The second main component of RRA is vulnerability, that, according to UN-ISDR (2009), is considered as a multidisciplinary concept encompassing the site-specific characteristics of a community increasing its sensitivity to hazards' impacts (e.g. physical, social, economic, and environmental factors). More specifically, in the RRA framework (Figure 3.1), vulnerability assessment requires the analysis of four main categories of factors: susceptibility factors *(sf),* value factors (*vf*), attenuation factors (*af*) and pathway factors (*pf*). *sf* are used to determine the susceptibility of a receptor to climate change hazards. Susceptibility is mostly represented by geo-physical or ecological factors (e.g. geomorphology, sediment budget, vegetation cover) and corresponds to the degree to which a receptor is affected, either adversely or beneficially, by climate-related stimuli (IPCC, 2007a). Accordingly, *sf* denote the dose-response relationship between the exposure of a receptor to climate stimuli and the resulting effects (Füssel and Klein, 2006). *vf* identify relevant environmental and socio-economic values of the receptors that need to be preserved for the interest of the community (e.g. land use, fishing areas, population density). *af* are elements that attenuate the intensity of the hazard associated with an impact: for instance, an artificial structure (e.g. a dike) able to reduce the hazard related to a storm surge flooding or to coastal erosion. Finally, *pf* stands for physical characteristics of the receptors (e.g. elevation, distance from coastline) which determine the possibility that climate change hazards would occur and therefore will support the identification of potential exposure areas.

Within the RRA methodology, *af* and *pf* are aggregated with $h_{k,s}$ which is provided by numerical models and time series analysis through an exposure function that is used for the construction of exposure scenarios for the final risk estimation. *sf* and *vf* are aggregated by means of Multi Criteria Decision Analysis (MCDA) functions in order to have an estimation of the susceptibility to climate change and of the value of each receptor to be used in the final estimate of risk and in the damage evaluation.

The proposed RRA methodology requires the management of a huge amount of heterogeneous parameters regarding both climate change hazard analysis and vulnerability assessment. Geographic Information Systems (GISs) are used to manage, manipulate, process, analyze, map and spatially organize data to facilitate hazard, vulnerability and risk analysis. MCDA techniques are used to aggregate vulnerability and hazard parameters in order to evaluate and rank targets, areas and risks from climate change at the regional scale. Experts' opinions and judgments are integrated, directly or indirectly, at each step of the RRA process (i.e. from hazard characterization to risk assessment) and are particularly important for the selection of the aggregation functions and in the assignment of weights and scores to risk assessment parameters.

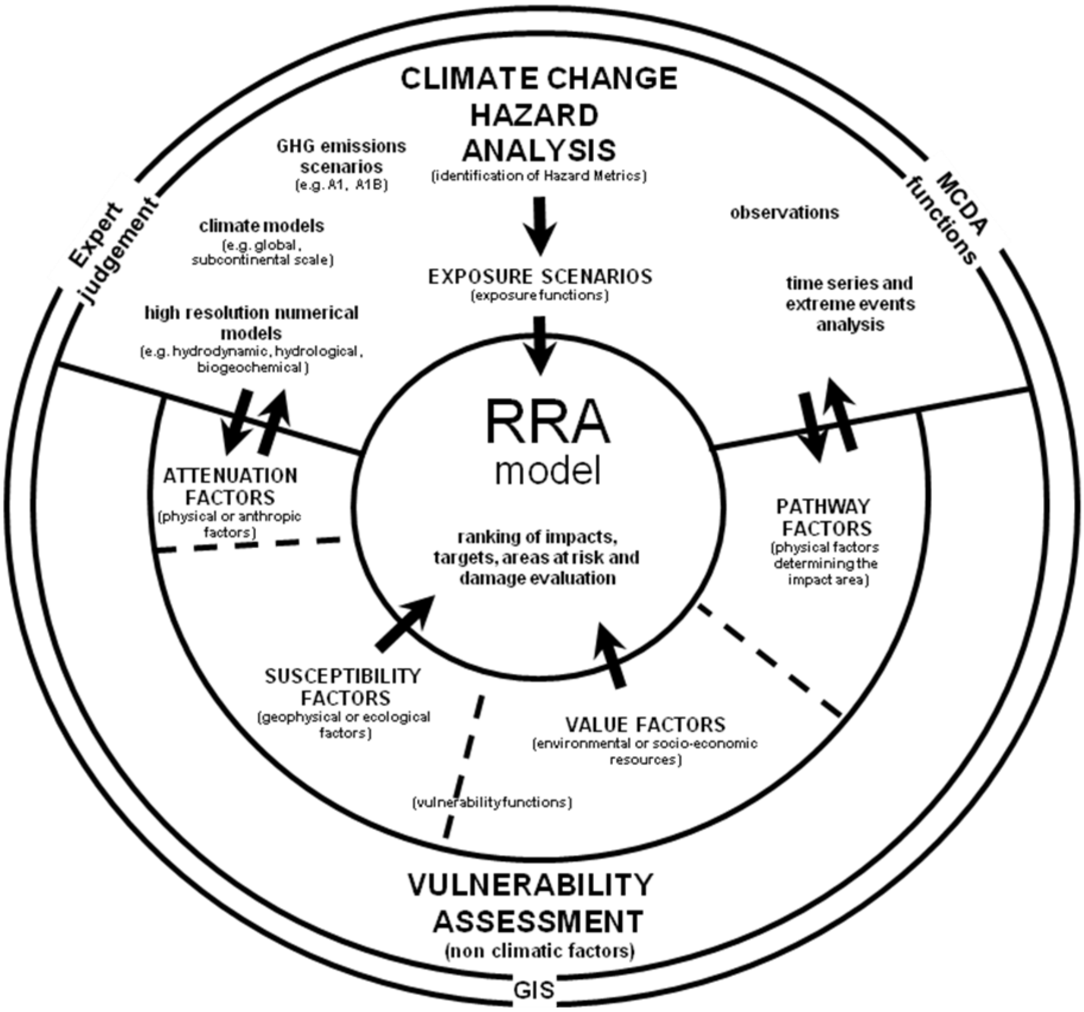


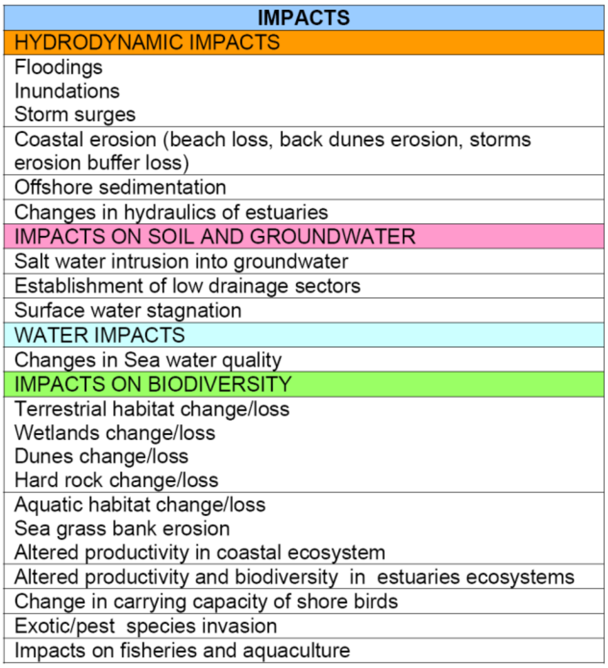
Figure 3.1. Regional Risk Assessment (RRA) conceptual framework (source: author of the thesis).

Finally, the proposed RRA conceptual framework represents a Source-Pathway-Receptor-Consequence (SPRC) framework (Ministry for the Environment of New Zealand, 2008) that considers multiple sources of hazards (i.e. climate change stressors) that may affect multiple receptors (e.g. beaches, wetlands, urban areas) through different patterns of pathways.

3.3 Description of coastal climate change impacts.

Due to coastal system complexity, impacts are mutually interrelated, therefore it is desirable to consider them as a whole in order to adopt an ecosystem approach in the risk assessment. Avoiding sectoral approach in favour of an ecosystem approach is also one of the guiding principles of European and Mediterranean ICZM Policy (Protocol on ICZM in the Mediterranean; COM(2000)547 final). Figure 3.2 includes the inventory of the main impacts that the RRA methodology can consider. These impacts are grouped in categories and regard different physical and biophysical aspects of coastal ecosystems.

In more detail, categories identified regard hydrodynamic impacts (e.g. storm surges and inundations phenomena, coastal erosion), impacts on soil and groundwater (e.g. surface water drainage and saltwater intrusion), impacts on water (water quality variations) and impacts affecting the biological component (e.g. impacts on vegetation and wetlands, on ecosystem productivity and on fishery and aquaculture).



IMPACTS
HYDRODYNAMIC IMPACTS
Floodings Inundations Storm surges
Coastal erosion (beach loss, back dunes erosion, storms erosion buffer loss)
Offshore sedimentation
Changes in hydraulics of estuaries
IMPACTS ON SOIL AND GROUNDWATER
Salt water intrusion into groundwater
Establishment of low drainage sectors
Surface water stagnation
WATER IMPACTS
Changes in Sea water quality
IMPACTS ON BIODIVERSITY
Terrestrial habitat change/loss Wetlands change/loss Dunes change/loss Hard rock change/loss
Aquatic habitat change/loss Sea grass bank erosion Altered productivity in coastal ecosystem
Altered productivity and biodiversity in estuaries ecosystems
Change in carrying capacity of shore birds
Exotic/pest species invasion
Impacts on fisheries and aquaculture

Figure 3.2. List of all impacts linked to climate change in coastal areas individuated within the DSS framework (source: author of the thesis).

Moreover, as shown in Figure 3.3 the impacts identified in the framework are linked by a series of mutual interrelations. Hydrodynamic impacts on coasts (inundations, storm surges and erosion) are the main impacts from which other hydrodynamic impacts can derive far from the coastline (sedimentation offshore) and on estuaries (hydraulics variations), impacts on main land and on groundwater (e.g. establishment of low-drainage sectors, surface water stagnation, saltwater intrusion into groundwater) and impacts on the land biological system (terrestrial habitat change/loss and change in carrying capacity for shore birds). Linked to the latter ones, there are other impacts both on water quality and on biological water systems and wetlands (change and loss of aquatic habitat, exotic and pest species invasion, impacts on fisheries and aquaculture and altered productivity in estuaries ecosystems). The scheme in Figure 3.3 allows to gain a whole vision of the main potential climate change impacts on coastal areas and has to be taken in account in the scenario construction and the impact and risk assessment, in order to follow as much as possible an ecosystem approach.

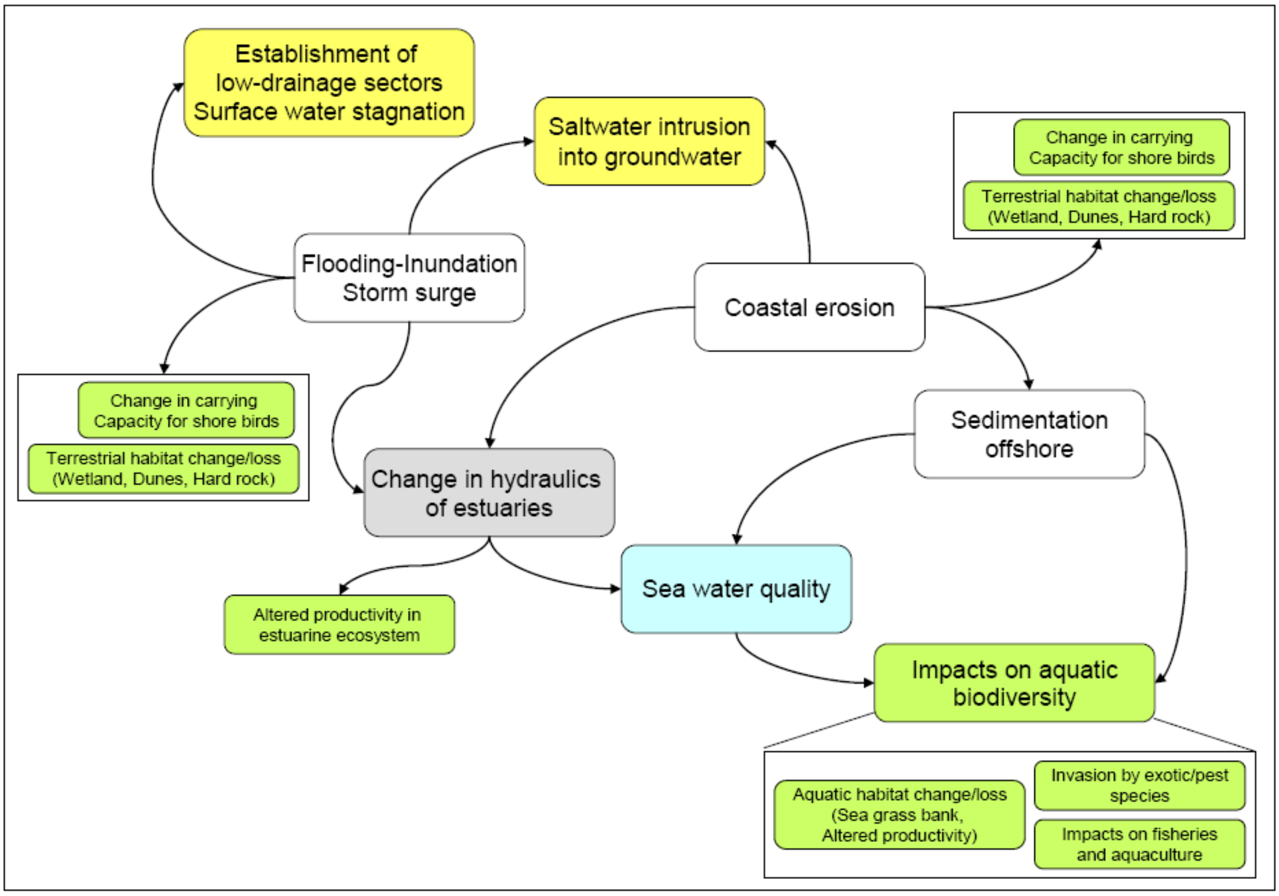


Figure 3.3. Scheme of the main relations identified among the investigated impacts in the proposed framework for integrated assessment of impacts and risks linked to climate change in coastal areas at regional scale (source: author of the thesis).

The regional risk assessment framework and methodology developed in this thesis are generally applicable to the assessment of multiple climate change impacts on coastal systems and on other systems intimately linked to them in an ecosystem perspective (e.g. aquifers, surface waters, river basins, estuaries, marine and terrestrial biodiversity) in order to respond to policy and decision-maker needs, legislative requirements, and guide the definition of adaptation strategies at the regional scale.

The main focus of this thesis is to investigate climate change impacts related to permanent inundation processes (i.e. sea-level rise and relative sea-level rise) and to coastal erosion processes. In particular, the methodology developed to study these impacts will be described in Chapter 4 and the results of its application for the case study area of the North Adriatic Sea will be reported in Chapter 7.

4. STEPS FOR THE APPLICATION OF THE REGIONAL RISK ASSESSMENT METHODOLOGY.

The Regional Risk Assessment (RRA) methodology requires several steps for its application, as it is shown in Figure 4.1.

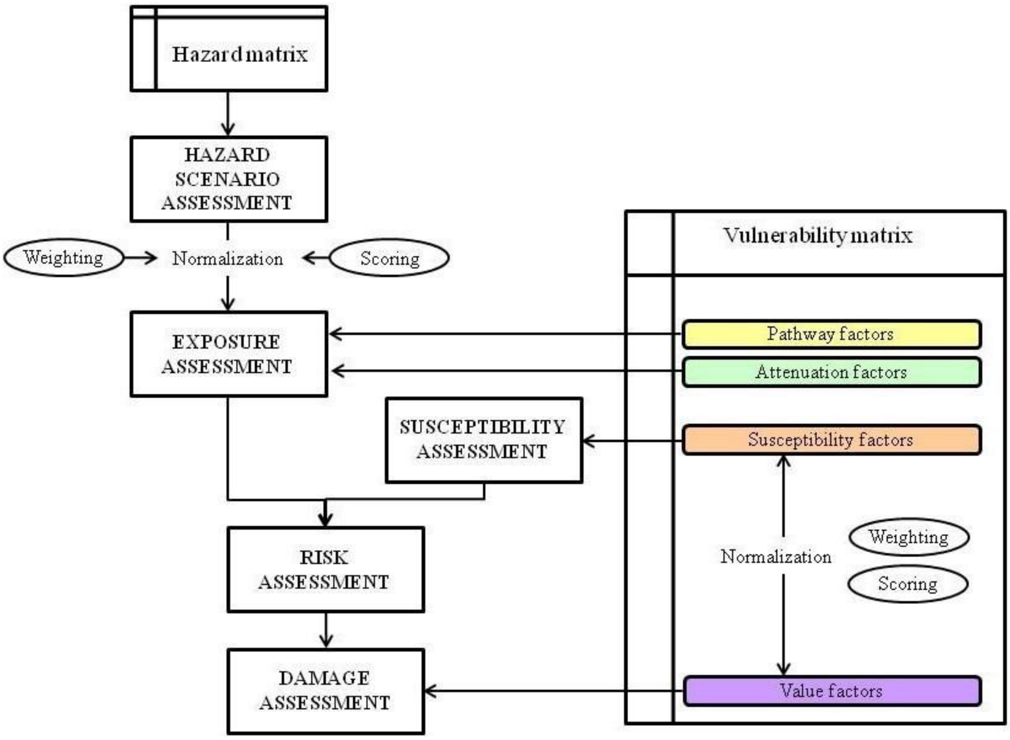


Figure 4.1. Steps for the application of the Regional Risk Assessment methodology (source: author of the thesis).

The hazard and the vulnerability matrixes are used to collect all the input data needed to apply the RRA and identify all the components contributing to the computation of risk in the case study area (i.e. stressors, impacts and receptors) and their relationships (Paragraph 4.1). Specifically, the hazard matrix allows identification of the stressors contributing in determining the investigated impacts and of the hazard metrics which are then used to characterize climate change hazard within the Hazard scenario assessment phase. The vulnerability matrix includes a subset of vulnerability factors representing physical, ecological and socio-economic indicators of the analyzed system. Vulnerability factors are first classified in pathway, attenuation, susceptibility and value factors and then employed in different stages of the RRA (i.e. exposure, susceptibility, damage assessment phases).

The first step for the implementation of the RRA is the Hazard scenario assessment (Paragraph 4.3) that is aimed at the characterization of climate change hazards that impact on a system. The second phase is the exposure assessment (Paragraph 4.3) that aims at identifying and classifying areas where the hazard can be in contact with the target (i.e. potential impacted areas). In this phase the hazard metrics can be normalized through the assignation of scores and weights and are aggregated with the pathway and attenuation factors using specific Exposure functions for each impact.

In order to provide an estimation of the susceptibility of the system to climate related hazards, the Susceptibility assessment phase requires the aggregation of susceptibility factors that are first normalized through the assignation of scores and weights and then aggregated by means of appropriate MCDA functions (Paragraph 4.4). The following Risk assessment phase (Paragraph 4.5) is aimed at identifying and classifying areas and targets at risk from different climate change impacts in the considered region. Accordingly, risk assessment integrates the information about the exposure to a given climate change hazard and about the susceptibility of a receptor to the examined hazard. Finally, the Damage assessment phase (Paragraph 4.6) aggregates the results of the Risk assessment phase with the assessment of the environmental and socio-economic value of a receptor, in order to provide a relative estimation of the potential social, economic and environmental losses associated with targets and areas at risk in the case study area (EC, 2007). The estimate of the receptors' value is performed aggregating the value factors, included in the vulnerability matrix and normalized through the assignation of scores and weights, by means of MCDA functions. The following paragraphs will describe in more detail each step of the RRA methodology.

4.1. Input data: vulnerability and hazard matrixes.

The first step for the implementation of the RRA methodology is the definition of the vulnerability and hazard matrixes which are used to collect all the input data needed to apply the RRA and identify all the components contributing to the computation of risk in the case study area (i.e. stressors, impacts and receptors) and their relationships.

Two examples of generic vulnerability and hazard matrixes for the regional assessment of the risks caused by climate change on coastal zones are reported in Appendix I. The main column of both vulnerability and hazard matrixes is an inventory of the main potential climate change impacts affecting coastal zones. This list include multiple interrelated impacts such as hydrodynamic impacts (e.g. storm surges and inundations phenomena, coastal erosion), impacts on soil and groundwater (e.g. surface water drainage and saltwater intrusion), impacts on water (water quality variations) and impacts affecting the biological component (e.g. impacts on vegetation and wetlands, on ecosystem productivity and on fishery and aquaculture).

The vulnerability matrix reported in Table IA of Appendix I represents a guideline for the identification of coastal receptors which could be affected by each climate change impact. Receptors represent important features within the exposure unit, or system at risk. They are natural or anthropogenic systems of interest due to ecological, economical, social reasons that are not equally affected by climate change hazards (UKCIP, 2003). Moreover, each cell of the vulnerability matrix includes a subset of vulnerability factors (i.e. pathway, attenuation, susceptibility and value factors) representing physical, ecological and socio-economic parameters/indicators relevant for the assessment of vulnerability related to each climate change impact. Pathway and attenuation factors are defined according to each climate change impact; susceptibility factors are defined based on the impact and receptor considered in the assessment; value factors, instead, are defined based on each specific receptor. A vulnerability factor can represent both a susceptibility and a value characteristic of the same receptor as it can describe both the degree to which a receptor could be affected by climate related stimuli, and relevant environmental and socio-economic values of the receptors that need to be preserved for the interest of the community.

The hazard matrix reported in Table IB of Appendix I is a tool supporting the construction of climate change hazard scenarios. In particular, a hazard matrix supports the user in the identification of those stressors that contribute to determine the investigated impacts and of the hazard metrics which can be used to construct hazard scenarios. Each climate change impact is caused by an ensemble of one or more stressors. A stressor can be defined as the cause of environmental hazard which impacts large geographic areas and can create a regional hazard to a population, species or ecosystems (Hunsaker et al., 1990). Each stressor can then be characterized by one or more metrics that are quantitative measures of climate variables deriving from statistical analysis of past measurement of weather, or from numerical models projections (UKCIP, 2003).

Hazard metrics are related to the considered impact and are variables that can change their values considering different emission scenarios (e.g. A1B) and timeframes (e.g. 2070-2100). Vulnerability factors are assumed as static values that represent the actual situation (reference scenario) and depend on the intrinsic characteristics of the territory.

The general vulnerability and hazard matrixes reported in Appendix I are flexible tools that needs to be adapted to the user purposes, to the specific case study context and according to the available data.

4.2. Hazard scenario assessment.

At the international level, hazard scenarios are widely considered as a key tool for climate change impact and risk assessment (UKCIP, 2003).

Within the conceptual framework and the RRA methodology the hazard scenario assessment phase is aimed at defining climate change hazards that impact on a system. Accordingly, climate change hazard scenarios: i) determine the future conditions of hazard to climatic changes against which a system needs to adapt in order to keep its ecological or socio-economical functions; ii) identify homogeneous hazard areas that may result from the aggregation of multiple hazard metrics; iii) consider not only changes in the mean state of climate but also changes in climate variability and extremes. Therefore, useful information for the hazard scenario assessment phase can be derived from three main sources:

1) The output of high resolution impact models forced by downscaled climate models (e.g. the forecasts derived from hydrodynamic models forced by regional climate models).

2) Climate scenario downscaling approaches (e.g. statistical and dynamical downscaling).

3) The analysis of past measurement of climate variables (e.g. statistical techniques of trend analysis, the use of weather generator output or other model-derived output based on observed data, such as the analysis of the return period of extreme storm surge events).

In the first source includes high resolution models (e.g. dedicated hydrodynamic, hydrologic or biogeochemical models for the system of interest) that are nested with Global Climate Models (GCMs) and

Regional Climate Models (RCMs) in order to provide information about regional/local climate change stressors.

The second source refers to climate scenario downscaling techniques in order to make a link between the state of some variable representing a large scale and the state of some variable representing a much smaller scale. This step often involves the nesting of a high-resolution limited area climate model to a RCM in order to develop a local climate scenario. Finally, the third source regards the analysis of past measurement of climate variables that can be an useful tool to provide regional/local information for hazard scenarios construction in impact and risk assessment and in particular for the analysis of extreme events.

A key issue of the hazard assessment phase is to choose and use suitable statistics deriving from numerical models and analysis of past measurement of climate variables in order to construct scenarios representing potentially significant hazards related to climate change. Since models forecasts provide a huge amount of model output for a detailed temporal resolution (i.e. every 6 hours, or every day or every month), the risk assessor needs to define statistics which can properly describe the trend of the parameter under analysis, for a reference period of typically 30 years (e.g. 2070-2100). Metrics provided by models are usually defined according to their spatial and temporal domains. This implies that, for example, an average value may be defined:

- spatially – at a point in time (an instantaneous spatial average);
- temporally – over a defined time interval (e.g. a 30-year average value for a particular global climate model (GCM) or regional climate model (RCM) grid-box).

In general, examples of statistics associated with metrics for climate change risk assessment are (UKCIP, 2003):

- mean or average, mode or median of values determined over a particular period;
- cumulative (time-integrated) value;
- the frequency or probability of particular values or events including percentiles,
- the frequency or probability that values of variables will fall between particular bounds, or exceed a particular (often extreme) threshold;
- absolute maximum or minimum values that may be recorded, usually over a particular interval of time;
- measures of variance, standard deviation or standard error, or more complete descriptions in terms of probability distributions or functions.

Within the RRA methodology, the selected statistics representing hazard metrics associated with each climate change impact are employed in the construction of hazard scenarios and then used in the Exposure assessment phase (Paragraph 4.3) together with pathway and attenuation factors for the construction of exposure maps.

4.3. Exposure assessment.

The exposure assessment phase is aimed at identifying and classifying areas where the hazard can be in contact with the target (i.e. potential impacted areas) using Exposure functions.

The exposure functions $E_{k,s}$ are defined for each climate change impact k and can be applied for different hazard scenarios s that represents the spatial distribution of climate change hazards in a specific timeframe (e.g. 2050, 2100) under specific emission scenario (e.g. IPCC SRES A1 or A2, Nakićenovićet al., 2000).

Moreover, within the RRA model, the $E_{k,s}$ aggregates hazard metrics ($h_{k,s}$), allowing the characterization of the nature and magnitude of climate change related hazards, with attenuation factors (*af*) attenuating the intensity of the hazard associated with an impact k and pathway factors (*pf*) determining the possibility of contact between targets and climate change hazards.

Accordingly, the general Exposure function associated with an impact k and a scenario s is represented by Equation 1:

$$E_{k,s} = F(h_{k,s}, P_k, At_k) \qquad \text{Equation 1}$$

where:

$E_{k,s}$ = exposure score related to an impact k and a scenario s;

$h_{k,s}$= hazard score related to the impact k and scenario s;

At_k= attenuation score related to the impact k;

P_k= pathway score related to the impact k.

The function F used in Equation 1 is defined according to the specific impact and can derive from scientific literature or can be a MCDA function aimed at integrating the hazard metrics reported in the cells of the hazard matrix (Appendix I, Table I B) and the attenuation and pathway factors reported in the cells of the vulnerability matrix (Appendix I, Table I A).

The hazard metrics can be normalized with the assignation of scores and weights, if it is specifically required in the Exposure function (e.g. in the Exposure function of the coastal erosion impact). Specifically, hazard classes are related to hazard metrics and represent different intensity of hazard to climatic stressors associated with each impact. Classes can be categorical (e.g. presence or absence of a particular indicator or indicator type) or can derive from continuous data. In the first case, the classes and scores can be founded in literature, or can be expressed by expert judgement. In the second case, classes can also be accomplished by using some mathematical data based techniques such as dividing the frequency distribution for data into quintiles. The set of the classes can be defined by the following mathematical definition $Cl_i = \{C_{i,1}, \dots, C_{i,n}\}$.

To each class, a score is assigned from a minimum value (i.e. 0) to a maximum value (i.e.1), with minimum representing no hazard and the maximum value representing the higher class compared to the others

(Preston et al., 2008). Finally, intermediate scores between 0 and 1 are assigned by experts following the linguistic evaluations reported in Table II A of Appendix II. The set of the scores associate do hazard classes can be defined by the following mathematical definition $S_i = \{s_{i,1}, \ldots, s_{i,n}\}$.

Moreover, weights ($w_{i,k}$) can be assigned to hazard metrics to represent their relative importance in the estimation of the exposure associated with each impact.

In more detail, with the aim to evaluate the relative importance of each hazard metric within each impact, the expert assigns a set of weights in the range 0–1 according to the linguistic evaluations proposed in Table III A. Hazard metrics denoted with an apex (‘) are metrics which have already been classified and weighted according to the following equation for a general hazard metric $h_{k,s}$:

$$h'_{k,s} = s_{i,k}\, w_{i,k} \qquad \text{Equation 2}$$

where:

$h'_{k,s}$ = weighted hazard metric;

$s_{i,k}$ = score of the i-th hazard metric for the impact k;

$w_{i,k}$ = weight of the i-th hazard metric for the impact k.

In the following paragraphs, the exposure equations proposed to investigate the impacts related to Sea-Level Rise (SLR), Relative Sea-Level Rise (RSLR) inundation and Coastal Erosion (CE) will be presented and discussed. For impacts affecting the terrestrial environment (i.e. SLR, RSLR and CE) the exposure function is used to project the information provided by sea water models inland.

Finally, it is important to highlight that the Exposure functions do not quantify the hazard related to climate change in an absolute scale, on the contrary their objective is to establish a relative ranking within the potential impacted areas and geographically define higher-exposed locations which could help to target priority areas for the further risk and damage analyses.

4.3.1. Exposure function for the sea-level rise inundation impact.

SLR inundation impact is considered as the overflowing onto low-lying coastal areas caused by SLR. It involves inundation of normally dry land by brackish or saline water (Smith and Ward, 1998) and doesn’t include erosion phenomena due to SLR.

The main stressor considered in this impact is the SLR that can be defined as the increase of the sea level both globally and locally over a period long enough to average out transient such as waves and tides (IPCC, 2007a). The correspondent hazard metric is the SLR water level defined as the height reached by the sea over the considered “zero” elevation level: i.e. considering a SLR projection resulting from model output and calculated according to a chosen IPCC SRES scenario (e.g. A1B, A2, Nakićenović et al., 2000).

The main pathway factor pf_1 considered in this impact is the topography of the territory determining the elevation of each cell of the case study area (i.e. the geographical unit defined for the spatial analysis) above the mean sea level.

The objective of the Exposure function for the SLR inundation impact ($E_{slr,s}$) (Equation 3) is therefore to determine and rank potential areas inundated by SLR based on the quantity of water staying at the top of each cell according to the following equation:

$$E_{slr,s} = min\left(max\left(\frac{h_{slr,s}-pf_1}{s_1}, 0\right), 1\right) \qquad \text{Equation 3}$$

where:

$E_{slr,s}$= exposure score related to SLR inundation impact in scenario s;

$h_{slr,s}$= projection of sea-level rise water level according to scenario s (cm);

pf_1= elevation of the cell (cm);

s_1= threshold given by the decision maker. It represents the amount of water above a cell which generates the maximum exposure (cm).

The hazard metric ($h_{slr,s}$) corresponds to the metric SLR water level described before; the pathway factor (pf_1) represents the topography of the territory (i.e. the elevation of the cell) and determines if the considered area can be reached by the hazard SLR or not. Finally, s_1 is a threshold given by the decision maker (DM) in order to normalize the value of the exposure function in the 0-1 range and to define the maximum water quantity above each cell (e.g. 60 cm) over which the Exposure function assumes its maximum value. A DM can therefore establish case by case what is the water level of tolerance for his community.

The Exposure function proposed for the SLR inundation impact permits to assign to each cell of the case study area a score ranging between 0 (i.e. no exposure) and 1 (i.e. maximum exposure).If the cell is higher than the SLR water level, the exposure score associated with the cell will be zero. On the contrary the maximum exposure is defined if the amount of water above a cell is higher than the threshold provided by DM. Values between 0 and 1 quantify the amount of water quantity staying at the top of each cell.

4.3.2. Exposure function for the relative sea-level rise inundation impact.

RSLR occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence (IPCC, 2007a). Specifically, RLSR impact is considered as the overflowing onto low-lying coastal areas caused by SLR and vertical land movements (i.e. subsidence and uplift). In addition to the hazard metric and pathway factor used for the characterization of the SLR inundation impact (Paragraph 4.3.1), this impact considers as pathway factor the vertical land movements that can be defined as a gradual sinking or increasing of land with respect to its previous level (http://www.nwrc.usgs.gov/fringe/glossary.html).

The objective of the Exposure function for the RSLR inundation impact (Equation 4) is to integrate SLR model projections and literature data concerning the rate of subsidence/uplift of the case study area in order to rank potential inundated areas due to SLR and local vertical land movements that can increase (subsidence) or decrease (uplift) the exposure of the territory to the inundation.

To this aim, the Exposure function for the RSLR inundation impact is described by the following equation:

$$E_{rslr,s} = min\left(max\left(\frac{h_{slr,s}-(pf_1+pf_2\cdot\Delta t_s)}{s_1}, 0\right), 1\right) \qquad \text{Equation 4}$$

where:

$E_{rslr,s}$= exposure score related to RSLR inundation impact in scenario s;

$h_{slr,s}$= projection of sea-level rise water level according to scenario s (cm);

pf_1= elevation of the cell (cm);

pf_2= rate of the vertical land movements (i.e. uplift/subsidence) according to literature data (cm/year);

Δt_s= ($t_s - t_0$) time interval where t_s is the final year of the considered scenario s and t_0 is the initial year where the uplift/subsidence rate is applied (year);

s_1= threshold given by the DM. It represents the amount of water above a cell which generates the maximum exposure (cm).

The hazard metric ($h_{slr,s}$) corresponds to the SLR water level, the pathway factor (pf_1) represents the topography of the territory (i.e. the elevation of the cell) and determines if the considered area can be reached by the hazard. Moreover, the rate of the vertical land movements pf_2 is multiplied by the time interval (Δt_s) in order to obtain the future subsidence scenario and thus the height of the cell in the considered timeframe, according with Carbognin et al. (2009) and Lambeck et al. (2010). If pf_2 is positive, it means that there is an uplift of the cell; if it is negative it means that there is a subsidence process acting in the considered cell. Finally, s_1 is a threshold given by the DM in order to normalize the value of the exposure function in the 0-1 range and to define the maximum water quantity above each cell over which the exposure function assumes its maximum value.

The exposure function proposed for the RSLR inundation impact permits to assign to each cell of the case study area a score ranging between 0 (i.e. no exposure) and 1 (i.e. maximum exposure). If the cell is higher than the RSLR, then the exposure score associated with the cell will be zero. On the contrary the maximum exposure is defined if the amount of water above a cell is higher than the threshold provided by DM. Values between 0 and 1 quantify the amount of water quantity staying at the top of each cell.

4.3.3. Exposure function for the coastal erosion impact.

The rate of coastal erosion (CE) is influenced by many factors but it is largely driven by the natural forcing acting upon it. These are mostly hydrodynamic (i.e. waves and water levels), although other forces such as wind and rainfall can be additional causes of erosion (Colin et al., 2007).

To date, local factors (e.g. wind patterns, offshore bathymetric changes, reduced fluvial sediment input) and changing wave conditions have been the main causes of detectable, systematic CE. However, it is expected that sea-level rise and changes in storms and wave climate will begin to dominate coastal processes over the next few decades (IPCC, 2007a). Accordingly, current erosion hotspots would be expected to increase in size and magnitude, and new localized eroding areas would emerge (Australian Government, 2009).

At the International and European level (EC, 2004; Australian Government, 2009 and Sharples et al., 2009) the approach used for the evaluation of the impacts caused by CE focuses on the analysis of multiple parameters within a Radius of Influence of Coastal Erosion (RICE), that corresponds to the areas located within 500 m from the coastline.

In order to characterize climate change hazard the methodology considers the main hydrodynamic stressors that may contribute to determine erosion processes (i.e. increases in mean sea-level, changes in wave height and variations in the extent of sediments deposition at the sea bottom) under projected changes in climatological forcing (i.e. under a climate change scenario generated from Regional Climate Models).

In this way it is possible to identify and prioritize coastal areas and targets that could be potentially affected by coastal erosion in changing climate conditions following Equation 5.

$$E_{ce,s} = \begin{cases} 0 & if\ pf_3 \geq s_2 \\ \left(\otimes_{i=1}^{n} \left[h'_{ce,i,s}\right]\right)(1 - At_{ce}) \cdot d_1 & otherwise \end{cases} \qquad \text{Equation 5}$$

where:

$E_{ce,s}$= exposure score related to coastal erosion impact *ce* in scenario *s;*

pf_3= distance of the center of the cell from the sea (always ≥ 1 m);

s_2= threshold given by the DM (cm). It represents the distance of the center of a cell from the sea which represents the Radius of Influence of Coastal Erosion (RICE);

$\otimes$ = “probabilistic or” function (Kalbfleisch J. G., 1985) (see the Box 1);

$h'_{ce,1,\ldots,n,s}$= hazard metrics from 1 to n related to the coastal erosion impact [already classified and weighted in (0,1)];

At_{ce}= Attenuation related to the presence of artificial protections from erosion (see the Box 2);

d_1= Distance factor related to distance from the shoreline. It is calculated through an hyperbolic function (see the Box 3).

The exposure function for the coastal erosion impact is composed by 3 main components: the hazard component that aggregates the normalized hazard metrics ($h'_{ce,i,s}$), corresponding to the output provided by models (e.g. bottom stress and wave height), through the “probabilistic or” function (Box 1); the attenuation component (At_{ce}) aimed at defining the role of the attenuation factors (i.e. artificial protections) in decreasing the magnitude of the CE hazard (Box 2); and the distance component (d_1) that considers the distance from the coastline in the definition of the exposure areas.

The Exposure function proposed for the CE impact assigns to each cell of the case study area a score ranging between 0 (i.e. no exposure) and 1 (i.e. maximum exposure). If the distance of the cell from the sea (pf_3) is larger than s_2 (i.e. the area RICE) the impact will not reach the cell and there is no exposure (i.e. $E_{ce,s} = 0$). Otherwise the exposure score is defined considering the equation that aggregates hazard, attenuation and distance components in order to provide a score ranging between 0 and 1 to each cell inside the area RICE. If the cell with the higher hazard score (defined by the “probabilistic or” function) is near the coastline and is not protected by attenuation factors (i.e. the distance components assumes a score equal to 1 and the attenuation assumes a score of 0), then the exposure score associated with the cell will be 1. On the contrary if in a cell there are no hazards (i.e. hazards assume a score of zero) or there are high attenuation factors (i.e. attenuation score is equal to one) or the distance from the coastline is higher than s_2, then the exposure score associated with the cell will be zero. Values between 0 and 1 characterize a cell where all of the exposure components (i.e. hazard, attenuation and distance components) are not simultaneously at their maximum value (i.e. 1) and also neither one of them is in its minimum value (i.e. 0).

Box 1. “Probabilistic or” function (Kalbfleisch J. G., 1985)**.**

$$\otimes_{i=1}^{4}[f_i] = f_1 \otimes f_2 \otimes f_3 \otimes f_4 \qquad \text{Equation 6}$$

where:

f_i= i-th generic factor f

The “probabilistic or” operator can be evaluated as follow, due to the associative and commutative proprieties:

$f_1 \otimes f_2 = f_1 + f_2 - f_1\, f_2 = F_1$

$F_1 \otimes f_3 = F_1 + f_3 - F_1\, f_3 = F_2$

$F_2 \otimes f_4 = F_2 + f_4 - F_2\, f_4 = \otimes_{i=1}^{4}[f_i]$

The process can be repeated until evaluating all operands.

If just a factor (*f*) assumes the maximum value (i.e. 1) then the result of the “probabilistic or” will be 1. On the other side, f with low scores contribute in increasing the final “probabilistic or” score: the more is the number of low factor scores, the greater is the final score.

Box 2. Attenuation function for the Coastal Erosion impact.

$$At_{ce} = af_1 \qquad \text{Equation 7}$$

where:

At_{ce}= attenuation determined by the presence of artificial protections;

af_1= value of the attenuation factor related to artificial protections, ranging between 0 (i.e. no attenuation) and 1 (i.e. maximum attenuation).

If the attenuation factor af_1 assumes its maximum value (i.e.1, presence of artificial protections), the attenuation function At_{ce} will be 1, and according to Equation 5, the exposure will assume the score of zero (i.e. the cell is not impacted by the coastal erosion as the attenuation is maximum). Otherwise, if the attenuation factor af_1 is minimum (i.e. 0, absence of artificial protections), the attenuation function At_{ce} will be 0 and the exposure function will assume its maximum score according to Equation 5.

Box 3. Distance function.

The proposed distance function (*d*) assumes an hyperbolic trend according to the following equation:

$$\boldsymbol{d(g,k,b)}\frac{\mathbf{1}}{\mathbf{max}\left(\mathbf{1},\frac{g}{\left(\frac{b}{k}\right)}\right)}=\frac{\mathbf{1}}{\mathbf{max}\left(\mathbf{1},\frac{g\,k}{b}\right)}=\mathbf{min}\left(\mathbf{1},\frac{b}{g\,k}\right) \qquad \text{Equation 8}$$

where:

g= distance of the center of the cell from the sea (pf_3) for the exposure to the coastal erosion (cm);

k= constant that defines the slope of the hyperbolic function;

b= *s*t*, where:

> *s*= is a threshold given by DM. s_2= represents the distance of the center of a cell from the sea which represents the Radius of Influence of Coastal Erosion (RICE);
>
> *t* = is a constant used in order to establish where to cut the hyperbolic function. For the exposure to the coastal erosion *t*= 1.

In order to estimate potential risks associated with coastal erosion, the results of the exposure assessment phase will be integrated with the susceptibility assessment that provides information about other relevant factors contributing in determining coastal erosion impacts (e.g. lithology, geomorphology, littoral drift rates, sediment budgets, coastal slope).

4.4. Susceptibility assessment.

The Susceptibility assessment phase is aimed at evaluating the degree to which the receptors could be affected by a given climate change impact (e.g. SLR, SSF, CE) based on site-specific territorial information.

To this aim, the susceptibility assessment phase aggregates the susceptibility factors (*sf*) defined in the vulnerability matrix using a Susceptibility function based on MCDA methods.

Since in the coastal territory a spatial unit (i.e. raster cell) can be characterized by two or more receptors (e.g. a cell is both a beach and a protected area) the susceptibility function is applied to all the *sf* listed in the vulnerability matrix for the considered impact *k*. In this way, if a cell is both a beach and protected area, its susceptibility will be evaluated considering the contribution of all the *sf* related to the cell taken only once time (i.e. the union of the *sf* related to receptors beach and protected areas). Moreover, it is assumed that a given *sf* play the same role in determining the susceptibility of different receptors in relation to the analyzed impact *k* (e.g. the vegetation cover has the same importance in determining the susceptibility of beaches and protected areas to coastal erosion).

In order to apply the Susceptibility function that makes relative rankings of coastal areas and receptors more sensitive to climate change impacts, the susceptibility factors (*sf*) must be classified, scored and weighted taking into account the expert judgment. Specifically, susceptibility factor classes are determined by thresholds reflecting variations in the degree to which the receptors may be affected by a climate-related impact. Scores related to susceptibility factors represent different degrees of possibility to which the receptors could be affected by climate-related stimuli in consideration of different impacts. The attribution of scores to susceptibility classes is performed by experts trough the compilation of questionnaires (Appendix II Table II B), where the Susceptibility factor score vary in a range from 0 (i.e. no susceptibility) to 1 (i.e. maximum susceptibility). Finally, intermediate scores between 0 and 1 are assigned by experts/decision makers following the linguistic evaluations reported in Appendix II, Table II A.

Moreover, individual susceptibility factors can be weighted to represent their relative importance in the estimation of susceptibility associated with each impact. In more detail, with the aim of evaluating the relative importance of each susceptibility factor within each impact, the expert/decision maker assigns a set of weights in the range 0–1 according to the linguistic evaluations proposed in Appendix III, Table III A. For instance, if a susceptibility factor is considered as the most important for the estimation of susceptibility associated with a particular impact, then the expert/risk assessor will assign the weight 1. Otherwise, if a susceptibility factor is considered as not important for that impact, then the expert/risk assessor will assign the weight 0. Finally, if a susceptibility factor has an intermediate importance, then the expert/risk assessor should assign a weight between 0 and 1 according to the linguistic evaluations reported in Appendix III, Table III A. Finally, if there is a lack of knowledge about the relative importance of a susceptibility factor compared to the others, then the same weight (e.g. 1) should be assigned to all the susceptibility factors related to the investigated impact.

Accordingly, factors denoted with an apex (‘) are factors which have already been classified and weighted through the following equation for a general susceptibility factor $sf_{i.k}$:

$$sf'_{i,k} = s_{i,k}\, w_{i,k} \qquad \text{Equation 9}$$

Where:

$sf'_{i,k}$ = weighted susceptibility factor score;

$s_{i,k}$ = score of the i-th susceptibility factor for the impact k;

$w_{i,k}$ = weigh of the i-th susceptibility factor for the impact k.

After the normalization and weighing, the susceptibility factors are aggregated using a specific Susceptibility function. More specifically, the Susceptibility function aggregates the major geo-physical and ecological factors that may influence the response of the coastal receptors to a given climate change hazard using the MCDA function named “probabilistic or” (Kalbfleisch J. G., 1985), defined as follows:

$$S_k = \otimes_i^n \left[sf'_{i,k}\right] \qquad \text{Equation 10}$$

where:

S_k= susceptibility score of the cell to the impact k;

$\otimes$= "probabilistic or" function (see the Box 1);

$sf'_{i,k}$= i^{th} susceptibility factor score related to the impact k (already classified and weighted in [0,1]).

Applying the "probabilistic or" function (Equation 10), if just a susceptibility factor (sf) assumes the maximum value (i.e. 1) then the susceptibility score will be 1. On the other side, sf with low scores contribute in increasing the final susceptibility score: the more is the number of low susceptibility factor scores, the greater is the final susceptibility.

The susceptibility function is evaluated for each cell of the considered region aggregating all the $sf'_{i,k}$ of the impact k. If a cell is comprised in two or more receptors, its susceptibility will result from the aggregation of all the $sf'_{i,k}$ susceptibility factors taken only once.

In the RRA model the Susceptibility function is used in the Risk function in order to evaluate the risk score associated with each receptor considered in the case study area as described in paragraph 4.5.

4.5. Risk assessment.

The Risk assessment phase is aimed at integrating information about the exposure to a given climate change scenario and the territorial susceptibility, allowing identification and prioritization of coastal receptors and areas at risk from different impacts related to climate change in the case study area.

Regional risk scores are not absolute predictions about the risks related to climate change. Rather they provide relative classifications about areas and targets that are likely to be affected by climate change impacts more severely than others in the same region.

According to the framework proposed by UN-ISDR (2009), which considers the risk as the product between hazard (i.e. a potentially damaging event or activity) and vulnerability (i.e. conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards), the general function for the estimation of the risk ($R_{k,s}$) related to a impact k is the product between the exposure score $E_{k,s}$ (representing the exposure associated with a given climate change hazard scenario) and the susceptibility score (representing the degree to which a receptor is affected by climate-related stimuli), according to the following equation:

$$R_{k,s} = E_{k,s} \cdot S_k \qquad \text{Equation 11}$$

where:

$R_{k,s}$= risk score related to an impact k and scenario s;

$E_{k,s}$= exposure score related with the impact k in scenario s, according to Equation 1;

S_k= susceptibility score to the impact k, according to Equation 6.

Risk score varies from 0 to 1, in which 0 means that in an area there is no risk (i.e. there is no exposure or no sensitivity for the considered impact and scenario) and 1 means higher risk for the considered target/area in the considered region. The risk score could be associated with each receptor j considering the cells of the territory associated with that receptor. Finally, the Risk function allows the estimation of statistics (e.g. percentage of the territory associated with each risk class, percentage and surface of receptors at risk to a specific impact for each administrative unit) useful to support the DM in the definition of adaptation measures (e.g. coastal zoning and land use planning, beach nourishment and sea defence structures).

4.6. Damage assessment.

The Damage assessment phase aggregates the results of the Risk assessment phase with the assessment of the environmental and socio-economic value of a receptor, in order to provide a relative estimation of the potential social, economic and environmental losses associated with targets and areas at risk in the case study area (EC, 2007).

In order to estimate the Value (Vj) associated with each receptor, the value factors (vf) must be normalized and weighted through the assignation of scores and weights. Specifically, value factors must be first classified in order to reflect variations in the environmental or socio-economic value associated with each receptor. Then, scores in the 0-1 range must be assigned to each value class in order to represent the relative importance (i.e. the socio-economic or environmental value) of each single class compared to the others. The attribution of scores to value classes is performed by decision makers trough the compilation of questionnaires (Appendix II, Table II C). Finally, value factor scores must be weighted in order to represent the relative importance of each value factor in the estimation of the value associated with each receptor. The decision maker assigns a set of weights in the range 0–1 with the compilation of questionnaires (Appendix III, Table III C).

Accordingly, Value Factors denoted with an apex (‘) are factors which have already been classified and weighted through the following equation for a general value factor $vf_{i.j}$:

$$vf' = s_{i,j}\, w_{i,j} \qquad \text{Equation 12}$$

where:

vf' = weighted value factor score;

$s_{i,j}$ = score of the i-th factor for the receptor j ;

$w_{i,j}$ = weigh of the i-th factor for the receptor j.

Normalized value factor scores (vf') need to be aggregated in order to estimate the Value (Vj) associated with each receptor. Since it is assumed that environmental and socio-economic values are additive in determining the total value of a receptor, the Value function (V_j) proposed to aggregate value factor scores (vf') is a weighted sum according to the following equation:

$$V_j = \sum_{i=1}^{n}\left[vf'_{i,j}\right] \qquad \text{Equation 13}$$

where:
V_j= value score of the receptor *j*;
$fv'_{i,j}$ = i^{th} value factor score related to the receptor *j* (already classified and weighted in [0,1]);
n= number of value factors.

The value function is aimed at identifying and classifying relevant environmental and socio-economic values of the receptors that need to be preserved for the interest of the community (e.g. land use, fishing areas). The Value score vary in a range from 0 to 1. The score 0 identifies the areas of a receptor that have no relevant environmental or socio-economic value (i.e. the areas where the value associated with all the *vf* is null). The score 1 identifies the areas of the analyzed receptor that are characterized by the higher environmental or socio-economic value in the examined case study area. In the cases where there are no available data to identify value factors for the investigated receptors, the value function cannot be calculated. Since the value function aggregates scores and weights assigned by DM, the judgment would be subjective and related to the interest of the DM. In order to obtain a consensus between DMs, Group Decision Theory (Kiker et al., 2005) techniques could be applied to facilitate involvement, preference elicitation and consensus evaluation. Finally, the value score (V_j) associated with each target *j* is integrated with relative risk scores ($R_{k,s}$) estimated for each impact *k* and scenario *s*, through the following Damage function:

$$D_{j,k,s} = R_{k,s} \cdot V_j \qquad \text{Equation 14}$$

where:
$D_{j,k,s}$= damage score related to an impact *k* and a receptor *j* in the scenario *s*;
$R_{k,s}$= risk score related to impact *k* in scenario *s,* according to Equation 11;
V_j= value score of receptor *j,* according to Equation 13.

The Damage function vary from 0 to 1. It assumes the higher value when the risk is higher (i.e.1) and the value score is higher, and assumes the minimum value (i.e. 0) when the risk and/or the value is 0. Finally, in the other cases, the damage score assumes values in the range 0-1, allowing identification and prioritization of the potential losses associated with targets and areas at risk in the considered region and supporting the identification of areas which require prior adaptation actions to prevent impacts and risk related to climate change.

The damage score is calculated for all the cells of the examined region where the receptor *j* is located. In order to have an overall estimate of the damage associated with the receptor *j* for the impact *k* it is possible to calculate some statistics (e.g. percentage of the receptor associated with each damage class, percentage and surface of the receptor with higher damage scores for each administrative unit). These statistics can be useful to support the DM in the definition and prioritization of adaptation measures.

4.7. Regional Risk Assessment outputs.

The main output of the RRA methodology include GIS-based exposure, susceptibility, risk and damage maps that are calculated based on exposure, susceptibility, risk and damage functions described above.

These maps to establish relative priorities for intervention, to identify suitable areas for human settlements, infrastructures and economic activities, and provide a basis for coastal zoning and land use planning.

All the hazard metrics and the vulnerability factors reported in Appendix I are represented in raster GIS layers allowing analysis and visualization of their spatial distribution in the case study area. Thus, the outputs of the risk assessment are also raster maps (i.e. cell based maps) representing the spatial distribution of exposure, susceptibility, risk and damage in the examined coastal territory.

As shown in Figure 4.2, exposure maps identify and classify the areas where the hazard can be in contact with the target (i.e. potential impacted areas) and derive from the aggregation of climate change hazard scenarios (represented by single or multiple hazard metrics) with pathway and attenuation factors; susceptibility maps represent the spatial distribution of environmental and socio-economic susceptibility factors (e.g. land use, vegetation cover, coastal slope) and are derived from the aggregation of susceptibility factors; risk maps identify and rank areas and receptors at risk from climate change related impacts in the considered region; finally, damage maps derive from combination of risk and value functions and provide a relative estimation of the potential social, economic and environmental losses.

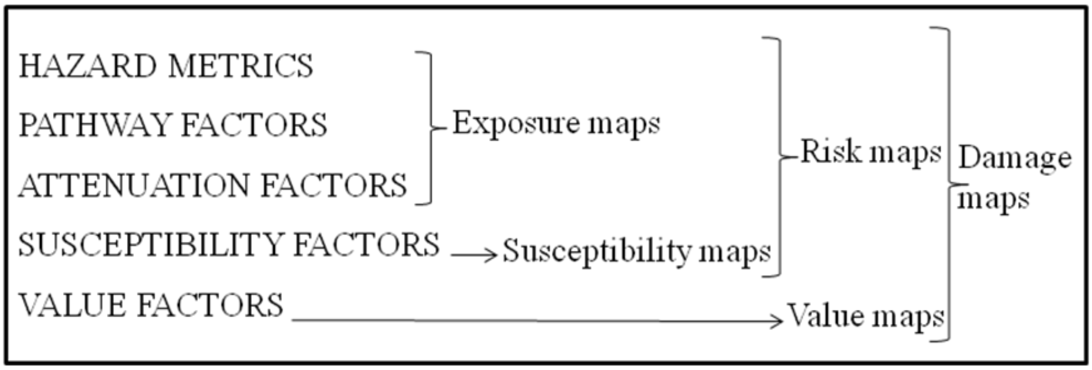


Figure 4.2. Output maps derived from the RRA methodology.

Specifically, exposure maps are related to different impacts *k* and to different scenarios *s*. Where the scenarios *s* are related to different time intervals (e.g. short-term or long-term temporal scenarios) and to different emission scenarios (e.g. IPCC SRES scenarios, Nakićenovićet al., 2000). Accordingly, the maximum number of exposure maps is *k***s*.

Susceptibility maps represent the spatial distribution of sensitivity in the considered region in relation to the impact *k*. The maximum number of susceptibility maps is therefore equal to *k*.

Moreover, considering that a risk map is derived from the product between exposure and susceptibility, the number of risk maps obtained for the analysed region is *k***s*. Using specific masks, representing the spatial location of each receptor in the analysed region, it is possible to visualise susceptibility and risk scores of the spatial unit (i.e. raster cells) included in each receptor. Finally, considering that a damage map is derived from the product between risk and value, the number of damage maps representing the spatial distribution of damage for all the analysed receptor is equal to *k***j***s*.

Section C

APPLICATION TO THE CASE STUDY AREA

5. DESCRIPTION AND CHARACTERIZATION OF THE CASE STUDY AREA.

The Regional Risk Assessment (RRA) methodology described in Chapter 4, was applied in this thesis to the coastal area of the North Adriatic sea. In particular, the analysis was focused on the evaluation of Sea-Level Rise (SLR), Relative Sea-Level Rise (RSLR) and coastal erosion (CE) impacts on multiple coastal receptors (i.e. beaches, wetlands, terrestrial biological systems, protected areas, urban areas and agricultural areas) at the regional/subnational scale.

Paragraph 5.1 introduces the case study area focusing on its natural, administrative and socioeconomic aspects. Emphasis is also given to the coastal issues that are associated with climate change threats in this area. Paragraph 5.2 depicts the available environmental and socio-economic dataset that was used as input to apply the RRA methodology.

5.1. The North Adriatic coastal area.

The area considered in the case study involves the coastal zone of Veneto and Friuli- Venezia Giulia regions, bordering the North Adriatic Sea with a overall length of about 286 km (Figure 5.1). The coast of the case study area runs along the Adriatic Sea from the national border between Italy and Slovenia to the mouth of the southern tributary of the Po Delta system (i.e. Po di Goro). From north-east to south-west, between the Slovenian border and the Timavo river mouth, the coast is high and rocky with few narrow beaches. In the rocky coast there can be found the gulf of Trieste and several bays (e.g. Sistiana bay). Moving southwards, from Monfalcone to the Po river delta the coast consists of low sedimentary shores. The overall continuity of the coast is interrupted by several river outlets (e.g. Tagliamento, Isonzo, Livenza, Piave, Brenta, Adige and Po) and lagoons (i.e. Marano, Grado and Venice lagoons and the lagoons of the Po river Delta). From a morphological point of view the sedimentary shores of the case study area include straight littoral coasts, lagoonal barrier islands, spits, river outlets and salt marshes.

Considering the administrative aspects, the case study area refers to the Friuli-Venezia Giulia Region, including 3 provinces and 8 coastal municipalities from the Slovenian border to Tagliamento river mouth; and to the Veneto Region, including 2 provinces and 10 municipalities from Tagliamento to Po river mouth.

The main coastal activities of the case study area are petrochemical industry, tourism, fishing, seaport/ port activities and ship traffics.

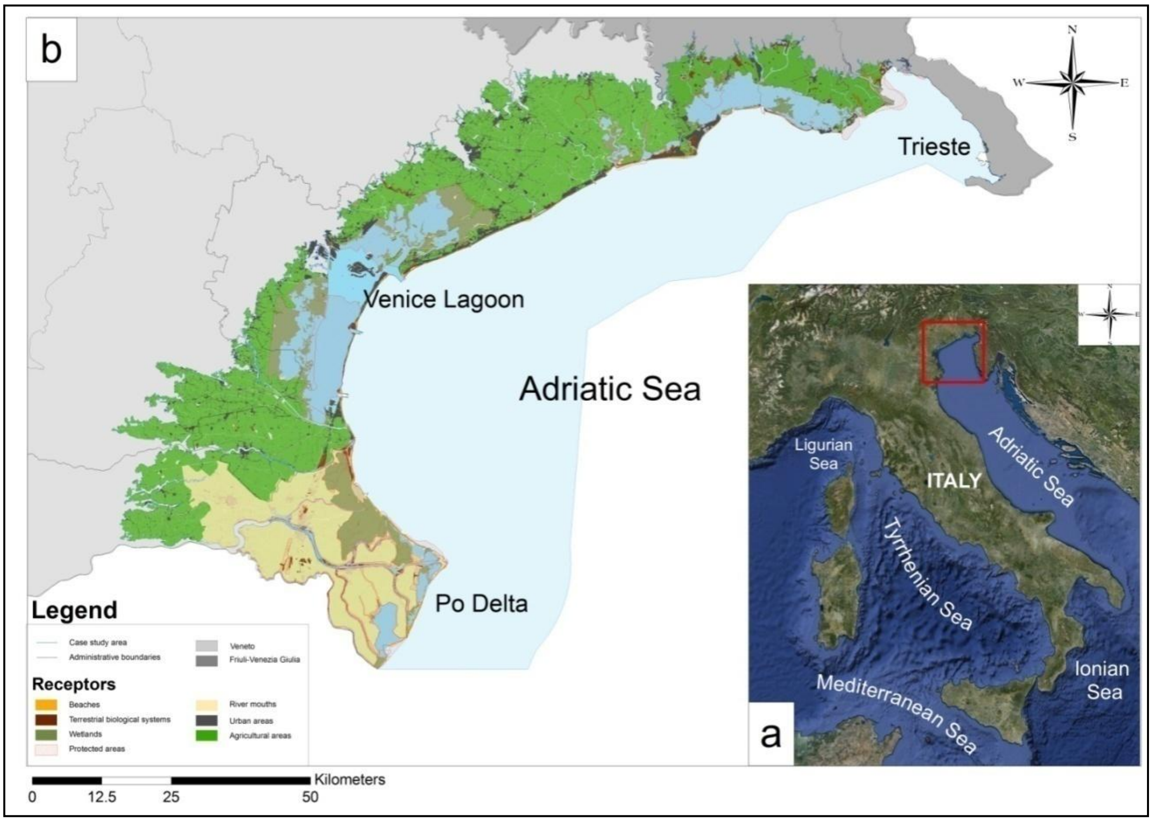


Figure 5.1. The case study area: a) the Northern Adriatic Sea (adapted from google maps: maps.google.it); b) the coast of the Veneto and Friuli Venezia Giulia regions (Italy).

On the whole, the Northern Adriatic Sea coast, comprises a very precarious coastal environment subject to continuous morphological changes that can be appreciable even over short geological time scales (Gambolati and Teatini, 2002). Moreover, erosion is still active in many areas both on the coastal sea floor and on the beach since the beginning of the 20th century and especially after 1960 (Bondesan et al., 1995). Many areas, particularly around the Po river Delta, are also located below the mean sea level and affected by natural or man-induced subsidence (Pirazzoli, 2005). Furthermore, the municipality of Venice has been experiencing an increase of high tide events with consequent flooding of the city (www.comune.venezia.it).

In Mediterranean sea rates of sea-level rise for the three longest tide-gauge stations ranged from 1.1 mm/yr to 1.3 mm/yr (Tsimplis and Spencer, 1997). However, spatially the change is not uniform and in the North Adriatic sea the observed sea level rate can vary from 1,2 mm/yr in Trieste to 2,5 mm/yr in Venice (Antonioli et al., 2007).

Therefore, climate change and sea-level rise is a prominent issue for the case study area both considering the vulnerability of fragile ecosystems such as coastal lagoons, and the concentration of cultural and socio-economic values.

Even if in recent years several studies were produced to evaluate potential impacts of storm surge and sea-level rise on the coasts of the Northern Adriatic sea (Bondesan et al., 1995; Gonella et al., 1998; Gambolati and Teatini, 2002; Lionello, 2008), only few significant local sites (e.g. the lagoon of Venice) were investigated with good detail. Existing studies were also often targeted to the analysis of specific physical processes (e.g. morphological evolution of deltas and transitional environments in response to sea-level rise) without considering other important factors contributing to coastal vulnerability to climate change such as distribution of coastal assets, inhabitants and ecosystems (Fontolan, 2001; Seminara et al., 2005; Ferla et al., 2007; Simeoni et al., 2007).

The complexity of the problems linked to climate change and the importance of natural and socioeconomic aspects in the study area ask instead for a broader integrated approach.

Accordingly, the RRA methodology proposed in this thesis is an innovative approach not only with respect to the spatial scale of analysis (e.g. the whole coastal area of the North Adriatic Sea), but also for the multi-disciplinary and integrated approach that takes into account downscaled climate change processes (e.g. sea-level rise, changes in currents and wave climate) to characterize climate change hazards at the regional scale; and biogeophysical and socio-economic factors (e.g. altimetry, geomorphology, land use and vegetation cover) to determine the susceptibility of the territory to climate change impacts and risks.

5.2. Available dataset.

The assessment of climate change impacts at the regional scale involves the collection of a huge amount of data in order to characterize spatially the targets of the analysis (e.g. beaches, wetlands, agricultural areas etc.) and define vulnerability indicators (i.e. susceptibility factors, attenuation factors, value factors and pathway factors) to be included in the vulnerability matrix (paragraph 4.1). Consequently, a survey of available information regarding physical, socio-economic and ecological features of the case study area was performed for the North Adriatic coasts.

Available data were provided by various public institutions in graphic format or database, and include: a 5 meters Digital Elevation Model (DEM) supplied by Veneto Region and a 10 meters DEM supplied by Friuli Venezia Giulia Region; the digital Corine Land Cover (CLC2000) database (e.g., wetlands, vegetation cover, hydrological systems, dunes) (http://www.clc2000.sinanet.apat.it/cartanetclc2000/clc2000/prodotti.asp); a list of Natura 2000 sites (i.e., ZPS and SIC areas) supplied by regional authorities; coastal data included in the geographic coastal information system (e.g., coastal morphology, sediment budget, artificial protections) implemented by the Italian Environmental Protection Agency (APAT, now called ISPRA; http://www.mais.sinanet.apat.it); technical regional maps supplied by the Veneto and Friuli Regions (www.regione.veneto.it /Ambiente+e+Territorio/; www.regione.fvg.it/rafvg/territorioambiente); and finally administrative boundaries of coastal municipalities and provinces furnished by regional authorities.

For the assessment of coastal vulnerability to sea-level rise at the regional/sub-national scale it would be of course preferable to use the higher spatial resolution and high vertical accuracy topographic datasets (i.e. high resolution data obtained by Light Detection and Ranging techniques (LIDAR). However, this was not totally feasible for the study area of concern, because only limited areas (i.e. the littoral zone of the Po River Delta and of the Venice lagoon) hold a free access LIDAR database. Consequently, the present analysis was done using the most detailed digital topographic dataset available for the whole coast of Veneto and Friuli Venezia Giulia (i.e. DEM with a horizontal resolution of 5 and 10 m respectively). With future improvements of available topographic data, a revised estimation of the potential impacts of sea-level rise would be possible and necessary.

Table 5.1 shows the dataset that was collected and used for the present study organized in the following fields: dataset, spatial domain and source.

Dataset	**Spatial domain**	**Source**
Contour lines 1:5000	FVG	FVG, 2006a
5m Digital Elevation Model (DEM)	VE	VE, 2006
Hydrologic basins: rivers and channels 1:25000	FVG	FVG, 2000
Corine Land Cover, 1:100.000	FVG	APAT, 2000
	VE	APAT, 2000
Land use, 1:25000	FVG	FVG, 2000a
Protected Areas, 1:150.000	VE, FVG	VE, 2005a, FVG, 2000b
Geographic Coastal Information System (SIGC)	Italy	APAT, www.mais.sinanet.apat.it/ cartanetms/coste/
Geologic and Geomorphological Map of the Po river delta, 1:50000	Po river Delta	Veneto Po Delta Regional Park Autority, 2002
Map of roads	North Adriatic	ESRI, www.esri.com/data/download/ basemap/index.html
Main cities	FVG	FVG, 2006b
Buildings (houses, industries, etc.)	FVG	FVG, 2006c
Administrative unit boundaries	VE	VE, 2005b
	FVG	FVG, 2006d
Location of primary rivers	VE	APAT, www.mais.sinanet.apat.it/ cartanetms/
	FVG	FVG, 2000
Satellite imagery	NA	http://image2000.jrc.it/
Population density data	VE, FVG	ISTAT, 2010
Vertical land movements	VE	Carbognin et al., 2009

Table 5.1. Available datasets in the case study area (i.e. the North Adriatic coasts). FVG = Friuli Venezia Giulia Region; VE = Veneto Region.

6. THE MULTI-MODEL CHAIN APPLIED TO DEFINE CLIMATE CHANGE HAZARD SCENARIOS IN THE NORTH ADRIATIC COASTAL AREA.

This Chapter is aimed at describing the numerical models chain applied to study climate change impacts on the coastal area of the North Adriatic Sea at the regional scale, the models involved in the chain and, finally, at summarising the information provided by the models for the construction of climate change hazard scenarios.

6.1. Chain of numerical models applied to the North Adriatic Sea.

In order to provide suitable information for the characterization of potentially significant hazard scenarios at the regional scale and build climate change hazard maps to be used in the risk assessment, a chain of models was set up for the study area of the North Adriatic Sea. The model chain was developed in the framework of the CMCC-FISR project (www.cmcc.it) and includes different types and spatial scales of numerical models simulating relevant circulation and morphodynamic processes recognized as influencing climate change impacts on coastal areas. Starting from Global Climate Models (GCMs) and Regional Climate Models (RCMs) representing the main atmosphere and ocean dynamics and covering large spatial domains (i.e. from the global to the sub-continental scale), the chain of models includes a suite of higher resolution impact models able to simulate ocean dynamics and circulation processes in coastal waters, with a spatial domain ranging from the sub-national/regional to the local scale.

Models included in the models chain were supplied by partners involved in the CMCC-FISR project that are: the National Institute of Geophysics and Volcanology (INGV) and the Marine Science Institute (ISMAR) of the Italian National Research Council (CNR). Figure 6.1 represents the models chain applied for the North Adriatic case study in its main components and interrelationships. As shown in Figure 6.1 the model chain is forced by the IPCC SRES scenario A1B that provides the climate forcing in terms of atmospheric concentrations of greenhouse gases (GHGs), ozone and aerosols (Nakićenović et al., 2000). The A1B scenario belongs to the A1 storyline family, which describes a future world of very rapid economic growth. In this potential future, global population peaks mid-century and declines thereafter, and new and more efficient technologies are rapidly introduced. Moreover, the A1B scenario predicts carbon dioxide emissions increasing until around 2050 and then decreasing, and it assumes a balanced emphasis between fossil fuels and other energy sources. The A1B climate forcing represent the input for the GCM and the nested RCM. The output of the RCM are used directly to construct downscaled climate hazard scenarios for the case study area (i.e. scenarios of temperature, precipitation and wind variations) and then represent the input for the suite of impact models running at higher resolution (i.e. from the Adriatic to the North Adriatic scale). In Figure 6.1 the impact models are represented by hydrodynamic and wave models that are used to investigate sea-level rise and coastal erosion hazards.

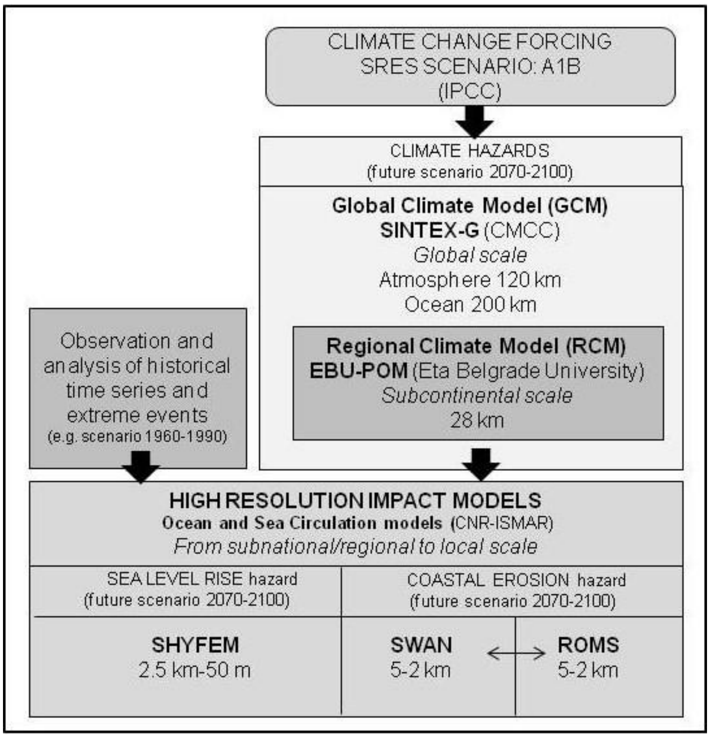


Figure 6.1. The multi-model chain applied to define climate change hazard scenarios in the North Adriatic coastal area. Names in brackets refer to partners who applied each model.

In addition to the climate forcing (i.e. the output of GCMs and RCMs.), impact models employ also time series analysis as input data. Specifically, in order to calibrate the model outputs and analyse the extreme event trends the impact models use an observation dataset related to the reference period 1960-1990.

The construction of a model chain is an effective way to supply relevant information about climate forcing and cascading processes ranging from the global/subcontinental scale to the regional/local scale. As shown in Figure 6.1, the information provided by high resolution impact models is used to investigate climate change hazards at a suitable spatial resolution for impact and risk assessment (i.e. from 5 km to 50 m) and for a future temporal scenario (i.e. the thirty year period 2070-2100).

The models included in the model chain belong to the following main categories:

- climate models (SXG, EBU-POM);
- ocean and sea circulation models (SHYFEM, ROMS);
- a wave model (SWAN).

The models included in the model chain were also classified according to the different hazard category investigated (i.e. climate hazards, sea-level rise hazards and coastal erosion hazards). For each hazard category, the following paragraphs will describe in more detail each model used in the model chain, its specific characteristic and the outputs used for the construction of hazard scenarios at the regional/local scale.

6.2. Climate hazard.

Models used for the characterization of climate hazard in the RRA are basically climate models that are mathematical representations of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedbacks (ukclimateprojections.defra.gov.uk). Global Climate Models (GCMs) are three dimensional numerical models that solve the equations for fluid motion and energy transfer around the globe and integrate these forward in time. Coupled Atmosphere-Ocean Global Climate Models (AOGCM) are complex climate models which involve coupling comprehensive three-dimensional atmospheric general circulation models within ocean general circulation models, with sea-ice models and with models of land-surface processes (ukclimateprojections.defra.gov.uk).

In order to provide information at sub-continental level, Regional Climate Models (RCMs) are used to model climate at a higher resolution for a finite area, driven by the boundary conditions of the GCM (ukclimateprojections.defra.gov.uk). On the whole, climate models provide information about many climate variables such as air and water temperature, wind and precipitation.

As shown in Figure 6.1, the climate models used in the model chain are: SINTEX-G (SXG) (Gualdi et al., 2008) and EBU-POM (Djurdjevic and Rajkovic, 2007). The main aim of these models is providing simulations of the evolution of climate variables at global and subcontinental scale respectively.

SXG is a global climate model with a remarkably high horizontal resolution, suitable to produce long climate simulations and climate change projections (Gualdi et al. 2008). In particular, climate simulations of the 20th and 21st Centuries have been conducted, integrating the model with forcing agents, which include greenhouse gases (CO_2, CH_4, N_2O, and CFCs) and sulfate aerosols, as specified in the protocol for the 20C3M experiment and for the scenario experiments (e.g., A1B, A2, etc.) defined for the Intergovernmental Panel on Climate Change (IPCC) simulations (Nakićenović et al., 2000). The model comprises the oceanic component and the atmospheric component. The oceanic component is the reference version 8.2 of the Océan Parallélisé (OPA; Madec et al. 1998) with the ORCA2 global ocean configuration. The resolution is of about 2°x2°, with increased meridional resolutions to 0.5° near the equator, and 31 vertical levels, 10 of which lie in the upper 100 m of the ocean. The atmospheric model component is the latest version of ECHAM4 (Roeckner et al. 1996). ECHAM-4 considers variables like vorticity, divergence, temperature, surface pressure, water vapour, clouds water. In particular, model outputs refer to seasonal total precipitation values, wind velocity, seasonal change in temperature and evaporation. The spatial resolution of ECHAM-4 varies from about 600 to about 120 kilometres (Bauer and Wulfmeyer, 2009). This model is not used directly in the Hazard Scenario Construction but is indispensable because its outputs are used as input for the subcontinental climate model EBU-POM. In SINTEX-G, ECHAM-4 is implemented with a global spatial resolution of about 120 km.

EBU-POM is a subcontinental ocean-atmosphere coupled model, built from the union of two models: EBU (Eta Belgrade University) that deals with atmosphere at a spatial resolution of 0.125 degree (approximately 10 km) and 32 vertical levels, and POM (Princeton Ocean Models) that focuses on the ocean with a horizontal resolution of 4 km and with 21 vertical levels (Djurdjevic and Rajković, 2007). In the integration of these two components in the EBU-POM, energy and matter exchange and air/water interface have been considered by means of an appropriate software that takes in account the differences in the respective spatial resolution since the atmospheric component has a resolution roughly four times coarser than the oceanic one. The output given by the EBU-POM is provided at a subcontinental scale, which includes the Mediterranean Sea area with a spatial resolution of 0,25° (approximately 28 kilometres). EBU-POM outputs produce climate hazard scenarios that are necessary as boundary conditions for higher spatial resolution impact models as the circulation and wave models discussed below.

6.3. Sea-level rise hazard.

The model for the characterization of the sea-level rise hazard is the Shallow water Hydrodynamic Finite Element Model (SHYFEM) (Umgiesser et al, 2004), used to solve hydrodynamic equations in environments such as lagoons, coastal marine areas, estuaries and lakes. The model is made of several modules: hydrodynamic, transport and diffusion, sediment transport, swell and an ecologic module. The modules used in the model chain are the hydrodynamic and sediment and transport ones. The grid of SHYFEM is divided in triangles whose detail level varies from some kilometres in the Adriatic sea to 50 metres in the Venice lagoon (i.e. from the regional to the local scale).

The output for the hydrodynamic and sediment transport modules include water levels, current velocity, water temperature and salinity, percentage of submerged areas (e.g. wetland areas) during storm phenomena, bottom stress.

6.4. Coastal erosion hazard.

In order to define the coastal erosion hazard, the wave model Simulating WAves Nearshore (SWAN) and the ocean and sea circulation model Regional Ocean Model System (ROMS) were used in the model chain.

SWAN is a wave movement model that works in the North Adriatic Sea and in Venice Lagoon (Booj et al, 1999). It is used to forecast waves trend on coastal environments since it is based on the wave movements in deep waters, on the wind, the batimetry, currents and tides.

The input data of these model include a European wave phenomena set called ERA-40 (started in 1957 and ended in 2002) produced for all European seas with a spatial resolution of 0,5° (approximately 56 kilometres).

As reported by Wolf et al. (2000), the SWAN model employs these input data to calculate the total number of wave events and their significant heights, wave energy and frequency of occurrences, mean duration of extreme wave events with certain intensity and the return period of extreme phenomena of the coastline.

Output parameters are calculated for the North Adriatic Sea with a spatial resolution that varies between 2 and 5 km. However, while for the thirty-year reference period (1960-1990) daily data are provided for the whole model domain, for the future scenario (2070-2100) the outputs of SWAN were provided only for several reference stations (i.e. 17 stations along the coastline) that are representative of the whole model domain. All the outputs produced by the SWAN model are listed in Table 6.1 and can be used to determine impacts in coastal system such as storm surge, flooding, coastal erosion and offshore sedimentation.

ROMS is a three-dimensional, free surface, terrain following numerical model that solves finite-difference approximations of the Reynolds-averaged Navier-Stokes (RANS) equations using the hydrostatic and Boussinesq assumptions with a split-explicit time stepping algorithm (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008). More specifically, ROMS solves finite-difference approximations of the three-dimensional Reynolds-averaged equations for conservation of mass, momentum, and heat using a two-equation submodel for turbulent mixing (Sherwood et al., 2004). This model includes accurate and efficient physical and numerical algorithms and several coupled models for biogeochemical, bio-optical, sediment, and sea ice applications (https://www.myroms.org/).

As shown in Table 6.1 the output data of this model include: bottom stress along coastline and offshore, sea water temperature and salinity, currents velocity. All the outputs are provided as daily data for the simulations of the future scenario (i.e. 2070-2100) and the thirty-year reference period (i.e. 1960-1990). ROMS data are available for the North Adriatic Sea on a model grid with a spatial resolution ranging from 2 to 5 km both for the reference and the future scenario. However, the same 17 reference stations of the SWAN model were selected as representative of the whole model domain. This model can be used to determinate impacts in a coastal zone such as coastal erosion, offshore sedimentation and water quality variations. ROMS can run concurrently with SWAN (two-ways coupling) whereby currents influence the wave field and waves affect the circulation. Via a two way nesting with SWAN model, ROMS considers nearshore processes including wave-current interactions such as effects of wave breaking, sediment morphology and a wetting and drying algorithm. The resulting integrated model is capable to predict coastal circulation of water and sediments dynamics in many regions such as estuaries and from the shelf through the surfzone and to assess scouring in the proximity of coastal structures (Carniel et al., 2007). In the models chain, the output of the two integrated coupled models are forced with climate change forcing and include metrics like wave energy and height, altered currents, bottom stress, temperature and salinity.

6.5. Information available for the construction of hazard scenarios for the case study area.

With the aim to support the hazard scenario construction and summarize available information provided by the model chain, Table 6.1 summarizes the information provided by the North Adriatic multi-model chain according to the following fields: the models name, category, domain and spatial resolution, the type of hazard metrics provided as output of the models, and the investigated time scenario. Hazard metrics are the main parameters used for the construction of hazard scenarios in the RRA methodology. As shown in the spatial scale field, the model chain approach provided sufficiently detailed information (i.e. from 50 m to 5 km) for the characterization of climate change hazards at the regional/subnational scale. Within the RRA the information summarized in Table 6.1 is used to construct climate change hazard scenarios that represent the physical manifestation of climatic variability or change (e.g. changes in temperature and precipitation patterns, sea-level rise inundation, wave storms) and have the potential to cause environmental or socio-economic impacts.

Climate change hazard	Name	Category	Domain	Spatial resolution	Hazard Metrics	Time Scenario
Climate hazard	SINTEX G	Climate Model	Global	Atmospheric resolution 120 km Oceanic resolution 200 km	Air/sea temperature Atmospheric pressure Cloudiness Rainfall Relative humidity Salinity Winds	2070-2100
	EBU-POM	Climate Model	Mediterranean sea	28 km	Air/sea temperature Atmospheric pressure Cloudiness Rainfall Relative humidity Salinity Winds	2070-2100
Sea-level rise hazard	SHYFEM	Ocean and sea Circulation model	North Adriatic sea	2.5 km-50 metres	Bottom stress Salinity Sea temperature Submerged areas Current velocity Water levels	2070-2100
Coastal erosion hazard	SWAN	Ocean and sea circulation model	North Adriatic sea	From 5 to 2 km (17 reference stations)	Wave energy Wave direction Wave height Wave period	2070-2100
	ROMS	Ocean and sea circulation model	Adriatic sea	From 5 to 2 km (17 reference stations)	Bottom stress Salinity Sea temperature Water velocity	2070-2100

Table 6.1. Summary of information provided by the multi-model chain developed for the definition of climate change hazard scenarios on North Adriatic coastal areas in order to support the construction of climate change hazard scenarios.

7. APPLICATION OF THE REGIONAL RISK ASSESSMENT TO STUDY SEA-LEVEL RISE AND COASTAL EROSION IMPACTS.

This Chapter is aimed at describing the results obtained from the application of the Regional Risk Assessment (RRA) methodology to study sea-level rise inundation and coastal erosion impacts in the coastal zone of the North Adriatic sea.

According to the step by step procedure delineated Chapter 4, this Chapter describes the input data used in the analysis (paragraph 7.1); the construction of hazard scenarios (paragraph 7.2); the identification of areas potentially exposed to hazard (paragraph 7.3); the susceptibility assessment (paragraph 7.4); and finally the relative risk assessment and damage estimate (paragraphs 7.5 and 7.6).

7.1. Input data: vulnerability and hazard matrixes.

As it is explained in Paragraph 4.1, the first step for the implementation of the RRA methodology is the definition of the vulnerability and hazard matrixes which identifies all the components contributing to the computation of risk in the case study area (i.e. stressors, impacts, receptors) and their relationships.

This paragraph presents the vulnerability and hazard matrixes constructed for the case study area of the North Adriatic sea (Table 7.1 and Table 7.4). The matrixes were defined taking into account the main features of the examined area (paragraph 5.1) and based on the available dataset for vulnerability and hazard assessment (paragraphs 5.2 and 6.5).

The vulnerability factors included in the vulnerability matrix, classified into pathway, attenuation, susceptibility and value factors, are described in Table 7.2. The selection of vulnerability factors was performed taking into account the availability of homogeneous GIS data for the whole case study area (Table 5.1). The receptors included in the vulnerability matrix are defined in Table 7.3. While the impacts Sea-Level Rise (SLR) and Relative Sea-Level Rise (RSLR) inundation were considered to be relevant for all the receptors included in the vulnerability matrix (i.e. inland and shoreline receptors), the Coastal Erosion (CE) impact was analyzed only for the receptors that have the major potential to be affected by shoreline and ocean dynamics (i.e. beaches, river mouths, wetlands and protected areas).

RECEPTORS IMPACTS	BEACHES	RIVER MOUTHS	WETLANDS	TERRESTRIAL BIOLOGICAL SYSTEMS	PROTECTED AREAS	URBAN AREAS	AGRICULTURAL AREAS
HYDRODYNAMIC IMPACTS							
Sea Level Rise Inundation	- Elevation	- Elevation	- Elevation	- Elevation	- Elevation	- Elevation	- Elevation
	- Protection level	- Protection level	- Protection level	- Protection level	- Protection level	- Protection level	- Protection level
	- Population density	- Population density	- Population density	- Population density	- Population density	- Urban typology	- Population density
	- Urban typology	- Urban typology	- Urban typology	- Urban typology	- Urban typology	- Population density	- Urban typology
		- Agricultural typology	- Wetland extension	- Vegetation cover	- Agricultural typology		- Agricultural typology
Relative Sea Level Rise Inundation	- Elevation	- Elevation	- Elevation	- Elevation	- Elevation	- Elevation	- Elevation
	-Vertical land movements	-Vertical land movements	-Vertical land movements	-Vertical land movements	-Vertical land movements	-Vertical land movements	-Vertical land movements
	- Protection level	- Protection level	- Protection level	- Protection level	- Protection level	- Protection level	- Protection level
	- Population density	- Population density	- Population density	- Population density	- Population density	- Urban typology	- Population density
	- Urban typology	- Urban typology	- Urban typology	- Urban typology	- Urban typology	- Population density	- Urban typology
		- Agricultural typology	- Wetland extension	- Vegetation cover	- Agricultural typology		- Agricultural typology
Coastal erosion	- Distance from coastline	- Distance from coastline	- Distance from coastline		- Distance from coastline		
	- Artificial protections	- Artificial protections	- Artificial protections		- Artificial protections		
	- Vegetation cover	- Vegetation cover	- Wetland extension		- Vegetation cover		
	- Coastal slope	- Geomorphology	- Vegetation cover		- Geomorphology		
	- Geomorphology	- Sediment budget	- Geomorphology		- Sediment budget		
	- Dunes	- Protection level	- Sediment budget		- Protection level		
	- Sediment budget	- Population density	- Protection level		- Population density		
	- Protection level	- Urban typology	- Population density		- Urban typology		
	- Population density	- Agricultural typology	-Wetland extension		- Agricultural typology		

Table 7.1 Vulnerability matrix defined for the North Adriatic Coasts in order to apply the regional risk assessment.

Factor	**Definition**	**Data source**
Pathway factors		
Elevation (cm)	The height of a geographic location above Mean Sea Level.	VE,2006; FVG, 2006a
Vertical land movements (cm/years)	Uplift or subsidence of the land surface. They are related to geological (e.g. compaction of sediments, deformation of the substratum) and anthropogenic causes (e.g. removal of subsurface fluids) (Carbognin and Tosi, 2002).	Carbognin et al., 2009.
Attenuation factors		
Artificial protection	Artificial protections (e.g. dikes) for the defence of the coastline from storm surge and coastal erosion impacts.	APAT, www.mais.sinanet.apat.it/ cartanetms/coste/
Susceptibility factors		
Wetland extension	The extent of wetlands in square kilometres (km^2).	APAT, 2000
Vegetation cover	The typology of vegetation that cover an area (i.e. natural grassland and meadow, shrub, forest).	APAT, 2000; FVG, 2000a
Coastal slope	Average topographic slope (in degrees) along the coastline.	VE, 2006
Geomorphology	Geomorphologic structure of the coastal zone. It refers to muddy, sandy or rocky coast typology.	APAT, www.mais.sinanet.apat.it/ cartanetms/coste/
Dunes	It refers to the presence or absence of natural dunes.	APAT, 2000
Sediment budget	The balance between the supply of sediment (e.g., sand) to a shore and the erosion or removal of sediment from that shore.	APAT, www.mais.sinanet.apat.it/ cartanetms/coste/
Mouth typology	It refers to the type of river mouths (i.e. estuary, delta).	APAT, 2000
% of urbanization	The percentage of urbanized areas within each municipality.	APAT, 2000
Value factors		
Protection level	The typology of protection of an area defined by the European Community (e.g. Natura 2000, Site of Community Importance).	VE, 2005a; FVG 2000b
Population density (inhabitants/km^2)	The average number of people who live on each square kilometre of land.	ISTAT, 2010.
Urban typology	The typology of buildings (e.g. residential, commercial, infrastructures).	APAT, 2000
Agricultural typology	The typology of farming in an area (e.g. permanent culture, stable meadow, arable).	APAT, 2000
Wetland extension (km^2)	The extent in square kilometre of wetlands.	APAT, 2000
Vegetation cover	The typology of vegetation that cover an area (e.g. poor vegetation and meadow, vegetation with shrubbery, wood).	APAT, 2000

Table 7.2. Vulnerability factors identified for the North Adriatic coasts and included in the vulnerability matrix.

Receptor	Definition
Beaches	This receptor analyzes beaches and the vegetation associated with them. Furthermore it analyzes natural and artificial protections to limitate impacts. Sandy coastal areas are important for tourism, recreation and residential development (Voice et al 2006). Sand grade sediments are generally defined to be those predominantly composed of grains ranging between 0.06 to 2.0 mm diameter (Pettijohn 1973). In the coastal environment, unconsolidated sediments within this grain size range are highly mobile and small enough to be easily eroded and transported by waves, currents and winds that frequently act on most shorelines, in contrast to larger (pebble/cobble/boulder) particles that are only moved by very energetic waves and hardly at all by wind (Sharples 2006).
River mouths	This receptor includes estuaries and deltas. Specifically, it analyzes not only their morphological and ecological aspects but also the presence of artificial and natural protections. Estuaries are important receptors because they contain significant habitats including seagrasses, mudflats/sandflats, saltmarsh, reed, sedge and rush communities and provide sheltered habitat, nursery and spawning areas for fish, crabs, prawns and shellfish (Voice et al 2006). Delta is a landform where the mouth of a river flows into the sea. It builds up sediment outwards into the flat area which the river's flow encounters (as a deltaic deposit) transported by the water and set down as the currents slow. Deltas present high biodiversity and significant habitats.
Wetland	The wetland receptor includes coastal wetlands along with vegetation, animal life and artificial and natural protections located in wetlands areas. Wetland is an environment at the interface between truly terrestrial ecosystems and aquatic systems making them inherently different from each other yet highly dependent on both. (Mitsch, 2007). For the aims of this assessment the following categories were considered: inland wetlands, salt marshes and intertidal wetlands.
Terrestrial biological systems	This receptor includes animal and plant terrestrial life, their habitats and the ecological functions they provide. Specifically, terrestrial biodiversity encompasses the total variety of life forms including plants, animals and micro-organisms and the processes and ecosystems they form (EPA,2002).
Protected areas	This receptor includes areas with biological, morphological or historical sensitive aspects. Example of protected areas include: wetlands, marine areas, national parks, national heritage. They provide tourism income, fisheries breeding and spawning grounds, ecosystem protection and protection of historical locations. (Voice et al 2006). A protected area is defined as an area of land and/or sea especially dedicated to the protection and maintenance of biological diversity and of natural and associated cultural resources, managed through legal or other effective means. (UNEP-WCMC, http://www.unep-wcmc.org/protected_areas/index.htm).
Urban areas	This receptor includes areas cover by countries, residential areas, commercial zones and industries. It includes areas in which a majority of the people are not directly dependent on natural resource-based occupations (http://www.mhhe.com/biosci/pae/glossaryu.html). Specifically, it includes areas mainly occupied by dwellings and buildings used by administrative/public utilities or collectivities, including their connected areas; areas mainly occupied by industrial activities of transformation and manufacturing, trade, financial activities and services, transport infrastructures for road traffic and rail networks, airport installations, river and sea port installations, including their associated lands and access infrastructures; areas voluntarily created for recreational use (Bossard et al., 2000)
Agricultural areas	This receptor includes areas comprised of arable land, gardens and other perennial plants, meadows and natural pastures (http://regionai.stat.gov.lt/en/savokos.html#Agricultural%20land). It includes: arable land (lands under a rotation system used for annually harvested plants and fallow lands, which are permanently or not irrigated), permanent crops (all surfaces occupied by permanent crops, not under a rotation system), pastures (lands, which are permanently used for fodder production) (Bossard et al., 2000).

Table 7.3. Description of the receptors included in the vulnerability matrix and identified as targets of the regional risk assessment methodology applied to the North Adriatic coast.

The hazard matrix proposed to study SLR, RSLR and CE impacts is reported in (Table 7.4). Stressors and hazard metrics identified for each impact results from the analysis of the output provided by the chain of numerical models (Table 6.1). As shown in Table 7.4 the only hazard metric identified for SLR and RSLR is projected water level that is provided by the SHYFEM model (Table 6.1). Regarding the coastal erosion impact, the main hazard metrics selected for the case study application include bottom stress and wave height as provided by the ROMs and SWAN model that are forced with climate change forcing and sea-level rise projections (Paragraph 6.1).

HAZARD MATRIX			CLIMATE CHANGE IMPACTS
STRESSORS			
BOTTOM STRESS	SEA LEVEL RISE	WAVE	
			HYDRODYNAMIC IMPACTS
	Projected water level		Sea Level Rise Inundation
	Projected water level		Relative Sea Level Rise Inundation
Bottom stress		Height	Coastal erosion

Table 7.4. Hazard matrix for the construction of climate change exposure scenarios applied to the North Adriatic Coasts.

7.2. Hazard scenarios assessment.

The hazard scenario assessment phase is aimed at identifying and selecting suitable statistics for the hazard metrics identified in the Hazard matrix (Table 7.4), in order to construct scenarios representing potentially significant hazards that could determine climate change impacts.

Accordingly, the following paragraphs are aimed at explaining and discussing the representative statistics selected for the construction of climate change hazard scenarios related to the SLR, RSLR and CE impacts in the future temporal scenario 2070-2100. The hazard statistics and scenarios defined in this phase are employed in the Exposure assessment phase (Paragraph 4.3) in order to construct exposure maps for each investigated impact.

7.2.1. Sea-level rise hazard scenarios.

The hazard scenarios assessment for the sea-level rise inundation impacts (i.e. SLR and RSLR) is performed considering the outputs provided by the SHYFEM model for the future scenario 2070-2100 (Table 6.1).

Specifically, the selection of the more appropriate statistics to construct future SLR and RSLR scenarios was focused on the output provided by the SHYFEM model for the year 2100, as it represents the worse sea-level rise conditions (i.e. the more cautelative conditions) for the future thirty-year period.

As described in paragraph 6.1, the SHYFEM model supplied data about future water level projections for the whole Adriatic Sea, using as climate forcing the parameters supplied by the regional climate model EBU-POM (i.e. temperature, precipitation, winds). Moreover, the SHYFEM projections were performed imposing as boundary conditions at the Otranto strait two sea-level rise scenarios: a low sea-level rise scenario equal to 20 cm and a high sea-level rise scenario equal to 45 cm. The boundary conditions at Otranto were set considering the lowest and highest IPCC global sea-level rise projections for the year 2100 according to the emission scenario A1B (i.e. 21 cm and 48 cm respectively; IPCC, 2007b) and assuming a linear sea-level rise trend for the future period 2070-2100.

The results of this assessment include two SLR hazard maps: a low sea-level rise scenario hazard map representing the water levels projected by SHYFEM for the North Adriatic sea, according to a SLR at Otranto equal to 20 cm (Figure 7.1); a high sea-level rise scenario hazard map representing the water levels projected by SHYFEM for the North Adriatic sea, according to a SLR at Otranto equal to 45 cm (Figure 7.2. As shown in Figure 7.1 and Figure 7.2. , most of the area of the North Adriatic Sea (i.e. from Po river Delta to the Italy-Slovenia border) is characterised by a sea-level rise ranging from 0.164 m to 0.169 m for the low sea-level rise map and from 0.414 m to 0.419 m for the high sea-level rise map. Accordingly, the maximum range of variability is equal to 0.5 cm.

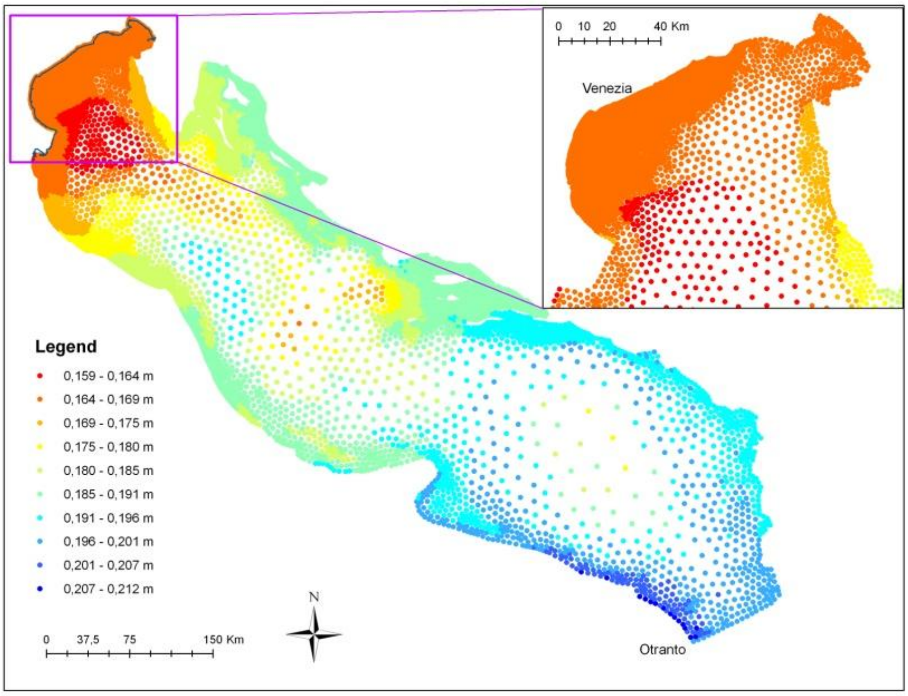


Figure 7.1. Hazard Map representing the Adriatic sea-level rise for the year 2100 (reference period 1960-1990). Sea-level changes are simulated by the SHYFEM model according to a SLR at Otranto of 20 cm (low scenario).

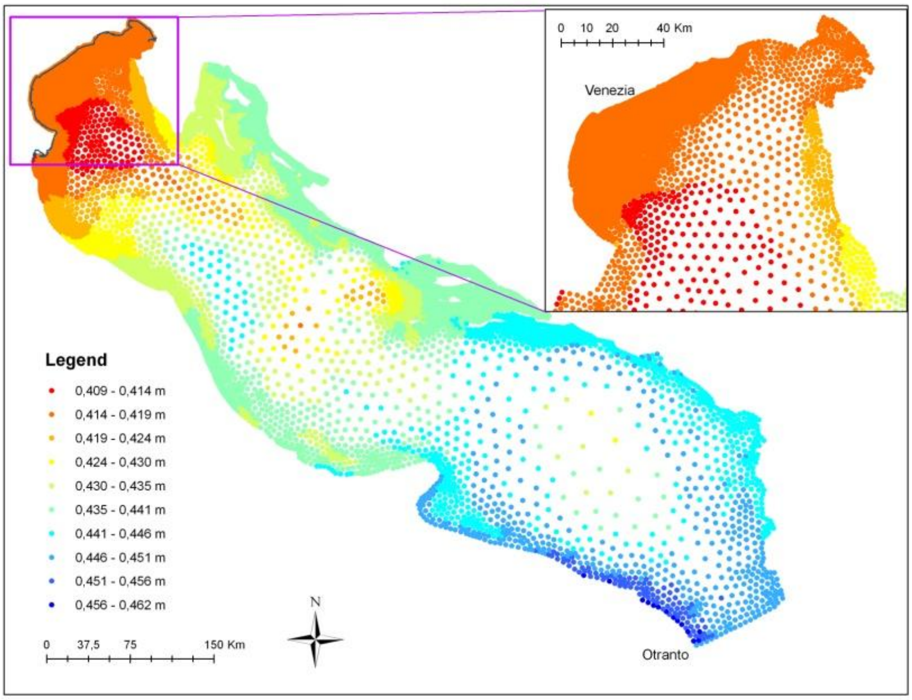


Figure 7.2. Hazard Map representing the Adriatic sea-level rise for the year 2100 (reference period 1960-1990). Sea-level changes are simulated by the SHYFEM model according to a SLR at Otranto of 45 cm (high scenario).

In order to determine a representative statistic to be used in the Exposure assessment phase for the SLR and RSLR impacts (Paragraph 7.3), a specific analysis was performed only to water level values corresponding to the dots adjoining to the shoreline of the case study area for the low and high hazard scenarios (Figure 7.1 and 7.2).

Table 7.5, shows the main statistics (i.e. minimum and maximum values, mean, range of variability and standard deviation) calculated from the SHYFEM simulations along the shoreline (i.e. dataset of about 1280 dots adjoining to the shoreline) for both the low and high sea-level rise scenarios.

Scenario	Minimum value (cm)	Mean value (cm)	Maximum value (cm)	Range (cm)	Standard deviation (cm)
Low Sea Level Rise	16,73	16,84	16,97	0,25	± 0.04
High Sea Level Rise	41,73	41,82	41,96	0,23	± 0.04

Table 7.5. Statistics applied to water levels projected by the SHYFEM model along the shoreline for the low and high sea-level rise scenarios.

Since the range of data variability and the standard deviation value are very low, the maximum value was selected as the more cautelative statistic for the projected water level and for the construction of SLR hazard scenarios for the entire case study area, both for the low and for the high sea-level scenarios. Accordingly, with an upper approximation, the hazard metrics values that will be used in the Exposure assessment phase corresponds to 17 cm for the low sea-level rise scenario and to 42 cm for the high sea-level rise scenario.

7.2.2. Coastal erosion hazard scenarios.

According to the model chain described in paragraph 6.1, the hazard scenarios for the CE impact are performed considering the emission scenario A1B (Nakićenović et al., 2000) and a long term temporal scenario corresponding to the thirty-year period 2070-2100. In particular, the construction of coastal erosion maps is based on the output provided by the ROMS and SWAN models (paragraph 6.4).

As described in Table 6.4, the ROMS and SWAN models can supply information about several variables that are relevant to study coastal erosion processes (i.e. bottom stress, water velocity, wave height and wave energy). However, in order to study the CE impact, only the metrics wave height and bottom stress were selected in the hazard assessment phase. In fact, bottom stress integrates the information of water velocity and wave height summarizes information of wave energy.

In order to summarize the huge amount of information provided by ROMs and SWAN models (paragraph 6.5), a procedure was proposed for the identification of the extreme events related to wave and bottom stress processes. The extreme events were identified by using a threshold and then calculating the number of events over the selected threshold. At the international level the 90th, 93rd or 95th percentiles are widely used as thresholds for the identification of extreme events (Vinoth and Young, 2011; William et al., 2008; Grabermann and Weisse, 2008). Grabermann and Weisse (2008) proposed to use the 99th percentile, for the analysis of climate change impact on extreme wave conditions in the North Sea. In general, an advantage of the use of percentiles, rather than absolute thresholds, is that they account for regional climate differences (William et al., 2008).

For the case study area of the North Adriatic the 90th percentile was selected as the most adequate threshold for the identification of relevant extreme events for coastal erosion. Specifically, in order to define the thresholds for the wave height and bottom stress parameters, the 90th percentile was calculated for the pixels along the coastline in the reference period 1960-1990. Table 7.6 shows the main statistics (i.e. maximum, minimum, mean and standard deviation) calculated for both the selected thresholds. The mean values of the 90th percentile calculated near the shoreline for wave height and bottom stress (i.e. 0.97 m and to 0.15 N/m^2 respectively) were considered the thresholds for the CE impact.

Hazard metric	Minimum	Mean	Maximum	Standard deviation
Wave height (m)	0,60	0,97	1,34	0,20
Bottom stress (N/m^2)	0,4	0,15	0,38	0,09

Table 7.6. Minimum, mean and maximum values of the 90th percentile for wave height and bottom stress in the reference period 1960-1990. The 90th percentile are calculated based on the output provided by the ROMS and SWAN models for the grid cells along the coastline.

More specifically, the statistic selected for the construction of CE maps corresponds to the number of wave height and bottom stress events that exceed the selected threshold in 4 seasons representative of the future scenario 2070-2100. The 4 analyzed seasons correspond to the following trimesters: January/February/March; April/May/June; July/August/September, October/November/December.

Accordingly, 8 hazard scenarios were produced for the period 2070-2100 in the case study area: 4 representing the number of events that exceeds the wave height threshold in the four seasons (Figure 7.3); and 4 representing the number of events that exceeds that exceeds the bottom stress threshold in the same seasons (Figure 7.4). The statistics were calculated as average values for each season of the thirty-year period 2070-2100.

As shown in Figure 7.3 and Figure 7.4 the same hazard classes were defined for the 4 seasons using the equal interval method. For each class, the range of events that exceed the threshold is specified.

The hazard statistics for the marine domain of the case study area were obtained by the linear interpolation of the values among the 17 reference stations considered as representatives of the output provided by the SWAN and ROMS models (paragraph 6.5). Based on this interpolation, hazard statistics were calculated for each cell adjoining to the shoreline and then used in the exposure assessment phase (paragraph 7.3).

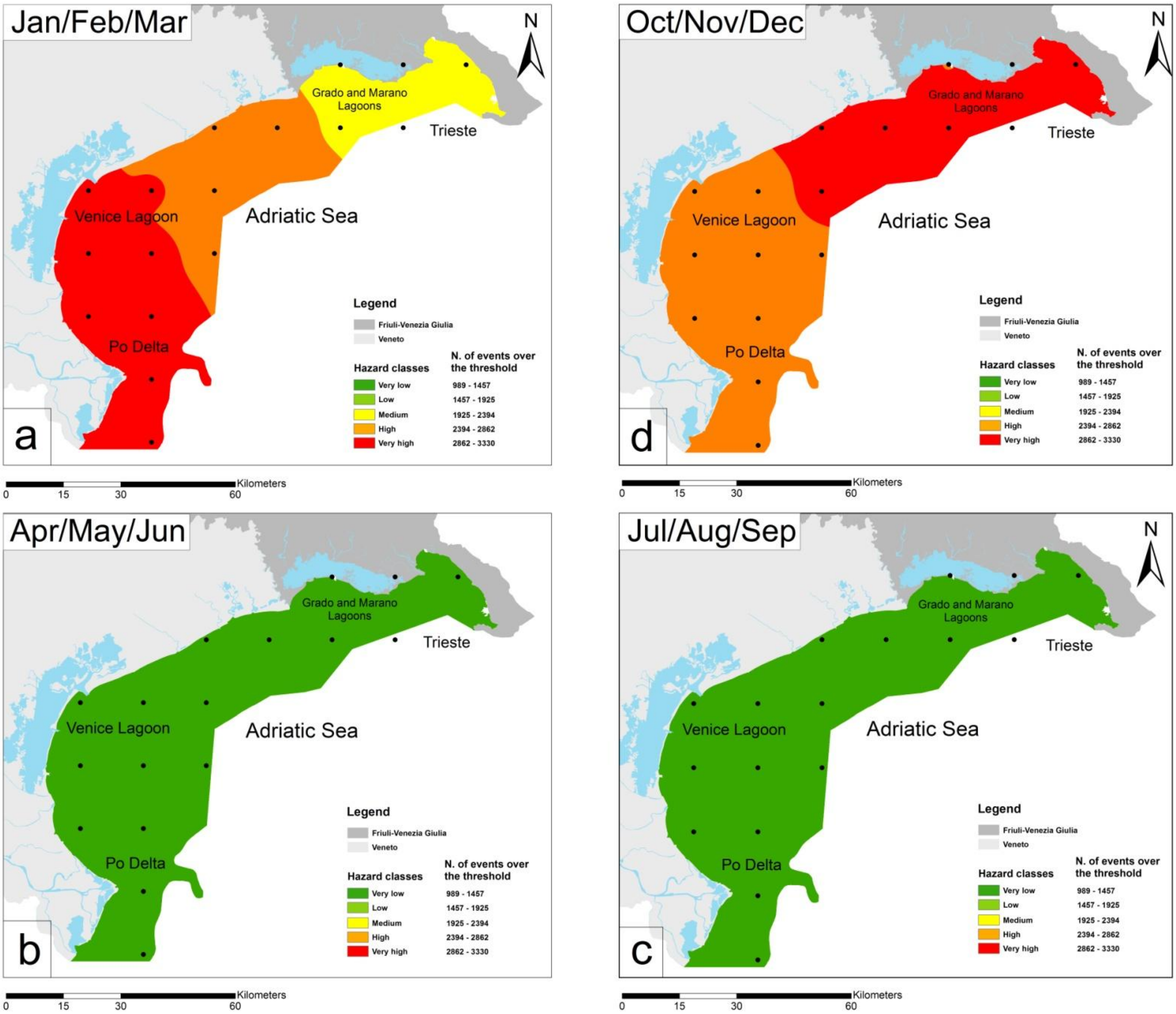


Figure 7.3. Hazard Map representing the number of events that exceeds the wave height threshold in the future scenario 2070-2100 in the 4 seasons: January/February/March (a), April/May/June (b), July/August/September (c), October/November/December (d). Black dots represent the 17 reference stations of the SWAN model.

Figure 7.3 shows the spatial variance of extreme wave height events in each season of the future scenario 2070-2100. The winter trimester (January, February, March, Figure 7.3a) shows a medium hazard class in the Friuli Venezia Giulia coast, a high class in the area between the Grado and Marano lagoons and the Venice lagoon, and a very high class from the Venice lagoon the Po River Delta. The spring and summer seasons of the year (Figure 7.3b and c) are characterized by very low hazard classes. This means that in these seasons there is a lower number of wave events that exceeds the threshold compared to other trimesters in the case study area. Finally, the months of October, November and December (Figure 7.3d) show a northern part with a very high hazard class and a southern part that is characterized by slightly lower class (i.e. high hazard class).

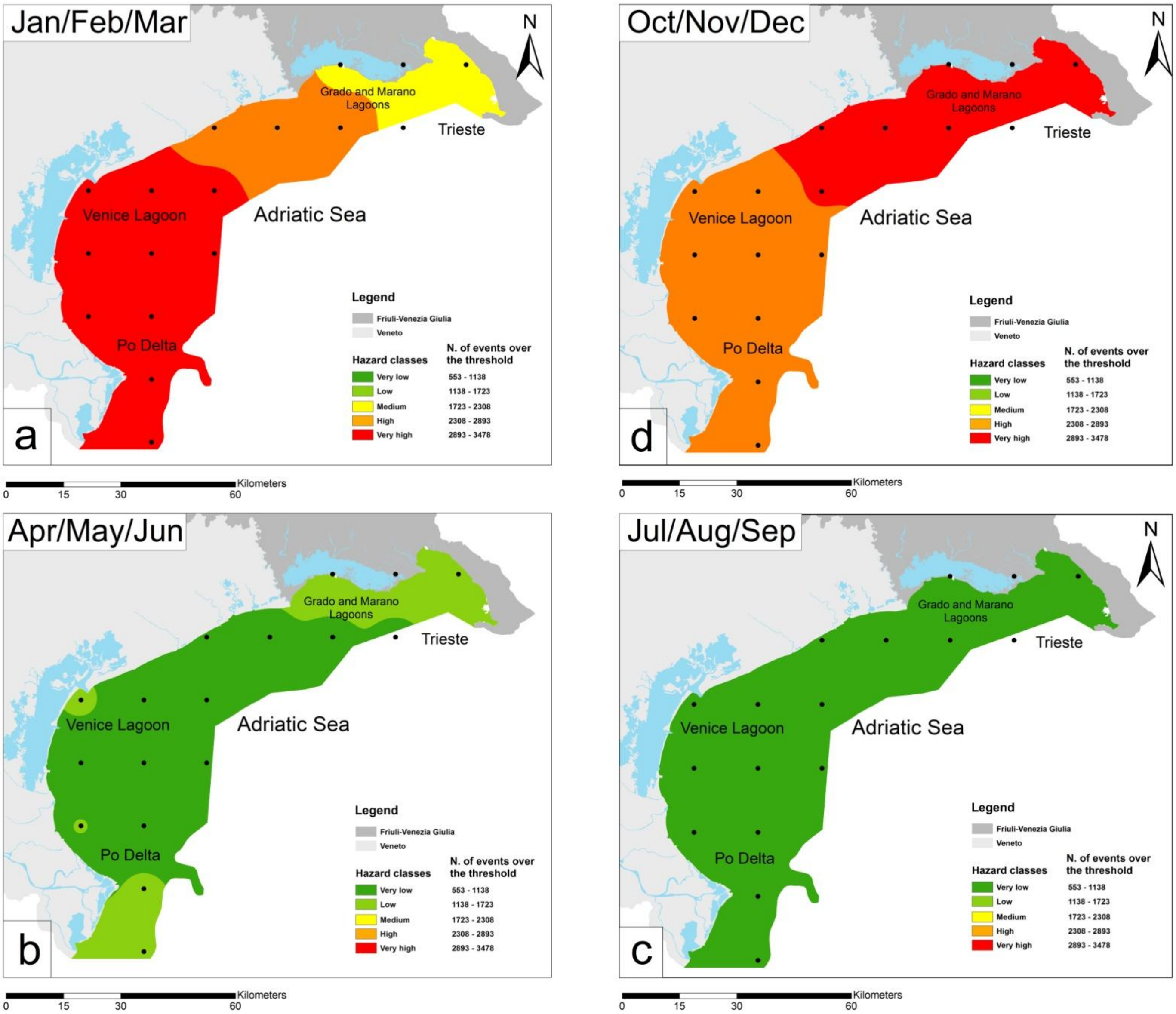


Figure 7.4. Hazard Map representing the number of events that exceeds the bottom stress threshold in the future scenario 2070-2100 in the 4 seasons: January/February/March (a), April/May/June (b), July/August/September (c), October/November/December (d). Black dots represent the 17 reference stations of the ROMS model.

Figure 7.4 shows the spatial variance of extreme bottom stress events in the 4 seasons of the future scenario 2070-2100. The trimester April/May/June shows a very low hazard class, except for few parts that show the low hazard class (Figure 7.4 b). The distribution of the classes for the other scenarios (Figure 7.4a, c and d) is similar to the distribution discussed for the wave height hazard metric.

In order to identify areas potentially exposed to the CE impact, only the pixels along the coastline were considered in the Exposure assessment phase (Paragraph 7.3). The projected number of extreme events (i.e. wave and bottom stress events exceeding the threshold) that interests the coastline of the North Adriatic Sea for the thirty-year future period 2070-2100 represent the hazard statistic that will be used in the Exposure assessment phase (Paragraph 7.3.2).

7.3. Exposure assessment.

The exposure assessment phase is aimed at producing exposure maps allowing identification and classification of areas where the hazard can be in contact with the target (i.e. potential impacted areas).

To this aim, for each analysed impact, the exposure assessment phase apply the exposure functions described in Paragraph 4.3 and integrates information about the hazard assessment phase (Paragraph 7.2.1) and about the pathway and attenuation factors listed in the vulnerability matrix (Table 7.1). In the following Paragraph the exposure maps obtained for the SLR and RSLR inundation impacts (Paragraphs 7.3.1) and for the CE impact (Paragraphs 7.3.2) will be presented and discussed.

7.3.1. Sea-level rise and relative sea-level rise inundation impacts.

The exposure maps for the SLR and RSLR impacts were developed applying the Equation 3 and 4 of Paragraph 4.3.1 and Paragraph 4.3.2 respectively.

The SLR exposure maps identify potential areas inundated by a SLR hazard scenario and provide information about the degree of inundation for each spatial unit of the analysis (i.e. the water table depth over each cell of the territory). In addition to SLR hazard scenarios, RSLR exposure maps consider literature data concerning the rate of subsidence/uplift of the case study area in order to rank potential inundated areas due both to projected sea-levels and to local vertical land movements that can increase (subsidence) or decrease (uplift) the exposure of the territory to the inundation.

As defined in the hazard scenarios assessment phase (Paragraph 7.2.1), the hazard metrics used in the Exposure assessment phase for the SLR and RSLR impacts correspond to 17 cm for the low sea-level rise scenario and to 42 cm for the high sea-level rise scenario. The threshold representing the amount of water above a cell which generates the maximum exposure for the SLR and RSLR impacts was considered equal to 60 cm. Data used to characterize the pathway factors (i.e. elevation of the territory and the rate of subsidence/uplift) are listed in Table 7.2. While the exposure maps for the SLR inundation impact were constructed for the entire case study area (i.e. coastal area of Veneto and Friuli Venezia Giulia Region), the exposure maps for the RSLR inundation impact refers only to the Coasts of Veneto Region. In fact, no comprehensive data regarding vertical land movements were found for the Friuli Venezia Giulia Region. Accordingly, in the present study, the comparison between the results obtained for the SLR and RSLR inundation impacts was performed only for the coastal area of Veneto.

The exposure maps developed for the SLR and RSLR impacts are reported in Figure IV A, B, C and D of Appendix IV. The method used for the identification of exposure classes is the Jenks Optimization method (Dent, 1996). It is a data classification method designed to determine the best arrangement of values into different classes. The main aim of the method is reducing the variance within classes and maximizing the variance between classes, in order to differentiate the classes and obtain a clear visualisation.

Specifically, exposure classes applied to SLR and RSLR impacts refers to exposure ranges illustrated in Table 7.7.

Exposure class	Exposure range	cm of SLR above the cell
Very low	0-0.13	< 7.8
Low	0.13-0.38	7.8-22.8
Medium	0.38-0.62	22.8-37.2
High	0.62-0.87	37.2-52.2
Very high	0.87-1	> 52.2

Table 7.7. Exposure classes with the exposure ranges and related cm of SLR above the cell.

From the analysis of the maps included in Appendix IV (Figures IV A, B, C, D) it is possible to identify the areas more exposed to the permanent inundation associated with low and high SLR and RSLR scenarios. These areas are basically located in two regions: the low-lying areas surrounding the Po River Delta and the Southern Venice lagoon and the hinterland region between the Northern Venice lagoon and the Grado-Marano lagoons. Moreover, the comparison between the exposure maps for the SLR and RSLR inundation impact highlights areas where the territory would be exposed to subsidence or uplift. For instance, while the Po Delta region in the low SLR exposure map (Figure IV A) is exposed both to very high and to low exposure zone; in the RSLR exposure map (Figure IV C) the same area is exposed only to a very high exposure (no areas have a low exposure). This is probably due to a projected subsidence process that worsen the exposure scenario for the RSLR impact.

Based on the exposure maps reported in Appendix IV, several statistics representing the territorial surface (km^2) and the percentage (%) of the case study area in each exposure class were calculated. Figure 7.5a shows the distribution of km^2 of the North Adriatic coast in each exposure class according to the low and high SLR scenarios. Moreover, Figure 7.5b provide a comparison between the percentage of the North Adriatic territory in the low and high SLR scenarios respectively.

	North Adriatic coasts	
	SLR low scenario (17 cm)	SLR high scenario (42 cm)
Class	Km^2	Km^2
Very low	1138,96	946,08
Low	349,99	108,69
Medium	90,71	134,58
High	88,03	325,69
Very high	1224,62	1377,26
tot	2892,31	2892,31

a)

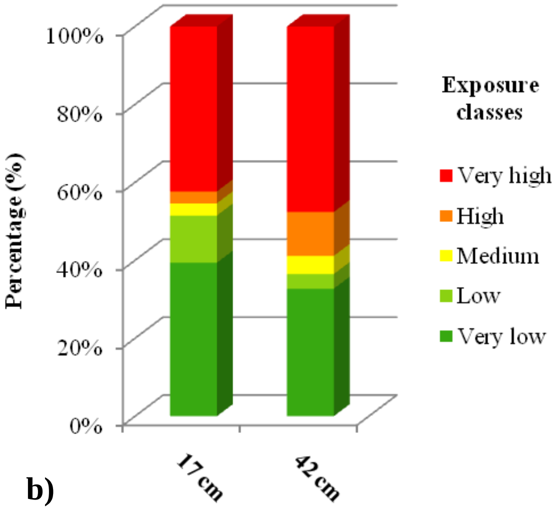


Figure 7.5. Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each exposure class for the North Adriatic coasts for the SLR low and high scenarios.

Figure 7.5 highlights that the territory potentially exposed to very high and high classes of SLR inundation increases of 10.5% from the low to the high scenario. Moreover, the territory potentially exposed to very low and low classes of SLR inundation impact decreases of about 15 % from the low to the high exposure scenario.

Figure 7.6.a shows the distribution of km^2 of the Veneto coast in each exposure class according to the low and high RSLR scenarios. Moreover, Figure 7.6.b provide a comparison between the percentage of the territory in the low and high RSLR scenarios respectively.

	Coasts of Veneto	
	RSLR low scenario (17 cm)	RSLR high scenario (42 cm)
Class	Km^2	Km^2
Very low	846,14	692,07
Low	116,42	84,70
Medium	118,41	97,48
High	113,30	115,98
Very high	1401,16	1605,17
tot	2595,42	2595,42

a)

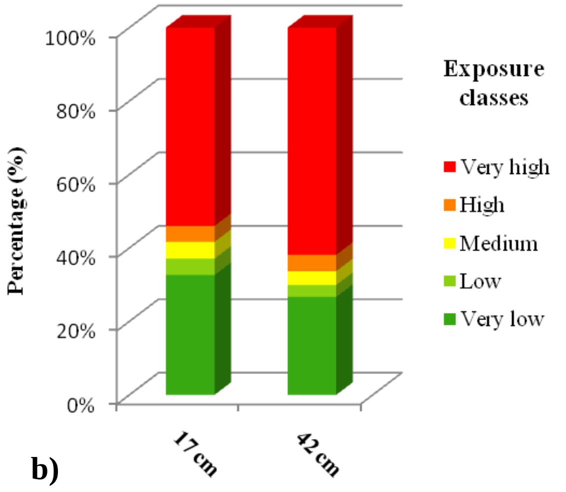


Figure 7.6. Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each exposure class for the Veneto coasts for the low and high RSLR scenarios.

Figure 7.7 shows the percentage of the Coasts of Veneto related to each exposure class: there is an increase of percentage of the territory equal to 7.96% in the very high and high exposure classes between the low and high RSLR scenarios and a decrease of 7.16% in the very low and low exposure classes of the same scenarios.

Non-climate-related local processes (such as vertical land movements) often amplify regional exposure and vulnerability associated with climate-related SLR (Nicholls and Cazenave, 2010), this is clear observable in the comparison between SLR and RSLR scenarios (Figure 7.7) for the coasts of Veneto.

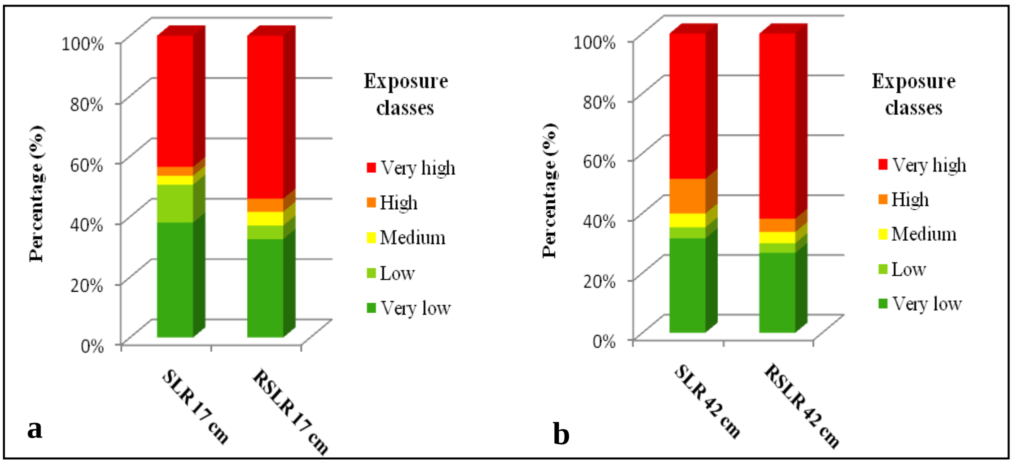


Figure 7.7. Comparison between the percentage of territory exposed to different exposure classes according to the low a) and high b) SLR and RSLR scenarios in the Coasts of Veneto.

In Figure 7.7a there is an increase of the very high class equal to 10.51% from the SLR to the RSLR low scenario, and a decrease of about 8% in the low exposure class associated with the same scenarios. Moreover, in Figure 7.7b there is an increase of about 13% in the very high class and a decrease of about 7% in the high class.

7.3.2. Coastal erosion impact.

The exposure maps for the CE impact were constructed by applying the Equation 5 of Paragraph 4.3.3.

The CE exposure maps identify coastal areas that could be more exposed to coastal erosion in changing climate conditions for the 4 seasons considered in the future scenario 2070-2100.

As defined in the hazard scenarios assessment phase (Paragraph 7.2.2), only the hazard statistics along the coastline were considered in the Exposure assessment phase. More specifically, in order to obtain the hazard metrics values to be classified and normalized, hazard statistics corresponding to the pixels near the shoreline were projected inland using the Euclidean allocation GIS function that assigns to each pixel within the studied region, the closest value of the coastline (Zald et al., 2006). The threshold representing the Radius of Influence of Coastal Erosion (RICE) for this application corresponds to 1 km. Data used to characterize the pathway factor (i.e. distance from the coastline) and the attenuation factor (i.e. artificial protection) are listed in Table 7.2.

According to the procedure defined in Paragraph 4.3.3, hazard statistics needs to be normalized in the 0-1 range, in which 0 means no hazard and 1 means maximum hazard for the case study area. Table 7.8 shows the hazard metrics identified in the case study area, the hazard classes defined using the equal interval method and the related scores assigned by an expert team (i.e. environmental scientists within the research group) following the linguistic evaluation of Table II A (Appendix II). The method used for the identification of hazard classes is the equal interval classification allowing the division of the range of attribute values into equal sized sub-ranges (Zald et al., 2006). Equal interval classification is useful when the objective of the spatial analysis is to emphasize the amount of an attribute value relative to other value. To this aim, the equal interval was selected as the most appropriate GIS-method in order to compare trimester scenarios each other.

Hazard metric	Class	Score
Wave height	989-1457	0.2
	1457-1925	0.4
	1925-2394	0.6
	2394-2862	0.8
	2862-3330	1
Bottom stress	553-1138	0.2
	1138-1723	0.4
	1723-2308	0.6
	2308-2893	0.8
	2893-3478	1

Table 7.8. Classes and scores associated with the hazard metrics identified in the hazard matrix for the coastal erosion impact in the North Adriatic coast.

Moreover, within this thesis, the same weight 1 was assigned to all the hazard metrics considered in the case study. In this way the same importance was attributed to each hazard metric in the final estimate of exposure for the coastal erosion impact (Paragraph 7.2.2).

Concerning pathway factors, “distance from coastline” was considered as a continuous value and no pathway classes and scores were assigned. Finally, a score of 1 was assigned to the presence of artificial protection and a score of 0 to the absence. The exposure maps resulting from the application of Equation 5 for the CE impact are reported in Figure IV E of Appendix IV. The method used for the identification of exposure classes is the equal interval classification (Zald et al., 2006). Specifically, exposure classes applied to the CE impact refers to exposure ranges illustrated in Table 7.9.

Exposure class	Exposure range
Very low	0-0.17
Low	0.17-0.37
Medium	0.37-0.50
High	0.50-0.67
Very high	0.67-1

Table 7.9. Exposure classes with the exposure ranges for the CE impact.

Appendix IV shows the exposure map for CE scenarios (Figure IV E) which identify the areas of the case study that could result more exposed to coastal erosion stressors under changing climate conditions, within the RICE area. It is possible to compare the exposure maps obtained for the 4 analyzed trimesters.

On the whole the exposure maps show that the exposure decrease moving inland from the shoreline: higher exposure classes are in front of the sea; decreasing exposure classes are located inside the RICE area (zoom of Figure IV E c), Moreover, the exposure is generally reduced where there is the presence of artificial protections (zoom of Figure IV E b). Finally, it is possible to see that the exposure maps reproduce the main distribution of hazard metrics highlighted in the hazard scenarios (Figure 7.3 and Figure 7.4).

The seasons most affected by the higher exposure classes are winter (i.e. trimester Jan/Feb/Mar) and autumn (i.e. trimester Oct/Nov/Dec).._Specifically, in the winter trimester the area more exposed to the CE impact is the Po River Delta (Figure IV E a) in which both the hazard metrics assumed a scores of 1 (i.e. the higher score). Concerning, the last trimester (i.e. Oct/Nov/Dic), the exposure map shown in Figure IV E d highlights a higher exposure in the coastal zone near the Grado-Marano lagoon (zoom of Figure IV E d). This situation is mainly due to the higher hazard scores gained by the two hazard metrics in that area.

Based on the exposure maps reported in Appendix IV, several statistics representing the territorial surface (km^2) and the percentage (%) of the case study area in each exposure class and for each trimester were calculated. Figure 7.8a shows the distribution of km^2 of the North Adriatic coast in each exposure class for each trimester. Moreover, Figure 7.8b provide a comparison among the percentage of the North Adriatic territory in the different exposure classes for the 4 seasons.

a)

	Case study area within the RICE area (Km^2)				
range	Class	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Sep	Oct/Nov/Dec
0-0,168	Very low	126,15	152,03	152,60	140,61
0,168-0,336	Low	28,72	18,94	18,66	24,45
0,336-0,504	Medium	14,92	23,67	23,78	20,21
0,504-0,672	High	7,94	152,03	0	9,77
0,672-0,84	Very high	17,32	0	0	0

b)

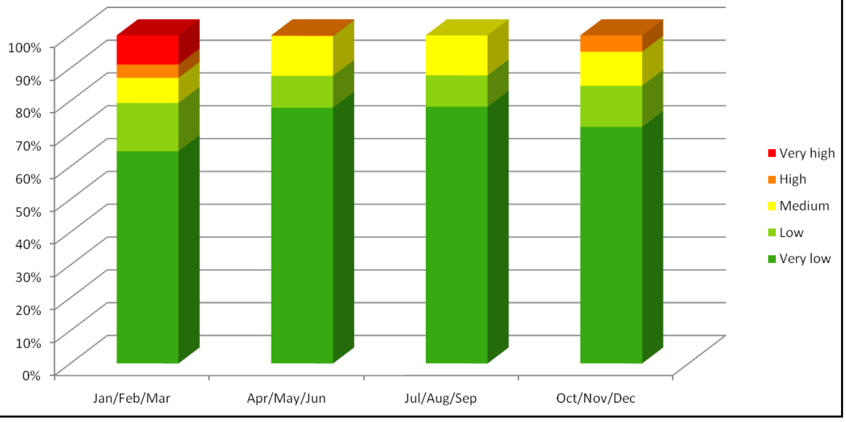


Figure 7.8. Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each exposure class for the North Adriatic coasts for the 4 seasons of the future scenario 2070-2100 (i.e. January-February-March; April-May-June; July-August-September; October-November-December).

Figure 7.8 highlights that the territory potentially exposed to the very high and high classes of CE impact is about 0.2% in spring, 5% in autumn and 12% in winter. Moreover, the territory potentially exposed to very low class of CE impact is about 65-78 % in all scenarios. In spring and summer there is the same percentage (78%) of the territory affected by a very low exposure class due to very low and low scores of the hazard metrics. In the same scenarios, the territory affected by a medium exposure class is about 12% and it refers to areas not protected to artificial protections (e.g. dikes) and near the coastline.

7.4. Susceptibility assessment.

The Susceptibility assessment phase is aimed at evaluating the degree to which the receptors could be affected by a given climate change impact based on site-specific territorial information. To this aim, for each analyzed impact, the susceptibility assessment phase aggregates the susceptibility factors defined in the vulnerability matrix (Table 7.1) and employs a Susceptibility function based on MCDA methods (Equation 9, Paragraph 4.4). In order to apply the Susceptibility function allowing to make relative rankings of coastal areas and receptors more sensitive to climate change impacts, the susceptibility factors must be classified, scored and weighted taking into account the expert judgment, as it is explained in Paragraph 4.4.

The following paragraph will explain the Susceptibility assessment done for the SLR and RSLR impacts (Paragraphs 7.4.1) and for the CE impact (Paragraphs 7.4.2) within the North Adriatic case study area.

7.4.1. Sea-level rise and relative sea-level rise inundation impacts.

As highlighted in the vulnerability matrix (Table 7.1), for the specific analysis of SLR and RSLR inundation impacts, no susceptibility factors were identified. In fact, it was assumed that a SLR/RSLR inundation event affect all the receptors in the same way, causing a permanent loss of receptors' sub-areas based only on the elevation of the cells, Accordingly, each cell of the territory was considered to have the same maximum susceptibility to SLR and RSLR impacts (i.e. susceptibility score equal to 1).

7.4.2. Coastal erosion impact.

In order to provide an estimation of the susceptibility of the system to the coastal erosion impact, the susceptibility factors were normalized through the assignation of scores and weights and then aggregated through the "probabilistic or" function (Paragraph 4.4).

Table 7.10 and Table 7.11 show the scores and weights provided by an expert team (i.e. environmental scientists within the research group) to the susceptibility factors identified in the vulnerability matrix (Table 7.1). Scores and weights vary from 0 to 1, in which 0 means no susceptibility/importance and 1 means maximum susceptibility/importance for the case study area. Table 7.10 shows the susceptibility factors identified in the case study area, the susceptibility classes defined by qualitative or quantitative attributes and the related scores (founded in literature or defined by the expert team).

SUSCEPTIBILITY FACTOR	CLASS	SCORE
Vegetation cover	Poor vegetation and meadow	1
	Vegetation with shrubbery	0.5
	Forest	0.2
Coastal slope (degrees)	0 – 1,02	0.2
	1,02 – 2,04	0.4
	2,04 – 3,07	0.6
	3,07 – 4,09	0.8
	4,09 – 5,12	1
Geomorphology	Muddy coast	1
	Sandy coast	0.5
	Rocky coast	0.2
Dunes	Absence	1
	Presence	0.2
Sediment budget	Advancing coast	0.2
	Stable coast	0.5
	Coast in erosion	1
Mouth-river typology	Estuary	1
	Delta	0.2
Wetland extension (km^2)	0 – 19,9	1
	19,9 – 39,8	0.8
	39,8 – 59,8	0.6
	59,8 – 79,7	0.4
	79,7 – 99,6	0.2
% of urbanization	< 5% of the land occupied by urban and industrial areas (per municipality)	0.2
	5% and 10% of the land occupied by urban and industrial areas (per municipality)	0.5
	> 10% of the land occupied by urban and industrial areas (per municipality)	1

Table 7.10. Classes and scores associated with the susceptibility factors identified in the vulnerability matrix for the coastal erosion impact in the North Adriatic coast.

Table 7.11 shows the weights assigned by experts to each susceptibility factor in order to represent their relative importance in the estimation of susceptibility associated with the impact CE.

SUSCEPTIBILITY FACTOR	WEIGHT
Vegetation cover	0.6
Coastal slope (degrees)	0.8
Geomorphology	0.8
Dunes	0.6
Sediment budget	0.8
Mouth-river typology	0.5
Wetland extension (km^2)	0.5
% of urbanization	0.4

Table 7.11. Weights associated with the susceptibility factors identified in the vulnerability matrix for the coastal erosion impact in the North Adriatic coast.

Coastal slope, geomorphology and sediment budget gained the higher weights in the present assessment since they represent geo-physical characteristics very important for the assessment of receptors' susceptibility to coastal erosion, compared to other susceptibility factors. Vegetation cover and dunes are considered slightly less important than the previous group of susceptibility factors and were assigned a weight equal to 0.6. Finally, the weights of 0.5-0.4 were assigned to the susceptibility factors most related to socio-ecological characteristics (i.e. mouth river typology, wetland extension and % of urbanization).

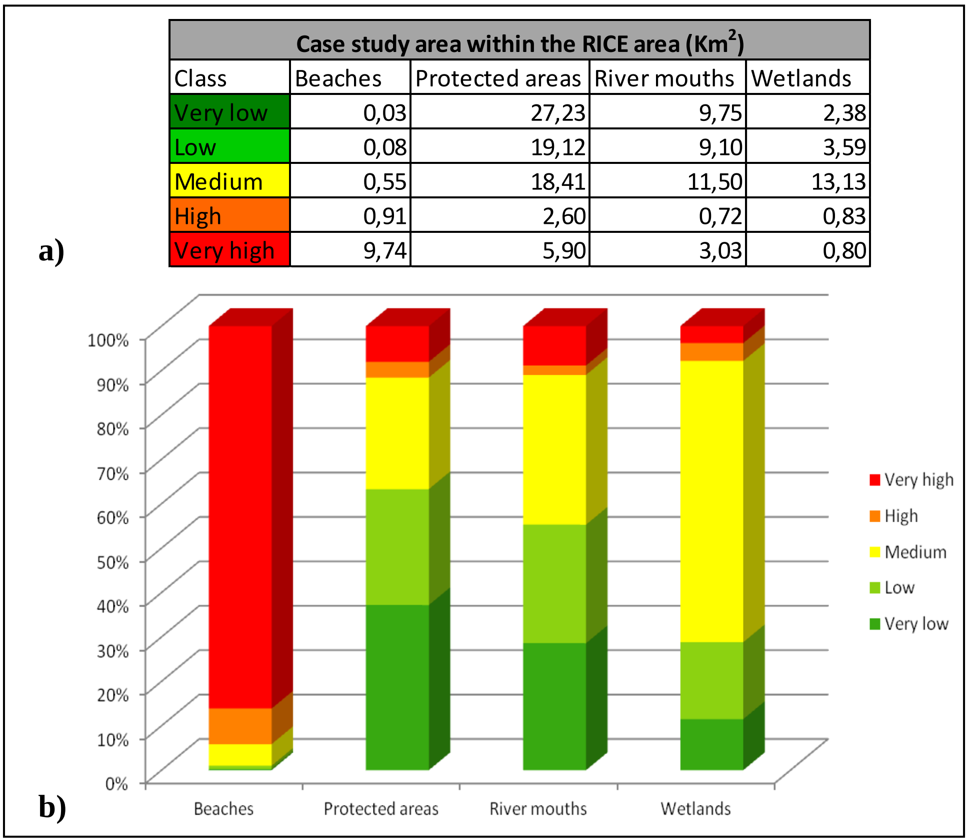
The method used for the identification of susceptibility classes is the equal interval (Zald et al., 2006) already explained in Paragraph 7.3.2.

Specifically, susceptibility classes applied to CE impact refers to susceptibility ranges illustrated in Table 7.12.

Susceptibility class	Susceptibility range
Very low	0,08-0,26
Low	0,26-0,45
Medium	0,45- 0,63
High	0,63-0,81
Very high	0,81-1

Table 7.12. Susceptibility classes with the susceptibility ranges for the CE impact.

Figure IV F (Appendix IV) provides a visualisation of the susceptibility for the case study area within the RICE area (i.e. 1 km from the coastline). Areas most susceptible to the CE impacts are beaches of the case study in which geophysical factors have a relevant contribution in determining the final susceptibility scores (Figure IV F 1 and 2). Moreover, the area near the Gulf of Trieste shows higher susceptibility values due to high scores related to coastal slope, percentage of urbanization and vegetation cover (Figure IV 3). Based on the susceptibility map reported in Appendix IV, several statistics representing the territorial surface (km^2) and the percentage (%) of the case study area in each susceptibility class and for each receptor were calculated. Figure 7.9 shows the distribution (km^2) and the percentage of the North Adriatic coast in each susceptibility class for each investigate receptor (i.e. beaches, protected areas, river mouth, wetlands).



a)

Case study area within the RICE area (Km^2)				
Class	Beaches	Protected areas	River mouths	Wetlands
Very low	0,03	27,23	9,75	2,38
Low	0,08	19,12	9,10	3,59
Medium	0,55	18,41	11,50	13,13
High	0,91	2,60	0,72	0,83
Very high	9,74	5,90	3,03	0,80

b)

Figure 7.9. Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each susceptibility class for the investigated receptors in the North Adriatic coasts.

Figure 7.9 b) highlights that the receptor more susceptible to CE is the beaches with 94% of the territory in the very high and high susceptibility class. Protected areas and river mouths with about 11% of the territory in the very high and high susceptibility class, and finally wetlands with 8% of the territory in the same susceptibility classes.

Wetland is the receptor showing more % of the territory in the medium susceptibility class (63% of the receptor) and protected areas has the higher percentage (i.e. 63%) of the receptor surface in the low and very low classes. In general, the susceptibility factors that most contribute in determining the final susceptibility score are geomorphology, coastal slope and sediment budget that are the three susceptibility factors associated with the geo-physical characteristics of the receptors.

7.5. Risk assessment.

The main aim of the Risk assessment phase is to perform the integrated assessment of multiple climate change impacts in coastal zones at the regional scale. To this aim, this phase of the RRA methodology integrate information about the exposure for a given climate change scenario and the territorial susceptibility in order to identify and prioritize coastal receptors and areas at risk from different impacts related to climate change in the case study area.

As it is explained in Paragraph 4.4, the risk assessment phase integrates the output of the exposure and susceptibility assessment phases according to Equation 11.

In the following paragraph the risk assessment phase for the SLR and RSLR impacts will be illustrated in order to provide a relative estimation of risks in coastal areas and targets of the considered region.

7.5.1. Sea-level rise and relative sea-level rise inundation impacts.

As explained in Paragraph 7.4.1, for the SLR and RSLR inundation impacts the susceptibility score for each cell of the analyzed region is considered equal to 1. Accordingly, the risk function described in Equation 11 (Paragraph 4.5) is simplified as follows:

$$R_{k,s} = E_{k,s} \qquad \text{Equation 15}$$

Where the risk score $R_{k,s}$ associated with the impacts SLR and RSLR for the scenario *s* correspond to the exposure score $E_{k,s}$ calculated in the cells of the coastal territory for the scenario *s*.

The risk scores calculated according to Equation 15 could be associated with each analysed receptor considering the cells of the territory that belong to that receptor.

Figures IV F and IV G of Appendix IV provide examples for the risk maps obtained for the receptor beaches and wetlands for the SLR impact. These maps include an overview of the beaches and wetlands located in the North Adriatic coasts and several zooms in order to highlight the more significant areas (e.g. beaches and wetlands with very high risk class of SLR inundation).

Risk classes were calculated using the Jenks Optimization method and allowing definition of the ranges shown in Table 7.13.

Risk class	Risk range	cm SLR above the cell
Very low	0-0.117	< 7.02
Low	0.117-0.274	7.02-16.44
Medium	0.274-0.278	16.44-16.68
High	0.278-0.282	16.68-16.92
Very high	0.282-1	> 16.92

Table 7.13. Risk classes with the risk ranges and the related cm of SLR above the cell.

Figure IV G (Appendix IV) shows the risk map of beaches for the high sea-level rise scenario. The zoomed areas highlights some zones affected by very high risk classes in the littoral zone of the Venice lagoon and in the Po River Delta. Moreover, Figure IV H (Appendix IV) shows the risk map of wetlands for the low sea-level rise scenario, where the zoomed areas shows parts of wetlands of the Po River Delta and of the Venice lagoon with a very high risk class.

Based on risk maps, relevant statistics were calculated for each climate change impact (i.e. SLR and RSLR) and for each investigated receptor. Moreover, specific statistics were proposed for each administrative unit (i.e. coastal municipality) in order to highlight the risk related to specific receptors at this spatial level.

The distribution of the surface (km^2) of each receptor within each risk class for the low and high SLR scenarios is reported in Table 7.14. Moreover, Figure 7.10 shows the distribution of risk classes according to the low and high SLR scenarios considering the percentage (%) of the total surface of each receptor in the North Adriatic coasts.

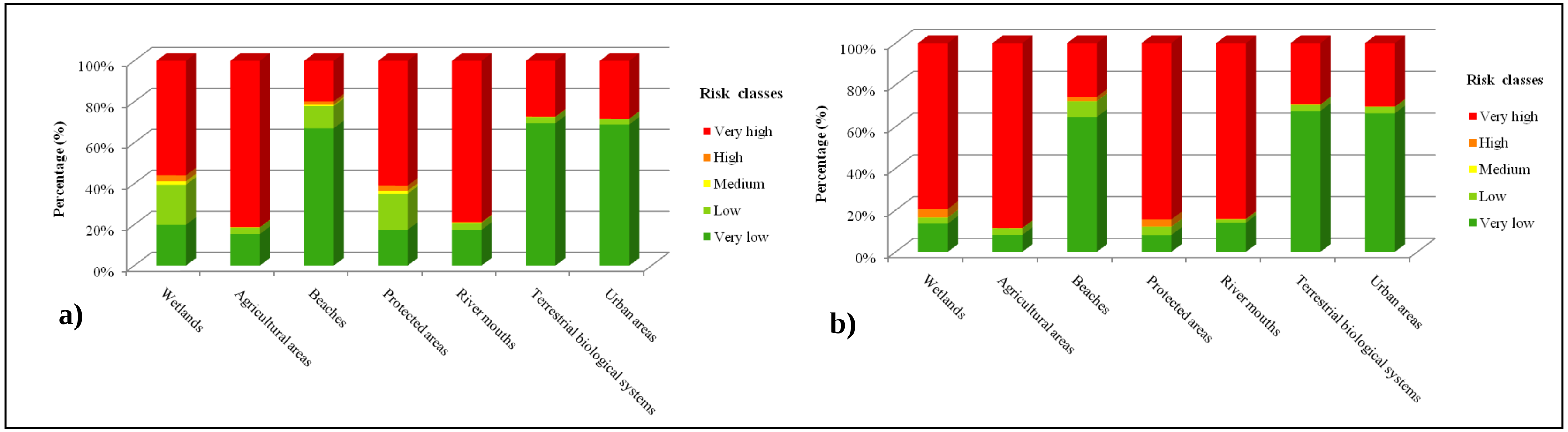


Figure 7.10. Distribution of the percentage of surface associated with each risk class for the receptors located in the North Adriatic coast according to the low a) and high b) SLR scenarios.

Receptor	Wetlands (km^2)		Agricultural areas (km^2)		Beaches (km^2)		Protected areas (km^2)		River mouths (km^2)		Terrestrial biological systems (km^2)		Urban areas (km^2)	
Class	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm
Very low	54,77	26,13	251,58	121,34	8,48	6,30	64,01	21,33	124,76	93,36	22,88	20,64	171,87	154,04
Low	53,92	5,61	52,20	48,01	1,37	0,74	64,57	10,35	23,26	10,43	0,98	0,88	6,61	7,01
Medium	4,77	0,23	1,48	1,21	0,10	0,01	5,47	0,35	1,64	0,30	0,04	0,03	0,23	0,19
High	7,94	0,20	1,59	1,23	0,20	0,03	9,20	0,34	2,60	0,28	0,05	0,02	0,30	0,16
Very high	153,99	243,23	1330,13	1465,19	2,51	5,58	223,59	334,45	564,14	612,03	8,97	11,34	70,55	88,16
tot	275,39	275,39	1636,98	1636,98	12,65	12,65	366,83	366,83	716,40	716,40	32,90	32,90	249,56	249,56

Table 7.14. Distribution of risk classes according to the low and high SLR scenarios considering the territorial surface for each receptor of the North Adriatic coasts.

Figure 7.10 together with Table 7.14 allowing visualisation of what are the receptors with higher percentages of territory with a high risk class, and therefore to identify areas and targets that would need adaptation measures. Wetland, Protected areas and River mouths are intimately connected receptors as often a wetland is also a river mouth and a protected area (e.g. the Po delta). These receptors together with Agricultural areas show very high percentages of the territory associated with very high risk class (i.e. from 56 % to 81 % for the low scenario, from 85% to 91 % for the high scenario).

A more specific statistic was also calculated for Beaches and Wetlands as shown in Table 7.15 and Table 7.16. This statistic highlights the territorial surface and percentage of beaches (Table 7.15) and wetlands (Table 7.16) with classes ranging from the very low to the very high for the SLR inundation impact for each municipality located in the coastal area of the North Adriatic sea.

Municipality	Prov.	SLR 17 cm		SLR 42 cm	
		km^2	%	km^2	%
Porto Viro	RO	0,20	56,50	0,26	70,7
Caorle	VE	0,63	50,55	0,90	71,8
Porto Tolle	RO	1,48	47,58	2,09	67,2
VENEZIA	VE	0,36	46,13	0,48	61,5
San Michele al Tagliamento	VE	0,48	43,67	0,67	60,9
Cavallino - Treporti	VE	0,43	39,67	0,72	65,8
Rosolina	RO	0,17	33,97	0,25	51,7
Marano Lagunare	UD	0,07	19,64	0,11	29,2
Lignano Sabbiadoro	UD	0,07	11,80	0,12	19,6
Chioggia	VE	0,04	5,29	0,11	16,9
Jesolo	VE	0,08	5,04	0,29	17,8
Eraclea	VE	0,01	3,72	0,05	20,9

Table 7.15. Surface (km^2) and percentage of beaches at risk to sea-level rise inundation impact for the municipalities of North Adriatic coasts.

Municipality	Prov.	SLR 17 cm		SLR 42 cm	
		km^2	%	km^2	%
Rosolina	RO	37,67	94,74	38,61	97,12
Jesolo	VE	16,44	93,89	17,12	97,77
Campagna Lupia	VE	32,50	92,36	33,70	95,76
Porto Viro	RO	43,98	92,29	45,42	95,31
Carlino	UD	0,51	90,01	0,53	93,67
Cavallino - Treporti	VE	5,94	86,87	6,49	94,90
Latisana	UD	0,89	84,52	0,98	93,10
VENEZIA	VE	38,64	83,81	42,71	92,65
Codevigo	PD	8,45	82,26	9,07	88,26
Porto Tolle	RO	20,76	80,26	23,06	89,15
Musile di Piave	VE	0,02	78,95	0,02	94,74
Caorle	VE	7,46	77,90	9,08	94,77
Chioggia	VE	8,39	74,18	9,84	87,05
Mira	VE	17,03	72,10	18,97	80,33
Ariano nel Polesine	RO	0,74	69,89	0,87	82,51
San Michele al Tagliamento	VE	2,67	69,87	3,26	85,28
Precenicco	UD	0,42	68,83	0,54	86,90
Quarto d'Altino	VE	0,15	60,87	0,20	80,31
Marano Lagunare	UD	5,18	58,51	6,87	77,58
Staranzano	GO	0,72	54,43	0,86	65,14
Aquileia	UD	0,17	51,82	0,20	61,57
Lignano Sabbiadoro	UD	0,10	46,25	0,12	57,96
San Canzian d'Isonzo	GO	0,03	42,27	0,04	70,10
Palazzolo dello Stella	UD	0,02	36,47	0,03	58,82
Muzzana del Turgnano	UD	0,01	33,33	0,01	63,64
Monfalcone	GO	0,04	13,93	0,14	51,91

Table 7.16. Surface (km^2) and percentage of wetlands at risk to sea-level rise inundation impact for the municipalities of the North Adriatic coasts.

About 70% of beaches would be lost for the SLR inundation impact (high scenario) in Porto Viro and Caorle (Table 7.15). The percentage decrease to about 56% for the low SLR scenario. Rosolina is the municipality with the higher surface at risk for wetlands receptor, with a percentage of the territory at risk of 94.74% in the low SLR scenario and 97.12 % in the high SLR scenario (Table 7.16). As far as the RSLR impact is concerned, the distribution of the surface of each receptor (km^2) within each risk class for the low and high RSLR scenarios is reported in Table 7.17. Moreover, Figure 7.11 shows the distribution of risk classes according to the low and high SLR scenarios considering the percentage (%) of the total surface of each receptor in the Veneto coasts.

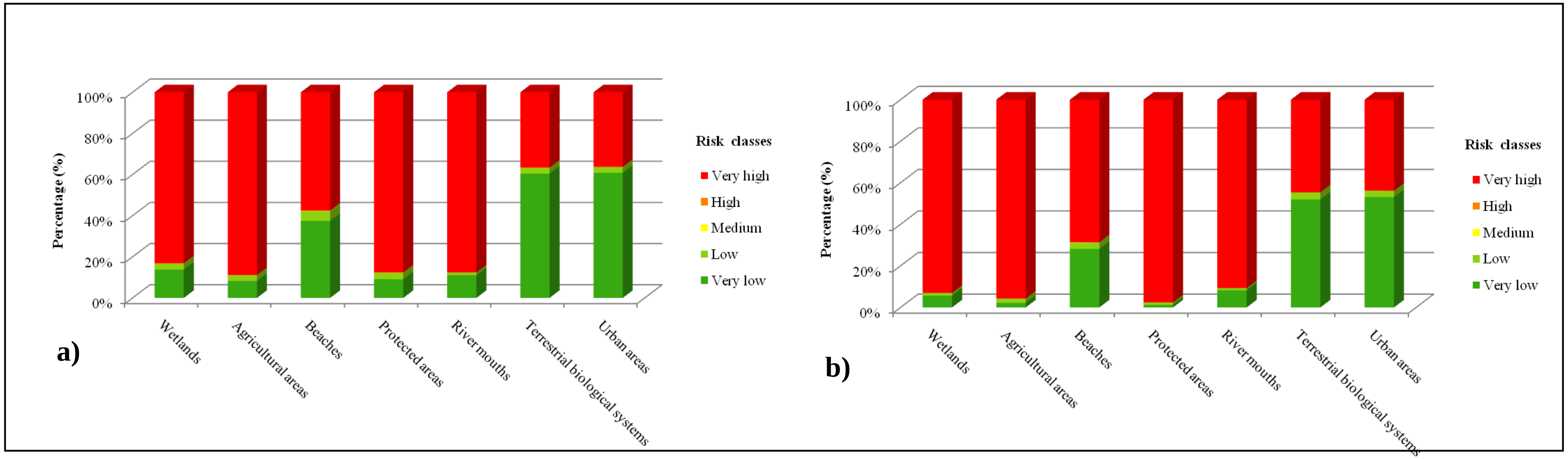


Figure 7.11. Distribution of the percentage of surface associated with each risk class for the receptors located in the Veneto coast according to the low a) and high b) RSLR scenarios.

Receptor	Wetlands (km^2)		Agricultural areas (km^2)		Beaches (km^2)		Protected areas (km^2)		River mouths (km^2)		Terrestrial biological systems (km^2)		Urban areas (km^2)	
Class	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm
Very low	35,64	14,68	123,09	32,47	4,11	3,09	31,18	3,98	79,51	59,20	13,06	11,22	136,39	118,95
Low	7,27	3,08	39,47	29,45	0,52	0,34	10,60	4,03	8,74	7,14	0,59	0,73	6,10	6,76
Medium	0,27	0,12	1,02	0,71	0,02	0,01	0,37	0,13	0,24	0,17	0,02	0,02	0,16	0,18
High	0,29	0,10	1,01	0,73	0,02	0,01	0,39	0,12	0,23	0,19	0,01	0,02	0,15	0,19
Very high	214,74	240,24	1316,91	1418,14	6,32	7,54	300,67	334,95	627,27	649,28	7,93	9,62	81,36	98,08
tot	258,21	258,21	1481,50	1481,50	10,98	10,98	343,22	343,22	715,99	715,99	21,61	21,60	224,17	224,17

Table 7.17. Distribution of risk classes according to the low and high RSLR scenarios considering the territorial surface for each receptor of the Coasts of Veneto.

Figure 7.11 and Table 7.17, as presented for the SLR inundation impact, shows that Beaches, together with Wetlands, Agricultural areas, Protected areas and River mouths are very impacted by RSLR, considering the Coasts of Veneto.

Table 7.18. and Table 7.19. report the territorial surface and percentage of the territory of beaches and wetland that would be lost in each municipality due to RSLR inundation impact.

Municipality	Prov.	RSLR 17 cm		RSLR 42 cm	
		km^2	%	km^2	%
Ariano nel Polesine	RO	0,05	98,73	0,05	98,73
Porto Viro	RO	0,32	88,56	0,33	92,20
Porto Tolle	RO	2,54	81,46	2,67	85,71
Rosolina	RO	0,36	73,46	0,40	82,18
Caorle	VE	0,83	66,10	0,92	73,35
San Michele al Tagliamento	VE	0,61	55,64	0,76	69,16
Cavallino - Treporti	VE	0,49	44,41	0,61	55,37
VENEZIA	VE	0,23	29,03	0,28	36,61
Eraclea	VE	0,05	23,50	0,09	39,26
Chioggia	VE	0,12	17,92	0,19	28,60
Jesolo	VE	0,21	13,14	0,40	24,98

Table 7.18. Surface (km^2) and percentage of beaches at risk to relative sea-level rise inundation impact for the municipalities of the Coasts of Veneto.

Municipality	Prov.	RSLR 17 cm		RSLR 42 cm	
		km^2	%	km^2	%
Rosolina	RO	38,91	97,87	39,22	98,64
Jesolo	VE	17,09	97,60	17,29	98,73
Caorle	VE	9,26	96,70	9,53	99,43
Porto Viro	RO	45,91	96,34	46,16	96,86
Porto Tolle	RO	24,77	95,74	25,27	97,68
Musile di Piave	VE	0,02	94,74	0,02	94,74
Cavallino - Treporti	VE	6,34	92,73	6,61	96,65
Campagna Lupia	VE	32,05	91,06	33,63	95,56
VENEZIA	VE	41,12	89,19	43,21	93,74
Chioggia	VE	9,88	87,41	10,39	91,88
Ariano nel Polesine	RO	0,90	85,24	0,91	86,54
San Michele al Tagliamento	VE	3,24	84,85	3,53	92,36
Quarto d'Altino	VE	0,18	75,45	0,20	83,12
Mira	VE	13,92	58,96	19,06	80,69
Eraclea	VE	0,01	9,15	0,02	18,95
Marcon	VE	0,00	0,92	0,06	10,69

Table 7.19. Surface (km^2) and percentage of wetlands at risk to Relative sea-level rise inundation impact for the municipalities of the Coasts of Veneto.

The municipalities most at risk from RSLR considering beaches and wetlands are in the first lines of Table 7.18. and Table 7.19. Circa 98% of beaches would be lost for the RSLR inundation impact (low and high scenarios) in Ariano nel Polesine that is the municipality with a higher risk. Rosolina is the municipality with the higher risk for wetlands receptor, where almost all the wetlands would be lost in the low and high RSLR scenarios.

7.5.2. Coastal erosion impact.

The risk assessment phase for the CE impact integrates the results of the exposure assessment with the susceptibility assessment.

The risk scores calculated according to Equation 11 are associated with each analysed receptor considering the cells of the territory that belong to that receptor.

Figures IV I and IV L of Appendix IV provide examples for the risk maps obtained for the beaches and river mouth receptors for the CE impact in the worst seasonal scenario (i.e. trimester January-February-March of the future period 2070-2100). These maps include an overview of the beaches and river mouths' areas located in the North Adriatic coast and several zooms in order to highlight the more significant areas (e.g. beaches and river mouth areas showing a very high risk class for CE).

Risk classes were calculated using the equal interval method already explained in Paragraph 7.3.2 and allowing definition of the ranges shown in Table 7.20.

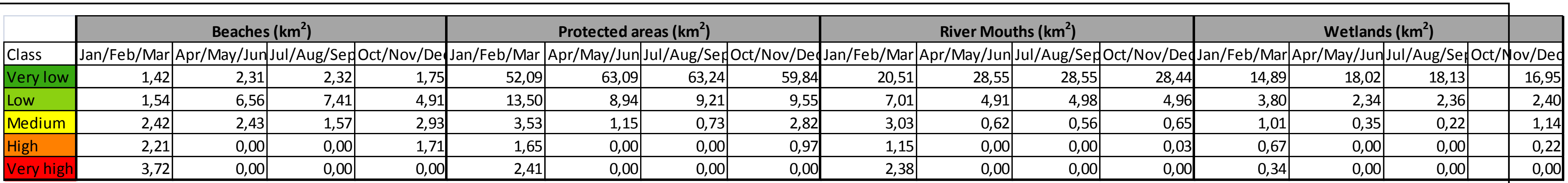
Risk class	Risk range
Very low	0,08-0,26
Low	0,26-0,45
Medium	0,45- 0,63
High	0,63-0,81
Very high	0,81-1

Table 7.20. Risk classes with the related risk ranges for the CE impact.

Figure IV I shows the risk map of beaches for the winter (i.e. trimester Jan/Feb/Mar) CE scenario which highlights three areas affected by a CE risk (i.e. areas along the Northern Veneto coast and the Po River Delta). The area along the Po River Delta (Box 1 of Figure IV I) is affected by a very high risk class mainly due to the very high exposure scores. Moreover, the areas located along the Veneto coastline (Box 2 and 3 of figure IV I) show the influence of the artificial protections in the evaluation of CE risk (i.e. the presence of dikes corresponds to the very low risk class).

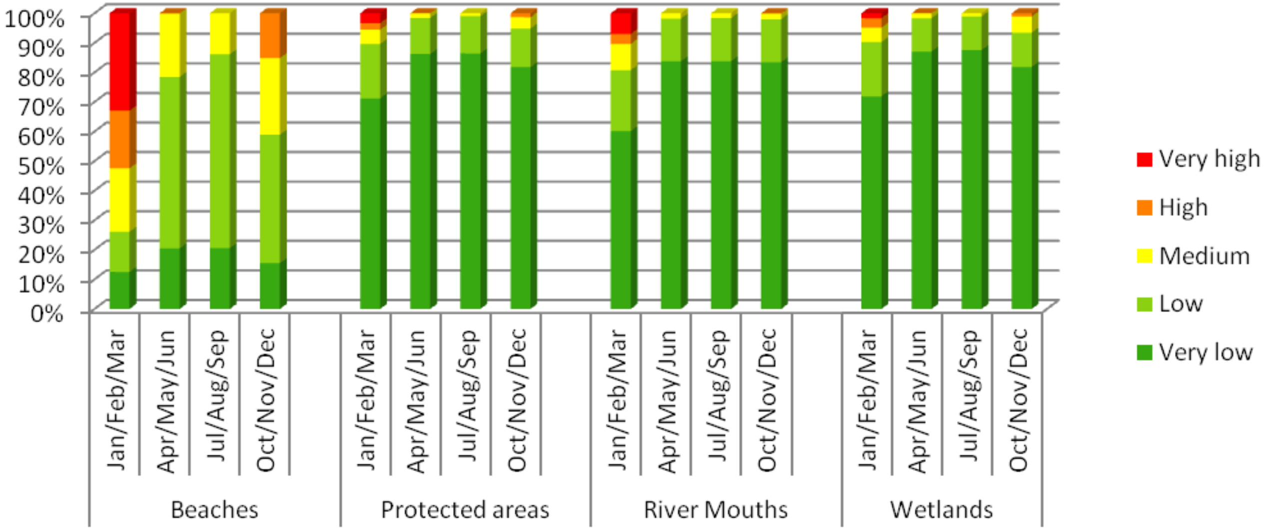
Figure IV L shows the risk map of river mouths for the winter (i.e. trimester Jan/Feb/Mar) CE scenario. The areas more affected by a very high risk class are situated in the southern part of the Delta in proximity of the coastline (Figure IV L 2).

Based on the risk maps produced for the case study area, relevant statistics were calculated for the CE impact and for each investigated receptor. Moreover, specific statistics were proposed for each administrative unit (i.e. coastal municipality) in order to highlight the risk related to specific receptors at this spatial level. Figure 7.12 shows the distribution (km^2) and the percentage of the North Adriatic coast in each risk class for each investigate receptor (i.e. beaches, protected areas, river mouth, wetlands) and for each seasonal scenario.



	Beaches (km²)				Protected areas (km²)				River Mouths (km²)				Wetlands (km²)			
Class	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Sep	Oct/Nov/De	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Se	Oct/Nov/De	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Sep	Oct/Nov/Dec	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Se	Oct/Nov/Dec
Very low	1,42	2,31	2,32	1,75	52,09	63,09	63,24	59,84	20,51	28,55	28,55	28,44	14,89	18,02	18,13	16,95
Low	1,54	6,56	7,41	4,91	13,50	8,94	9,21	9,55	7,01	4,91	4,98	4,96	3,80	2,34	2,36	2,40
Medium	2,42	2,43	1,57	2,93	3,53	1,15	0,73	2,82	3,03	0,62	0,56	0,65	1,01	0,35	0,22	1,14
High	2,21	0,00	0,00	1,71	1,65	0,00	0,00	0,97	1,15	0,00	0,00	0,03	0,67	0,00	0,00	0,22
Very high	3,72	0,00	0,00	0,00	2,41	0,00	0,00	0,00	2,38	0,00	0,00	0,00	0,34	0,00	0,00	0,00

a)



b)

Figure 7.12. Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each risk class for the investigated receptors in the North Adriatic coast for each CE hazard scenario.

Figure 7.12 highlights that the receptor with the higher risk classes (i.e. very high, high and medium) is the beach in the four investigated CE scenarios, this is due to the susceptibility score that is assumed by beaches for the CE impact (see Paragraph 0). Specifically, the percentage surface of beaches with the higher risk classes is about 72% in the first trimester, 21% in the second, 14% in the third and 41% in the fourth. Moreover, the trimester Jan/Feb/Mar is the CE scenario in which the risk scores is the higher related to the other trimesters, this is due to the high value of the hazard metrics (i.e. wave height and bottom stress in that scenario (Paragraph 7.2.2).

A more specific statistic was also calculated for beaches and river mouths as shown in Table 7.21 and Table 7.22. This statistic highlights the territorial surface and percentage of beaches (Table 7.21) and river mouths (Table 7.22) with very high and high risk classes in the RICE area of each municipality of the North Adriatic sea.

		Jan/Feb/Mar		Oct/Nov/Dic	
Municipality	**PROV.**	Km^2	%	Km^2	%
Porto Viro	RO	0,26	92,65	0	0
Rosolina	RO	0,41	92,31	0	0
Venezia	VE	0,57	78,23	0	0
Ariano nel Polesine	RO	0,04	74,68	0	0
Chioggia	VE	0,50	72,26	0	0
Porto Tolle	RO	1,88	70,36	0	0
Cavallino Treporti	VE	0,72	67,89	0	0
Jesolo	VE	0,68	43,33	0,26	16,69
Eraclea	VE	0,08	37,54	0,08	37,54
Grado	GO	0	0	0,21	30,81
San Michele al Tagliamento	VE	0,30	28,17	0,30	28,17
Caorle	VE	0,35	28,11	0,35	28,11
Lignano Sabbiadoro	UD	0,07	13,10	0,37	70,60
Monfalcone	GO	0	0	0,01	35,48
Duino Aurisina	TS	0	0	0,02	100,00
Marano Lagunare	UD	0	0	0,12	37,45

Table 7.21. Surface (km^2) and percentage of beaches surface at the higher risk to the CE impact for the municipalities of North Adriatic coasts within the RICE area.

		Jan/Feb/Mar		Oct/Nov/Dic	
Municipality	**PROV.**	Km^2	%	Km^2	%
Porto Tolle	RO	2,30	16,43	0	0
Staranzano	GO	0	0	0,02	12,69
Grado	GO	0	0	0,01	11,96
Porto Viro	RO	0,29	6,69	0	0
Rosolina	RO	0,59	5,65	0	0
Ariano nel Polesine	RO	0,06	5,49	0	0

Table 7.22. Surface (km^2) and percentage of river mouths surface at the higher risk to the CE impact for the municipalities of North Adriatic coasts within the RICE area.

In the winter trimester (Jan/Feb/Mar), about the 92 % of beaches and 6-7% of river mouths result at higher risk for the CE impact in Porto Viro and Rosolina (Table 7.21 and Table 7.22). Moreover, about 78 % of beaches in Venice show higher risk related to the CE impact. Also Ariano nel Polesine, Chioggia, Porto Tolle and Cavallino Treporti are characterized by high percentages of beaches (from 68 to 75%) at higher risk for the CE impact. In the trimester Oct/Nov/Dic, Duino Aurisina would be the municipality most at risk for the CE impact considering the beach receptor (i.e.100% of beaches at risk) followed by Lignano

Sabbiadoro (70%). Table 7.22 highlights that the municipalities with a considerable percentage (16-12%) of river mouths at higher risk for the CE impact are Porto Tolle, Staranzano and Grado in the winter and autumn trimester respectively.

7.6. Damage assessment.

The Damage assessment phase aggregates the results of the Risk assessment phase (Paragraph 7.5) with the assessment of the environmental and socio-economic value of a receptor, in order to provide a relative estimation of the potential social, economic and environmental losses associated with targets and areas at risk in the case study area (EC, 2007). Damage maps derive from the aggregation of risk maps and value maps and are calculated using the damage function described in Paragraph 4.6.

In the following Paragraphs, the damage maps obtained for the SLR and RSLR impacts (Paragraph 7.6.1) and for the CE impact (Paragraph 7.6.2) in the North Adriatic case study will be presented and discussed.

7.6.1. Sea-level rise and relative sea-level rise inundation impacts.

The first step required for the damage assessment phase is to estimate the value associated with each receptor through a weighted sum (Equation 13). To this aim, it was necessary to classify and provide scores and weights to the value factors identified in the vulnerability matrix (Table 7.1).

Table 7.23 shows the value classes and the related scores defined for the value factors identified for the coastal receptors analysed in the case study area.

VALUE FACTOR	CLASS	SCORE
Protection level	National area	1
	Regional area	0.5
	Nature 2000 area	0.2
Urban typology	Residential building	1
	Commercial building	0.5
	Infrastructures	0.2
Agricultural typology	Permanent culture	1
	Stable meadow	0.5
	Arable	0.2
Wetland extension (Km^2)	0 – 19,9	0.2
	19,9 – 39,8	0.25
	39,8 – 59,8	0.5
	59,8 – 79,7	0.75
	79,7 – 99,6	1
Vegetation cover	Poor vegetation and meadow	0.2
	Vegetation with shrubbery	0.5
	Wood	1
Population density	< 100 inhabitants per municipality	0.2
	100-300 inhabitants per municipality	0.5
	> 300 inhabitants per municipality	1

Table 7.23. Classes and scores associated with the value factors identified in the vulnerability matrix for the SLR and RSLR impacts.

Individual value factors were scored in the 0-1 range following the linguistic evaluations reported in Table II A (Appendix II).

According to the RRA methodology, the assignation of scores to value factors requires the involvement of decision makers. However, in the present work, scores were assigned by a limited group of environmental scientists, in order to do a preliminary test of the methodology. Moreover, within this thesis, the same weight 1 was assigned to all the value factors considered in the case study. In this way the same importance was attributed to each value factor in the final estimate of the value associated with each receptor. This is a conservative approach to use in those cases where there is a lack of knowledge about the relative importance of risk assessment parameters. For the cell composing each receptor, the value function aggregates the value scores described in Table 7.14 thus obtaining one value map for each analysed receptor. In this way value maps allow visualization of receptor sub-areas associated with each value class.

An example of value map obtained from the aggregation of the value factors for the receptor agricultural areas is reported in Figure IV M of Appendix IV. The value map shows the distribution of the value classes within the agricultural areas. The 60 % of the territory show a low value class due to the presence of factors with lower value scores (e.g. Nature 2000 protected areas, commercial buildings, population density < 100 inhabitants per municipality). The area with the higher value class is located between the Venice lagoon and the Grado-Marano lagoon and correspond to areas characterized by high values for factors population density and protection level.

For each value map the value scores were classified using the Jenks Optimization method as shown in Table **7.24**. Figure 7.13 shows the territorial surface of each receptor (km^2) and the percentage of the total surface of each receptor (%) that is associated with each value class in the North Adriatic coastal area.

Value class	**Value range**
Very low	0-0.20
Low	0.20-0.50
Medium	0.50-0.65
High	0.65-0.8
Very high	0.8-1

Table 7.24. Value classes with the related value range.

a)

	Receptors (km^2)						
Class	Wetlands	Agricultural areas	Beaches	Protected areas	River mouths	Terrestrial biological systems	Urban areas
Very low	31,73	575,65	4,89	134,85	320,96	16,73	34,40
Low	63,54	857,84	4,41	134,91	343,05	9,86	84,94
Medium	95,76	149,13	1,88	87,03	36,07	4,75	84,16
High	77,96	47,40	0,08	8,91	14,08	1,10	38,19
Very high	6,46	6,96	0,03	1,13	0,68	0,25	7,35
tot	275,45	1636,98	11,29	366,83	714,84	32,69	249,04

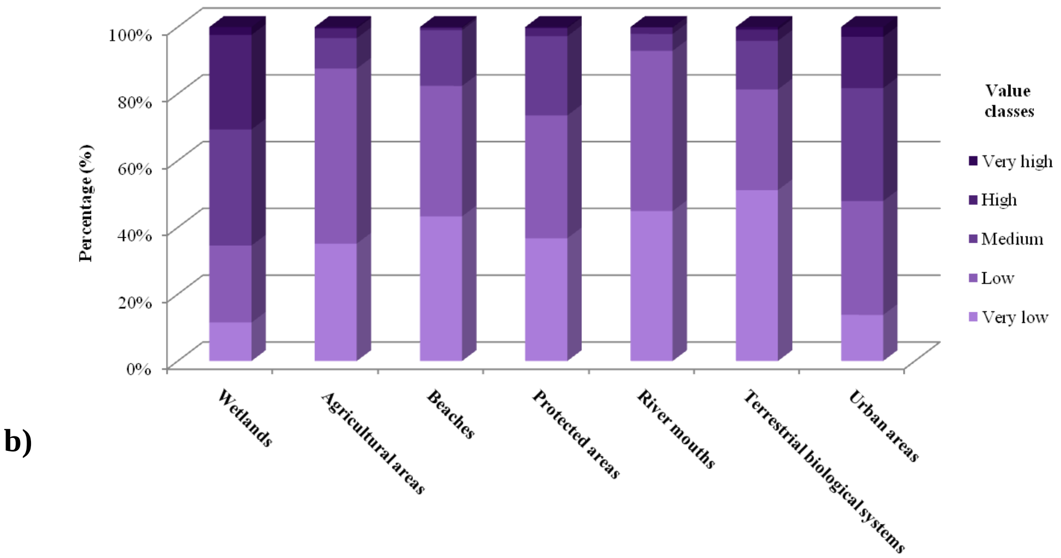


Figure 7.13. Distribution of the territorial surface (km^2) a) and of the percentage of surface b) that is associated with each value class for the receptors located in the North Adriatic coast for the SLR and RSLR impacts.

As regard the distribution of value classes, Figure 7.13 shows that the percentage of receptors in the middle and low classes is higher than the percentage in the very high class. Wetland is the receptor with the higher value (i.e. 20% of very high value class).

After estimating the value associated with each receptor analyzed in the case study area, the damage function proposed in Equation 14 was applied in order to produce damage maps.

Figures IV N and IV O represent two examples of damage maps developed for agricultural and urban areas. For the agricultural areas (Figure IV N) areas at higher damage are located near Jesolo (Figure IV N 1) and near Campagna Lupia (located in the hinterland of Venice, Figure IV N 2) For the urban areas (Figure IV O) high damage areas correspond to areas located near Jesolo (Figure IV O 1) and Porto Viro (Figure IV O 2), In general, for the RSLR impact, areas at higher damage corresponds to areas where subsidence processes are relevant (i.e. areas with higher risk scores). Moreover, these areas corresponds also to zones characterized by higher value scores (i.e. areas with higher environmental or socio-economic value).

Damage scores were classified using the Jenks Optimization method and the ranges of scores associated with each class is shown in Table 7.25.

Damage class	**Damage range**
Very low	0-0.01
Low	0.01-0.13
Medium	0.13-0.28
High	0.28-0.41
Very high	0.41-1

Table 7.25. Damage classes with the related damage range.

The distribution of the surface of each receptor (km^2) within each damage class for the low and high SLR scenarios is reported in Table 7.26. Moreover, Figure 7.14 shows the distribution of damage classes according to the low and high SLR scenarios considering the percentage (%) of the total surface of each receptor in the North Adriatic coasts.

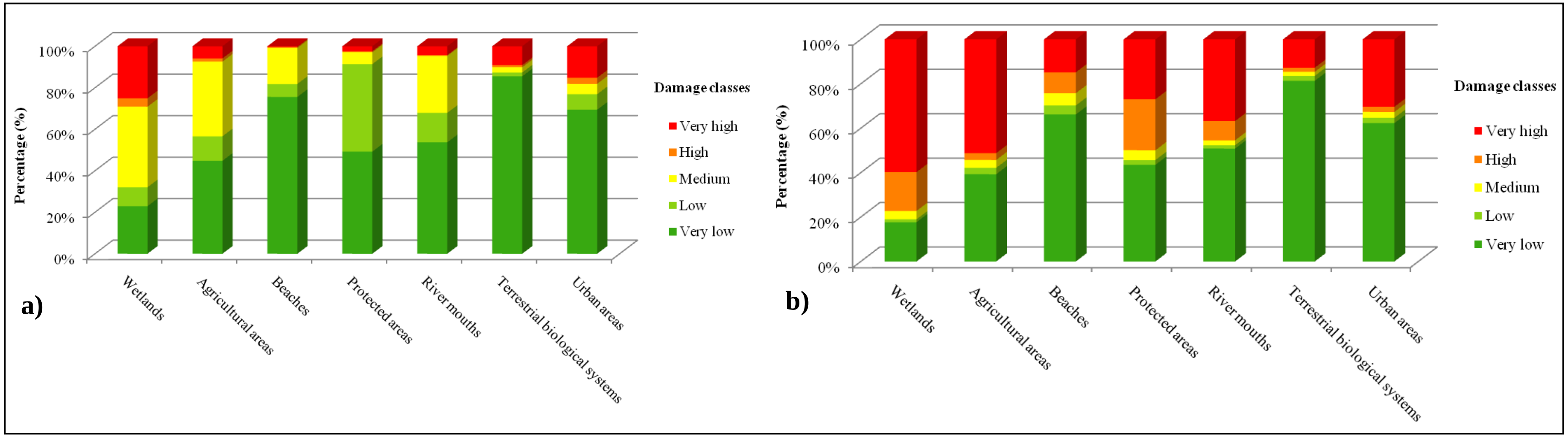


Figure 7.14. Distribution of the territorial percentage associated with each damage class according to the low a) and high b) SLR scenarios for the receptors located in the North Adriatic coasts.

Receptor	Wetlands (km^2)		Agricultural areas (km^2)		Beaches (km^2)		Protected areas (km^2)		River mouths (km^2)		Terrestrial biological systems (km^2)		Urban areas (km^2)	
Class	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm	SLR 17 cm	SLR 42 cm
Very low	63,09	48,66	732,59	642,67	9,56	8,37	180,46	159,71	384,53	364,28	28,13	26,76	173,16	155,44
Low	25,09	3,58	193,81	47,15	0,79	0,52	154,69	7,81	101,63	10,55	0,60	0,73	18,64	5,89
Medium	106,85	10,42	589,15	58,11	2,20	0,70	20,89	16,21	196,62	16,07	0,84	0,60	12,59	6,72
High	11,21	48,14	25,22	50,29	0,07	1,19	2,01	84,22	3,20	62,01	0,33	0,61	7,26	5,73
Very high	69,14	164,59	96,20	838,76	0,03	1,88	8,78	98,88	30,43	263,49	3,00	4,20	37,92	75,77
tot	275,39	275,39	1636,98	1636,98	12,65	12,65	366,83	366,83	716,40	716,40	32,90	32,90	249,56	249,56

Table 7.26. Distribution of damage classes according to the low and high SLR scenarios considering the territorial surface for each receptor of the North Adriatic coasts.

Figure 7.14 and Table 7.26 show that for the majority of receptors, the percentage of territory in the lowest damage class is the most relevant. Moreover, the percentage of the territory within the very high class increases in the high scenario compared to the low scenario (Figure 7.14 b). The receptors with the high percentage (i.e. from 3 to25 % for the low scenario and from 27 to 60 % for the high scenario) of the very high damage class are Wetlands, Agricultural areas, Protected areas and River mouths .

A more specific statistic was calculated for Urban and Agricultural areas and showed in Table 7.27 and Table 7.28. This statistic evaluates the percentage and surface of the territory of each urban class (i.e. residential or commercial) showing a very high damage class for each municipality of the North Adriatic sea. The percentage refers to the total surface of urban territory of each municipality.

Table 7.27 shows the municipalities with higher percentages of territory with a very high damage class in the residential building class for the North Adriatic coasts, that are Porto Viro, Porto Tolle, Loreo, Taglio di Po and Eraclea (about 31-43 % of the territory).For the commercial buildings the municipalities with higher percentages of territory with a very high damage class are Porto Viro, Taglio di Po and Torre di Mosto (about 14-30 % of the territory).

Municipality	Prov.	SLR 17 cm				SLR 42 cm			
		Residential buildings		Commercial buildings		Residential buildings		Commercial buildings	
		%	Km^2	%	Km^2	%	Km^2	%	Km^2
Porto Viro	RO	41,53	3,89	29,20	2,73	43,70	4,09	29,68	2,78
Porto Tolle	RO	40,13	4,05	1,04	0,10	40,82	4,12	1,05	0,11
Loreo	RO	31,39	0,84	0,02	0,00	34,53	0,92	0,02	0,00
Taglio di Po	RO	30,31	1,67	14,73	0,81	34,12	1,89	15,86	0,88
Eraclea	VE	30,27	2,15	9,10	0,65	33,48	2,38	10,77	0,77
Cavarzere	VE	24,19	1,75			27,21	1,97	9,46	0,68
Ariano nel Polesine	RO	23,98	1,06	0,28	0,01	29,08	1,28	0,30	0,01
Latisana	UD	22,33	0,52	8,65	0,20	28,33	0,66	11,80	0,27
Terzo d'Aquileia	UD	20,68	0,07	12,48	0,04	22,10	0,08	13,37	0,05
Musile di Piave	VE	14,72	0,58	3,51	0,14	17,64	0,69	3,76	0,15
Concordia Sagittaria	VE	12,10	0,51	3,78	0,16	15,08	0,64	4,14	0,18
Cona	VE	11,50	0,38	18,54	0,61	13,41	0,44		
Torre di Mosto	VE	10,80	0,39	14,22	0,51	13,53	0,49	15,18	0,55
San Canzian d'Isonzo	GO	10,67	0,02			14,33	0,03		
Adria	RO	10,01	1,01	8,69	0,88	14,51	1,47	11,93	1,21
Caorle	VE	9,61	1,08			12,47	1,40		
Santo Stino di Livenza	VE	9,22	0,43	9,66	0,45	12,13	0,57	10,50	0,49
Correzzola	PD	9,18	0,35	0,13	0,01	15,03	0,57	0,54	0,02
Chioggia	VE	8,54	0,83	1,19	0,12	11,06	1,07	1,29	0,13
Candiana	PD	8,54	0,14	9,34	0,15	12,54	0,21	10,29	0,17

Table 7.27. Percentage and territorial surface (km^2) of urban typologies (i.e. residential buildings and commercial buildings) for the 20 municipalities most interested by very high damage scores in the North Adriatic coast for the high and low SLR scenarios.

Table 7.28 highlights the territorial percentage and surface of each agricultural class (i.e. permanent culture, stable meadow, arable) with very high damage class for each municipality. The percentage refers to the total surface of agricultural territory of each municipality. Table 7.28 considers the 15 municipalities with higher percentages of the territory with very high damage class in the permanent culture class.

Municipality	Prov.	SLR 17 cm						SLR 42 cm					
		Permanent culture		Stable meadow		Arable		Permanent culture		Stable meadow		Arable	
		%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2
Terzo d'Aquileia	UD	10,79	2,15					12,17	2,42				
Annone Veneto	VE	10,19	0,37	2,51	0,09			17,00	0,61	2,91	0,10		
Jesolo	VE	9,57	4,55	0,40	0,19	0,04	0,02	11,12	5,29	0,74	0,35	0,04	0,02
Cessalto	TV	7,79	0,22	0,02	0,00			15,45	0,43	0,39	0,01	0,05	0,00
Candiana	PD	7,50	0,75	0,54	0,05	0,01	0,00	8,66	0,87	0,82	0,08	0,04	0,00
Fossalta di Portogruaro	VE	6,91	0,16					8,70	0,20				
Lignano Sabbiadoro	UD	6,83	0,16	0,26	0,01	64,26	1,55	8,33	0,20	0,62	0,02	73,68	1,77
Musile di Piave	VE	6,00	1,76	0,43	0,13	0,01	0,00	6,89	2,02	0,51	0,15	0,02	0,01
Meolo	VE	5,73	0,29	0,93	0,05			7,23	0,37	1,11	0,06		
San Dona' di Piave	VE	5,71	2,15	0,65	0,25	48,13	18,12	6,83	2,57	1,07	0,40	57,12	21,50
Conselve	PD	5,66	0,03			10,30	0,05	8,88	0,04			17,76	0,09
Pettorazza Grimani	RO	5,53	0,81	0,01	0,00			6,11	0,89	0,01	0,00		
Agna	PD	5,20	0,42	0,16	0,01			6,93	0,56	0,23	0,02		
Eraclea	VE	5,10	3,96	0,71	0,55	0,01	0,01	5,51	4,28	0,92	0,71	0,01	0,01
Latisana	UD	4,98	0,46			36,85	3,43	6,83	0,64			48,64	4,52

Table 7.28. Percentage and surface (km^2) of agricultural typologies (i.e. permanent culture, stable meadow, arable) for the 15 municipalities most interested to a very high damage scores in the North Adriatic coast for the high and low SLR scenarios.

Table 7.27 and Table 7.28 shows that the values do not vary appreciably between the selected scenarios and the percentage of urban classes are higher than the percentage of agricultural classes. The municipalities showing higher percentages of the territory with the very high damage class for each agricultural typology are: Terzo d’Aquileia, Annone Veneto, Jesolo and Cessalto for the permanent culture (with about 8-17 % of the territory for the low and high SLR scenario); Jesolo for the stable meadow (with about 0.40-0.70 % of the territory for the low and high SLR scenario); Lignano Sabbiadoro San Donà di Piave and Latisana for the arable area, (with about 37-74 % of the territory for the low and high SLR scenario).

Regarding the RSLR inundation impact, the distribution of the surface of each receptor (km^2) within each damage class for the low and high RSLR scenarios is reported in Table 7.29. Moreover, Figure 7.15 shows the distribution of damage classes according to the low and high RSLR scenarios considering the percentage (%) of the total surface of each receptor in the Coasts of Veneto.

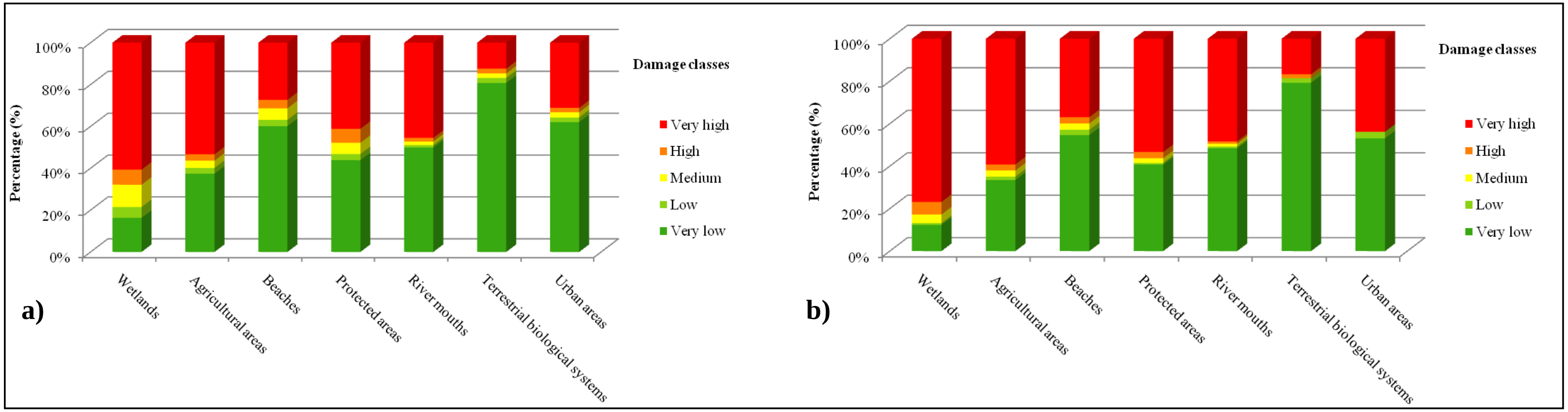


Figure 7.15. Distribution of damage classes according to the low a) and high b) RSLR scenarios considering the territorial percentage for each receptor in the Coasts of Veneto.

Receptor	Wetlands (km^2)		Agricultural areas (km^2)		Beaches (km^2)		Protected areas (km^2)		River mouths (km^2)		Terrestrial biological systems (km^2)		Urban areas (km^2)	
Class	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm	RSLR 17 cm	RSLR 42 cm
Very low	42,12	31,92	553,98	495,48	6,60	6,00	150,58	139,88	357,45	346,76	17,46	16,62	139,12	118,95
Low	13,39	2,17	40,96	24,11	0,33	0,27	10,11	2,58	8,37	5,73	0,51	0,45	4,96	6,76
Medium	27,48	10,43	51,37	43,23	0,61	0,33	18,31	7,78	12,19	9,84	0,47	0,65	5,64	0,18
High	18,69	15,34	45,06	41,71	0,44	0,33	22,99	9,97	12,46	7,78	0,49	0,39	4,65	0,19
Very high	156,53	198,34	790,13	876,97	3,00	4,06	141,23	183,00	325,53	345,87	2,68	3,50	69,81	98,08
tot	258,21	258,21	1481,50	1481,50	10,98	10,98	343,22	343,22	715,99	715,99	21,61	21,61	224,17	224,17

Table 7.29. Distribution of damage classes according to the low and high RSLR scenarios considering the territorial surface for each receptor of the Coasts of Veneto.

Figure 7.15 and Table 7.29 shows that most of the investigated receptors (i.e. Wetlands, Agricultural areas, Protected areas, river mouths, Terrestrial biological systems) are interested by high and very high damage classes. This is due to the subsidence process that tends to increase the areas exposed to RSLR inundation impact.

A more specific statistic was also calculated for Agricultural and Urban areas and showed in Table 7.30 and Table 7.31. This statistic highlights the territorial percentage and surface of each urban class (i.e. residential and commercial) with the very high damage scores for each municipality. The percentage refers to the total surface of urban territory of each municipality.

Table 7.30 considers the 20 municipalities showing higher percentages of the territory in the very high damage class for the residential building category in the North Adriatic coasts.

Municipality	Prov.	RSLR 17 cm				RSLR 42 cm			
		Residential buildings		Commercial buildings		Residential buildings		Commercial buildings	
		%	Km^2	%	Km^2	%	Km^2	%	Km^2
Porto Viro	RO	44,35	4,15	30,15	2,82	46,15	4,32	31,19	2,92
Porto Tolle	RO	41,69	4,21	1,22	0,12	41,83	4,22	1,23	0,12
Loreo	RO	35,83	0,96	0,02	0,00	39,11	1,05	0,07	0,00
Taglio di Po	RO	35,32	1,95	16,21	0,90	39,56	2,19	17,08	0,94
Eraclea	VE	35,10	2,50	11,13	0,79	39,10	2,78	13,36	0,95
Ariano nel Polesine	RO	29,86	1,32	0,30	0,01	34,69	1,53	0,33	0,01
Cavarzere	VE	27,97	2,02	9,44	0,68	31,31	2,27	10,98	0,79
Corbola	RO	19,08	0,28	3,69	0,05	32,49	0,48	9,48	0,14
Musile di Piave	VE	17,61	0,69	3,78	0,15	21,22	0,83	4,43	0,17
Adria	RO	15,65	1,58	13,11	1,33	20,63	2,09	17,49	1,77
Concordia Sagittaria	VE	15,44	0,65	4,26	0,18	19,94	0,84	4,77	0,20
Torre di Mosto	VE	15,28	0,55	15,49	0,56	20,24	0,73	16,27	0,58
Caorle	VE	14,24	1,60			19,72	2,22		
Santo Stino di Livenza	VE	13,79	0,65	11,20	0,52	18,33	0,86	12,48	0,58
Cona	VE	12,73	0,42			14,89	0,49		
Correzzola	PD	12,60	0,48	0,28	0,01	18,83	0,72	0,80	0,03
Jesolo	VE	10,76	1,62	7,51	1,13	15,77	2,37	10,48	1,57
Ceggia	VE	10,75	0,31	21,22	0,61	13,85	0,40	22,95	0,66
Chioggia	VE	10,61	1,03	1,31	0,13	13,68	1,32	1,43	0,14
San Dona' di Piave	VE	10,40	1,21	2,08	0,24	13,27	1,55	3,94	0,46

Table 7.30. Percentage and surface (km^2) of urban typologies (i.e. residential buildings and commercial buildings) for the 20 municipalities most interested by very high damage scores in the Veneto coast for high and low RSLR scenarios.

Table 7.31 highlights the territorial percentage and surface of each agricultural class (i.e. permanent culture, stable meadow, arable) in the very high damage class for each municipality. The percentage refers to the total surface of agricultural territory of each municipality. Table 7.31 considers the 15 municipalities with the higher percentage of the territory in the very high damage class for the permanent culture category.

Municipality	Prov.	RSLR 17 cm						RSLR 42 cm					
		Permanent culture		Stable meadow		Arable		Permanent culture		Stable meadow		Arable	
		%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2
Motta di Livenza	TV	22,64	0,11					39,59	0,19				
Annone Veneto	VE	20,24	0,73	3,17	0,11			25,98	0,93	3,78	0,14		
Cessalto	TV	19,51	0,54	0,77	0,02	0,07	0,00	27,89	0,77	1,09	0,03	0,09	0,00
Jesolo	VE	11,07	5,27	0,75	0,36	0,04	0,02	12,17	5,79	1,56	0,74	0,04	0,02
Fossalta di Portogruaro	VE	8,62	0,20					10,05	0,23				
Candiana	PD	7,73	0,77	0,58	0,06	0,02	0,00	8,90	0,89	0,89	0,09	0,04	0,00
Noventa di Piave	VE	7,06	0,10	1,20	0,02	17,69	0,26	10,15	0,15	3,23	0,05	28,96	0,42
Musile di Piave	VE	6,99	2,05	0,55	0,16	0,03	0,01	7,86	2,31	0,74	0,22	0,04	0,01
San Dona' di Piave	VE	6,83	2,57	1,23	0,46	59,99	22,58	8,20	3,09	1,55	0,58	68,99	25,97
Agna	PD	6,71	0,54	0,21	0,02			8,06	0,65	0,33	0,03		
Meolo	VE	6,56	0,34	1,04	0,05			8,13	0,42	1,17	0,06		
Portogruaro	VE	6,48	1,65	0,72	0,18			8,26	2,11	0,98	0,25		
Conselve	PD	6,31	0,03			11,33	0,05	9,27	0,04			20,33	0,10
Pettorazza Grimani	RO	6,09	0,89	0,01	0,00			6,32	0,92	0,01	0,00		
Eraclea	VE	5,67	4,41	0,99	0,77	0,01	0,01	5,99	4,65	1,13	0,87	0,01	0,01

Table 7.31. Percentage and surface (km^2) of agricultural typologies (i.e. permanent culture, stable meadow, arable) for the 15 municipalities most interested by very high damage scores in the Veneto coast for high and low RSLR scenarios.

Table 7.30and Table 7.31 show that the values do not vary appreciably among the selected scenarios and the percentage of urban classes characterized by high damage class are higher than the percentage of agricultural classes characterized by the same damage class. Finally, the same considerations emerged for the SLR can be remarked also for the RSLR inundation impact.

7.6.2. Coastal erosion impact.

As already explained for the SLR and RSLR inundation impacts in Paragraph 7.6.1, the first step of the damage assessment phase is to classify and provide scores and weights to the value factors identified in the vulnerability matrix (Table 7.1).

Table 7.32 shows the value classes and the related scores defined for the value factors identified for the coastal receptors analysed in the case study area.

VALUE FACTOR	CLASS	SCORE
Protection level	National area	1
	Regional area	0.5
	Nature 2000 area	0.2
Population density	< 100 inhabitants per municipality	0.2
	100-300 inhabitants per municipality	0.5
	> 300 inhabitants per municipality	1
Agricultural typology	Arable	0.2
	Stable	0.5
	Permanent	1
Urban typology	Infrastructure	0.2
	commercial	0.5
	residential	1

Table 7.32. Classes and scores associated with the value factors identified in the vulnerability matrix for the CE impact.

According to the RRA methodology, the considerations proposed for the SLR and RSLR are here applied for the CE impact. For this reason, the group of environmental scientists have defined the scores for the value factors and the same weight 1 was assigned to all the value factors considered in the case study. For the cells composing each receptor, the value function aggregates the value scores described in Table 7.32 thus obtaining one value map for each analysed receptor. In this way value maps allow visualization of the receptor sub-areas associated with each value class.

For each value map the value scores were classified using the equal interval method and obtaining the ranges shown in Table 7.33.

Value class	Value range
Very low	0-0.19
Low	0.19-0.33
Medium	0.33-0.47
High	0.47-0.61
Very high	0.61-1

Table 7.33. Value classes with the related value range for the CE impact.

An example of value map obtained from the aggregation of the value factors for the protected areas is reported in Figure IV P of Appendix IV. About the 77 % of the territory show a very low value class due to the presence of factors with lower value scores (e.g. Nature 2000 protected areas, commercial buildings, population density < 100 inhabitants per municipality). The area with the higher value class is located in the Gulf of Trieste in which the population density value factor assumed the higher score (i.e. 1). Figure 7.16 shows the territorial surface of each receptor (km^2) and the percentage of the total surface of each receptor (%) that is associated with each class in the North Adriatic coastal area.

a)

	Case study area within the RICE area (km^2)			
Class	Beaches	Protected areas	River mouths	Wetlands
Very low	9,00	57,73	6,19	0,37
Low	2,23	11,79	10,72	9,07
Medium	0,15	4,56	15,51	10,02
High	0,04	0,48	0,41	0,64
Very high	0,00		0,15	1,21

b)

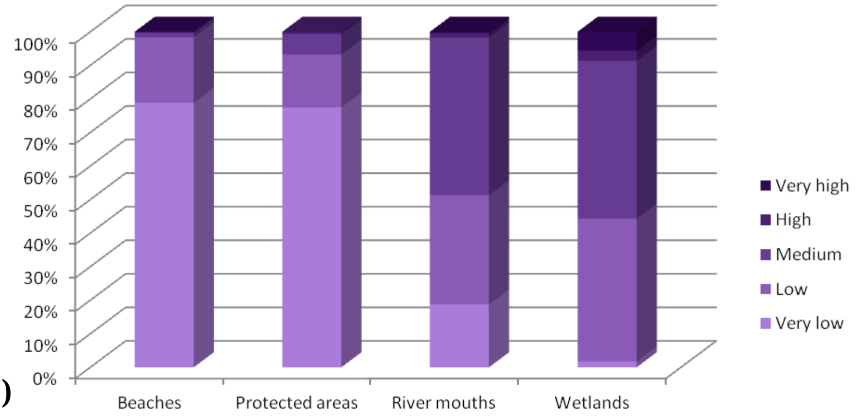


Figure 7.16. Distribution of the territorial surface (km^2) a) and of the percentage of surface b) that is associated with each value class for the receptors located in the North Adriatic coasts for the coastal erosion impact.

Figure 7.16 shows that the territory percentage in the lower classes is higher than the percentage in the very high class for beaches and protected areas. This is due to the wide presence of factors with lower value scores (e.g. Nature 2000 protected areas, commercial buildings, population density < 100 inhabitants per municipality). For river mouths and wetlands the territory percentage in the middle value class is higher than the percentage in the other value classes, due to the middle scores that the value factors assumed in the case study area.

After estimating the value associated with each receptor analyzed in the case study area, the damage function proposed in Equation 14 was applied in order to produce damage maps.

Damage scores were classified using the equal interval method and the ranges of scores associated with each class is shown in Table 7.34.

Damage class	Damage range
Very low	0-0.09
Low	0.09-0.18
Medium	0.18-0.27
High	0.27-0.36
Very high	0.36-0.45

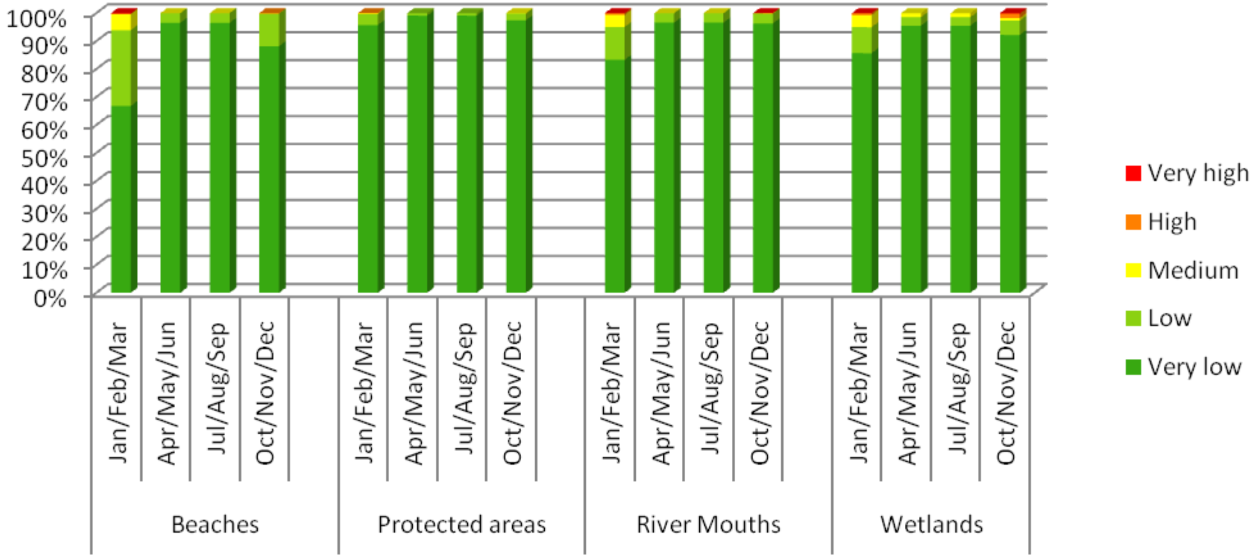
Table 7.34. Damage classes with the related damage range for the CE impact.

Figures IV Q and IV R (Appendix IV) represent two examples of damage maps developed for beaches and wetland. Figures IV Q and IV R highlights areas of beaches and wetlands affected by a higher CE damage in the North Adriatic coast within the RICE area. The spatial distribution of the damage classes in the damage maps of Appendix IV shows that the study area is mostly interested by the lower damage classes due to the the presence of factors with lower value scores.

Figure 7.17 shows the distribution (km^2) and the percentage of the North Adriatic coast in each damage class for each investigate receptor (i.e. beaches, protected areas, river mouth, wetlands) and for each CE hazard scenario.

	Beaches (km^2)				Protected areas (km^2)				River Mouths (km^2)				Wetlands (km^2)			
Class	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Sep	Oct/Nov/Dec	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Sep	Oct/Nov/Dec	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Sep	Oct/Nov/Dec	Jan/Feb/Mar	Apr/May/Jun	Jul/Aug/Sep	Oct/Nov/Dec
Very low	7,62	11,01	11,01	10,05	70,52	73,00	73,00	71,78	27,45	31,84	31,84	31,75	18,18	20,27	20,27	19,57
Low	3,09	0,39	0,39	1,32	2,88	0,67	0,67	1,74	3,88	1,10	1,10	1,14	1,97	0,64	0,64	1,08
Medium	0,65	0,00	0,00	0,01	0,26	0,00	0,00	0,14	1,42	0,03	0,03	0,04	0,92	0,31	0,31	0,21
High	0,02	0,00	0,00	0,01	0,01	0,00	0,00	0,00	0,21	0,00	0,00	0,01	0,14	0,00	0,00	0,33
Very high	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,00	0,00	0,04

a)



b)

Figure 7.17. Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each damage class for the investigated receptors in the North Adriatic coast for each CE hazard scenario.

Figure 7.17 show that for the majority of receptors, the percentage of territory in the lowest damage class is the most relevant. Moreover, the percentage of the territory within the higher classes is visible especially in the trimester Jan/Feb/Mar, due to the hazard scores that the hazard metrics assumed in the winter trimester.

A more specific statistic was calculated for protected areas and showed in Table 7.35. This statistic evaluates the percentage and surface of the territory of each protection class (i.e. Regional area and Nature 2000 area) with a damage class for each municipality of the North Adriatic sea. The percentage refers to the surface of protection level of each municipality in the RICE area for the months most affected by CE damage (i.e. January, February, March, April, June and July).

		Jan/Feb/Mar/Apr/Jun/Jul			
		Nature 2000 area		**Regional area**	
Municipality	**PROV.**	Km^2	%	Km^2	%
Monfalcone	GO	0,78	100	0	0
Lignano Sabbiadoro	UD	0,63	100	0	0
Marano Lagunare	UD	2,56	100	0	0
San Michele al Tagliamento	VE	5,16	100	0	0
Eraclea	VE	0,71	100	0	0
Caorle	VE	5,63	100	0	0
Jesolo	VE	0,49	100	0	0
Venezia	VE	1,44	100	0	0
Cavallino Treporti	VE	2,48	100	0	0
Trieste	TS	5,23	97,02	0,16	2,98
San Canzian d'Isonzo	GO	0,40	95,94	0,02	4,06
Porto Viro	RO	4,76	92,94	0,36	7,06
Chioggia	VE	0,29	82,04	0,06	17,96
Duino Aurisina	TS	3,26	81,21	0,76	18,79
Grado	GO	0,49	77,37	0,14	22,63
Rosolina	RO	4,11	57,57	3,03	43,43
Porto Tolle	RO	9,81	52,90	8,74	47,10
Ariano nel Polesine	RO	0,19	18,01	0,86	81,99
Staranzano	GO	0,22	5,85	3,53	94,15

Table 7.35. Surface (km^2) and percentage of protection level (i.e. Nature 2000 area and Regional area) for the municipalities interested by damage in the North Adriatic coast within the RICE area for the CE impact (for the first semester of the thirty-year future scenario).

Table 7.35 highlights that the Nature 2000 areas would show CE damage for almost all the municipalities within the RICE area (i.e. 17 municipalities show a damage between 53 to 100% for the Nature 2000 areas) and only Ariano nel Polesine and Staranzano would show a high % of CE damage for the Regional areas.

Conclusions.

The thesis described the development of a Regional Risk Assessment (RRA) methodology for the integrated assessment of climate change impacts in coastal zones at the regional scale and its application to the case study of the North Adriatic coast in Italy.

Specifically, the RRA methodology was applied for the assessment and prioritization of targets and areas at risks in relation to possible sea-level rise and erosion impacts, considering a climate change scenario for the period 2070-2100 in the North Adriatic coastal area.

A strength of the proposed approach consists in the use of outputs coming from a multi-model chain in order to gain information about the spatial and temporal distribution of climate change hazards at the regional scale (e.g. sea-level rise projections, wave height and bottom stress). Moreover, the originality of the approach consist in the use of Multi-Criteria Decision analysis (MCDA) techniques in order to obtain relative rankings of targets and areas at risk in the examined coastal territory and to identify homogeneous geographic sites for the definition of adaptation and management strategies. Finally, the extensive use of Geographic Information Systems (GIS) allowed a detailed analysis of the results and the estimation of several indicators and statistics for key coastal targets and administrative units (e.g. km^2 of beaches at higher risk for each coastal municipality; percentage of residential buildings and commercial buildings with higher damage in the considered region).

On the whole, the RRA outputs (i.e. exposure, susceptibility, risk and damage maps) and the related indicators can be considered as a first-pass assessment for the spatial identification of areas and targets at higher risk from climate change and for the definition of sustainable management options at the regional (i.e. sub-national) scale.

In order to properly use the RRA results it is important to underline that the rankings produced by the methodology are unit less numbers, expressed in qualitative classes (i.e. very high, high, medium, low, very low), that judge the relative degree of risk and damage for the analyzed receptors. Accordingly, regional risk and damage classifications do not provide absolute predictions about the impacts of climate change, rather they are relative indices which provide information about the sub-areas and targets within a region that are more likely to be affected by climate change impacts than others.

For what concern the accuracy of the results coming from the risk assessment process, it should be considered that the proposed methodology adequately takes into account the best available geographical information at the regional scale, thus requiring a great effort to deal with a huge amount of data at a detailed spatial resolution. Moreover, numerical models simulations used for the construction of climate change hazard scenarios and exposure maps were validated through the comparison with observed data for a control period (Gualdi et al., 2008, Djurdjevic and Rajkovic, 2008).

An important issue is related to the collection and organization of data coming from different sources into homogeneous formats for the whole case study area. In fact, it was necessary to perform a huge pre-processing phase in order to manage data with different geographic coordinate systems and allow the GIS overlay and calculations. All this steps represent potential sources of uncertainty and of geometrical errors in the final risk estimate.

Future improvements of the methodology can be obtained by eliciting more potential receptors and extending their subset of vulnerability factors. Furthermore, the consistency of results provided by the methodology can be properly tested trough a sensitivity analysis allowing the ascertainment of how much the output of the assessment could be influenced by its input parameters (i.e. scores and weights).

A relevant feature of the methodology is represented by its flexibility to manage input data (i.e. raster or shape files) provided by different numerical models and vulnerability datasets. This characteristic allows the methodology to be in principle applied at different spatial scales (i.e. from the local to the national and supra-national scales) and to be updated with the analysis of new climate change impacts on further ecosystems (e.g. groundwater, river basins, human health etc.). Moreover, based on available data and models, the methodology could be improved considering not only scenarios of climate change but also land use and population dynamics. It has also the potential to be integrated with socio-economic models in order to obtain a quantitative estimation of damages and losses associated with climate related impacts.

Finally, the proposed methodology can take advantage from the involvement of stakeholders early in the process in order to improve the exchange of knowledge on relevant climate-related risks, to identify well defined needs and data gaps at the regional to local scale, and better support decision making processes in a climate service perspective.

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APPENDIX I

Guidelines for the construction of the Vulnerability and Hazard matrixes.

CLIMATE CHANGE IMPACTS	VULNERABILITY MATRIX									
	RECEPTORS									
	BEACHES AND DUNES	RIVER MOUTHS	WETLANDS	HYDROLOGICAL SYSTEMS	TERRESTRIAL BIOLOGICAL SYSTEMS	MARINE BIOLOGICAL SYSTEMS	PROTECTED AREAS	FISHERIES AND AQUACULTURE	URBAN AREAS	AGRICULTURAL AREAS
HYDRODYNAMIC IMPACTS										
SLR/RSLR inundation	Elevation	Elevation	Elevation		Elevation		Elevation	Elevation	Elevation	Elevation
	Vertical land movements	Vertical land movements	Vertical land movements		Vertical land movements		Vertical land movements	Vertical land movements	Vertical land	Vertical land movements
	Protection level	Protection level	Protection level		Protection level		Protection level	Protection level	Protection level	Protection level
	Population density	Urban typology	Wetland extension		Vegetation cover		Urban typology		Urban typology	Urban typology
		Agricultural typology	Population density		Population density		Agricultural typology		Population density	Agricultural typology
		Population density					Population density			Population density
Storm surge Flooding	Elevation	Elevation	Elevation	Elevation	Elevation		Elevation	Elevation	Elevation	Elevation
	Distance from coastline	Distance from coastline	Distance from coastline	Distance from coastline	Distance from coastline		Distance from coastline	Distance from coastline	Distance from	Distance from coastline
	Artificial protections	Artificial protections	Artificial protections	Water body configuration	Vegetation cover		Artificial protections	Fish farms	Artificial protections	Artificial protections
	Vegetation cover	Vegetation cover	Vegetation cover	Protection level	Coastal slope		Vegetation cover	Protection level	Coastal slope	Coastal slope
	Coastal slope	Coastal slope	Wetland extension	Population density	Protection level		Coastal slope		Protection level	Protection level
	Geomorphology	Geomorphology	Protection level		Population density		Geomorphology		Urban typology	Agricultural typology
	Dunes	Protection level	Population density				Protection level		Population density	Population density
	Protection level	Urban typology					Urban typology			
	Population density	Agricultural typology					Agricultural typology			
		Population density					Population density			
Coastal erosion	Distance from coastline	Distance from coastline	Distance from coastline		Distance from coastline		Distance from coastline			
	Artificial protections	Artificial protections	Artificial protections		Artificial protections		Artificial protections			
	Vegetation cover	Vegetation cover	Vegetation cover		Vegetation cover		Vegetation cover			
	Coastal slope	Geomorphology	Sediment budget		% of urbanization		Sediment budget			
	Geomorphology	Sediment budget	Wetland extension		Protection level		Geomorphology			
	Dunes	Mouth typology	% of urbanization		Population density		% of urbanization			
	Sediment budget	% of urbanization	Protection level		Urban typology		Protection level			
	% of urbanization	Protection level	Population density				Population density			
	Protection level	Urban typology	Urban typology				Urban typology			
	Population density	Population density								
	Urban typology									
Change in hydraulics of estuaries		Stability of estuarine wetland habitats	Stability of estuarine wetland	Water body configuration		Seagraasses	Resilience of natural species			
		Coastal plan-form				Zooplankton	Parks and reserves			
		Position of main rivers and deltas				Phytoplankton	Ramsar areas			
		Seagrasses								
Offshore sedimentation		Seagrasses				Seagrasses				
IMPACTS ON SOIL AND GROUNDWATER										
Saltwater intrusion	Presence of freshwater aquifers	Groundwater table level		Groundwater table level	Vegetation cover					
		River bottom slope		Presence of freshwater aquifers						
		Riverine and estuarine morphology								
Establishment of low-drainage sectors	Elevation				Presence of low-lying habitats					
	Vegetation cover									
Surface water stagnation	Substrate permeability		Hinterland slope		Hinterland slope		Hinterland slope			
	Hinterland slope									
IMPACTS ON WATER										
Water quality variations		Resilience of natural species	Resilience of natural species	Water bodies classification		Resilience of natural species		Distribution of fisheries		
		Seagrasses		Seagrasses		Bathymetry		Distribution of mariculture		
		Phytoplankton		Position of main river and deltas		Presence and distribution of biodiveristy		Timing of spawning		
		Zooplankton		Resilience of natural species		Tegnue		Distribution of fish farms		
		Bathymetry		Bathymetry		Seagraasses		Resilience of natural species		
						Zooplankton				
IMPACTS ON BIODIVERSITY										
Invasion by exotic/pest species					Rare and endangered species	Rare and endangered species	Rare and endangered species	Rare and endangered species		
					Resilience of natural species	Resilience of natural species	Resilience of natural species	Resilience of natural species		

🟨	**Pathway factors**	physical characteristics of the receptors determining the possibility of contact with climate change hazards and therefore potential exposure areas (e.g. elevation, distance from coastline).
🟩	**Attenuation factors**	elements able to attenuate the intensity of the hazard associated to an impact (e.g. artificial protection).
🟧	**Susceptibility factors**	determine the degree to which a receptor is affected, either adversely or beneficially, by climate-related stimuli (e.g. geomorphology, sediment budget, vegetation cover).
🟪	**Value factors**	identify relevant environmental and socio-economic values of the receptors that need to be preserved for the interest of the community (e.g. land use, fishing areas, population density).

Table I A. Vulnerability matrix for the assessment of coastal vulnerability to climate change at the regional scale.

HAZARD MATRIX																		CLIMATE CHANGE IMPACTS
STRESSORS																		
SALINITY	p H	CONTAMINANTS	NUTRIENTS	TURBIDITY	CO2	SEA TEMPERATURE	AIR TEMPERATURE	GROUNDWATER	BOTTOM STRESS	ALTERED CURRENTS	EXTREME STORMS SURGE	RAINFALL	WIND	RIVER FLOW	SEA LEVEL RISE	TIDE	WAVE	
																		HYDRODYNAMIC IMPACTS
															Projecting change in height Water level			SLR/RSLR Inundation
											Water level return period	Rainfall factors	Wind factors		Projecting change in height Water level	Tidal range	Height Direction	Storm surge flooding
									Bottom stress	Current patterns Velocity	Frequency Intensity Direction Fixed return period Water level		Wind factors		Projecting change in height Water levels Velocity	Tidal range	Height Direction Energy Period	Coastal erosion
										Current patterns Velocity	Water level	Rainfall factors		River discharges	Projecting change in height	Tidal range		Change in hydraulics of estuaries
									Bottom stress	Current patterns Velocity			Wind factors	River discharges	Projecting change in height	Tidal range	Height Direction	Offshore sedimentation
																		IMPACTS ON SOIL AND GROUNDWATER
												Rainfall factors			Projecting change in height	Tidal range		Saltwater intrusion
												Rainfall factors			Projecting change in height	Tidal range		Establishment of low-drainage sectors
												Rainfall factors			Projecting change in height	Tidal range		Surface water stagnation
																		IMPACTS ON WATER
Salinity	Profile and spatial distribution	Metals concentration PCB concentration	Nutrients concentration	Suspended matter concentration	Concentration	Seasonal changes in T Mean T	Seasonal changes in T Seasonal changes in evaporation			Current patterns Velocity		Rainfall factors		River discharges				Water quality variations (fresh and salt water)
																		BIODIVERSITY
Salinity						Seasonal changes in T Mean T	Seasonal changes in T Seasonal changes in evaporation			Current patterns Velocity		Rainfall factors	Wind factors					Invasion by exotic/pest species

Table I B. Hazard matrix for the construction of climate change exposure scenarios at the regional scale.

APPENDIX II

Guideline for the application of scores.

Linguistic Evaluation	**Scores ($s_{i,n}$)**
Most important class	1
Weakly less important class	0.8
Rather less important class	0.6
Strongly less important class	0.4
Less important class	0.2
No vulnerability/hazard	0

Table II A. Linguistic evaluations supporting the expert/decision maker in the assignation of relative scores to vulnerability and hazard classes.

Factor	**Class**	**Score ($s_{i,n}$)**				
		Impact 1	**Impact 2**	**Impact 3**	**...**	**Impact n**
Susceptibility factors						
sf_1	$c_{1,1}$					
	$c_{1,2}$					
sf_2	$c_{2,1}$					
	$c_{2,2}$					
	$c_{2,3}$					
sf_3	$c_{3,1}$					
	$c_{3,2}$					
	...					
	$c_{3,n}$					
...						
sf_n						
Hazard metrics						
h_1	$c_{1,1}$					
	$c_{1,2}$					
h_2	$c_{2,1}$					
	$c_{2,2}$					
	$c_{2,3}$					
h_3	$c_{3,1}$					
	$c_{3,2}$					
	...					
	$c_{3,n}$					
...						
h_n						

Table II B. Example of questionnaire to be administrated to experts for the assignation of relative scores to susceptibility factors (*sf*) and hazard (*h*) classes.

Value Factor	**Class**	**Score ($s_{i,n}$)**				
		Receptor 1	**Receptor 2**	**Receptor 3**	**…**	**Receptor 4**
vf_1	$c_{1,1}$					
	$c_{1,2}$					
	$c_{1,3}$					
vf_2	$c_{2,1}$					
	$c_{2,2}$					
vf_3	$c_{3,1}$					
	$c_{3,2}$					
	...					
	$c_{3,n}$					
…						
vf_n						

Table II C. Example of questionnaire to be administrated to decision makers for the assignation of relative scores to value (vf_n) classes.

APPENDIX III

Guideline for the application of weights.

Linguistic Evaluation	**Weights ($w_{i,k}$)**
Most important vulnerability factor/hazard metric	1
Weakly less important vulnerability factor/hazard metric	0.8
Rather less important vulnerability factor/hazard metric	0.6
Strongly less important vulnerability factor/hazard metric	0.4
Demonstratively less important vulnerability factor/hazard metric	0.2
Not important vulnerability factor/hazard metric	0

Table III A. Linguistic evaluations supporting the expert/decision maker in the assignation of weights to vulnerability factors and hazard metrics.

Susceptibility factors					
	Impacts				
	i_1	**i_2**	**i_3**	**…**	**i_n**
sf_1					
sf_2					
sf_3					
…					
sf_n					
Hazard metrics					
	Impacts				
	i_1	**i_2**	**i_3**	**…**	**i_n**
h_1					
h_2					
h_3					
…					
h_n					

Table III B. Example of questionnaire to be administrated to experts for the assignation of relative weights to susceptibility factors (*sf*) and hazard metrics (*h*).

Value factor	**Receptors**				
	r_1	**r_2**	**r_3**	**…**	**r_n**
vf_1					
vf_2					
vf_3					
…					
vf_n					

Table III C. Example of questionnaire to be administrated to decision makers for the assignation of relative weights to value factors (vf_n).

APPENDIX IV

Regional Risk Assessment maps for the analysis of sea-level rise, relative sea-level rise and coastal erosion impacts in the North Adriatic coast.

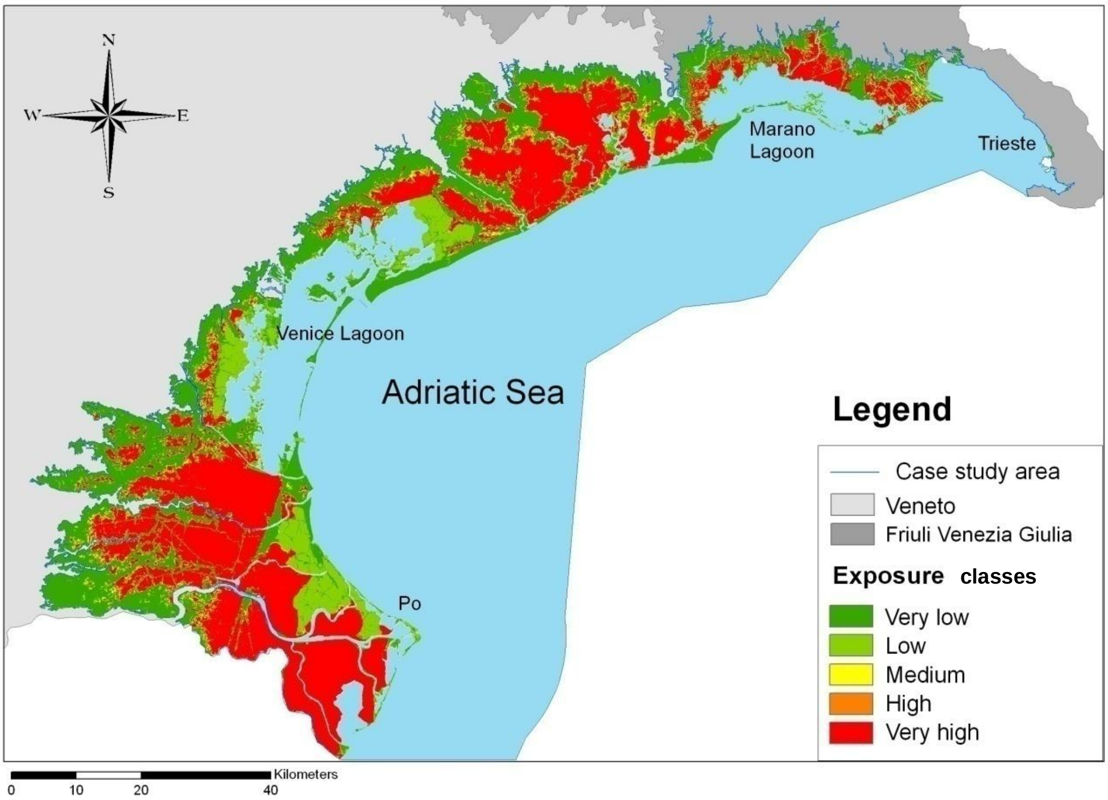


Figure IV A. Low exposure map for the sea-level rise inundation impact (projected water level of 17 cm) for the North Adriatic coast.

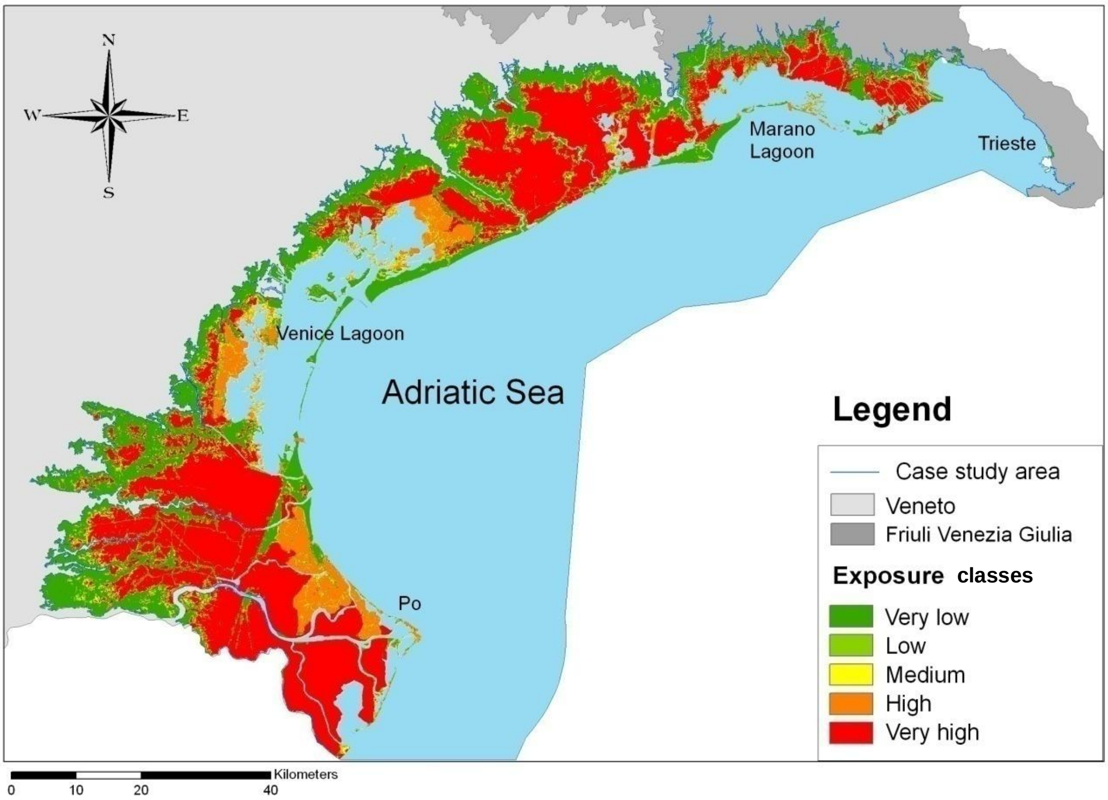


Figure IV B. High exposure map for the sea-level rise inundation impact (projected water level of 42 cm) for the North Adriatic coasts.

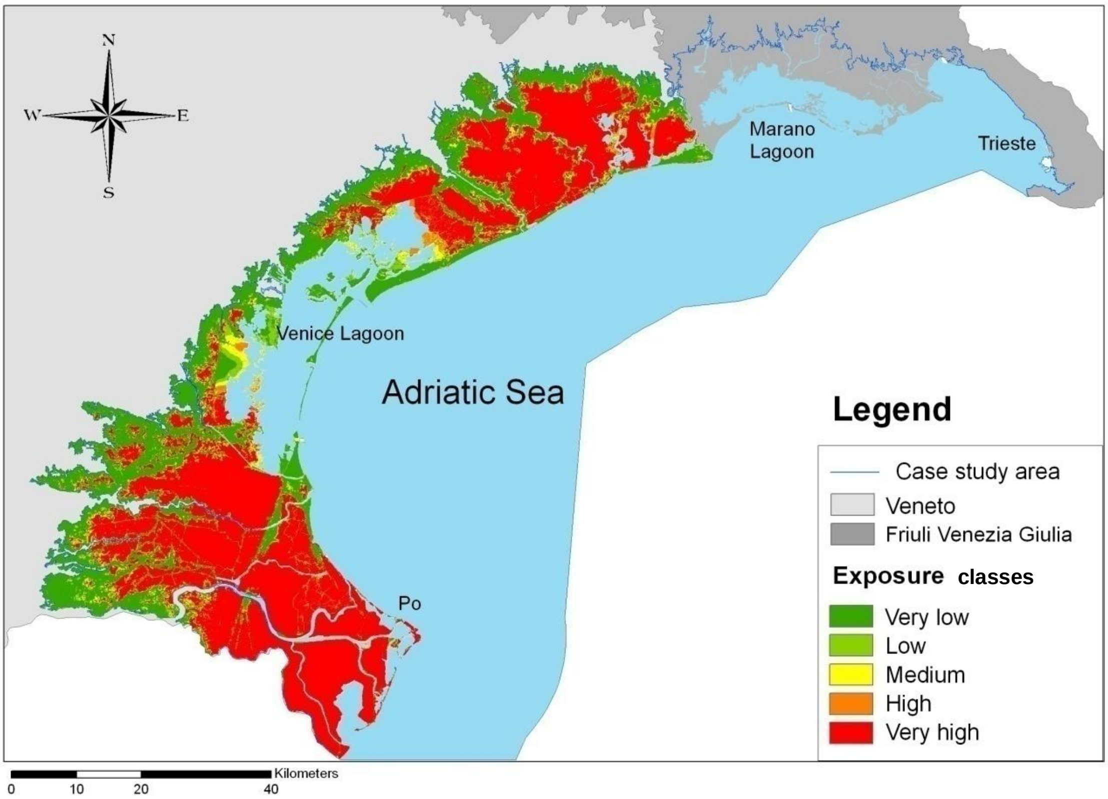


Figure IV C. Low exposure map for the relative sea-level rise inundation impact (projected water level of 17 cm) for the coasts of Veneto.

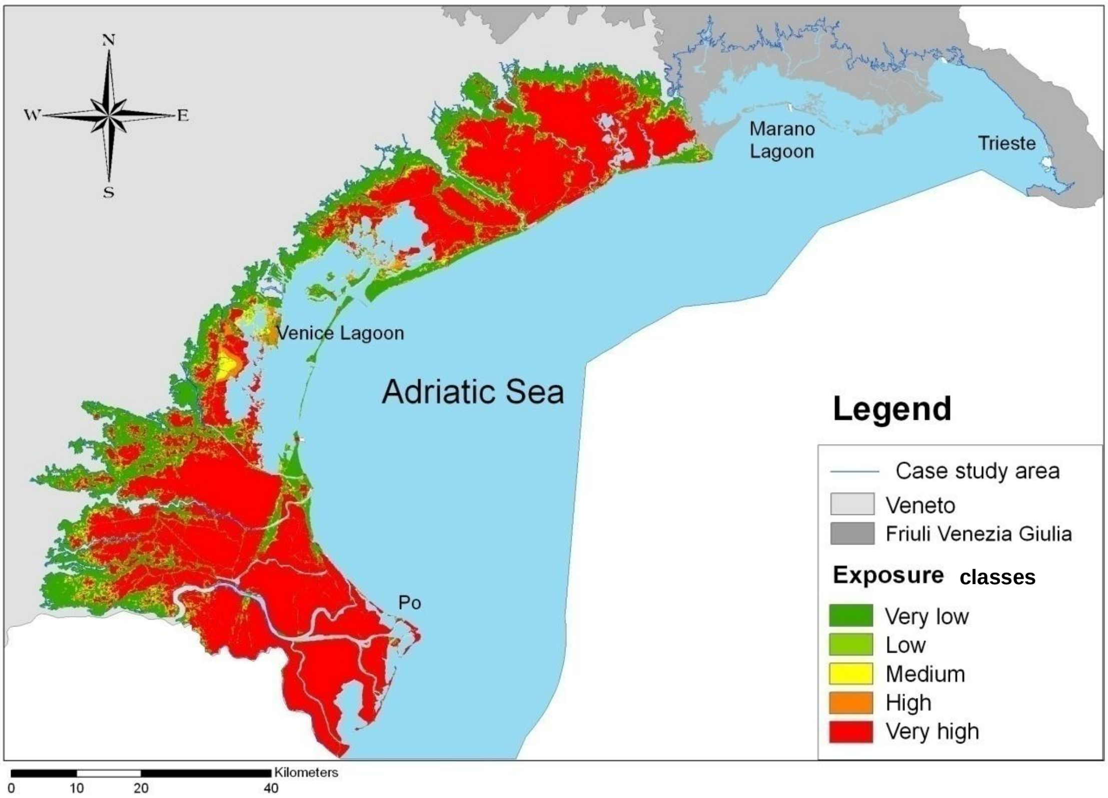


Figure IV D. High exposure map for the relative sea-level rise inundation impact (projected water level of 42 cm) for the coasts of Veneto

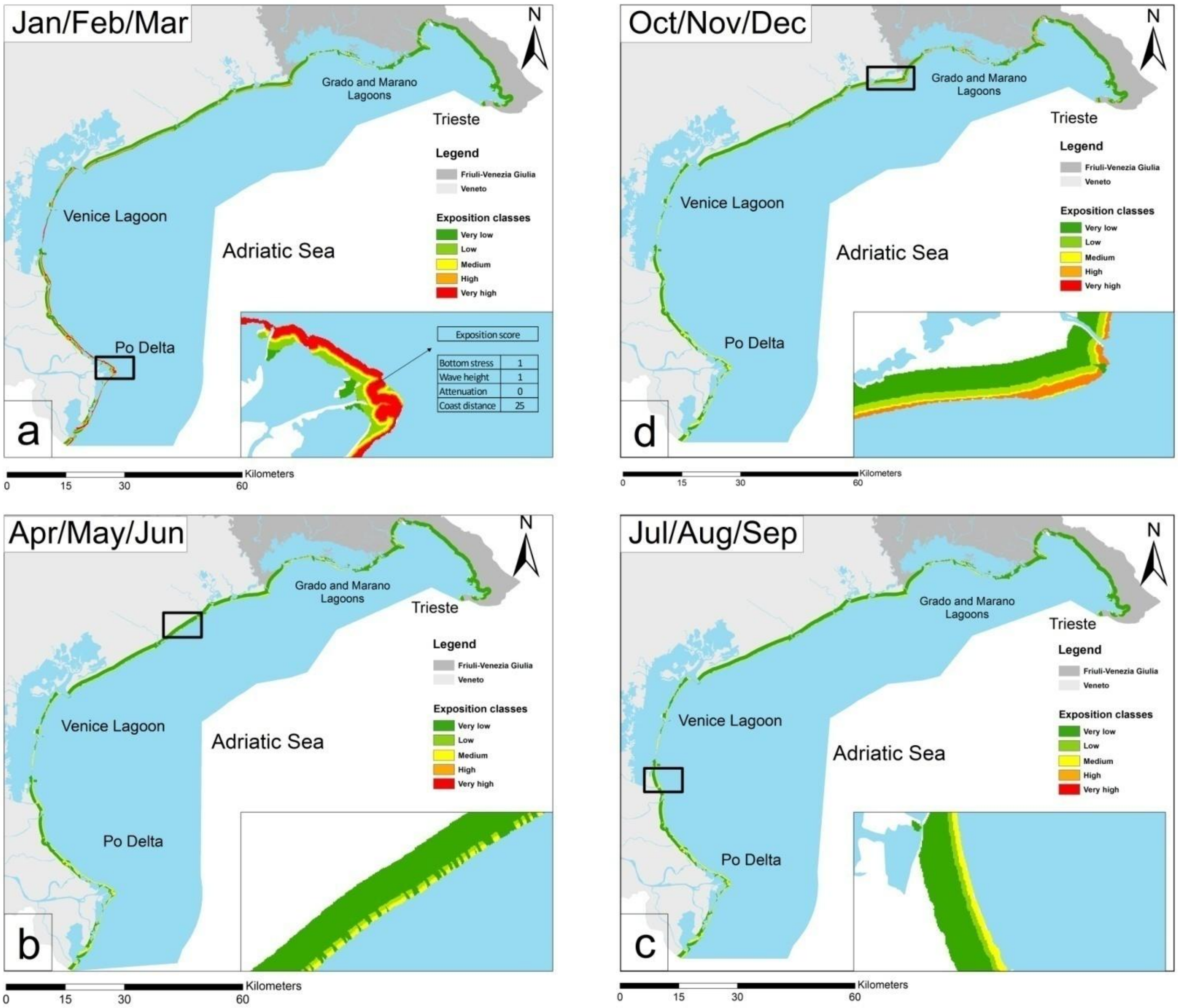
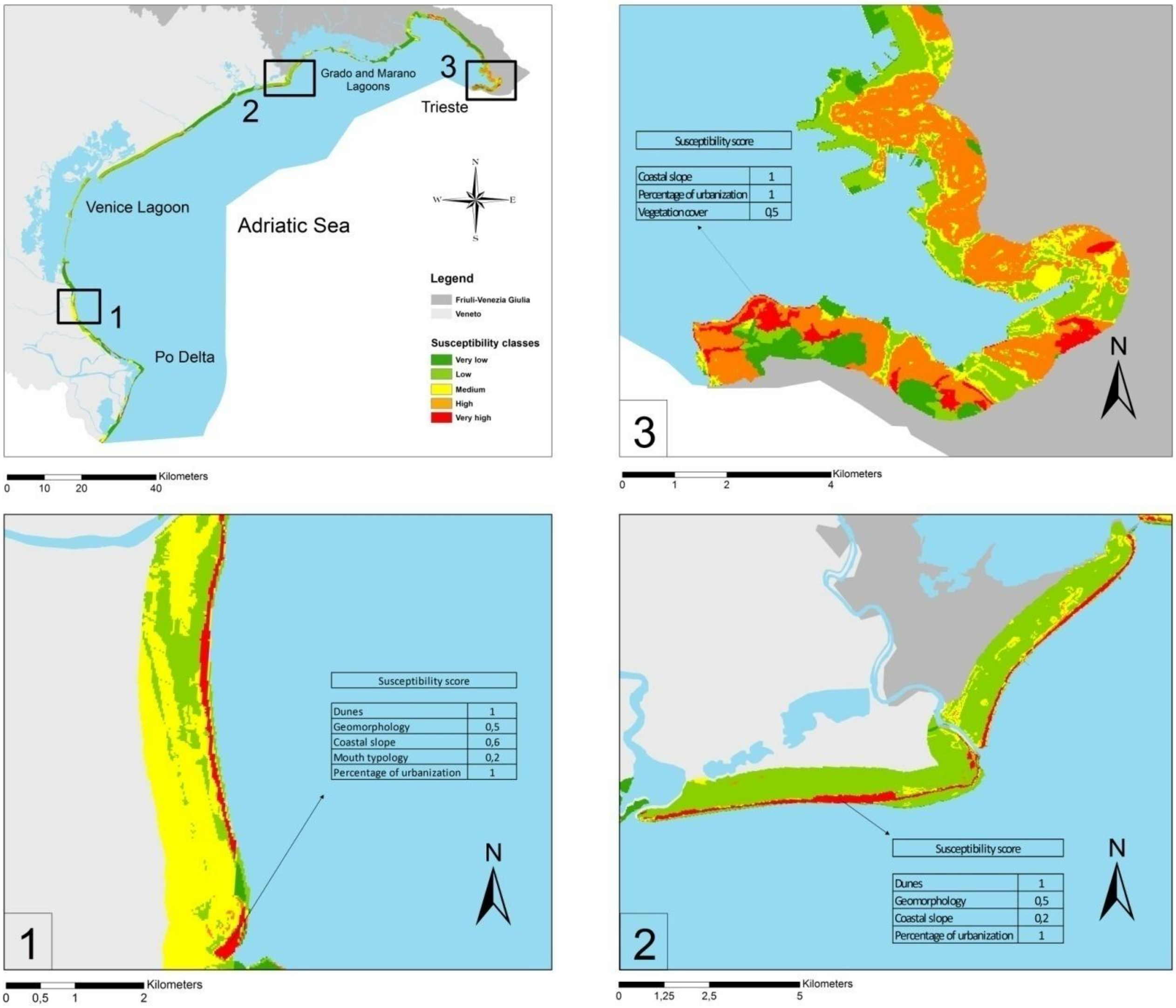


Figure IV E. Exposure map for the coastal erosion impact within the RICE area for the North Adriatic coast.



Susceptibility score

Coastal slope	1
Percentage of urbanization	1
Vegetation cover	0,5

Susceptibility score

Dunes	1
Geomorphology	0,5
Coastal slope	0,6
Mouth typology	0,2
Percentage of urbanization	1

Susceptibility score

Dunes	1
Geomorphology	0,5
Coastal slope	0,2
Percentage of urbanization	1

Figure IV F. Susceptibility map for the coastal erosion impact within the RICE area for the North Adriatic coast.

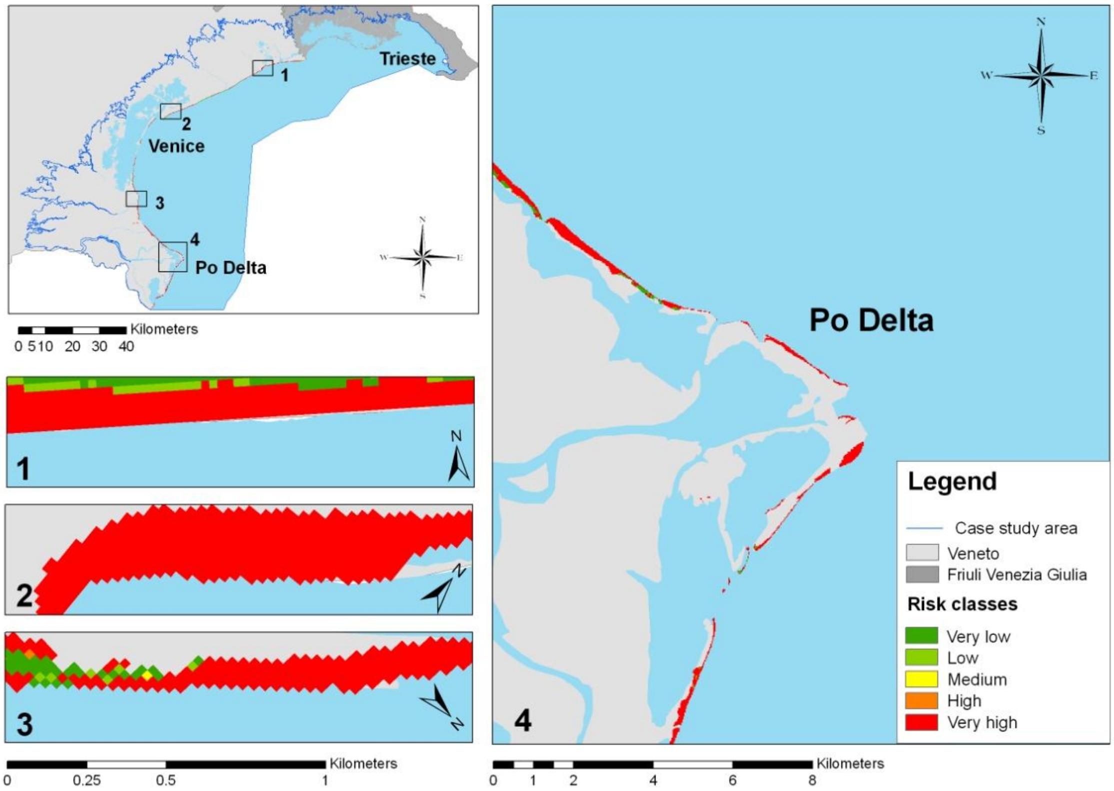


Figure IV G. Risk map of beaches for the high sea-level rise scenario (projected water level 42 cm) for the North Adriatic coasts.

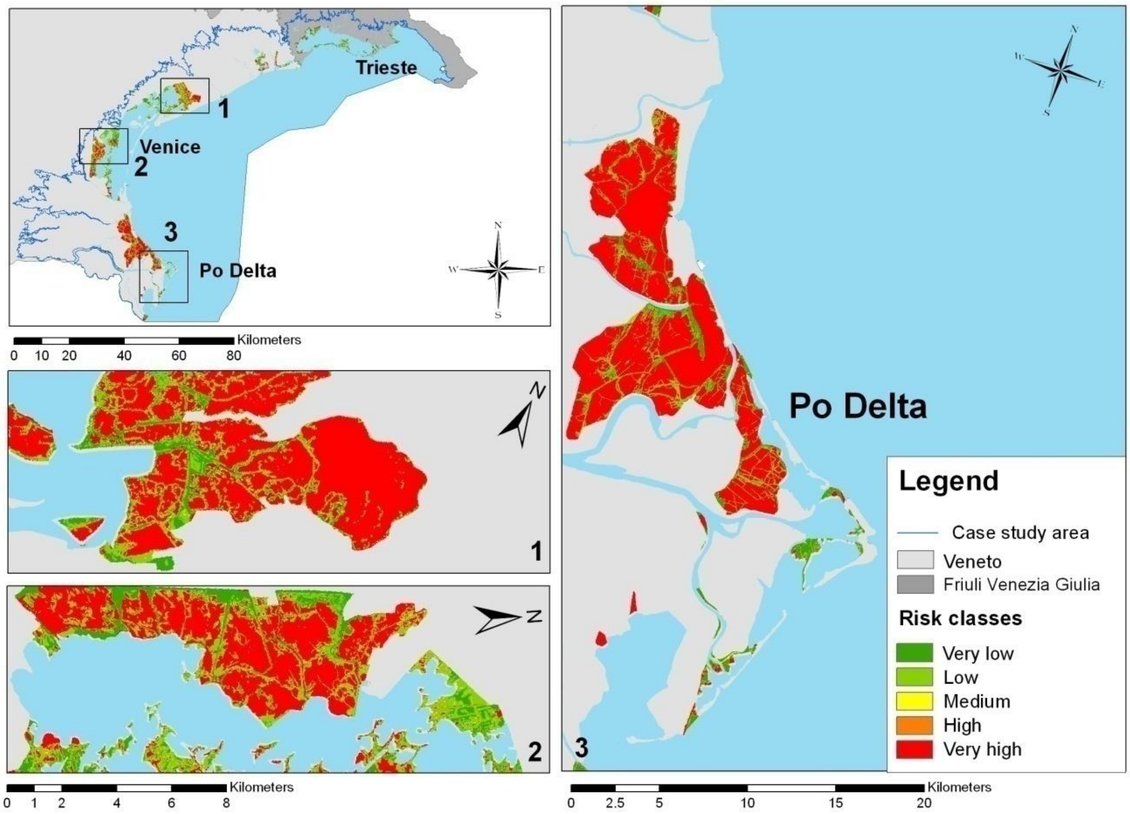


Figure IV H. Risk map of wetlands for the low sea-level rise scenario (projected water level of 17 cm) for the North Adriatic coasts.

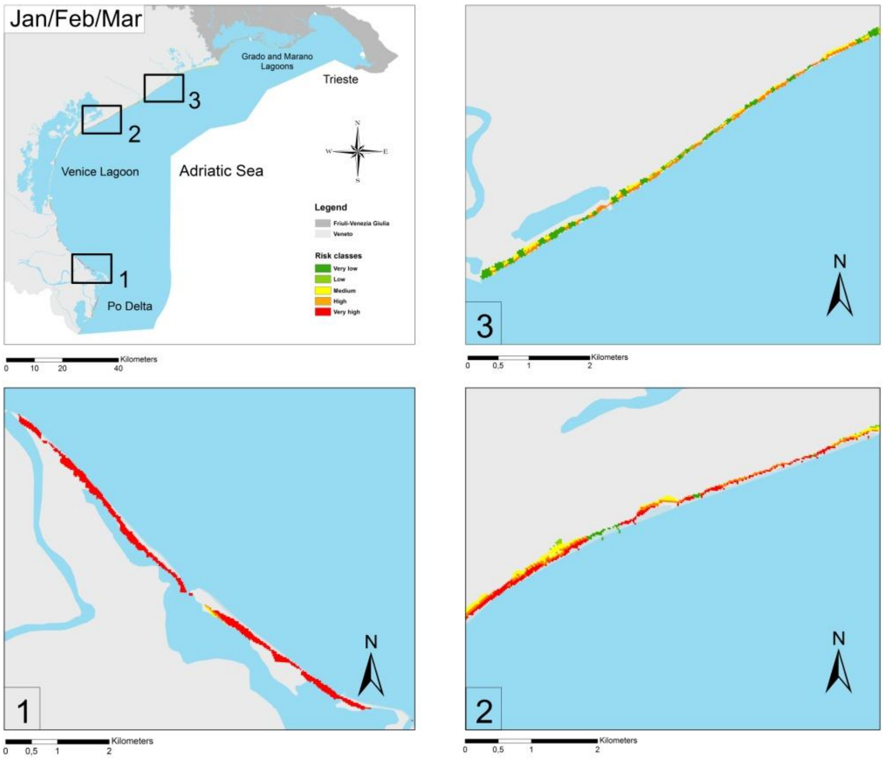


Figure IV I. Risk map of beaches for the coastal erosion impact within the RICE area for the North Adriatic coast for the trimester Jan/Feb/Mar.

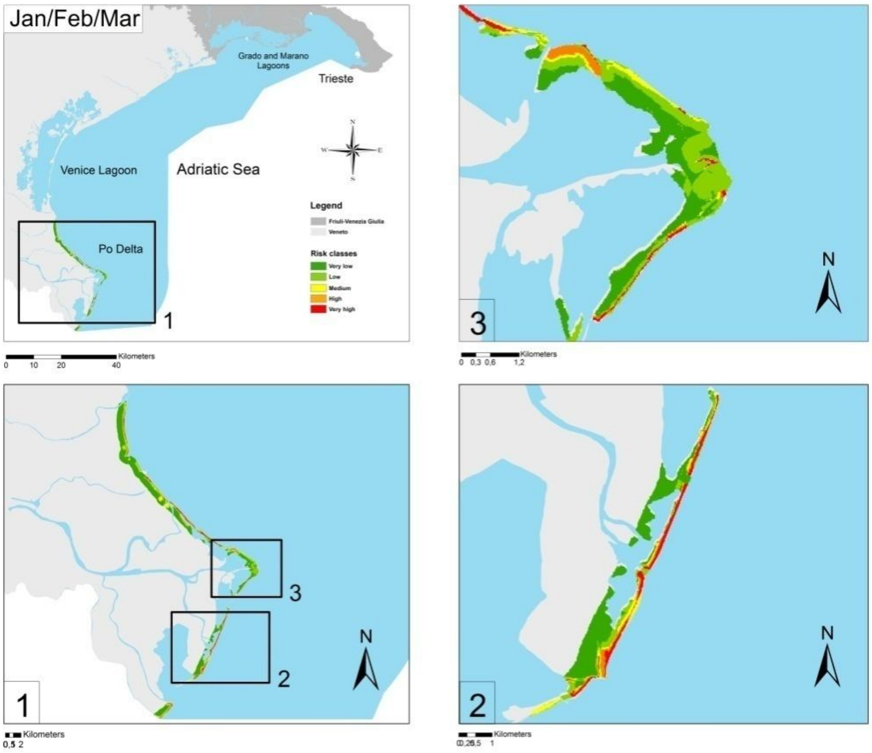


Figure IV L. Risk map of river mouths for the coastal erosion impact within the RICE area for the North Adriatic coast for the trimester Jan/Feb/Mar.

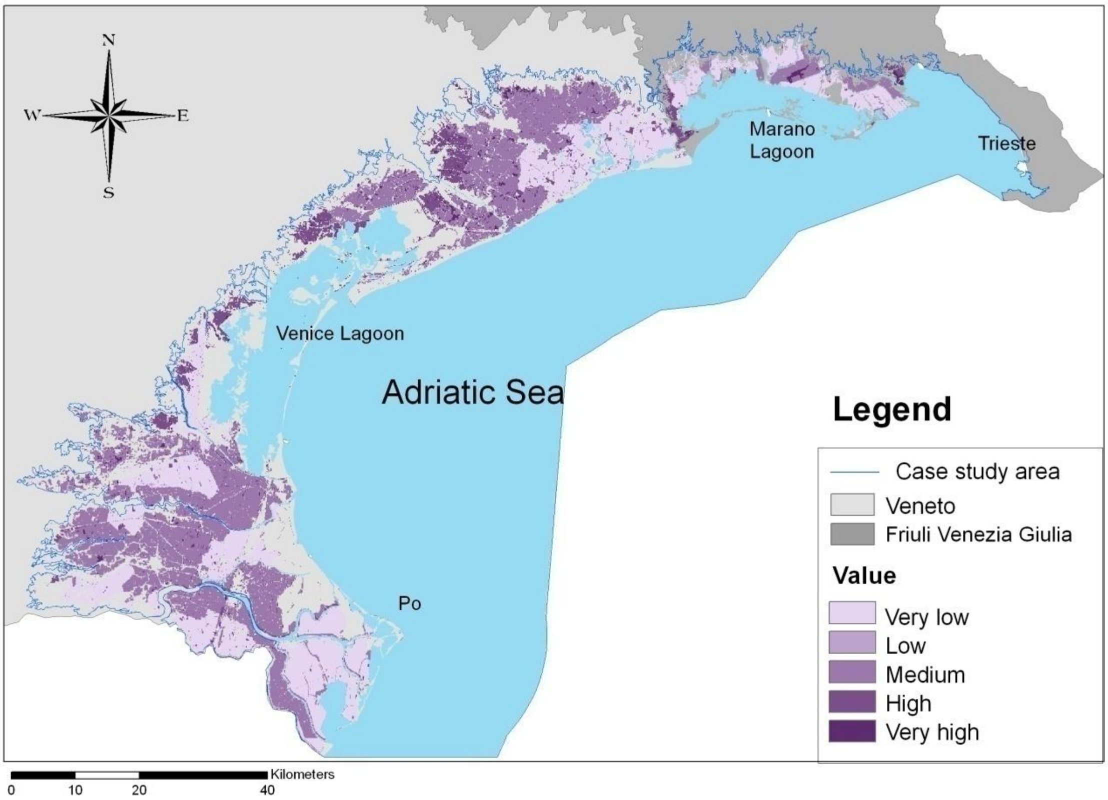


Figure IV M. Value map for the agricultural areas receptor for the North Adriatic coasts for the sea-level rise and relative sea-level rise impacts.

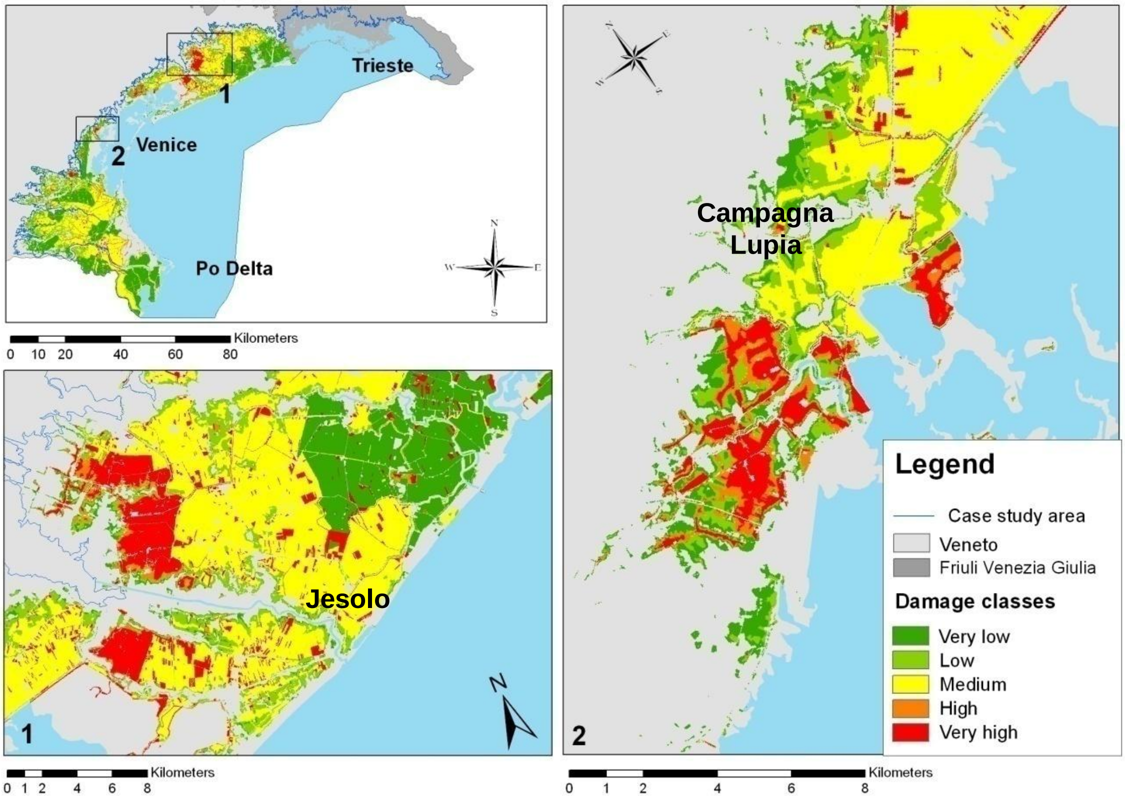


Figure IV N. Damage map of agricultural areas for the low relative sea-level rise scenario (projected water level of 17 cm) for the coasts of Veneto.

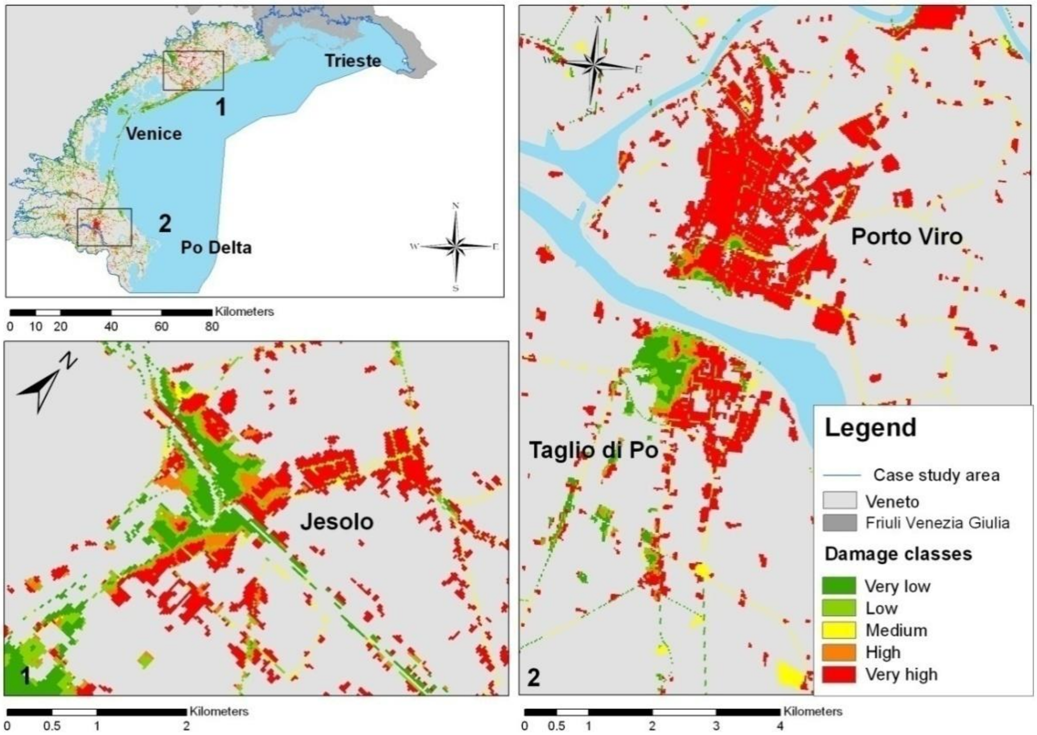


Figure IV O. Damage map of urban areas for the high relative sea-level rise scenario (projected water of 42 cm) for the coasts of Veneto.

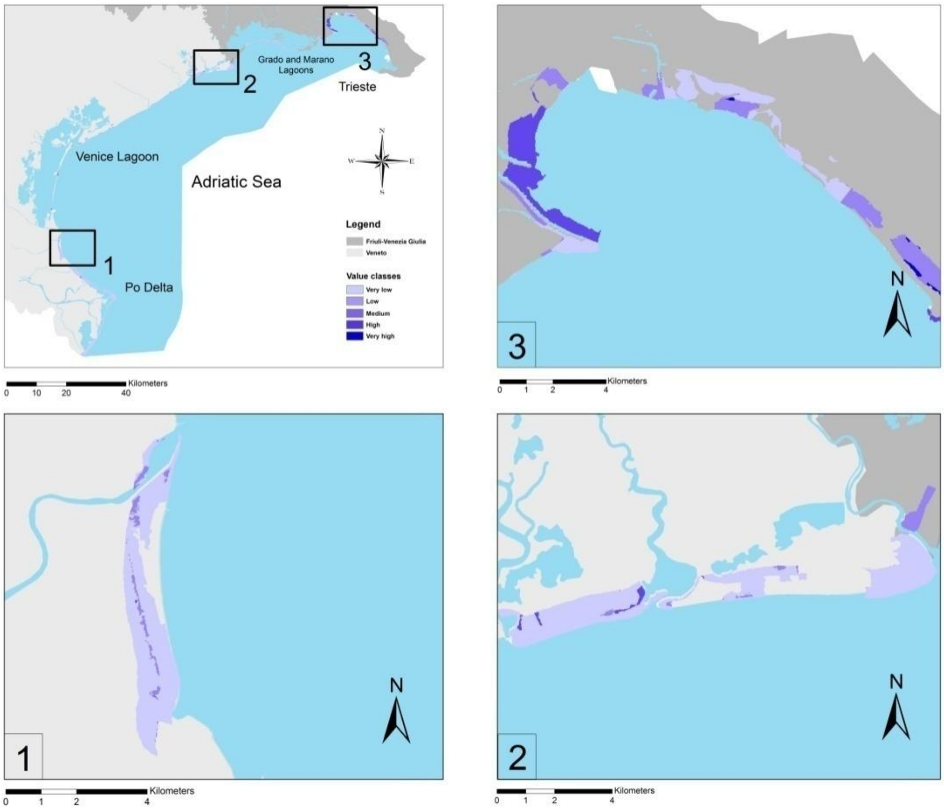


Figure IV P. Value map for the protected areas within the RICE area for the North Adriatic coast for the coastal erosion impact.

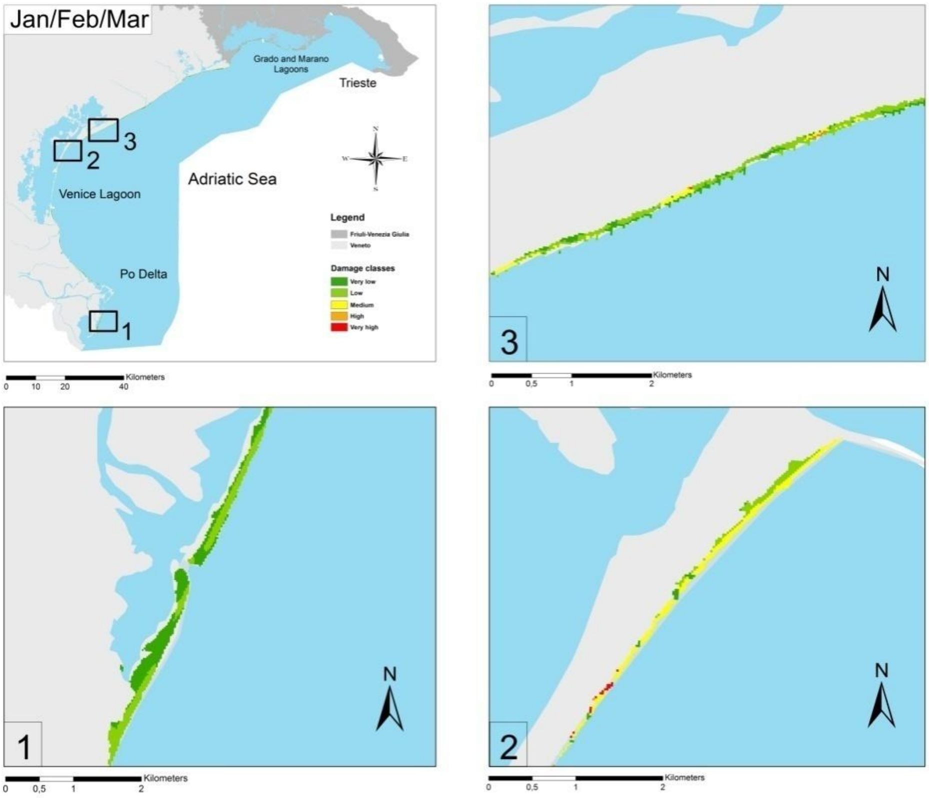


Figure IV Q. Damage map of beaches for the coastal erosion impact within the RICE area for the North Adriatic coast for the trimester Jan/Feb/Mar.

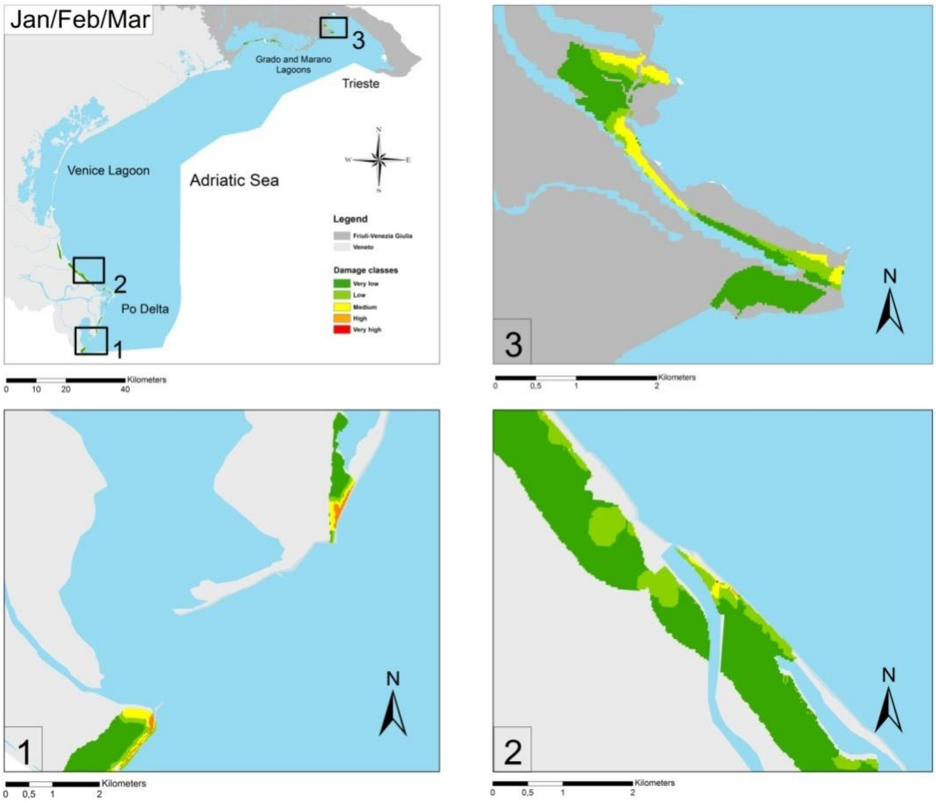


Figure IV R. Damage map of wetlands for the coastal erosion impact within the RICE area for the North Adriatic coast for the trimester Jan/Feb/Mar.