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GIS-based Regional Risk Assessment and its implementation in a Decision Support Systems for studying coastal climate change impacts

SETTORE SCIENTIFICO DISCIPLINARE DI AFFERENZA: Chim/12

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To my family and Yao

Summary

Climate change represents a global challenge and is one of the most pressing environmental issues that scientists, economists, policy makers and the whole society is facing today.

The main objectives of this thesis are the development of a GIS-based Regional Risk Assessment (RRA) methodology and its implementation within the GIS-based DEcision support SYstem for COastal climate change impact assessment (DESYCO). The methodology aims to evaluate and rank the potential risks of climate change impacts (i.e. storm surge flooding and marine water quality variations) on a variety of terrestrial and marine receptors (e.g. infrastructures, building, agricultural areas, population, marine water ecosystems). The proposed RRA is a cross-sectorial and interdisciplinary methodology considering the complex dynamics and interactions between coastal systems and other systems closely related to them (e.g. surface waters, river basins, estuaries). The implementation of the methodology within the DSS allows to transfer the information about climate-related risks to policy planners and decision makers, in order to guide them in the definition of appropriate adaptation actions.

The RRA methodology and the DSS DESYCO were applied to the coastal area of the North Adriatic sea in order to analyse the potential consequences of climate change on storm surge flooding (for extreme events with different return periods, i.e. 20, 50, 100, 200 and 500 years), and on marine water quality variations (for the future scenarios 2070 and 2100).

Results of the RRA application concerning the storm surge flooding impact showed that hazard will be quite high all along the coastline of the considered region, where extreme events will be quite intense. Inside the Lagoon of Venice, higher hazard will be in the southern part of the Lagoon due to the dominance of east-winds during extreme events and due to the lower number of islands and to the simpler morphology. The coastal strip exposed to storm surge in usually few km large. The receptor population is characterised by the lower risk, while beaches, wetlands, agricultural and natural areas are characterised by higher relative risk scores. Finally, also risk for buildings will be quite low all over the considered region, with higher risk in places with older urbanization where there is higher concentration of buildings.

As far as the analysis of water quality variations on marine coastal water bodies is concerned, results showed that the main drives of hazard and risks are represented by a decrease of salinity and an increment of the temperature. Within the considered region variations of these parameters are mainly due to the presence of river mouths or to the inlets of the Lagoon of Venice. In fact, water bodies close to the Po River delta and up to the Chioggia inlet, and from the Lido's inlet to Caorle, are characterised by a higher risk. Moreover higher risk will be during the spring

season, from April to May. Finally, it was demonstrated that all the area is characterised by medium/low damages scores.

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Seminars and training

- Environmental impacts, Risk assessment and Decision Support Systems, TAES, Tianjin, 9 August 2013.
- Decision Support Systems as a multidisciplinary tool Supporting decisional processes, Peking University, 21 July 2013.
- Basic GIS training, FLACSO, Quito, Ecuador, 27-31 May 2013 (40 hours).
- Advanced training on GIS, Puerto Ayora, Santa Cruz, Galapagos, Ecuador, May/June 2013 (40 hours).
- Introduction to GIS and DSS for risk assessment in the Environmental sector, ESPOL, Guayaquil, Ecuador, 8 April 2013.
- Introduction to GIS and DSS for risk assessment in the Environmental sector, FLACSO, Quito, Ecuador, 2 April 2013.
- DSS as Useful Tool to Support Policy Maker in the Context of Climate Changes, Tsinghua University, Beijing, China, 11 December 2012

- GIS-based Decision Support System (DSS) to support the collaboration between scientists and decision makers in the environmental sector, CRAES, Beijing, China, 6 December 2012-
- GIS-based Decision Support Systems for Supporting Environmental Risk Assessment, University of Hong Kong, Hong Kong, China, 19 November 2012
- Training on GIS for Contaminated Sites, CRAES, Beijing, China, 12 October 2012.

International experiences

- July – December 2012 – Beijing, China
- April – May 2013 – Galapagos, Ecuador
- July – August 2013 – Beijing, China

Abbreviations

EC: European Commission

EEA: European Environmental Agency

FD: Flood Directive

GUI: Graphical User Interface

GIS: Geographic Information System

ICZM: Integrated Coastal Zone Management

IPCC: Intergovernmental Panel on Climate Changes

MCDA: MultiCriteria Decision Analysis

MSFD: Marine Strategy Framework Directive

RRA: Regional Risk Assessment

SLR: Seal-Level Rise

SRES: Special Report on Emissions Scenarios

SSF: Storm Surge Flooding impact

UNISDR: United Nation International Strategy for Disaster Reduction

WFD: Water Framework Directive

WQV: Water Quality Variation impact

Introduction

Background, motivations and objectives

Recent studies demonstrated that human activities changed and continue to change the composition of the Earth's surface and atmosphere, generating direct or indirect impacts on the energy balance of the Earth and are thus one of the main drivers of climate change (IPCC, 2013). These changes led to alterations in the frequency, intensity, spatial extent, and duration of weather and climate extremes, including climate and hydro meteorological events such as heat waves, heavy precipitation events, droughts and tropical cyclones (IPCC, 2012). Such changes, in a context of increasing vulnerability, will increase the stress on human and natural systems and generate adverse effects in many places all over the world (UNISDR, 2009a; UNISDR, 2011). Particularly important are coastal zones, that are considered key climate change hotspots worldwide (EEA, 2010 a; IPCC, 2007b; Voice et al., 2006). These areas represent one of the main targets of several impacts caused by climate changes, and by global warming in particular, such as sea level rise, coastal erosion, storms surges, decreasing of water quality (IPCC, 2007; IPCC, 2013).

Coastal areas are characterized by the presence of many different ecosystems, maintaining an ecological balance that accounts for shoreline stability, beach nourishment and generation and recycling of nutrients (IPCC, 1995). As so, Italian coasts are characterised by a high biodiversity and are highly vulnerable and exposed to a growing anthropic pressure, including an increasing percentage of built-up areas whose negative effects are exacerbated by climate changes. Furthermore, in coastal zones many different uses and interests (e.g. urban centres, harbours, areas for seaside tourism, terrestrial and marine protected areas, fisheries and aquaculture, industrial zones) sometimes create conflicts among them. Accordingly, it is important to regulate and plan coastal zones in order to avoid negative consequences of climate change.

Coastal issues and potential impacts of climate change have been seriously considered by many institutions, especially by the European Commission (EC). Several documents and directives consider or specifically focus on coastal zones or climate change related issues. Specifically, the great importance of coastal areas was recognized by the protocol for the implementation of Integrated Coastal Zone Management (ICZM; 2002/413/EC) for the sustainable management of these systems (UNEP MAP, 2008) signed by the European Commission in 2008. In addition, the need to preserve and protect coastal areas in order to achieve a sustainable development appeared in the Water Framework Directive (WFD; 2000/60/EC), in the Marine Strategy Framework Directive (MSFD; 2008/56/EC) and in the Green and White Papers about the adaptation to climate change (COM(2007)354; COM(2009)147).

Several tools supporting policy and decision makers in the implementation of the European recommendations and directives were developed in recent years. Some of them are useful to support the assessment of vulnerability and risks related to climate change and the definition of adaptation measures (Ramieri et al, 2011). Among the different tools, Decision Support Systems (DSS) are particularly relevant and several successful examples already revealed their usefulness and effectiveness (Iyalomhe et al., 2012; Ramieri et al., 2011).

The main aim of this thesis is to propose and apply a Regional Risk Assessment (RRA) methodology (Landis, 2005) for the assessment of potential climate change impacts on natural and human ecosystems (e.g. beaches, wetlands, agricultural areas, buildings and population) and its implementation within a Spatial Decision Support System (i.e. DESYCO). The proposed approach allows the ranking and prioritization of receptors and targets potentially at risk in the considered region with the final aim of providing suitable information for the definition of adaptation measures.

The RRA methodology is based on the integration of numerical models output for the construction of future climate change scenarios (e.g. biogeochemical models) with bio-physical and socio-economic data related to the considered region (e.g. topography, landuse). The proposed approach employs Multi Criteria Decision Analysis (MCDA) functions that allow the evaluation and ranking of different scenarios, taking into account multiple aspects of a decision involving many actors (i.e. Decision makers and Experts) (Giove et al., 2009). Entering into details, MCDA aggregate quantitative and qualitative environmental and socio-economic indicators based on both expert judgments and stakeholders' preferences. The final outputs of the RRA are exposure, vulnerability, risk and damage maps for the considered region identifying and ranking homogeneous areas allowing the establishment of hotspot risk areas and supporting the definition of priorities for intervention.

The methodology has been implemented within a DEcision support SYstem for COastal climate change impact assessment (DESYCO). DESYCO is an open source software allowing to manage input data (e.g. raster, vector and text files) regarding both climate change hazard scenarios (e.g. global and regional climate projections, high resolution hydrodynamic, hydrological and biogeochemical simulations) and site-specific physical, ecological and socio-economic features of the analysed region (e.g. coastal topography, geomorphology, presence and distribution of vegetation cover, location of artificial protection etc). The Graphical User Interfaces (GUI) of DESYCO guide the user step by step in the application of the RRA and in the analysis of the outputs of the tool (i.e. GIS-based exposure, vulnerability, risk and damage maps).

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.

The thesis was developed in cooperation with two projects: PEGASO and CLIMDAT. The PEGASO (PEople for Ecosystem-based Governance in Assessing Sustainable development of Ocean and coast, http://www.pegasoproject.eu) project, funded under the European Commission 7th Framework Program (2010-2014), is aimed at the definition and application of tools supporting the implementation of the ICZM protocol in the coastal zones of the Mediterranean Sea and Black Sea basins. CLIMDAT is a project in partnership between the Venice Research Consortium and ISPRA (Istituto Superiore per la Protezione e Ricerca Ambientale) which aims at getting deeper understanding of the impacts caused by climatic changes in the coastal area of the North Adriatic Sea, with a particular focus on storm surge floodings.

Thesis structure

This thesis is structured in seven chapters, the first two (i.e. Chapters 1 and 2) are methodological chapters; the following five chapters (i.e. Chapters 3, 4, 5, 6 and 7) are related to the results of the research:

- Chapter 1 describes the RRA methodology for the assessment of climate change impacts on coastal zones, the framework of the approach and the steps of the methodology;
- Chapter 2 introduces the topic of DSS for climate change impact assessment and reviews several existing tools to highlight need and gaps;
- Chapter 3 presents and describe the DSS DESYCO, its software architecture and its functionalities;
- Chapter 4 describes the North Adriatic case study area and the used dataset;
- Chapter 5 illustrates the model chain applied for the contruction hazard scenarios pre the water quality variation impact;
- Chapter 6 introduces and describes the RRA methodology for the SS impact assessment and its application to the coastal area of the Veneto and Friuli Venezia Giulia regions;
- Chapter 7 introduces and describes the RRA methodology for the WQ impact and its application to the marine water bodies defined by the Veneto and Friuli Venezia Giulia regions.

1. The RRA methodology

A Regional Risk Assessment (RRA) methodology is generally used to analyse problems affecting large geographic areas (i.e. a region, a country) taking into account multiple stressors (e.g. climate change) and targets (e.g. the marine aquatic ecosystem) considering their spatial relationships (Hunsaker et al., 1990; Landis, 2005). The proposed approach allows analysing multiple pressures at different spatial and time scales, and identifying the different elements at risk in the considered region. Moreover, the RRA methodology uses Multi Criteria Decision Analysis (MCDA) functions in order to estimate relative risks in the considered region, and identify and prioritize areas at risk, selecting those with a higher risk requiring adaptation measures or deeper investigations. The final aim of the methodology is to identify and prioritize areas and targets at risk in the considered region and can be applied in different case studies and spatial scales.

The present chapter will introduce the RRA methodology aimed at the assessment of climate change impacts on coastal zones. After the introduction of the RRA and of the key terms used in the methodology will be described (Paragraph 1.1), the underlying framework (Paragraph 1.2) and the methodological steps (Paragraph 1.3) will be presented and discussed.

1.1. Definitions

Different research communities, such as the climate change and the natural hazard ones, addressed climate change impacts in recent years. Each community is using its own terminology, sometimes generating misunderstandings.

Climate change researchers define vulnerability as a function of three components (IPCC, 2007): i) exposure (i.e. the magnitude and rate of climate variations to which a system is exposed); ii) sensitivity (i.e. the degree to which a system could be affected by climate related stimuli), iii) adaptive capacity (i.e. the ability of a system to adjust or to cope with climate-change consequences).

Natural hazard researchers, instead, analyse impacts based on two main components (UN-ISDR, 2009a): i) 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); ii) system vulnerability (i.e. the characteristics of a system that increase its vulnerability to the impact of climate induced hazards). Vulnerability is often expressed in a number of indexes and is a key step toward risk assessment and management (Romieu et al., 2010).

According to recent reports (IPCC, 2012) also the climate change community is adopting the definitions of the natural hazards community; accordingly in the present thesis, the natural hazard community was choose as reference. In order to clarify the meaning used in the thesis, in the following paragraph are presented the definitions of the key terms according to the international literature.

- **Hazard:** it represents the physical phenomenon related to climate change (e.g. sea level rise, storm surges) that has the potential to cause damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources (UNISDR, 2009a; IPCC, 2012).
- **Exposure:** it represents elements potentially at risk (i.e. receptors) such as the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected (UNISDR, 2009a; IPCC, 2012).
- **Vulnerability:** it represents the propensity or predisposition of a community, system, or asset to be adversely affected by a certain hazard. In a broad sense it should include economic, social, geographic, demographic, cultural, institutional, governance, and environmental factors (UNISDR, 2009a; IPCC, 2012)
- **Risk:** it quantifies and classifies potential consequences of a hazard events on the investigated areas and receptors (i.e. elements potentially at risk) combining hazard, exposure and vulnerability. It can be expressed in probabilistic or relative/semi-quantitative terms.
- **Value:** it represents the environmental and socio-economic values of the investigated areas and receptors. In is expressed in a semi-quantitative quantitative way and not in monetary terms.
- **Damage:** it quantifies and classifies potential loss of value deriving from a hazard events on the investigated areas and receptors (i.e. elements potentially at risk) combining value and risk. It can be expressed in probabilistic or relative/semi-quantitative terms.

1.2. RRA framework

The proposed RRA methodology is based on the conceptual framework presented in Figure 1 integrating two main components: the climate change hazard analysis and the exposure, vulnerability and damage assessment.

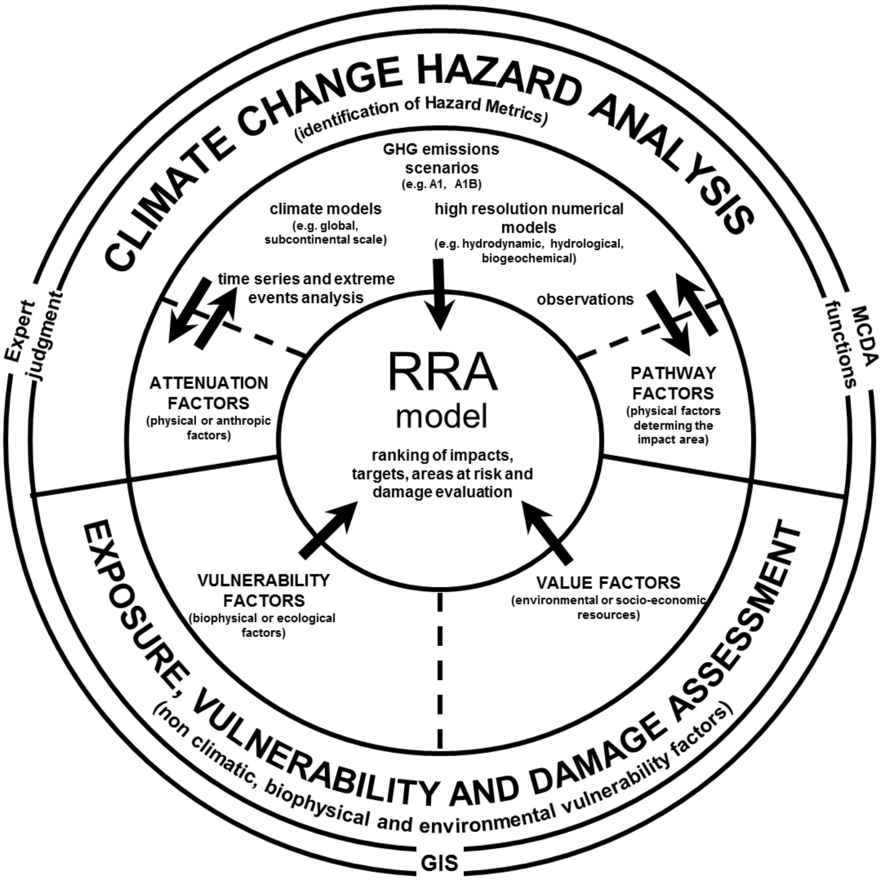


Figure 1. Regional Risk Assessment (RRA) conceptual framework.

The climate change hazard analysis is represented by the assessment of changes of climate parameters and variables (e.g. increase in the mean sea-level, increase of extreme storm surge intensity) that can cause an impact (e.g. temporary or permanent inundation, floods, droughts) on the considered region. It is based on the use and integration of data coming from different sources, e.g. climate simulation from the global to the regional scale, physical processes high resolution models (e.g. biogeochemical, hydrodynamic and hydrological models), time series of extreme events and observations. 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 analysed during the simulation. 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. Hazard metrics are successively integrated with pathway and attenuation factors, defined as reported below.

- **Pathway factors (pf):** physical characteristics of the receptors (e.g. elevation, distance from the coastline) which determine the possibility that climate change hazards would occur and therefore will support the identification of potential exposure areas.
- **Attenuation factors (af):** 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.

Attenuation and pathway factors are aggregated with hazard metrics through a hazard function – specific for each considered impact – that is used for the construction of hazard scenarios for the final risk estimation. The integration of hazard metrics with pathway and attenuation factors take into account also experts' judgement and uses MCDA functions.

The second main component of RRA is exposure, vulnerability and damage assessment that requires the analysis of two other categories of factors, defined below.

- **Vulnerability factors (vuf):** determine the vulnerability of a receptor to climate change hazards. Vulnerability 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, vuf denote the dose-response relationship between the exposure of a receptor to climate stimuli and the resulting effects (Füssel and Klein, 2006).
- **Value factors (vaf):** 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).

Vulnerability and value factors are aggregated in order to have an estimation of the vulnerability to the considered climate change and of the value of each receptor for the final estimation of the risk and of the damage using MCDA functions and integrating experts and stakeholders' judgement.

In order to manage and elaborate the huge quantity of spatial data required by the proposed RRA methodology, the application of the proposed RRA methodology requires the management of big quantities of heterogeneous spatial data. Accordingly, Geographic Information Systems (GIS) are used to manage, manipulate, process, analyse, map and spatially organize data to facilitate hazard, vulnerability, risk and damage analysis. MCDA techniques are used to aggregate vulnerability and hazard parameters in order to evaluate and rank targets and areas at 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.

1.3. Steps of the RRA

The RRA methodology involves five different steps (Figure 2): 1) Hazard assessment; 2) Exposure assessment; 3) Biophysical and environmental vulnerability assessment; 4) Relative Risk assessment; 5) Damage assessment.

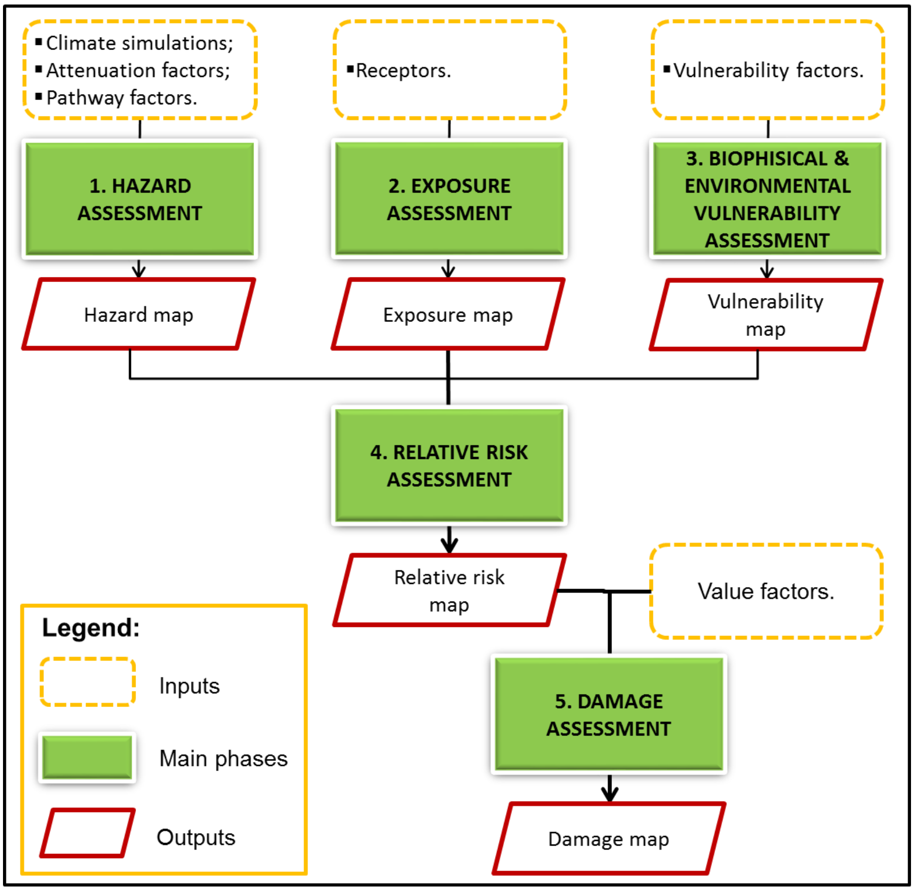


Figure 2. Steps for the application of the Regional Risk Assessment

1 **Hazard assessment:** aims at identifying metrics (e.g. sea-level rise, flow velocity, water depth, flood extension) derived from climatic, hydrodynamic and/or hydrogeological models. These models might be implemented from the global to the regional scale, and use as input the different future climate scenarios to be investigated in the analysis.

2 **Exposure assessment:** aims at identifying and selecting receptors (i.e. elements at risk) that can be subject to potential impacts in zones affected by climate change. This step

requires the analysis of datasets useful for the localization of people, environmental resources, infrastructures and social, economic or cultural assets that could be adversely affected by the identified hazards.

3 **Biophysical and environmental vulnerability assessment:** aims at evaluating the degree to which receptors could be affected by a hazard based on physical/environmental site-specific information (e.g. vegetation cover, slope, soil type).

4 **Bio-physical and environmental vulnerability assessment:** aims at evaluating the degree to which receptors could be affected by storm surge flooding based on physical/environmental site-specific information. This step is based on the selection, classification and aggregation of Vulnerability factors (e.g. geomorphology, sediment budget, vegetation cover) that are defined according to each receptor.

5 **Risk assessment:** defines an integrated relative risk index that allows identifying and classifying areas, receptors and hotspots at risk in each case study. This phase combines the information about hazard scenarios, exposure and biophysical/environmental vulnerability assessment, providing a relative evaluation of risks for each analysed receptor.

The main outputs of the RRA are GIS-based maps of receptor-related risks and damages useful to communicate the potential implications of floods in non-monetary terms to stakeholders and administrations. These maps can be a basis for the management of climate change coastal risks. Moreover, they can provide suitable information for setting priority for prevention measures and for land use planning and land management. Finally, through the DESYCO tool several statistics can be calculated in order to synthesize relevant information coming from RRA maps (e.g. percentage of receptors associated with each risk/damage class, percentage and surface of receptors with higher risk/damage scores for each administrative unit) and support the decision making process.

All maps and statistics produced by DESYCO can be useful to support the implementation of the European Strategic Environmental Assessment (SEA) Directive (2001/42/EC), requiring the evaluation of significant effects of climate change in the development of policies, plans and programs (Posas, 2011). For instance, in order to implement the principles of SEA in the field of climate change, sensitive key systems should be prioritized and indicators to assess the effects of climate change and the vulnerability to climate change should be identified (Gigli and Agrawala, 2007). Maps produced by DESYCO can be also helpful for the implementation of Environmental Impact Assessment (EIA). In fact, EIA requires the exploration of different options in order to evaluate more-sustainable future scenarios, taking into account also the possible effects of climate change (Duinker and Greig, 2007).

An important aspect of the proposed approach is represented by the participation of stakeholders within the assessment process. Specifically, experts and stakeholders can give their contribution during the vulnerability assessment and during the damage assessment. In the vulnerability should be involved experts (e.g. technicians and scientists) that can identify, classify and weight – in an objective way – the factors that contribute the definition of the vulnerability. In the damage assessment, instead, several stakeholder should identify, classify and weight factors that - according to their interest and opinion - contribute to the definition of the losses due to climate change impacts.

1.4. MCDA functions used within the RRA

Within the proposed RRA methodology, MCDA is used to integrate experts and stakeholder's opinion into the evaluation process and is used to aggregate factors using scores and weights. Among the used operators, two of them will be described in the following paragraph as are quite peculiar: the *probabilistic or* operator (Kalbfleisch J. G., 1985) and the *ordered weighted average* (OWA; Yager, 1988).

2.4.1. Probabilistic or

The *probabilistic or* function is used to aggregate several values in order to summarize them obtaining a single value. The *probabilistic or* operator can be applied to several operands simultaneously, an example of its compact representation is as following:

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

Where:

$$f_i = i^{th}\ generic\ factor\ f$$

In this example, the *probabilistic or* operator can be evaluated as follow, due to its 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.

It important to note that 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, many factors with low scores can contribute in increasing the final *probabilistic or* score: the more is the number of low factor scores, the greater is the final score.

2.4.2. Ordered Weighted Average (OWA)

In this thesis the OWA operator is used to compare the variation of range of values and to make an estimate of the left and right excesses $(\Delta_1^m, \Delta_1^M), \dots, (\Delta_n^m, \Delta_n^M)(\Delta_1^{\mathrm{m}}, \Delta_1^{\mathrm{M}}), \dots, (\Delta_{\mathrm{n}}^{\mathrm{m}}, \Delta_{\mathrm{n}}^{\mathrm{M}})$ in respect to the reference range where:

$$\Delta_{i,j}^m = \max\left(H_{i,j}^m - F_{i,j}^m, 0\right)$$

$$\Delta_{i,j}^M = \max\left(F_{i,j}^M - H_{i,j}^M, 0\right)$$

Figure 3 reports a graphical explanation of the involved quantities.

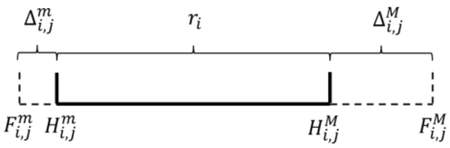


Figure 3. Graphical explanation of the quantities used by the OWA operator.

The OWA operator account heavily for the bigger value and less for the smaller one. The OWA definition adapted to this situation can be defined as follows:

$$H_{i,j} = w_M \cdot \max\left(\Delta_{i,j}^m, \Delta_{i,j}^M\right) + w_m \cdot \min\left(\Delta_{i,j}^m, \Delta_{i,j}^M\right)$$

Where:

$w_M = importance\ weights\ related\ to\ the\ bigger$;

$w_m = importance\ weights\ related\ to\ the\ smaller\ differences$;

$w_M \gg w_m;\ w_M + w_m = 1.$

2. DSS for climate change impact assessment

A Decision Support System (DSS) is a software aimed at assisting decision makers in their decision processes, supporting rather than replacing their judgment and, at length, improving effectiveness over efficiency (Janssen, 1992). DSS have been developed and used to address complex decision-based problems in varying fields of research, such as environment, economy, planning. For instance, in the environmental resource management sector, DSS are generally classified into two main categories:

- Spatial Decision Support Systems (SDSS): tools specifically designed to provide users with a decision-making environment allowing the analysis of geographical information to be carried out in a flexible manner (Densham, 1991).
- Environmental Decision Supports Systems (EDSS): tools integrating Geographical Information System (GIS) several environmental models (including climate change and impact models), databases and other assessment tools (Fabbri, 1998; Poch et al., 2004; Uran et al., 2003).

DSS addressing climate change are the result of the combination of SDSS and EDSS, and are specifically addressed to support decision makers in the sustainable management of natural resources and in the definition of possible adaptation and mitigation measures (Torresan et al., 2010). A key role in these system in represented by Geographic Information Systems (GIS). The latter can be defined, from an informatics prespective, as set of computer tools that can capture, manipulate, process and display spatial data (ESRI, 1992) in which the enhancement of spatial data integration, analysis and visualization can be conducted (Matthies et al., 2007; Nobre and Ferreira, 2009). In the framework of DSS for climate change, GIS can have a twofold role: i) they can be used to manage, elaborate and analyse data in the assessment process; ii) they can be used to visualise data to be communicated to stakeholders and decision makers (Nobre and Ferreira, 2009).

The following paragraphs will briefly summarize the results of a review of GIS-based DSS, highlighting major features and describing the applicability of each DSS in order to support the selection of DSS tailored on users specific application needs.

2.1. State of the art on DSS for climate change

Several DSS were compared based on the basis of a literature review in order to evaluate their main characteristics and identify possible gaps. The 20 reviewed tools are listed in Table 1. Selected software were designed to support the decision making-process related to climate change and environmental issues in coastal environments. The review was conducted based on criteria grouped into three categories (Table 2): i) general technical criteria; ii) specific technical criteria; iii) availability and applicability criteria. The **general technical criteria** describe main general features of each considered tool, including: the target coastal regions and ecosystems domain, the supported regulatory frameworks and legislations, the considered climate change impacts and related scenarios and the objectives. The **specific technical criteria** include main functionalities, analytical methodologies and inference engine (i.e. structural elements) of the systems. Finally, **availability and applicability criteria**, considered scale and study areas, flexibility, status and availability of the examined systems. Detailed results of the review are reported in the Annex 1.

Name	Developer	Years of Development	Reference Source
CLIME: Climate and Lake Impacts decision support system	Helsinki University of Technology, Finland	1998-2003	Jolma et al., 2010 clime.tkk.fi
CORAL: Coastal Management Decision Support Modelling for Coral Reef Ecosystem	Within a World Bank funded Project :LA3EU	1994-1995	Westmacott, 2001
COSMO: Coastal zone Simulation MOdel	Coastal Zone Management Centre, Hague	1992	Feenstra et al., 2008
Coastal Simulator decision support system.	Tyndall Centre for Climate Change Research, UK.	2000-2009	Nicholls et al., 2009
CVAT: Community Vulnerability Assessment Tool	National Oceanic and Atmospheric Administration, US.	1999	[20] www.csc.noaa.gov/products/nchaz/startup.htm
DESYCO: Decision Support SYstem for COastal climate change impact assessment	Euro-Mediterranean Centre for Climate Change, (CMCC) Italy.	2005-2010	Torresan et al., 2010
DITTY: Information technology tool for the management of Southern European lagoons	Within the European region project: DITTY	2002- 2005	Agnetis et al., 2006
DIVA: Dynamic Interactive Vulnerability Assessment	Potsdam Institute for Climate Impact Research, Germany	2003-2004	Hinkel and Klein, 2009 www.dinas-coast.net.
ELBE: Elbe river basin Decision Support System	Research Institute of Knowledge System- RIKS, Netherland	2000-2006	BfG, 2003 www.riks.nl/projects/Elbe-DSS
GVT:Groundwater Vulnerability Tool	University of Thrace and Water Resource Management Authority, Greece.	2003-2004	Gemitzi et al., 2006
IWRM: Integrated Water Resources Management Decision Support System	Institute of Water Modelling, Bangladesh	2002-2010	Zaman et al., 2009 www.iwmbd.org
KRIM decision support system	Within the KRIM Project in Germany.	2001-2004	Schirmer et al., 2003 www.krim.uni-bremen.de

MODSIM decision support systems	Labadie of Colorado State University, US	1970	Salewicz et al., 2004; Labadie, 2006 www.modsim.engr.colostate.edu
RegIS-Regional Impact Simulator	Cranfield University, UK	2003-2010	Holman et al., 2008 www.cranfield.ac.uk/sas/naturalresources/research/projects/regis2.html
RAMCO: Rapid Assessment Module Coastal Zone Management	Research Institute of Knowledge System- RIKS, Netherland	1996-1999	De Kok et al., 2001; Uljee et al., 1996 www.riks.nl/projects/RAMCO
SimLUCIA: Simulator model for St LUCIA	Research Institute of Knowledge System- RIKS within the UNEP Project, Netherland	1988-1996	Engelen et al., 1995 www.riks.nl/projects/SimLUCIA
SimCLIM: Simulator model System for Climate Change Impacts and Adaptation	University of Waikato and CLIMsystem limited, New Zealand.	2005	Warrick, 2009 www.climsystems.com
STREAM: Spatial Tools for River Basins and Environment and Analysis of Management Options	Vrije Universiteit Amsterdam and Coastal Zone Management Centre, Hague	1999	Aerts et al., 1999 www.geo.vu.nl/users/ivmstream/
TaiWAP: Taiwan Water Resources Assessment Program to Climate Change	National Taiwan University, Taiwan	2008	Liu et al., 2009
WADBOS: decision support systems	Research Institute of Knowledge System- RIKS, Netherland	1996-2002	Van Buuren et al., 2002; Engelen, 2000 www.riks.nl/projects/WADBOS

Table 1. List of existing DSS for coastal zones.

Categories	Criteria
General technical criteria	• Coping with regulatory framework. This indicates the particular legislation or policy, the DSS refers to and which phase of the decision-making process is supported at the National, Regional and Local level (e.g., EU WFD, ICZM, IWRM, SMP, GRM, and HEM). • Study/ field of application area. The coastal zones where this DSS has been applied and tested (e.g., coastal zone, lakes, river basin, lagoon, groundwater aquifer etc.) • Objective. It specifies the main aims of the DSS. • Climate change impacts. This refers to relevant impacts due to climate change on the system (e.g., sea-level rise, coastal flooding, erosion, water quality). • Climate Change Scenarios. The kind of scenarios considered by the DSS, which are relevant to the system analysis and connected to climate change (e.g., emission, sea level rise, climatic scenarios).
Specific technical criteria	• Functionalities. These indicate relevant functionalities (key outcomes) of the system useful to the decision process: environmental status evaluation, scenarios import (climate change and socio-economic scenarios) and analysis, measure identification and/or evaluation, relevant pressure identification and indicators production. • Methodological tools/ (analytical tools). These indicate the methodologies included in the system such as risks analysis, scenarios construction and/or analysis, integrated vulnerability analysis, Multi-Criteria Decision Analysis (MCDA), socio-economic analysis, uncertainty analysis, ecosystem-based approach etc. • Structural elements. The three major components of the DSS: dataset (i.e., the typology of data), models (e.g., economic, ecological, hydrological and morphological), interface (i.e., addressing if it's user-friendly and desktop or web-based).
Availability and applicability	• Scale and area of application. This specifies the spatiality of the system (e.g., local, regional, national, supra-national and global) within the case study areas. • Flexibility. The characteristics of the system to be flexible, in terms of change of input parameters, additional modules or models and functionalities. It is also linked to the fact that it can be apply on different coastal regions or case study areas. • Status and Availability. This specifies if the system is under development or already developed and ready for use, and if it is restricted to the developer and case study areas only or the public can access it too and the website where information about the DSS can be found.

Table 2. List of criteria used for the comparison of existing DSS.

Most of the available DSS were developed for the regional or local scale, according to the requirements of policy and regulatory frameworks. As a consequence, reviewed tools appear to effectively support coastal decision makers in the definition and planning of adaptation measures to the effects of climate change.

Several DSS (i.e. 15 out of 20) are mainly focus on the analysis of a single climate change impact or on the analysis of climate change impacts on a specific economic sector: Further developments should aim at the adoption of an ecosystem approach considering complex dynamics and interactions involving coastal systems and other systems (e.g. coastal aquifers, surface waters, river basins, estuaries), and at the implementation of multi-risk approaches allowing to analyse the interaction of different climate change impacts on the considered region.

Finally, it is important to remark the need to involve the end users and relevant stakeholders since the initial steps of the development process of these tools, in order to satisfy their actual requirements, especially in the perspective of providing useful climate services.

3. The DSS DESYCO

DESYCO (DEcision support SYstem for COastal climate change impact assessment) is a GIS based Decision Support System (DSS) for the assessment and management of multiple climate change impacts in coastal areas and related ecosystems (e.g. beaches, river deltas, estuaries and lagoons, wetlands, forests, protected areas, groundwater, urban and agricultural areas).

The overall aim of DESYCO is to mainstream climate risk information in coastal adaptation planning. It is an open source software able to combine different scenario data (e.g. raster, vector or text files) resulting from climate models (e.g. global and regional climate projections) and high resolution models (e.g. hydrodynamic, hydrological and biogeochemical simulations) with vulnerability analysis of environmental and socio-economic features of the territory, in order to provide GIS-based maps identifying hot-spot areas and receptors at risk from climate change.

The final output of the tool are GIS-based maps, providing spatially resolved information about downscaled climate change hazard scenarios and regional/local vulnerability, risks and damages.

The first version of DESYCO was released in 2010 as a product of the CMCC-FISR project. Typical applications of the tool require the involvement of a team of experts and technicians (e.g. climate experts, environmental risks experts, GIS analysts), together with the interested stakeholders and decision makers (e.g. regional and local administrations involved in coastal zone management).

After a brief description of the main components and functionalities of DESYCO and its software architecture, main outputs and results, related to the case studies already mentioned (Chapter 3), will be illustrated in order to highlight functionalities and capabilities of the tool.

3.1. Software architecture

DESYCO is a stand alone software, aimed at supporting the application of the proposed RRA methodology (Chapter 2), by facilitating the procedures for integrating the outputs of external numerical models and geographical vulnerability indicators, by means of GIS functions and MCDA routines.

The structure of DESYCO is composed of 4 main components: i) a **geodatabase** for the storage of bio-physical and socio-economic data related to the study area; ii) a **multi-scale scenarios module** to deal with data provided by numerical models simulations or time series analysis; iii) a **Relative Risk Model** (RRM) that integrates Multi Criteria Decision Analysis (MCDA) techniques for the application of the RRA methodology; iv) **Graphical User Interfaces** (GUI) that facilitate the interaction of the final user with the system and simplify results analysis and understanding. The core of the system is the RRM that integrates climate change hazards analysis, based on the elaboration of output from climate, hydrodynamic, hydrological, hydrogeological and biogeochemical models, with the analysis of environmental and socio-economic features of the territory.

In order to make the software easily extendable and with a high level of flexibility and interoperability, DESYCO was implemented on a multi-tier architecture composed of three levels: i) Data tier; ii) Logic tier; iii) Presentation tier (Figure 4). The software was developed by making use of two open source libraries for the management of geographic data, i.e. GDAL and OGR, and programmed using the Phyton and C# languages. The GDAL and the OGR libraries were selected taking into account their wide applicability and stability; they represent the *de facto* standard for open source GIS-based applications. GDAL (http://www.gdal.org) is a translator library for the management of raster geospatial data formats, while OGR (http://www.gdal.org/ogr/), which is a subproject of GDAL, is a C++ library providing access to a variety of vector file formats. The choice of using open source libraries and applications, which adoption is continuously increasing over last years, allows DESYCO to be independent from commercial, and often expensive, software. Moreover, the number of people voluntarily supporting the development and maintenance of these libraries is rapidly growing following the general growth of open source software (von Krogh and Spaeth, 2007).

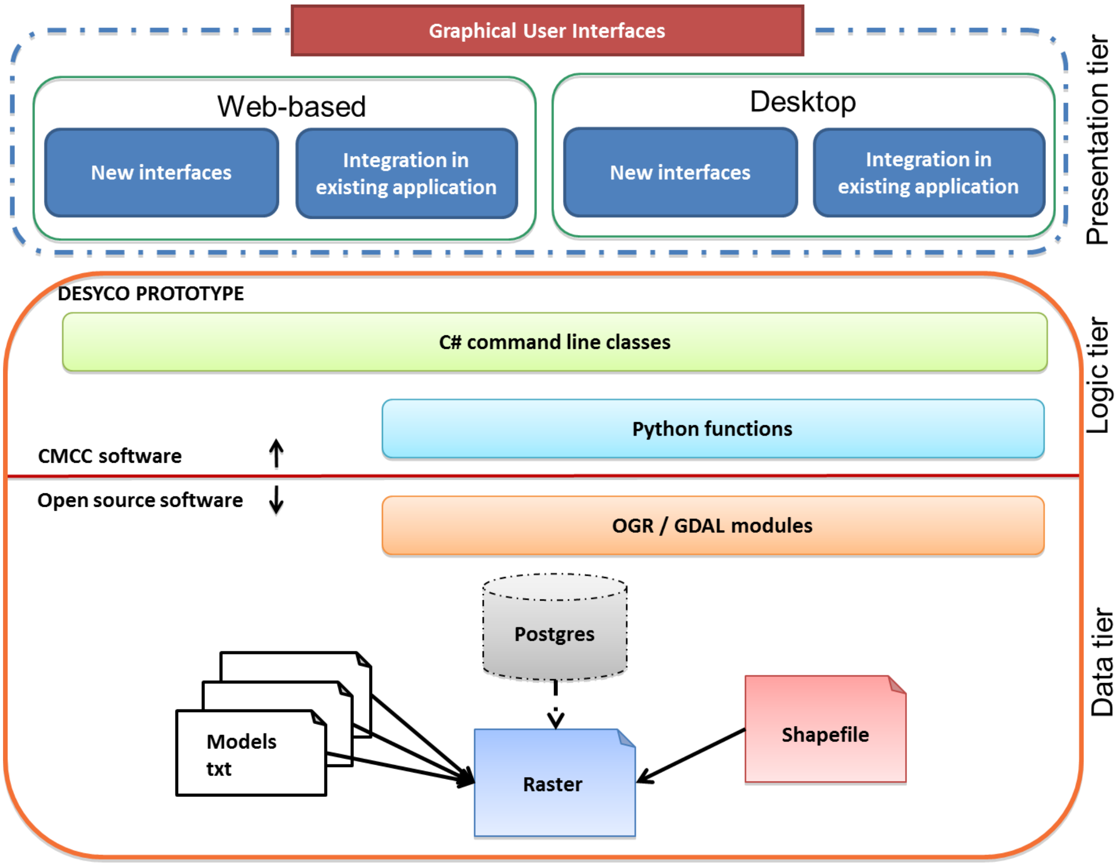


Figure 4. The multi-tier architecture of DESYCO.

The first tier of the software architecture, the **Data Tier**, is represented by a geodatabase and by system folders containing input and output data elaborated by the software. Input data are represented by environmental and socio-economic data related to the area of concern and useful to represent pathway, attenuation, vulnerability, and value factors (e.g. coastal topography, geomorphology, presence and distribution of vegetation cover, location of artificial protection etc.). Moreover, input data include parameters provided by numerical models or time series analysis, representing hazard metrics in the RRA (e.g. temperature, precipitation, sea level rise projections etc.). For each case study area all input data must be homogenized before being loaded through the software's GUI in order to have the same reference system, geographical extension and pixel dimension.

Output data are represented by exposure, vulnerability, risk and damage maps elaborated during the application of the RRA methodology, by statistics calculated at the end of the assessment and by a report showing the main results and all the configuration parameters (e.g. scores and weights used for vulnerability and value factors).

The **Logic Tier**, corresponding to the second level of the architecture, is a library composed of basic and advanced functions implementing the RRA's equations. The basic functions represent building blocks allowing to perform simple, general, operations (i.e. weighted sum, probabilistic or, weighted average) required by the RRA model. Such functions are then integrated into advanced functions (e.g. the equations supporting the implemented Multi Criteria Decision Analysis) allowing to perform all the more complex operations required by the RRA model (i.e. hazard, exposure, vulnerability, risk, value and damage functions). Basic functions were programmed in Python, and make use of the open source libraries GDAL and OGR, while advanced functions were programmed in C#.

Finally, the third level, the **Presentation Tier**, is represented by the Graphical User Interfaces (GUI). This tier manages all the interactions between the system and the user and allow to deal with the different steps of the application. Due to the layered architecture of DESYCO, its GUI can be implemented both in desktop or web environments. More specifically the DSS can have desktop interfaces within stand alone applications (e.g. as a Java application executable in different operating systems) or it can be integrated as a plug-in within third parties' open source (e.g. QGIS) or commercial (e.g. ArcGIS) GIS software. The same also applies for web interfaces which can be stand-alone applications or integrations of new modules within existing web applications (e.g. p.mapper). The first version of DESYCO was implemented as a C# stand-alone application which can be launched directly as well as from the QGIS (Quantum GIS, http://www.qgis.org) open source software.

3.2. Functionalities

The DSS DESYCO was developed to produce climate risk information at the regional (sub-national) scale, providing functionalities to support the integration of climate scenarios and environmental modelling outputs (e.g. simulation of hydrodynamic, hydrological or biogeochemical processes for the case study) with biophysical and socio-economic vulnerability assessment, by means of GIS functions and Multi-Criteria Decision Analysis techniques (MCDA). It is a flexible tool that can be in principle applied at broader spatial scales (e.g. from national to sub-continental) and at more detailed ones (i.e. local scale), managing different input data (i.e. raster, vector or text files) provided by different scenarios models and datasets. The spatial scale of application depends on the purposes of the analysis and on the availability of scenarios models and vulnerability datasets. The DSS does not provide modelling routines but allows to easily import data from external models, in order to visualize and analyse long-term hazard scenarios and risks maps related to climate change and extreme climate/weather events, adopting and applying a Source-Pathway-Receptor-Consequence risk assessment approach.

The integrated RRA approach implemented by DESYCO allow the system to investigate different climate change impacts (e.g. sea level rise inundation, storm surge flooding, water quality variations) associated to specific climate change hazard scenarios at the regional scale and identify/prioritize targets and areas vulnerable to or at risk from different climate change impacts in the considered study area (multi-target vulnerability and risk assessment). Moreover, it allows to produce interactive raster GIS-based maps with a two-dimensional visualization (i.e. exposure, vulnerability, risk and damage maps) for different natural and human receptors (e.g. beaches, wetlands, natural environments, urban and agricultural areas) and to integrate GIS spatial analysis to calculate indicators and indexes (e.g. distance and surface calculation, intersection, union, merge) for the assessment of climate-related risks in coastal zones.

It is also possible to customize scores and weights used for the application of the RRA model and to explore both intermediate and final outputs during the assessment phases. In this way, the system allows to make queries about the risk assessment elements (e.g. hazards metrics or vulnerability factors) which mainly compete to define specific results.

The functionalities offered by the tool enable various stakeholders (e.g. municipalities, regions, policy makers, port and river basin authorities) which have a mandate for coastal zone management, to obtain climate risk information that can be used operationally for optimizing coastal zoning and land use planning, in light of the potential impacts of global climate change. Specifically, DESYCO can be used as screening tool producing suitable information for the development of climate-proofed programs and projects within Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA), for adapting infrastructures investments and economic planning to climate variability and change and for defining suitable risk reduction strategies (e.g. by reducing exposure and vulnerability to climate change).

3.3. Interfaces

The Graphical User Interfaces (GUI) of DESYCO were developed in order to simplify the interaction of the end-user with the system guiding the step by step application of the RRA methodology and facilitating results understanding (i.e. GIS-based hazard, exposure, vulnerability, risk and damage maps).

The GUI are composed by two main elements: i) the tab bar and the navigation buttons, placed in the bottom part of the GUI, allow a sequential navigation through the different steps of the RRA methodology, ii) the main interface, located in the centre of the GUI, shows all commands/information related to the selected tab (Figure 5).

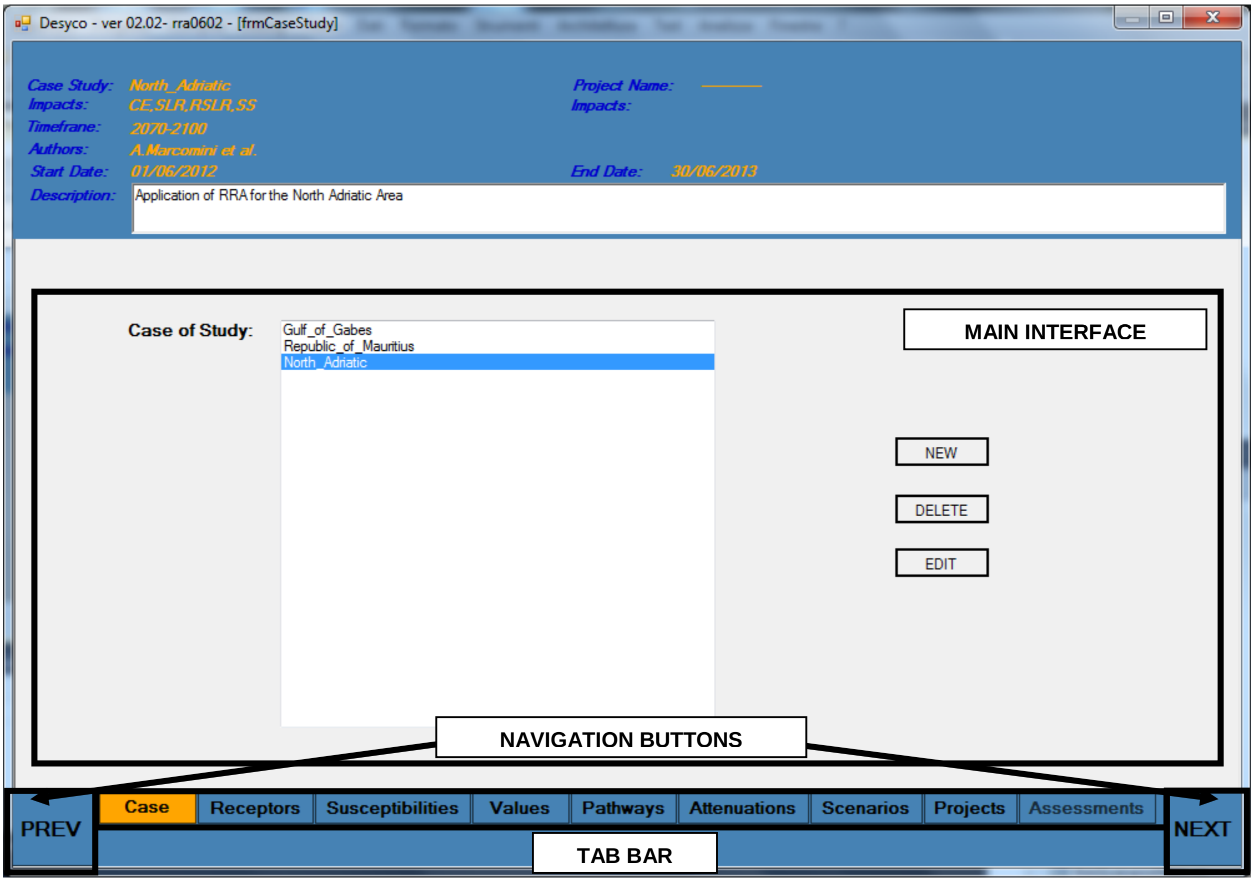


Figure 5. The starting interface of the desktop version of DESYCO showing the main components of the GUI.

Several tabs (i.e. *tab bar*, Figure 5) support the upload of input data necessary to run the DSS for a specific case study (i.e. receptor masks, susceptibility, value, pathway and attenuation factors). The amount, level of detail and the spatial resolution of vulnerability data depend on the objectives and on the scale of the ongoing application.

Successively, the user can start the upload of hazard metrics data necessary to characterize hazard scenarios. Figure 10 shows the interface for the definition of scenarios. It is possible to define one or more hazard scenarios - related to different impacts or timeframes - based on available models output (e.g. global and regional climate models or hydrodynamic, hydrological and hydrogeological models). Moreover, a hazard scenario can require the upload of one or more hazard metrics' maps, based on the hazard function specifically defined for each investigated impact.

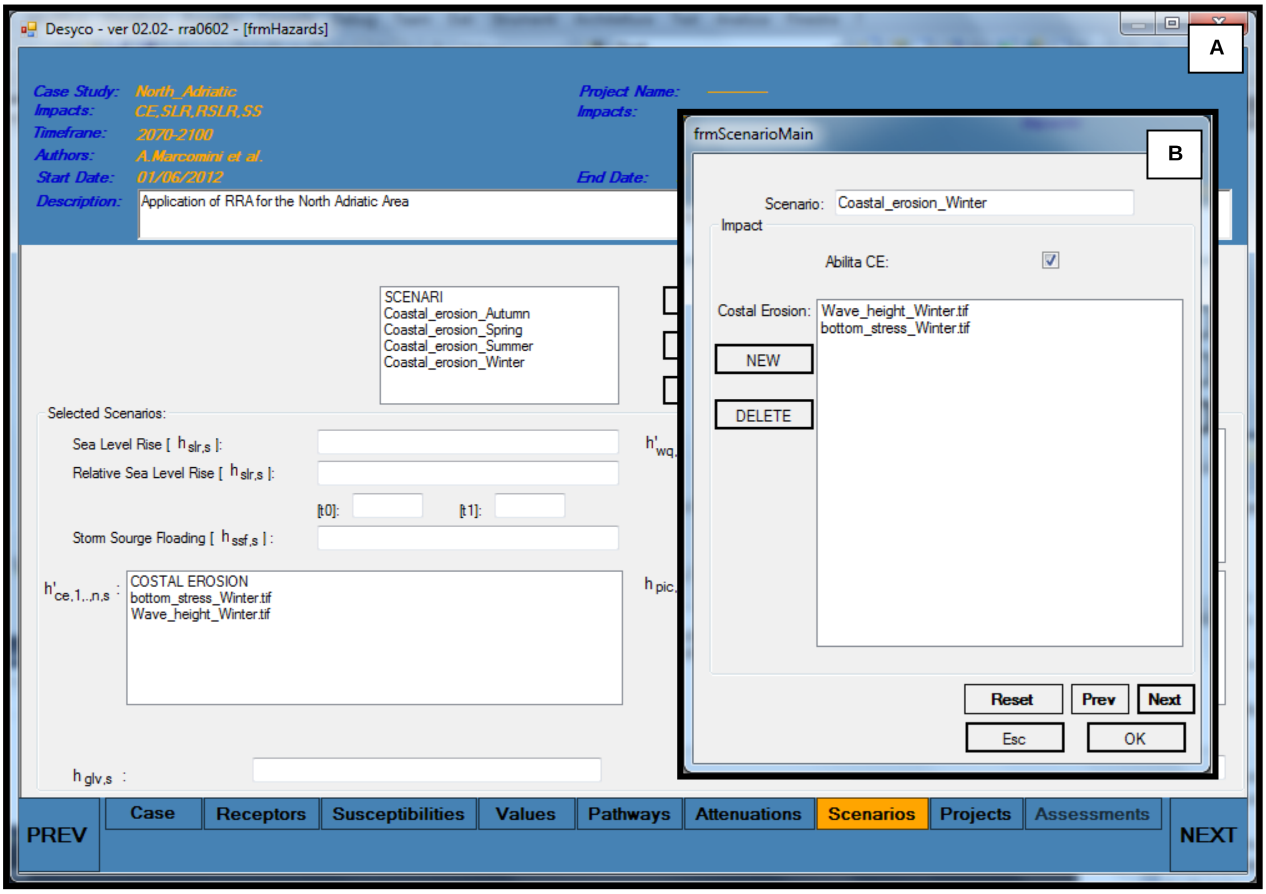


Figure 6. DESYCO interface used for setting hazard scenarios (A) and specific interface used for uploading hazard metrics (B).

Subsequently, the user can start the creation of one or more projects through the projects interface (Figure 7). Within a case study, a project represents a link between the different elements involved in the RRA methodology: future hazard scenarios, impacts, exposed receptors, vulnerability and value factors. The possibility to create different projects within the same case study allows to use the same input data to create and test several configurations of the application (e.g. in order to compare the result obtained by the use of different scores and weights for the same factors). Projects interface highly improve the flexibility of the DSS, enabling the user to perform several assessments among the same input data.

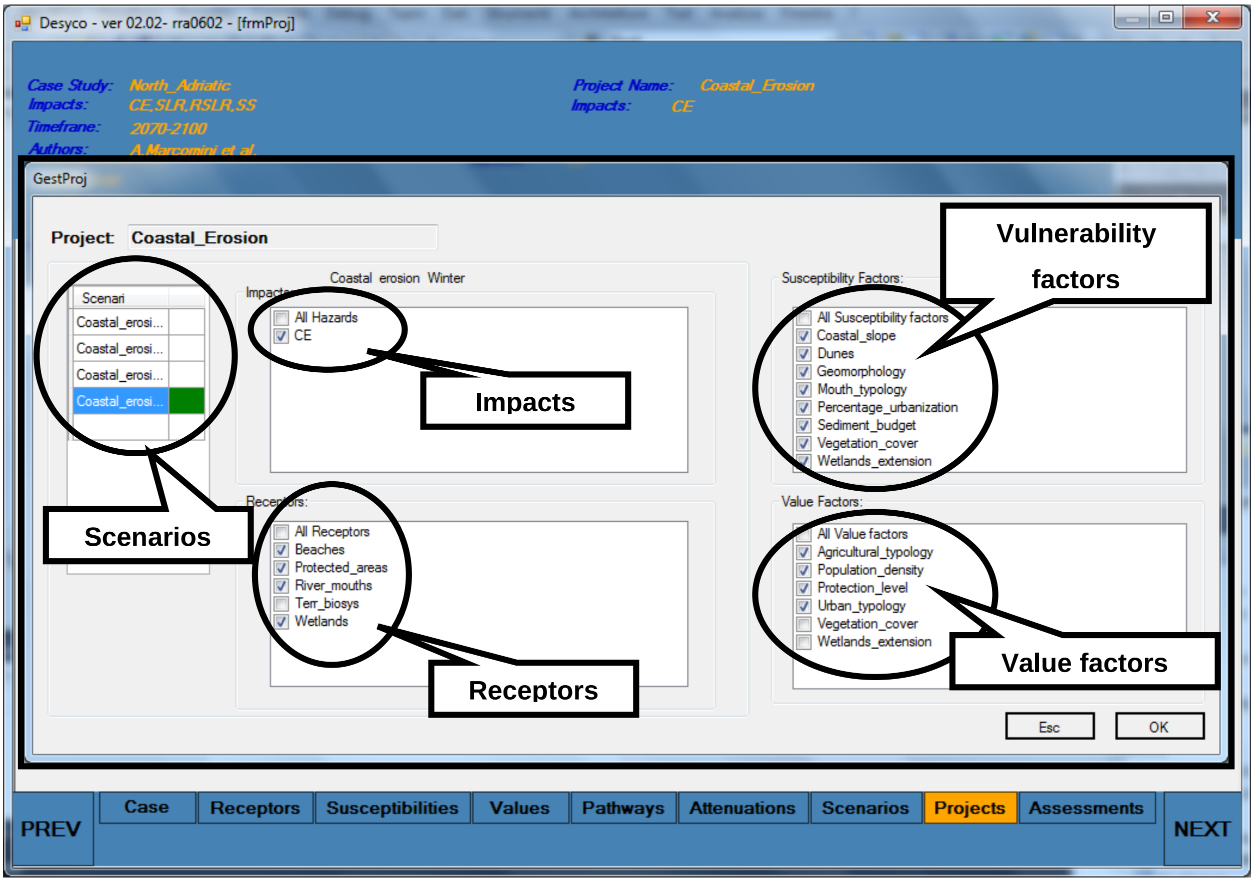


Figure 7. Project interface of DESYCO showing the set of scenarios, impacts receptors, vulnerability and value factors.

Finally, the assessments interface (Figure 8) allows the user performing all the steps of the RRA methodology (i.e. hazard scenario, exposure, susceptibility, risk and damage assessments) and calculate the related statistics. The maps produced by the DSS can be directly visualized in QGIS or can be opened in any other commercial or open source GIS software. This allows to further perform spatial analysis overlaying the RRA results with other maps of the considered region, in order to highlight hotspots and produce further information useful for decision makers (e.g. information about infrastructures, economic activities and other public services in higher risk or damage zones).

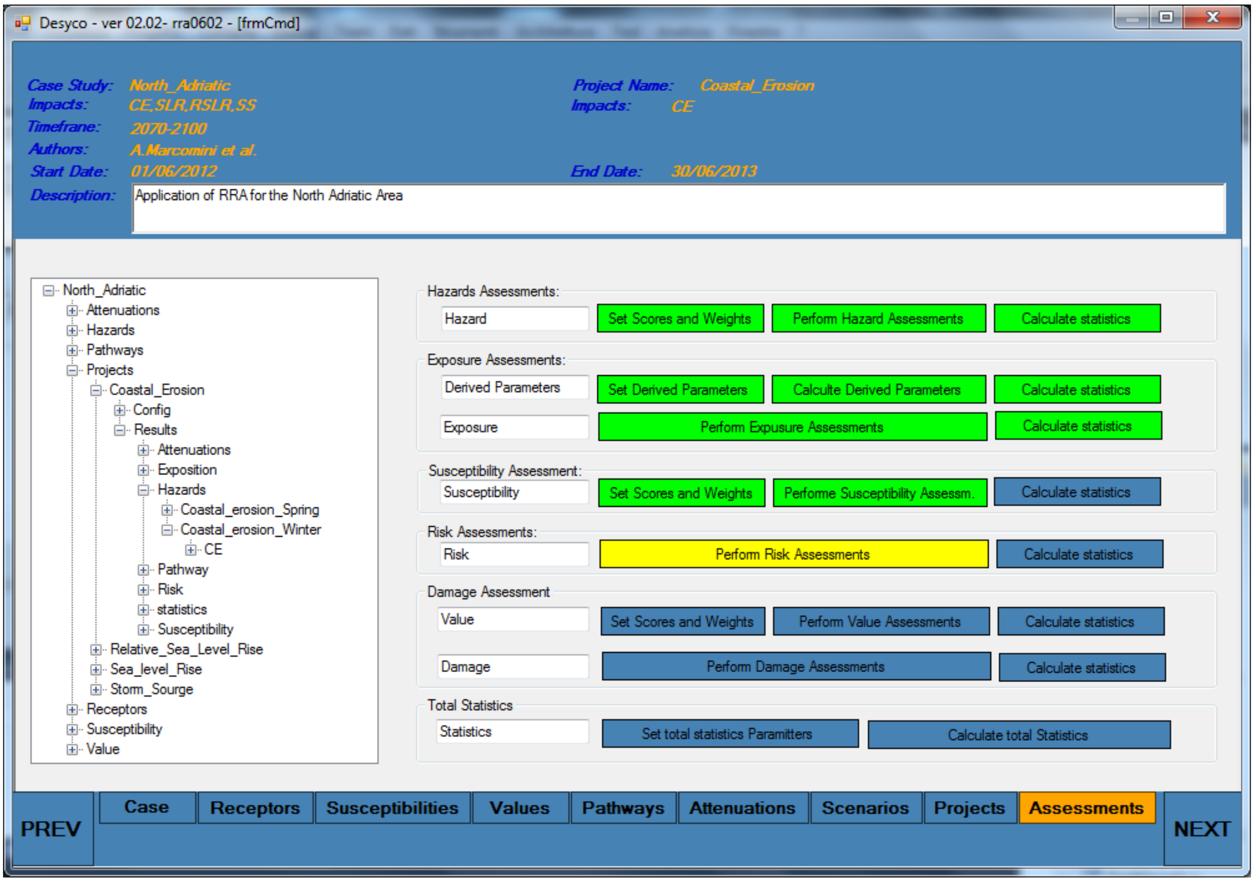


Figure 8. Assessments interface useful to perform all the steps of the RRA methodology. The tree diagram - in the box on the left - allows the exploration of the system folders of the project.

3.4. Improvements of DESYCO

The DSS DESYCO is in continuous development and several improvements were implemented since its first release. Improvements included the implementation of new functions allowing to consider a higher number of impacts, the simplification of the use and the improvement of the transparency of the software. Several improvement were achieved in the framework of the PhD thesis and are based on the results of participatory methods implemented in the framework of the PEGASO project. Specifically, several stakeholders were involved through a workshop and a questionnaire in the identification of gaps and possible improvements of DESYCO. In the following paragraphs, such improvements will be presented.

4.4.1. Statistical elaborations

Based on the output maps (i.e. exposure, susceptibility, risk and damage maps), the user can better understand results performing some statistical and geostatistical analysis through a specific interface of DESYCO (Figure 9). These statistics can be calculated for the entire case study area, for each considered receptor or for other homogenous areas (e.g administrative units), according to the needs of the end-user. The output of the statistics' calculation is represented by graphs (e.g. histograms) and tables allowing to easily analyse and compare the results. Moreover, the user can customize several parameters (e.g. the number of classes, the method used to define classes) through the interface. Basic standard statistics are represented by the calculation of the territorial surface and of the percentage of the case study area (or of a receptor or other homogeneous areas) in each exposure, vulnerability, risk or damage class (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). Specifically, the new interface allows the following specific functions:

- select for which output statistics will be calculated,
- customize the number of qualitative classes used for the different output,
- select geographical units (e.g. receptors) to be used as geographical basis for statistic calculation;
- customize the legend (colour and text).

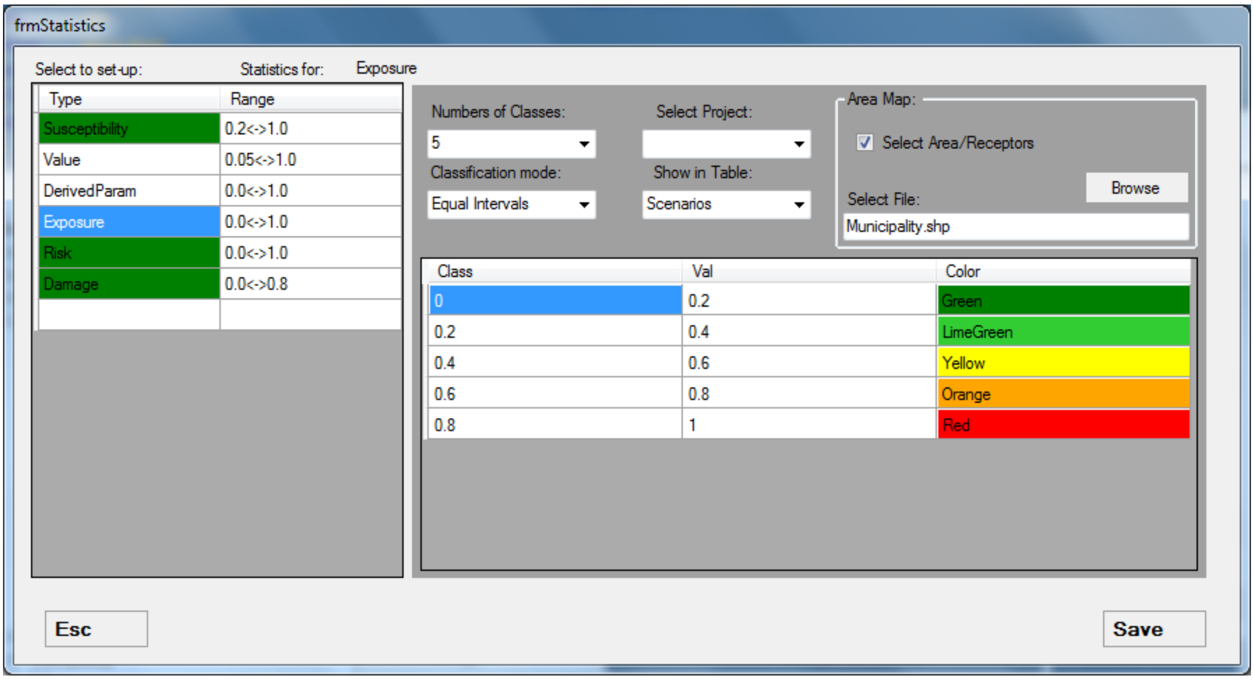


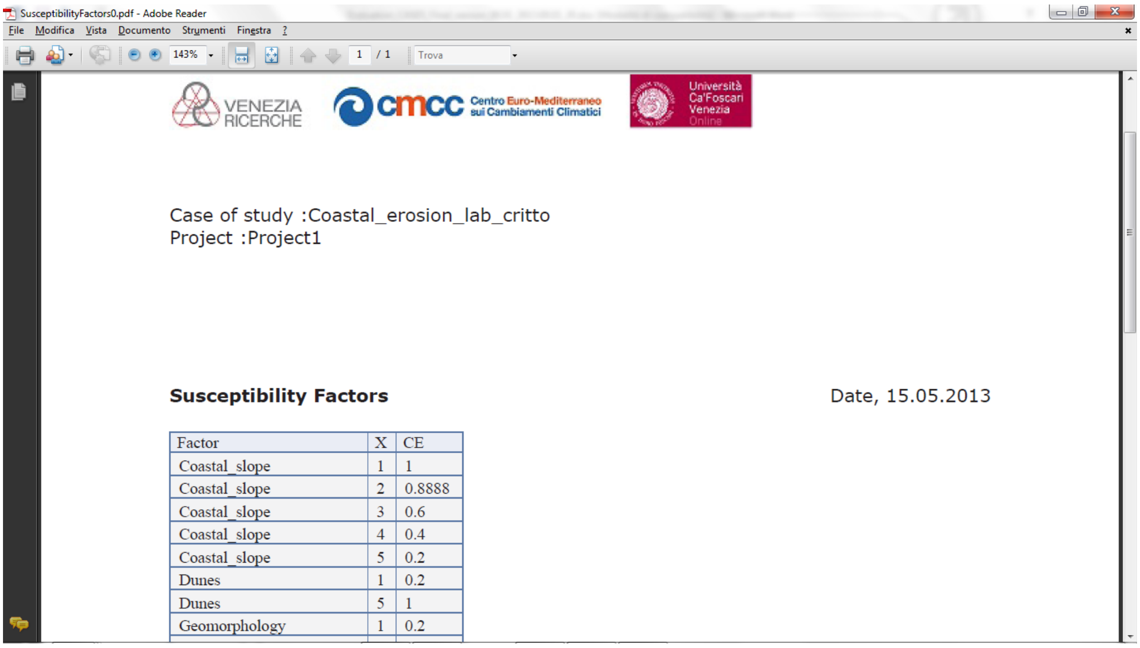
Figure 9. DESYCO interface for the calculation of exposure, vulnerability and risk statistics.

4.4.2. Production of reports

The main output of the DSS DESYCO is represented by: i) maps showing the spatial distribution of the hazard, vulnerability and risk over the considered region; ii) graphs and tables presenting the results of statistics calculations. Stakeholders suggested that this information could be better analysed and evaluated if the user can have a clear picture of how these results were produced. Accordingly, it was implemented an additional output represented by a PDF report containing the following information:

- list of vulnerability and value factors;

- value of used constants;
- classification of hazard and vulnerability factors;
- weights of hazard and vulnerability factors.


Case of study :Coastal_erosion_lab_critto
Project :Project1

Susceptibility Factors

Date, 15.05.2013

Factor	X	CE
Coastal_slope	1	1
Coastal_slope	2	0.8888
Coastal_slope	3	0.6
Coastal_slope	4	0.4
Coastal_slope	5	0.2
Dunes	1	0.2
Dunes	5	1
Geomorphology	1	0.2

Figure 10. Example of report produced by DESYCO.

4.4.3. Connection with QGIS

In order to prepare input data and explore the output of DESYCO a GIS software is required. It can be a commercial or open source software. Involved stakeholders do not use always the same software, but all suggested to integrate DESYCO within a GIS software. In order to avoid costs related to licences, it has been decided to integrate DESYCO with QGIS, an open source software. Specifically, a new toolbar was added to QGIS in order to execute the DSS (Figure 11) and the output can be visualized directly in QGIS from the DESYCO software (Figure 12).

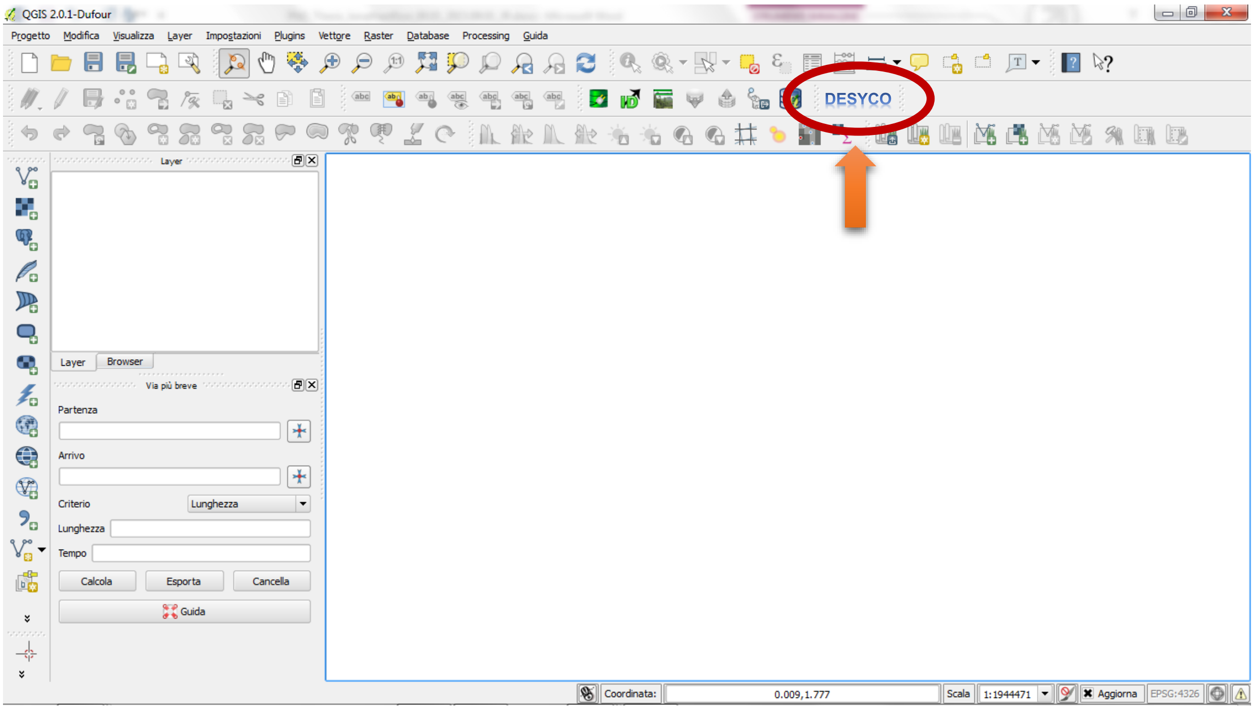


Figure 11. The DESYCO toolbar added in QGIS.

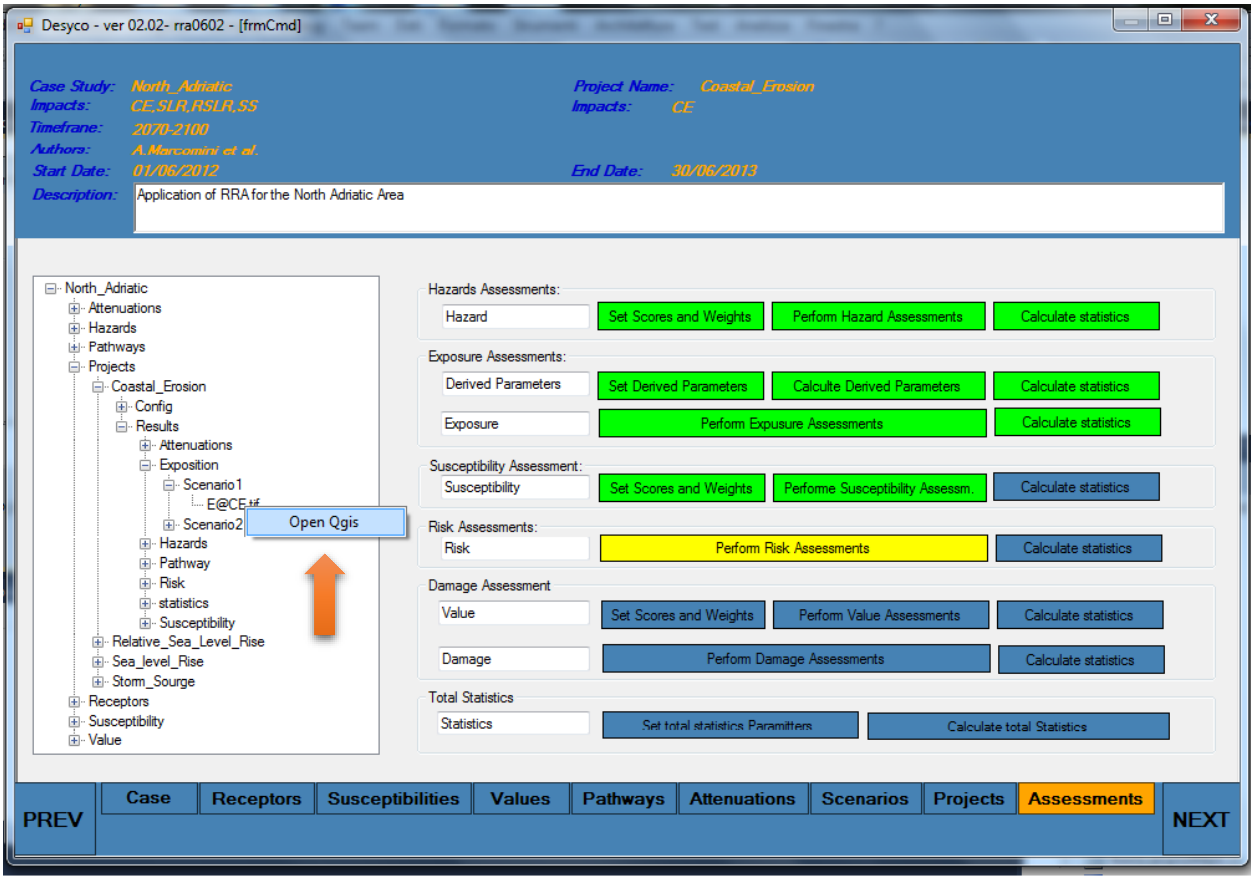


Figure 12. Menu used to open the produced output in QGIS.

4.4.4. Definition of print layouts

The discussion with stakeholders allowed also to understand how final users prefer having the RRA output. The possibility to visualize the map on a PC is fundamental, but also a printed version of the map would be very useful. Accordingly, it has been added a specific function able to produce print layout of the produced output (Figure 13).

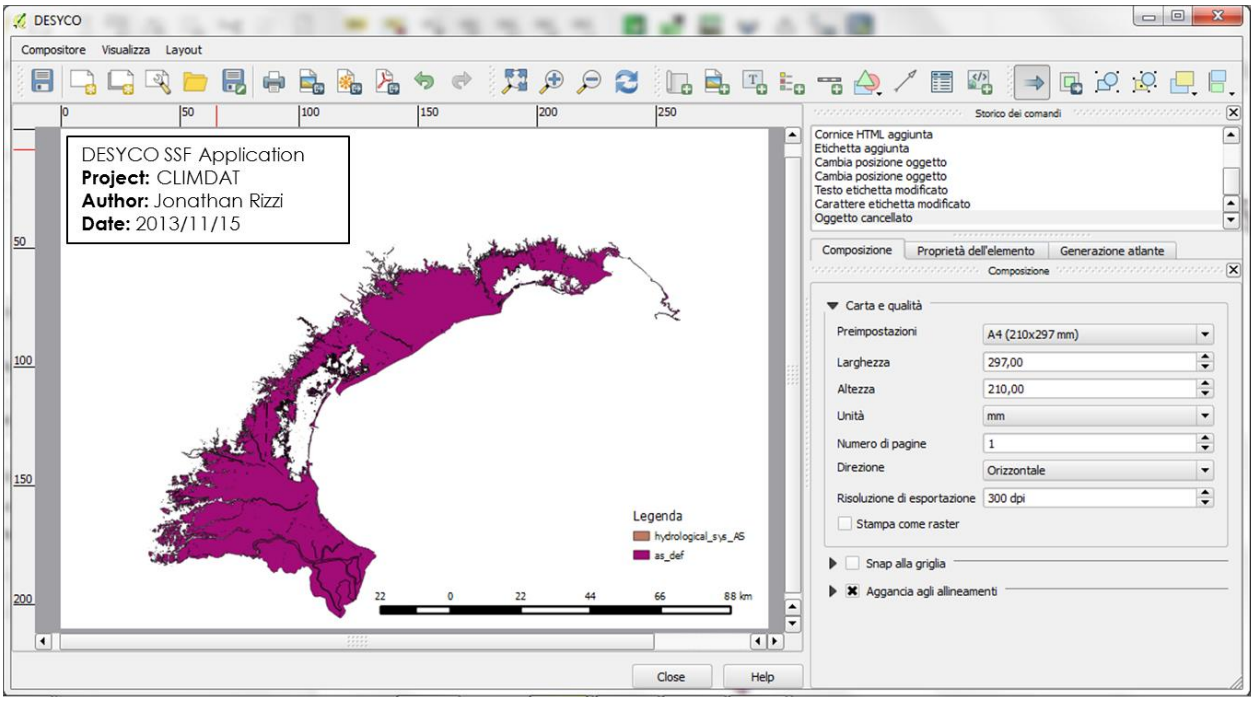


Figure 13. Interface for the production of layout.

4. Description and characterization of the case study area

The Regional Risk Assessment (RRA) methodology previously described (Chapter 2) was applied to the coastal area of the North Adriatic Sea. The analysis was focused on two impacts: Storm Surge Flooding (SSF) and Water Quality Variation (WQV). The application was performed over several different targets. For the SSF impact (Chapter 7) the receptors were identified based on the targets identified by the Flood Directive (i.e. buildings, population, infrastructures, cultural heritage) with a higher level of detail, compared to directive, on the environmental receptors (i.e. beaches, wetlands, agricultural areas and natural and semi-natural areas). As far as the WQV impact is concerned (Chapter 8) only one receptor, coastal water, was considered by the analysis.

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 describe the available dataset used as input for the application of the RRA methodology.

4.1. The North Adriatic coastal area

The area considered in the case study involves the terrestrial and marine coastal zone of Veneto and Friuli Venezia Giulia regions, which include a coastline bordering the North Adriatic Sea with an overall length of about 286 km (Figure 14). The coast of the case study area starts 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 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. the Marano and Grado Lagoon and the 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. The bathymetry of the marine part of the case study area is quite low an is never lower than 20 meters.

Figure 14. The case study area.

The main processes defining the physical properties and dynamics of the case study are atmospheric forcings (e.g. wind stress and heat flux) and freshwater inputs of the major rivers along the coastline. The intense evaporation during winter, caused by cold and dry winds blowing over the North Adriatic, contributes to the formation of dense waters (Artegiani et al. 1989; Gačić et al. 1999). Sirocco (from the southeast) and Bora (from the northeast) are the dominant winds in the region. The circulation induced by the Bora, more frequent in autumn and winter, might generate a configuration able to push the Po freshwater flux up to the Istrian coast and the Gulf of Trieste on the eastern part of the basin (Kuzmić and Orlić 2006). Moreover, Sirocco events tend to pile up water along the Italian coast and the circulation results more uniform. The Po river in the southern part of the North Adriatic and the Isonzo River in the Gulf of Trieste are regulators of the circulation of the water masses (Malačič and Petelin 2001; Querin et al. 2006) and main external nutrient source (Olivotti et al. 1986). These physical features and the large freshwater discharges (mainly from the Po River), generate a marked west–east gradient of nutrient and chlorophyll concentrations (Socal et al. 2008; Solidoro et al. 2009).

Considering the administrative aspects, the case study area refers to the Friuli-Venezia Giulia Region, including 4 provinces and 23 municipalities from the Slovenian border to Tagliamento river mouth; and to the Veneto Region, including 4 provinces and 102 municipalities from Tagliamento to Po river mouth.

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

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 vulnerability of the territory to climate change impacts and risks.

4.2. Available dataset

The application of the RRA methodology to the coastal areas of the North Adriatic sea requires the collection of a huge quantity of data useful for the characterization of the considered targets (e.g. beaches, wetlands, agricultural areas, coastal waters, etc.) and to define exposure and vulnerability indicators (e.g. presence and typology of vegetation cover, geomorphology, coastal slope, population density, artificial protections, wetlands extension). In order to identify available data, a survey regarding physical, socio-economic and ecological features of the case study area was performed. As a result, several data in graphic format or database were requested and retrieved by many public institutions Table 3 and Table 4 show the dataset used for the application, described in the Chapters 6 and 7.

Dataset	Spatial domain	Source
Digital Elevation Model (DEM)	FVG, 10m	FVG, 2006
	VE, 5m	VE, 2007
Land Cover -Regional Scale-	FVG 1:25000	FVG, 2000
	VE, 1:10000	VE, 2009
Protected Areas	VE, FVG, 1:150.000	VE, 2008, FVG, 2007
Soyl type, Geologic map	FVG, 1:150000	FVG, 2006
	VE, 1:100000	VE, 2009
Administrative unit boundaries	FVG, 1:5000	FVG, 2012
	VE, 1:10000	VE, 2012
Population census data	VE, FVG	ISTAT, 2001
Infrastructures	FVG, 1:5000	FVG, 2006
	VE, 1:5000	VE, 2011

Table 3. Available datasets in the case study area (i.e. the North Adriatic coasts) for the storm surge flooding impact. FVG = Friuli Venezia Giulia Region; VE = Veneto Region.

Dataset	Spatial domain	Source
Fish species' abundance	VE, FVG	Adri.Blu project (Laboratory of marine biology and fisheries, University of Bologna), 2006
Fish production and turnover related to the fish market placed in the North Adriatic Sea	VE, FVG	Veneto Agricoltura, Socio-Economic Observatory of Fishing and Aquaculture, 2006
Seagrasses	VE, FVG	Adri.Blu project , 2006
Tegnùe	VE, FVG	Adri.Blu project , 2006
Aquaculture typology	VE, FVG	Adri.Blu project , 2006
Protected areas, ZTB, natural reserves and zones for fish repopulation	VE, FVG	Adri.Blu project , 2006

Table 4. Available datasets in the case study area (i.e. the North Adriatic coasts) for the water quality variation impact. FVG = Friuli Venezia Giulia Region; VE = Veneto Region.

5. The model chain for the North Adriatic coastal area.

In order to evaluate potential climate change hazard on the coastal zones of the North Adriatic sea, a model chain was defined allowing the identification of several hazard metrics to be used as input in hazard assessment step of the RRA methodology (Chapter 2). 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.

The proposed model chain (Figure 15) is composed by different typologies of numerical models with different resolution (i.e. from the global to the local one) simulating relevant circulation and morphodynamic processes influencing climate change impacts on coastal zones. It includes: i) Global Climate Models (GCM) and Regional Climate Models (RCM) representing the main atmosphere and ocean dynamics and covering large spatial domains (i.e. from the global to the sub-continental scale), ii) 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.

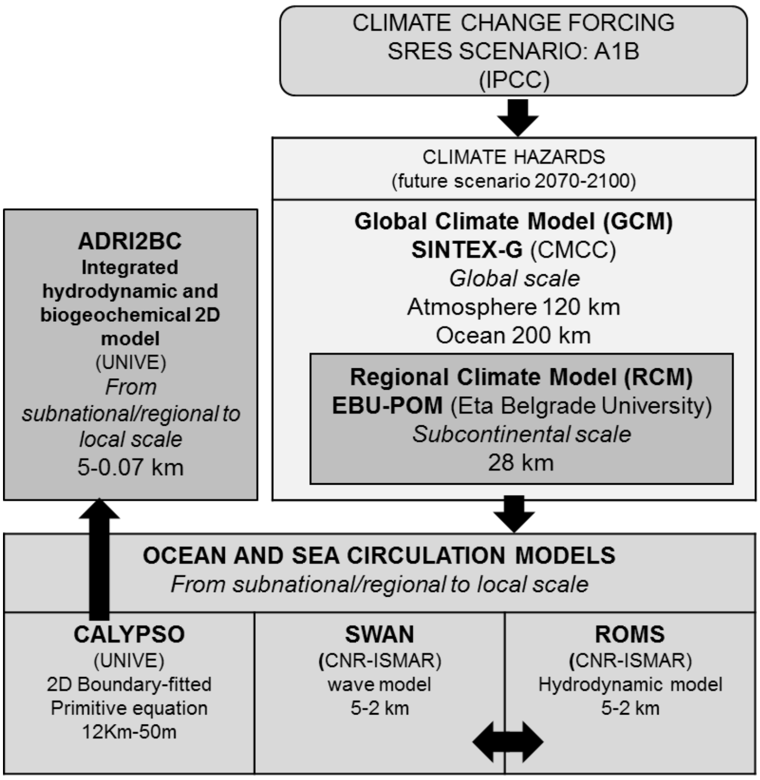


Figure 15. Model chain applied in the North Adriatic coastal area to define hazard scenarios.

The model chain is forced by the IPCC SRES scenario A1B providing inputs such as the atmospheric concentrations of greenhouse gases, ozone and aerosols (Nakićenović et al., 2000) to the GCM (i.e. SINTEX-G) and to the GCM (i.e. EBU-POM). The selected SRES scenario (i.e. A1B) scenario belongs to the A1 storyline family, describing a future world with a very rapid economic growth that will have global population peaks in the middle of the 21st century and declines thereafter, where new and more efficient technologies will be rapidly introduced. Going into details, the A1B scenario predicts CO_2 emissions increasing in the first half of the 21st century and then decreasing, assuming a balance between fossil fuels and other energy sources.

The outputs provided by the RCM (i.e. EBU-POM) are represented by climate parameters (e.g. precipitation, wind, temperature) and are used as input by the ocean and sea circulation models with a higher resolution (i.e.CALYPSO, SHYFEM, SWAN and ROMS).

As shown in Figure 15. , 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). In the following paragraphs the used models and their final output will be described.

5.1. Description of models

Models used within the described chain are mathematical representations of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedbacks.

A GCM is a 3-D numerical model solving equations for fluid motion and energy transfer around the word for futures times. A GCM can be coupled with a model of the atmosphere to set-up a coupled Atmosphere-Ocean Global Climate Model (AOGCM), a complex climate model integrating a comprehensive three-dimensional atmospheric general circulation model within a ocean general circulation model, with a sea-ice model and with a model of land-surface processes.

SINTEX-G is a high resolution AOGCM producing long climate simulations and climate change projections (Gualdi et al., 2008). Forcing agents, including greenhouse gases (CO_2, CH_4, N_2O, and CFCs) and sulfate aerosols, were integrated within the simulations for the XXth and for the XXIst Centuries, as specified by specific protocols for the for the scenario experiments (e.g., A1B, A2, etc.) defined for the IPCC simulations (Nakićenović et al., 2000). The model include both the oceanic and the atmospheric component. The oceanic component is the Océan Parallélisé (OPA; Madec et al. 1998) model using the ORCA2 global ocean configuration. The resolution is around 2°, with the meridional resolutions increasing up to 0.5° close to the equator; moreover, the model has and 31 vertical levels, 10 of which lying in the upper 100 m of the ocean. The atmospheric component is the ECHAM4 (Roeckner et al. 1996) model. ECHAM-4 considers several variables: vorticity, divergence, temperature, surface pressure, water vapour, clouds water. Outputs of the model include seasonal total precipitation values, wind velocity, seasonal change in temperature and evaporation. The spatial resolution of ECHAM-4 can range from about

600 km to about 120 km (Bauer and Wulfmeyer, 2009). The outputs of this model, who has a resolution of about 120 km in the proposed application, represent the input for the EBU-POM model.

A RCM is used provide information at sub-continental level modelling climate at a higher resolution for a finite area, driven by boundary conditions coming from a GCM (or a AOGCM). Within the model chain the output of the SINTX-G model (i.e. a AOGMM) are used as input by the EBU-POM model (i.e. a RCM).

EBU-POM is a subcontinental coupled model of ocean and atmosphere, including two models: i) the EBU (Eta Belgrade University) atmosphere model, with a spatial resolution of 0.125° (around 10 km) and 32 vertical levels; ii) the POM (Princeton Ocean Models) ocean model, with a horizontal resolution of 4 km and 21 vertical levels (Djurdjevic and Rajković, 2007). Energy, matter exchange and air/water interface are taken into account in their integration; moreover, the difference of resolution between the atmospheric and the oceanic components (i.e. the atmosphere model has a resolution around three times higher than the ocean model) is menaged by a specific software. The output of the EBU-POM model cover the Mediterranean Sea with a spatial resolution of 0.25° (around 28 km). and include climate hazard scenarios representing boundary conditions for higher spatial resolution impact models (e.g. the ocean and circulation models included in the model chain).

CALYPSO is a shallow water hydrostatic 2D hydrodynamic model used to simulate aspects of both general and small scale oceanic features occurring in the composite system constituted by the Adriatic Sea and the Lagoon of Venice (Lovato et al., 2010). Based on the use of a technique for the treatment of movable lateral boundaries, the model efficiently simulates dry up and flooding processes. The output of CALYPSO were used to investigate: i) small-scale coastal circulation features observed at the interface between the Adriatic Sea and the Lagoon of Venice, consisting of ten of vertical dipoles connected with the tidal flow of Adriatic water entering and leaving the Venice Lagoon and with along-shore current fields connected with specific wind patterns; ii) residual oscillations, which are often connected to meteorological forcing over the considered region.

ADRI2-BC is a coupled model composed by a transient early diagenesis model and a reaction-transport pelagic biogeochemical model used for the simulation of both pelagic and benthic biogeochemical processes (Brigolin et al., 2011). The model was applied to the shallow coastal area of the Northern Adriatic Sea, in order to simulate: i) the seasonal dynamics of fluxes of macronutrients (i. e. N and P), at the sediment–water interface; ii) the spatial variability in both sediment concentration profiles and benthic–pelagic fluxes of NH_4^+, NO^{3-}, DIP and O_2. The integrated model could be further applied for research investigations and management purposes.

To this regard, its use for the assessment of aquaculture impacts on sediment geochemistry and nutrient recycling looks appropriate.

SWAN is a wave movement model customised for the North Adriatic Sea and the Lagoon of Venice (Booj et al, 1999). It is based on the wave movements in deep waters, on the wind, the bathymetry, currents and tides and it is used to forecast waves trend on coastal environments. Input data of this 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). The SWAN model uses 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 (Wolf et al. 2000). Output parameters are calculated for the North Adriatic Sea with a spatial resolution that ranges between 2 and 5 km.

ROMS is a 3D, free surface, terrain following numerical model that solves finite-difference approximations of the Reynolds-averaged Navier-Stokes equations using the hydrostatic and Boussinesq assumptions with a split-explicit time stepping algorithm (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008). 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. Output data 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) include: i) bottom stress along coastline and offshore, ii) sea water temperature and salinity, iii) currents velocity. Data for the North Adriatic Sea have a spatial resolution ranging from 2 to 5 km. This model can be used to determinate impacts in a coastal zone such as coastal erosion, offshore sedimentation and water quality variations.

ROMS and SWAN were coupled on two-ways 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 coupled model can 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).

5.2. Outputs of the model chain

All the output produced by the models included in the model chain are listed in Table 5. , summarizing the main information: model's name, category, domain and spatial resolution, outputs metrics and investigated time scenario. Highlighted output represent parameters that will be used for the construction of hazard scenarios in the RRA methodology. The spatial scale field of the models producing the output used by the RRA are sufficiently detailed to perform analysis at the regional/subnational scales (i.e. from 5 km to 50 m).

Name	Category	Domain	Spatial resolution	Metrics	Time Scenario
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
CALYPSO	Coastal and sea circulation model	Adriatic Sea and Lagoon of Venice	From 12 to 0.05 km	Bottom Stress Current velocity Water levels Submerged areas	2070-2100
ADRI2-BC	Integrated hydrodynamic and biogeochemical 2D model	North Adriatic sea	From 5 to 0.7 km	**Primary production** **Dissolved inorganic nitrogen** **Reactive phosphorus** **Dissolved oxygen** **pH**	2070-2100
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
SWAN	Ocean and sea circulation model	North Adriatic sea	From 5 to 2 km	Wave energy Wave direction Wave height Wave period	2070-2100
ROMS	Ocean and sea circulation model	Adriatic sea	From 5 to 2 km	Bottom stress **Salinity** **Sea temperature** Water velocity	2070-2100

Table 5. Summary of information provided by the model chain.

6. Storm Surge Flooding

Storm surge floodings represent one of the main natural disaster causing several impacts on coastal areas that can be significatively affected by climate change through rising sea levels and increased frequency of extreme events (IPCC, 2012). In fact, storm surges are generated by wind driven waves and winter storms (Smith et al., 2000), and are greatly influenced by the long term trends of the global mean sea level rise (Woodworth et al., 2005). The 4th IPCC Assessment Report showed that the rise in mean sea level and variations in regional climate led to a likely increase in the trend of extreme high water levels worldwide in the late XXth century (IPCC, 2007). Moreover, expected sea level rise is projected to have impacts on Europe's coastal areas by causing land loss, groundwater and soil salinization, and damage to property and infrastructure (Devoy, 2008). Moreover, coastal areas, which are experiencing adverse impacts such as coastal erosion and inundation, will continue to do so in the future (IPCC, 2012).

Coastal areas have a great environmental, economic, social, cultural and recreational importance. They are characterized by the presence of many different ecosystems, representing source of food and habitat for many species, and maintain an ecological balance that accounts for shoreline stability, beach nourishment and generation and recycling of nutrients (IPCC, 1995). Coastal zones, due to their richness of resources, support also many economic activities and represent one of the most exploited areas worldwide (Post and Lundlin, 1996). Moreover, they host many human settlements: 21% of the world's population live within 30 km of the coast and about 10% of the world's population lives in low-elevation coastal zones below 10 m elevation (Nicholls and Cazenave, 2010). People living in these areas is rapidly growing and urbanization and associated land use changes will exacerbate climate change related risk. In fact, exposure (i.e. elements located in areas potentially at risk) and vulnerability (i.e. economic, social, geographic, cultural, and physical/environmental characteristics of the exposure) to inundation from sea level rise and large storm surges are increasing with climate change (IPCC, 2012), calling for new integrated management approaches and adaptation strategies (EEA, 2010 b, Hennessy et al., 2007, Nicholls et al., 1999).

The importance of storm surge floodings has been recognized also by the European Commission, by issuing Flood Directive in 2007 (EC, 2007) with the aim of establishing a framework for the assessment and management of flood risk in Europe, considering frequency, magnitude and consequences of floods. The directive is addressed to several different typologies of floods, including those from the sea in coastal areas, and takes into account also the influence of climate change on the occurrence of floods. The directive commits member states to create flood hazard and risk maps by June 2013 (de Moel et al., 2009). Hazard maps should identify areas that may be affected by floods with different probabilities and are based on the integration of extreme events estimates (i.e. maximum water height level with different return periods) and sea level rise scenarios. The probability of occurrence of extreme storm surge along coasts is usually statistically estimated from series of local observations (Pirazzoli and Tomasin, 2007). Several methods can be adopted, e.g. the Gumbel formalism (Gumbel, 1954) the Generalized Extreme Values (GEV) method (Coles, 2001) or the Joint Probability Method (JPM, Pugh and Vassie, 1979). The latter has the advantage, compared to the others, to be efficient also when dealing with short periods of recordings, e.g. less than a dozen years; however,, the JPM tends to overestimate the extreme levels that should be observed in the considered period (Tomasin and Pirazzoli, 2008).

Based on the hazard maps, flood risk maps showing the potential adverse consequences associated with different flood scenarios should be prepared, as required by the directive. They can be qualitative risk maps showing how different receptors can be affected by floods, i.e. population, buildings, infrastructures, agriculture, natural and seminatural environments and cultural heritage. Risk is usually defined as the product of hazard and vulnerability (Apel et al., 2009). Several methodologies have been proposed to evaluate flooding related risks at different scales, from the local/municipal one (Grunthal et al., 2006), to the regional (Gallina et al., 2012), the national (Hall et al., 2004), and the European scale (Schmidt-Thomé et al., 2006). The regional and local scales appear the most suitable for the definition of flood risk management plans, as the considered phenomena will not be uniform, but will assume specific regional or local characteristics (Ramieri et al., 2011).

Most of the proposed methodologies developed to support the implementation of the Flood Directive are related to river floods (Semenzin et al., 2011). The ones related to coastal floods are focused usually on specific aspects (e.g. on the physical aspects of storm surges; Jemenez et al., 2009) or on specific receptors, such as population (e.g. Crowell, 2010) or ports (e.g. Hallegatte et al., 2010). Only few methodologies attempt to provide an overall assessment of climate change risks in coastal zones at the national scale (e.g. Ramsbottom et al., 2012), while those at regional scale are focused only on specific receptors (e.g. population; Nicholls et al., 2005). Accordingly, there is the need to develop new methodologies at the regional scale integrating information from storm surge models with social and economic aspects of the region of interest to evaluate flood risks for different receptors/elements at risk, as required by the Flood Directive (i.e. people, economic activities, cultural heritages, natural and semi-natural systems).

The main aim of this chapter is to present the RRA methodology adapted for the Storm Surge Flooding (SSF) impact and its application to coastal are of the Veneto and Friuli Venezia Giulia regions. The RRA methodology presented in Chapter 2 was adapted for the SSF impact based on the 4 steps summarized in Figure 16. Accordingly in the next paragraphs, the RRA methodology will be described in detail (Chapter 7.1) and the produced outputs (i.e. hazard, exposure, vulnerability and risk maps) will be presented and discussed (Chapter 7.2).

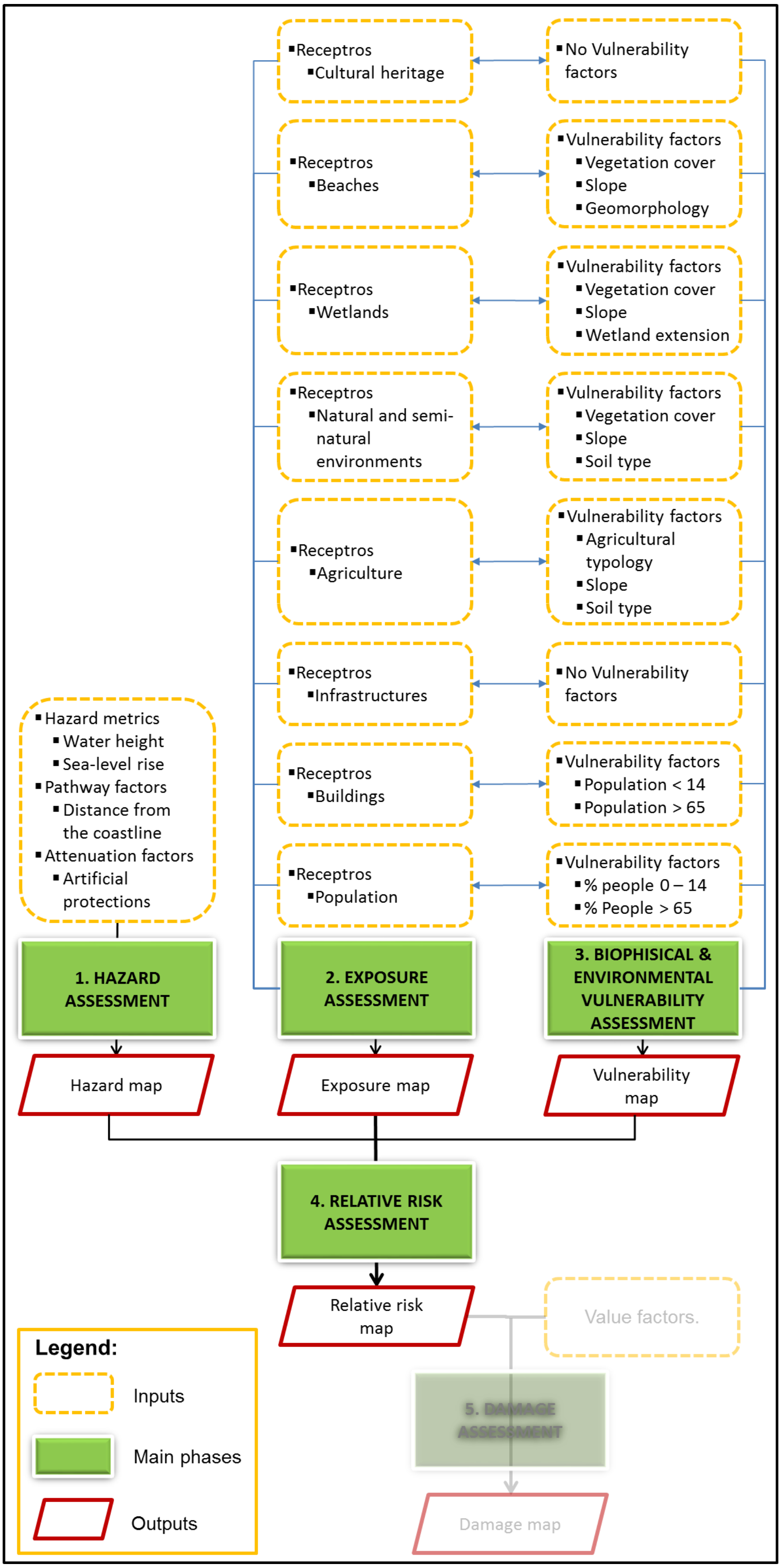


Figure 16. RRA methodology steps for the Storm Surge Flooding impact

6.1. RRA methodology for Storm Surge Flooding

6.1.1. Hazard assessment

The hazard assessment phase is aimed at identifying areas that could be inundated by a storm surge based on storm surge height scenarios along the coasts of the Veneto and Friuli Venezia Giulia regions. A storm surge is defined as the temporary rising of sea level and it overflowing onto normally dry land due to extreme storm surge events (UKCIP, 2003). It is determined by three components (Figure 3): i) the mean sea-level, ii) the astronomical tide (i.e. the normal high tide), iii) the meteorological tide (i.e. the storm surge).

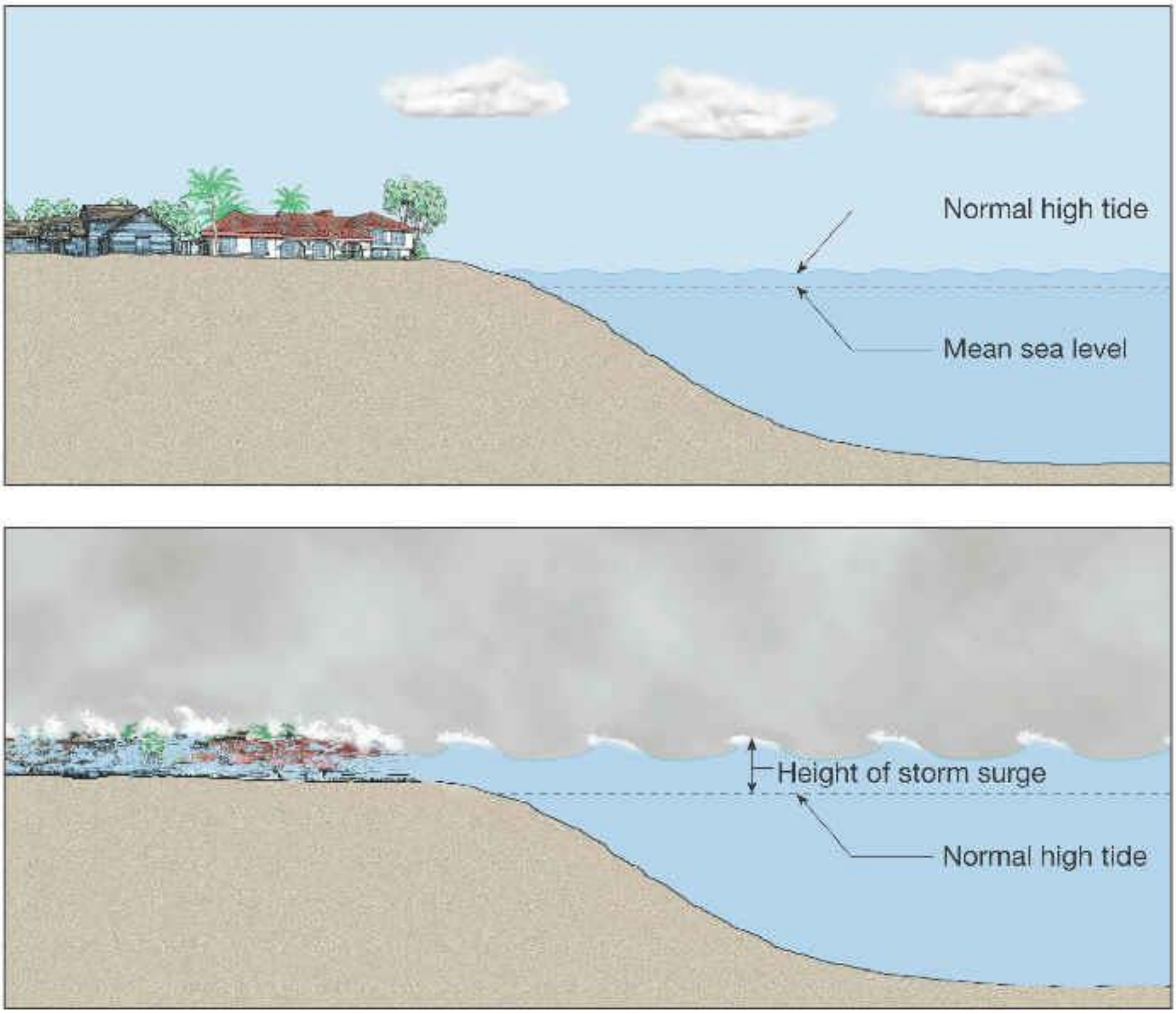


Figure 17. Components contributing to a Storm surge (Source: http://www.geography.hunter.cuny.edu)

Sea-level rise will exacerbate impacts related to storm surge floodings because extreme water levels will be increased of a value corresponding to the forecasted increment of the mean sea-level.

Accordingly, the main components that will be analysed to develop hazard scenarios for this impact are: i) sea-level rise, that is the permanent increase of the mean sea-level due to climate change; ii) storm surge, that is the temporary increase in sea level, above the level of the astronomical tide, caused by low atmospheric pressure and strong winds (UKCIP, 2003).

For the definition of sea-level rise scenarios, several numerical climate models have been evaluated and compared, but projections available for certain areas such as the North Adriatic basin don't really completely agree in the foreseen changes. In fact, the uncertainty associated to climate projections is connected to the complexity and quantity of information to be considered in the computation of sea level change scenarios. A common practice in sea-level research is to analyse separately the different processes and components that can contribute to sea level variability.

The major forcing to be considered for the analysis of sea level change are:

- Thermosteric effect: thermal expansion at Mediterranean basin-scale;
- Halosteric effect: changes in salinity;
- Mass addition: it's due to changes in mass budget of the Mediterranean Sea (almost compensated by halosteric effect);
- Dynamical effect: due to local changes in oceanic circulation;
- Change of near-Atlantic sea level due to all the processes including ice melting (glaciers or ice sheets);
- Changes in sea floor;
- Storm surges (local and snapshot effect);
- Tides (periodic effect).

The table below summarizes sea level rise scenarios projected by several climate and ocean models, from global to regional scale and under different emission scenarios. This table specifies the data source, model's category, domain and spatial resolution, major climate forcing and emission and timeframe scenario (Table 5.1).

The sea-level rise scenarios selected for this study are the ones realised by CMCC and CNR-ISMAR by the application of a multi-model chain including coastal hydrodynamic models for the North Adriatic region (Torresan et al, 2009) for the future scenario 2070-2100. Results include two sea-level rise scenarios: i) a low sea-level rise returning an average rise of 17 cm and a high sea-level rise returning an average rise of 42 cm.

Data source	Category	Domain	Spatial resolution	Sea level forcing	Emission senario	Time Scenario	Sea level rise value (cm)	
IPCC, 2007	Several models	Global	Different spatial resolution related to the model	Sea temperature (thermal expansion)	B1	2081-2100	LOW:	17
					A1F1		HIGH:	60
IPCC, 2013	Several models	Global	Different spatial resolution related to the model	Sea temperature (thermal expansion)	RCP2.6	2081-2100	LOW:	25
					RCP8.5		HIGH:	80
Vermeer and Rahmstorf 2009	Simplified models	Global	Different spatial resolution related to the model	Sea temperature (thermal expansion)	B1	2100	LOW:	75
					A1F		HIGH:	190
ENEA	Ocean and sea Circulation models	Mediterranean sea	50 km	Sea temperature (thermal expansion)	A1B	2041-2050	LOW:	4
							MEDIUM:	15
				Oceanic circulation			HIGH:	27
CMCC and CNR-ISMAR	Model chain	North Adriatic sea	2.5 km-50 metres	Sea temperature (thermal expansion)	A1B	2070-2100	LOW:	17
				Oceanic circulation			HIGH:	42

Table 6. Sea level rise scenarios projected by model from global to regional scale under different emission and timeframe scenarios.

As far as the storm surge height is concerned, the Joint Probability Method (JPM, was used and applied to the North Adriatic sea. The JPM (Pugh-Vassie, 1979) is aimed at forecasting the return period and estimating the frequency of extreme events. It is a method where the separate action of tide and surges is considered. Astronomical tides and surges were tabulated to produce normalized frequency distributions in bands with a tabulating interval of 5 cm and the frequency distributions of the observations was assumed to be representative of the probability of future events. Briefly, the probability for the sea level to reach the value M is the joint probability (hence, a product) for the surge to be M and the tide to be zero, plus the probability for the surge to be $M-1$ and the tide to be unitary. Obviously, also surge being $M+1$ and tide being -1 were considered, and so on.

The calculations was based on the hourly measurements. This choice is important because the focus of the present study is the North Adriatic Sea, where the separation of different surges is made almost impossible by seiches (Tomasin-Pirazzoli, 1999), the free oscillations of the basin after a storm, very persistent due to the shape of the local morphology.

The dataset was based on the use of data coming from tide gauge stations lacated along the Adriatic coast and in the Lagoon of Venice and in the Lagoon of Marano and Grado. Available data coming from tide gauge stations were collected, validated and organized within a geodatabase. More specifically historical series coming from 28 tide gauge stations located in the Venice Lagoon, in the Marano and Grado Lagoon and the in the North Adriatic (including Ancona, Ravenna and Trieste) from the year 1989 were analysed. Accordingly, the amount of data made available was of about 700 years, with an average of 25 years for each station.

To ensure high quality information, raw data have was submitted to a series of quality checks, both using numerical filters within the same time series and comparing data collected in nearby stations. Doubtful data or low quality series were dismissed. Moreover, harmonic constants were calculated from checked data to obtain the astronomical tide (Figure 18), useful for extra quality checks (time check). When a series passed all validation step, it was released. Moreover, the analysis of harmonic constants series allowed to monitor changes in the water levels related to the interaction Earth-Sun-Moon. Significant changes in the harmonic constants series can be related to changes in hydraulic assets of an area (Figure 19).

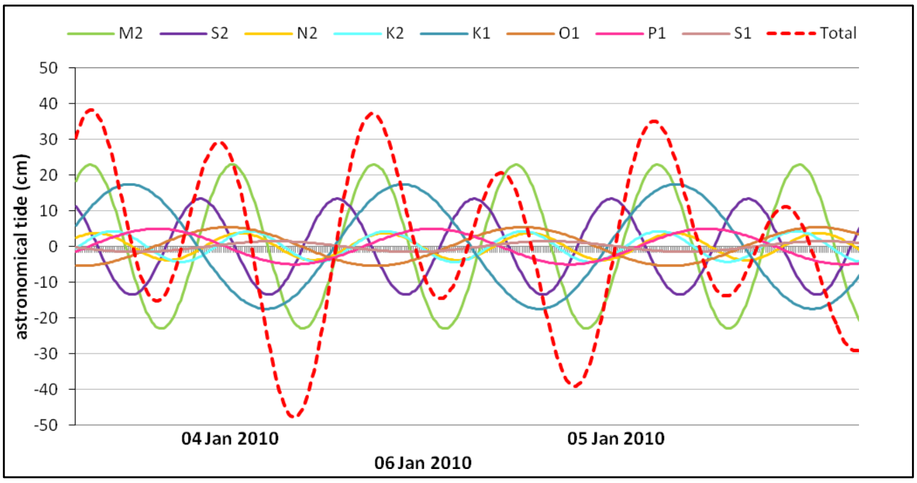


Figure 18. Astronomical tide (dotted line) and its components.

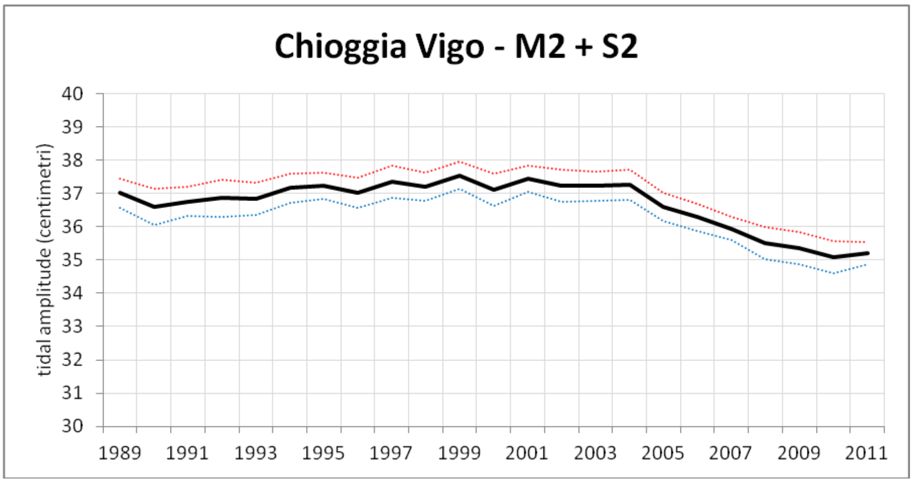


Figure 19. Long term variation of astronomical tide components (harmonic constants).

Among the 28 station for which time series were prepared, 10 representative stations (5 in the Lagoon of Venice, 1 in the Lagoon of Marano and Grado and 4 in the Adriatic Sea) were selected in order to apply the Joint Probability Method.

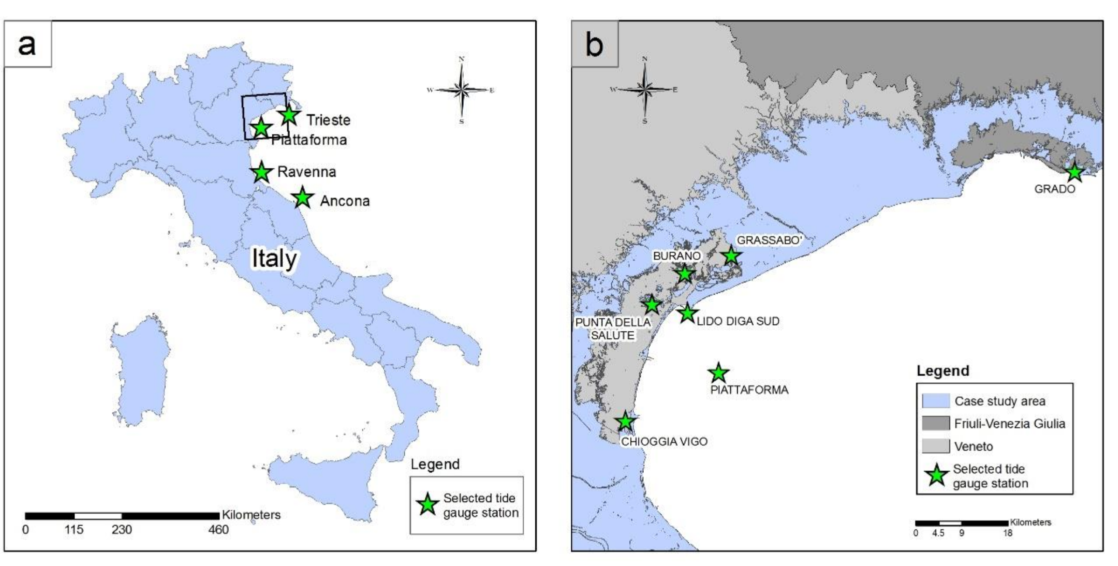


Figure 20. The 10 tide gauge stations selected for the application of the JPM.

The detailed output of the JPM are reported in Annex 2 and include several information:

- Probability (%) of having events of a defined water level;
- Cumulated percentage of having events of a defined water level;
- Expected number of hours/year of events of a defined water level;
- Expected number of hours/year of events higher or equal of a defined water level;
- Average duration of events of a defined water level;
- Return periods (years, months) of events of a defined water level.

Based on these output, water level related to the return period defined by the FD and by the Italian law (i.e. D.Lgs. n.49 of the 23rd February 2010) were identified. Specifically five return periods (i.e. 20, 50, 100, 200 and 500 years) related to three different typologies of floods were identified for each tide gauge station. Results are reported in Table 7.

The output of the JPM do not include the mean sea level thus it was required to add this level. The mean sea-level was calculated for each tide gauge station considering all the years usied during the application of the JPM (i.e. 1989-2012). Values are reported in Table 7.

Moreover, water levels returned by the JPM were referred to different reference systems (e.g. Trieste has not the same reference system of Ancona and Ravenna) and do not use the same reference system of the Digital Elevation Models of the considered regions, using IGM Genova 1942 as reference. Specifically, two tide gauge stations (i.e. Ancona and Ravenna) used IGM Genova 1942 as reference system, one tide gauge station (i.e. Trieste) used the zero level of the Talassographic Insititue of Trieste and seven stations considered the zero level of Punta della Salute. Consequently, values obtained by the JPM were increased/decreased in order to use the IGM Genova 1942 as reference system for all data. Values used to set all stations are reported in Table 7.

	Adriatic Sea					Venice Lagoon					Marano and Grado Lagoon
	Return period (years)	**Ancona**	**Ravenna**	**Piattaforma**	**Trieste**	**Chioggia**	**Lido Diga Sud**	**Punta della Salute**	**Burano**	**Grassabò**	**Grado**
Floods with a high probability	**20**	92	119	147	158	163	151	150	142	141	152
	50	95	124	153	176	170	156	154	149	146	158
Floods with a medium probability	**100**	96	127	156	188	175	160	158	154	149	161
	200	97	129	159	199	179	162	160	158	152	164
Floods with a low probability	**500**	99	133	163	210	183	165	163	162	155	168
Mean sea level		-2,80	5,21	25,88	161,14	25,18	26,08	25,80	27,79	26,65	25,82
IGM		0,00	0,00	-23,00	-163,74	-23,00	-23,00	-23,00	-23,00	-23,00	-23,00
Floods with a high probability	**20**	89	124	150	155	165	154	153	147	145	155
	50	92	129	156	173	172	159	157	154	150	161
Floods with a medium probability	**100**	93	132	159	185	177	163	161	159	153	164
	200	94	134	162	196	181	165	163	163	156	167
Floods with a low probability	**500**	96	138	166	207	185	168	166	167	159	171

Table 7. JPM output for the considered tide gauge stations.

The final water levels considered for the hazard assessment were defined combining the output provided by the JPM (i.e. astronomical tide, meteorological tide and mean sea-level, Table 7)) and high and low Sea Level Rise (SLR) scenarios (i.e. 17 and 42 cm) according to the following equation:

$$SSH = (AT + MT + MSL) + SLR$$

Where

$SSH = Storm\ Surge\ Height$

$AT = Astronomical\ Tide$

$MT = Meteological\ tide$

$MSL = Mean\ Sea - Level$

$SLR = Sea - Level\ Rise$

The baseline scenario (i.e. without SLR) and the 2 scenario of SLR (i.e. 17 an 42 cm) are reported in Table 8.

	NO SLR	Floods with a high probability		Floods with a medium probability		Floods with a low probability
	Return period (years)	**20**	**50**	**100**	**200**	**500**
Adriatic Sea	**Ancona**	89	92	93	94	96
	Ravenna	124	129	132	134	138
	Piattaforma	150	156	159	162	166
	Trieste	155	173	185	196	207
Venice Lagoon	**Chioggia**	165	172	177	181	185
	Lido	154	159	163	165	168
	Punta della Salute	153	157	161	163	166
	Burano	147	154	159	163	167
	Grassabò	145	150	153	156	159
Marano and Grado Lagoon	**Grado**	155	161	164	167	171

	SLR 17	Floods with a high probability		Floods with a medium probability		Floods with a low probability
	Tempo di ritorno (anni)	**20**	**50**	**100**	**200**	**500**
Adriatic Sea	**Ancona**	106	109	110	111	113
	Ravenna	141	146	149	151	155
	Piattaforma	167	173	176	179	183
	Trieste	172	190	202	213	224
Venice Lagoon	**Chioggia**	182	189	194	198	202
	Lido	171	176	180	182	185
	Punta della Salute	170	174	178	180	183
	Burano	164	171	176	180	184
	Grassabò	162	167	170	173	176
Marano and Grado Lagoon	**Grado**	172	178	181	184	188

	SLR 42	Floods with a high probability		Floods with a medium probability		Floods with a low probability
	Tempo di ritorno (anni)	**20**	**50**	**100**	**200**	**500**
Adriatic Sea	**Ancona**	131	134	135	136	138
	Ravenna	166	171	174	176	180
	Piattaforma	192	198	201	204	208
	Trieste	197	215	227	238	249
Venice Lagoon	**Chioggia**	207	214	219	223	227
	Lido	196	201	205	207	210
	Punta della Salute	195	199	203	205	208
	Burano	189	196	201	205	209
	Grassabò	187	192	195	198	201
Marano and Grado Lagoon	**Grado**	197	203	206	209	213

Table 8. Storm surge extreme height levels (cm) for different return periods without SLR (top), with 17 cm of SLR (middle) and with 42 cm of SLR (bottom).

In order to evaluate the hazard along the shoreline, data of the considered tide gauge stations were interpolated using the Inverse Distance Weighted (IDW) method, assigning to each 10x10 m pixel of the coastline the estimated water level. This method was considered appropriate as the considered phenomenon (i.e. the water level) increase/decrease linearly if the 2 station are close to each other. Obtained values were successively used to calculate the extension of potentially inundated areas using a function of decrease of the water level with the increase of distance from the coastline.

The function calculating the decrease of water level is hyperbolic (Figure 21, blue line) and has been truncated in 2 part of the curve: all values higher than 1 are set equal to 1 and successively the water level is decreased k times until the distance s_1.

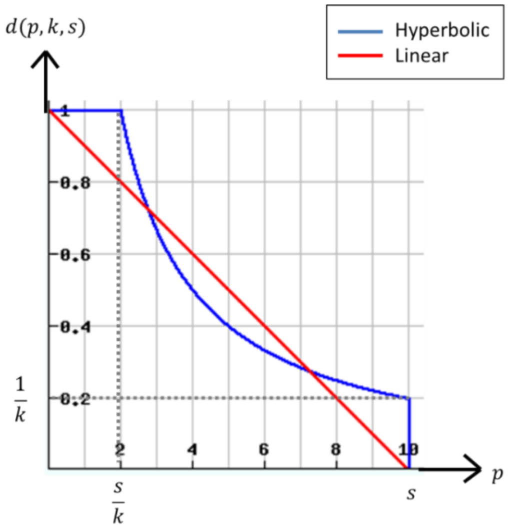


Figure 21. Function of decrease of the water height level. Blue: hyperbolic; Red: linear.

Data of Table 8 was used to calculate the hazard score for the considered region according to the following Equation.

$$H_{ssf,s} = \begin{cases} 0 & if\ pf_1 \geq b \\ min\left[max\left(\frac{\left(\left(h_{ssf,s}\left(1 - Af_1\right)\right) - pf_2\right) d_1}{s_1}, 0\right), 1\right] & otherwise \end{cases}$$

Where:

$H_{ssf,s} = hazard\ score\ for\ the\ scenario\ s;$

$h_{ssf,s} = projection\ of\ the\ water\ height\ of\ a\ storm\ surge\ according\ to\ a\ scenario\ s;$

$af_1 = attunuation\ factor\ resulting\ from\ artificial\ protections;$

$pf_2 = elevation\ of\ the\ cell\ according\ to\ the\ Digital\ Elevation\ Model\ DEM;$

$d_1 = D_{\frac{hip}{lin}}(pf_1, l, b) = istance\ factor\ related\ to\ distance\ of\ water\ penetration$;

$l = number\ of\ times\ the\ height\ of\ the\ water\ is\ reduced\ before\ being\ truncated$;

$b = s_1 t = distance\ from\ the\ sea\ representing\ the\ maximum\ distance\ of\ water\ income$;

$t = constant\ defining\ at\ which\ distnace\ the\ water\ penetration\ is\ truncated$;

$s_1 = amount\ of\ water\ above\ a\ cell\ which\ generates\ the\ maximum\ impact$;

$pf_3 = distance\ of\ the\ center\ of\ the\ cell\ from\ the\ sea\ (always\ \geq\ 1)$.

The values of $H_{SS,s}$ range from the 0 (i.e. no flooding) to 1 (estimated water level higher or equal than the constant value s_1.

Detailed data of the height of artificial protections was missing for the North Adriatic coastal zones; accordingly, adopting a precautionary approach, their effect was not considered within the considered region.

6.1.1. Exposure assessment

The exposure assessment is aimed at identifying and selecting receptors (i.e. elements at risk) that can be subject to potential losses due to storm surge floodings. According to several definitions, exposure represents the presence of people, livelihoods, environmental services and resources, infrastructures, or economic, social, or cultural assets in places that could be adversely affected (UNISDR, 2009a; IPCC, 2012). Exposure to storm surge flooding includes receptors listed and described in Table 9. Receptors were identified based on the indications coming from the Flood Directive, indicating people, economic activities, cultural heritages, natural and semi-natural systems as target to be considered during the assessment. For the North Adriatic case study some receptors were divided in order to have a higher level of detail in the analysis. Specifically, economic activities were divided into infrastructures, buildings, and agricultural areas and from natural and semi-natural systems, beaches and wetlands were extracted and considered as autonomous receptors.

The output of this step is represented by an exposure map of each considered receptor where 0 indicate absence of exposure and 1 indicate exposure to the considered impact for five impacts, i.e. infrastructures, beaches, wetlands, natural and semi-natural environments and agricultural areas. The data used to identify this receptors is represented by the land use maps (Table 3).

For population and buildings, exposure is represented by the number of inhabitants and constructions respectively. These receptors were localized on the case study are using land use maps (Table 3) and the numbers quantifying the exposure are retrieved from the census data of the year 2001.

	Description
Population	This receptor can be defined as the number of people living in the residential areas, which are the major hotspot where people live (Gallina et al., 2012)
Buildings and Infrastructures	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).
Agriculture	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).
Natural and seminatural environments	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).
Wetlands	The wetland receptor includes coastal wetlands along with vegetation, animal life and artificial and natural protections located in wetlands areas. Wetlands are 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 et al., 2009). For the purposes of this assessment the following categories were considered: inland wetlands, salt marshes and intertidal wetlands.
Beaches	This receptor analyzes beaches and the vegetation associated to them. Furthermore it analyzes natural and artificial protections to limitate impacts. 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 diameter (Pettijohn, 1975). 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).
Cultural heritage	This receptor can be defined as the architectural heritage, historic buildings and sites as well as objects of art standing alone or firmly attached as an integral part of buildings (Gallina et al., 2012).

Table 9. Description of the exposed receptors.

The output of this step is represented by an exposure map where 0 indicate absence of exposure and 1 indicate exposure to the considered impact, that will be presented and discussed in Section 7.1.

6.1.2. Biophysical and Environmental Vulnerability assessment

Vulnerability represents the propensity or predisposition of a community, system, or asset to be adversely affected by a certain hazard (UNISDR, 2009; IPCC, 2012). The biophysical and environmental vulnerability assessment is used within the RRA to evaluate the degree to which coastal receptors could be affected by storm surge floods, based on a subset of vulnerability factors defined according to available site-specific physical/environmental information. The biophysical and environmental vulnerability is then carried out by classifying and normalizing the selected vulnerability factors and applying a Multi-Criteria Decision Analysis function, the *probabilistic or* function, to obtain an overall vulnerability score. This activity was performed by a group of experts in environmental risk assessment who defined classes and scores for each vulnerability factor. Normalized factors' scores range from 0 to 1, according to the degree of vulnerability associated to each factors' class: 0 represents no vulnerability and 1 represents the higher vulnerability class for the considered factor. The following equation shows how vulnerability is calculated.

$V_{ssf} = \otimes_1^n [vf'_{i,k}]$

Where:

$V_{ssf} = Biophysical\ and\ Environmental\ Vulnerability\ score\ for\ the\ receptor\ k$;

$\otimes_1^n = Probabilitic\ or\ operator\ applied\ to\ all\ the\ considered\ vulnerability\ factors$;

$v'_{i,k} = Normalized\ Vulnerability\ factors\ for\ the\ receptor\ k.$

The vulnerability factors and scores selected for the receptors population, agriculture, natural and seminatural environments, wetlands and beaches are listed in Table 10 and Table 11. For the other analysed receptors (i.e. infrastructures, cultural heritage and buildings) no vulnerability factors were identified and the vulnerability score was considered as the maximum (i.e. 1). This is due to the fact that infrastructures can not be used during floods causing an interruption of services. Moreover, as far as cultural heritage are concerned, they are considered to be particularly vulnerable to floods as they can be easily damaged by a flood event.

Population	Agriculture	Natural and seminatural environments	Wetlands	Beaches
- % people 0-14 years and 65 years	- Agricultural tipology	- Vegetation cover	- Vegetation cover	- Vegetation cover
	- Slope	- Slope	- Slope	- Slope
	- Soil type	- Soil type	- Wetland extension	- Geomorphology
			- Wetland typology	

Table 10. Vulnerability factors selected for the storm surge flooding impact applied to the North Adriatic coastal water bodies and related scores.

For each vulnerability factors, scores were then identified based on literature information and on expert judgement. All classes and scores defined for the North Adriatic case are listed in Table 11.

Factor	Source	Legend	Score
% people 0-14 and >65	ISTAT, 2001	0% - 20%	0.2
		20% - 40%	0.4
		40% - 60%	0.6
		60% - 80%	0.8
		80% - 100%	1
Agricultural tipology	Corine Land Cover, EEA, 2009	Permanent crops	0.2
		Stable meadow-Pastures	0.6
		Arable land	1
Slope (degrees)	Veneto region, 2009; Friuli Venezia Giulia region, 2009	Plains: 0°- 6°	1
		Gentle to moderate slope terrain: 6°- 20°	0.6
		Steep slope terrain: 20°- 37.7°	0.2
Soil type	Veneto region, 2009; Friuli Venezia Giulia region, 2006	Low permeability	1
		Moderate permeability	0.5
		High permeability	0.2
Vegetation cover	Corine Land Cover, EEA, 2009	Natural grassland and meadow	1
		Vegetation with shrubbery	0.6
		Forest	0.2
Wetland extension (Km^2)	Corine Land Cover, EEA, 2009	0 - 5.96	1
		5.97 - 11.93	0.8
		11.94 - 17.89	0.6
		17.90 - 23.86	0.4
		23.87 - 29.83	0.2
Geomorphology	Veneto region, 2009; Friuli Venezia Giulia region, 2006	Muddy coast	1
		Sandy coast	0.5
		Rocky coast	0.2
Wetland typology	Corine Land Cover, EEA, 2009	Inland welands (marshes, peatbogs)	1
		Coastal wetlands (salt masrhes, salines, intertidal flats)	0.5

Table 11. Vulnerability factors selected for the storm surge flooding impact applied to the North Adriatic coastal receptors and related scores.

People older than 65 years old and between 0 and 14 years old are considered more vulnerable to possible impacts of climate change and natural hazards (Ford et al. 2006; Granger, 2003; McCann, 2011). Accordingly, the higher is the percentage of people in these classes, the higher is the susceptibility. Also an higher density of population is considered a factor increasing vulnerability (Granger, 2003), thus the higher is this value, the higher is the vulnerability of the receptor population. Based on the **agricultural typology**, agricultural areas can have different vulnerability score: arable land have lower protective cover than other identified classes (French, 2001); accordingly they are characterized by higher vulnerability scores. The **slope** defines the energy of the impact of the water on the land and can how easily a storm surge flooding can move inland from the coastline, accordingly, the lower is the slope, the higher is the vulnerability (Sharples, 2006). The permeability, defined based on the **soil type** or of the urbanised areas, can contribute to reduce the duration of a flooding derived form a storm surge event as permeable soil can drain water. Urbanised areas and areas with low permeable soil fill remain flooded for a longer time, thus will be characterised by a higher vulnerability. The **vegetation cover** indicates whether natural and semi-natural environments can support a temporary flood generated by storm surges: forest will be less affected by a temporary flood and will be characterised by the lower vulnerability, while other typologies will have and increased score, with grassland and meadows being the more vulnerable (Preston, 2008; McLaughlin and Cooper, 2010; Torresan, 2008). **Wetlands** can be affected more severely by storm surge flooding if their **extension** is smaller because will have a lower recovery potential. Accordingly, the larger is wetlands extension, the lower is the vulnerability score and vice versa (Torresan et al., 2008; Torresan et al., 2012). Moreover costal and different **wetlands typologies** are affected by floods in different way: coastal wetlands, which are already in contact with marine water, are less vulnerable to floods while inland wetlands, which are in contact with freshwater, can be affected more severely and, as a consequence, are considered more vulnerable. Finally, the **geomorphology** of beaches can be classified as sandy or rocky, with sandy beaches characterised by a higher vulnerability to the considered impact (Sharples, 2006).

After the classification and normalization of vulnerability factors in the 0-1 range, the final vulnerability score is calculated by aggregating vulnerability factors using a MCDA function.

The final vulnerability score can range from 0 (no vulnerability) to 1 (maximum vulnerability for the considered region).

The output is a vulnerability map of each considered receptor of the North Adriatic coastal area allowing the identification and prioritization of areas more vulnerable to storm surge floods based on 5 qualitative classes from Very low to Very High vulnerability (i.e. 0-0.2; 0.2-0.4; 0.4-0.6; 0.6-0.8; 0.8-1). Vulnerability maps can support decision makers in the definition of measures aimed at boosting the resilience of receptors in the considered region (e.g. change cultures in agricultural areas).

6.1.3. Risk Assessment

The Risk assessment phase, according to the UN-ISDR (2009b), is aimed at integrating SSF hazard scenarios, exposure and vulnerability scores of the different considered receptors to allow the identification and the prioritization of coastal receptors and areas at risk in the considered region. The definition of the risk score is based on the following equation:

$$R_{ssf,s,k} = H_{ssf,s} \cdot E_{SS,k} \cdot V_{SS,k}$$

Where:

$R_{ssf,s,k} = risk\ score\ related\ to\ the\ scenario\ s\ and\ the\ receptor\ k$;

$H_{ssf,s} = hazard\ score\ for\ the\ scenario\ s$;

$E_{SS,k} = exposure\ score\ for\ the\ SS\ impact\ for\ the\ receptr\ k$;

$V_{ssf,k} = \ vulnerability\ score\ for\ the\ receptor\ k.$

Risk scores range between 0 and 1: 0 means no risk (i.e. there is no exposure or no vulnerability) and 1 means maximum risk for the considered scenario and target/area in the considered region.

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.

The output of this step is represented by relative risk maps showing the distribution of the relative risk scores for each considered scenario and receptor useful to support decision makers in the definition of adaptation measures (e.g. coastal zoning and land use planning, construction of sea defence structures). Moreover, specific statistics can be calculated in order to have a summarized overview of the results and easily compare the different receptors and scenarios (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).

6.2. Results

In the following paragraphs, results obtained through the application of the RRA methodology (i.e. hazard, exposure, vulnerability and risk maps and statistics) will be presented and discussed.

6.2.1. Hazard maps

Hazard maps show how the considered region can be affected by floods in the 15 different considered scenarios. As described in paragraph 6.1, these scenarios are the result of the combination of storm surge levels related to five different return periods (i.e. 20, 50, 100, 200 and 500 years) with three SLR scenarios, i.e. without SLR (Figure 22) with the low SLR scenario (i.e. 17 cm, Figure 23**Errore. L'origine riferimento non è stata trovata.**) and with the high SLR scenario (i.e. 42 cm, Figure 24**Errore. L'origine riferimento non è stata trovata.**). Each figure allows the hazard comparison between the different return periods. Specifically each map indicate the intensity of inundation above each considered are, depending on the level of water along the coastline, on the distance from the coastline and on the difference between the estimated water level in each area and the Digital Elevation Model (DEM). It clearly emerge that flooded areas do not significantly change for extreme events related to different return periods (i.e. 20, 50, 100, 200 and 500 years) in all the three SLR scenarios. Moreover, from the analysis of the statistics calculated for the hazard maps (Figure 25) it is possible to see that the hazard increase as the return period and SLR increase. As a consequence it is possible to clearly identify two extreme scenarios representing the better and worse future conditions: the best scenario is represented by events with a return period of 20 years with no SLR, while the worst scenario is represented by events with a return period of 500 years and 42 cm of SLR.

Figure 8, 9 and 19 indicate (with gray lines) areas where are located existing artificial protections which could potentially reduce the hazard derived from extreme storm surges. Even if it was possible to localize the presence of existing artificial protections in the case study area, their height was not known, and therefore it was not possible to evaluate their level of protection against the hazard.

Moreover, produced maps consider only storm surge flooding coming from the sea, and do not include the contribution from a potential flood coming from rivers. Accordingly, inundated areas close to rivers can be exposed to higher hazard if a river flood occur at the same time.

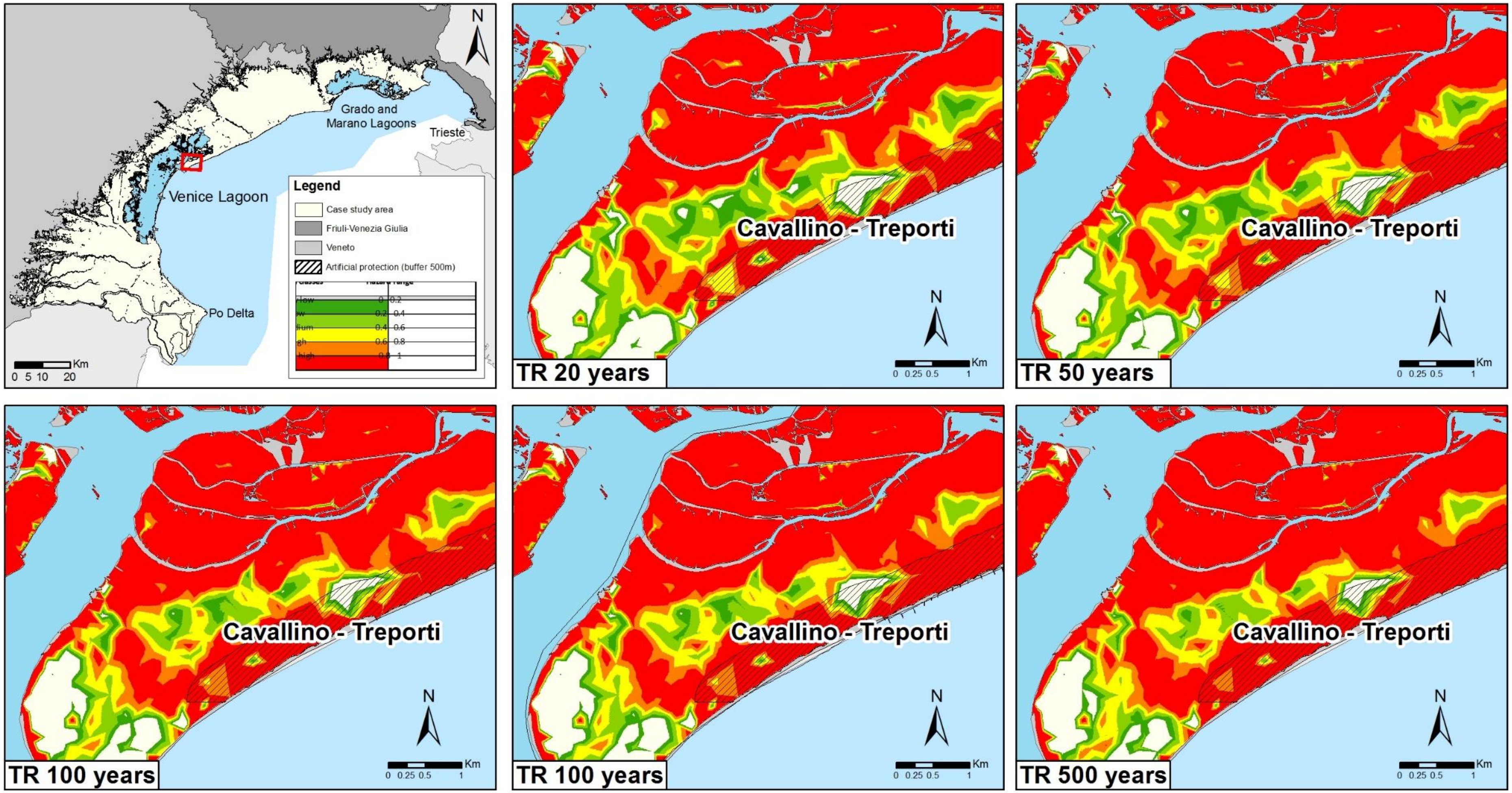


Figure 22. Hazard maps for the different return periods without considering SLR.

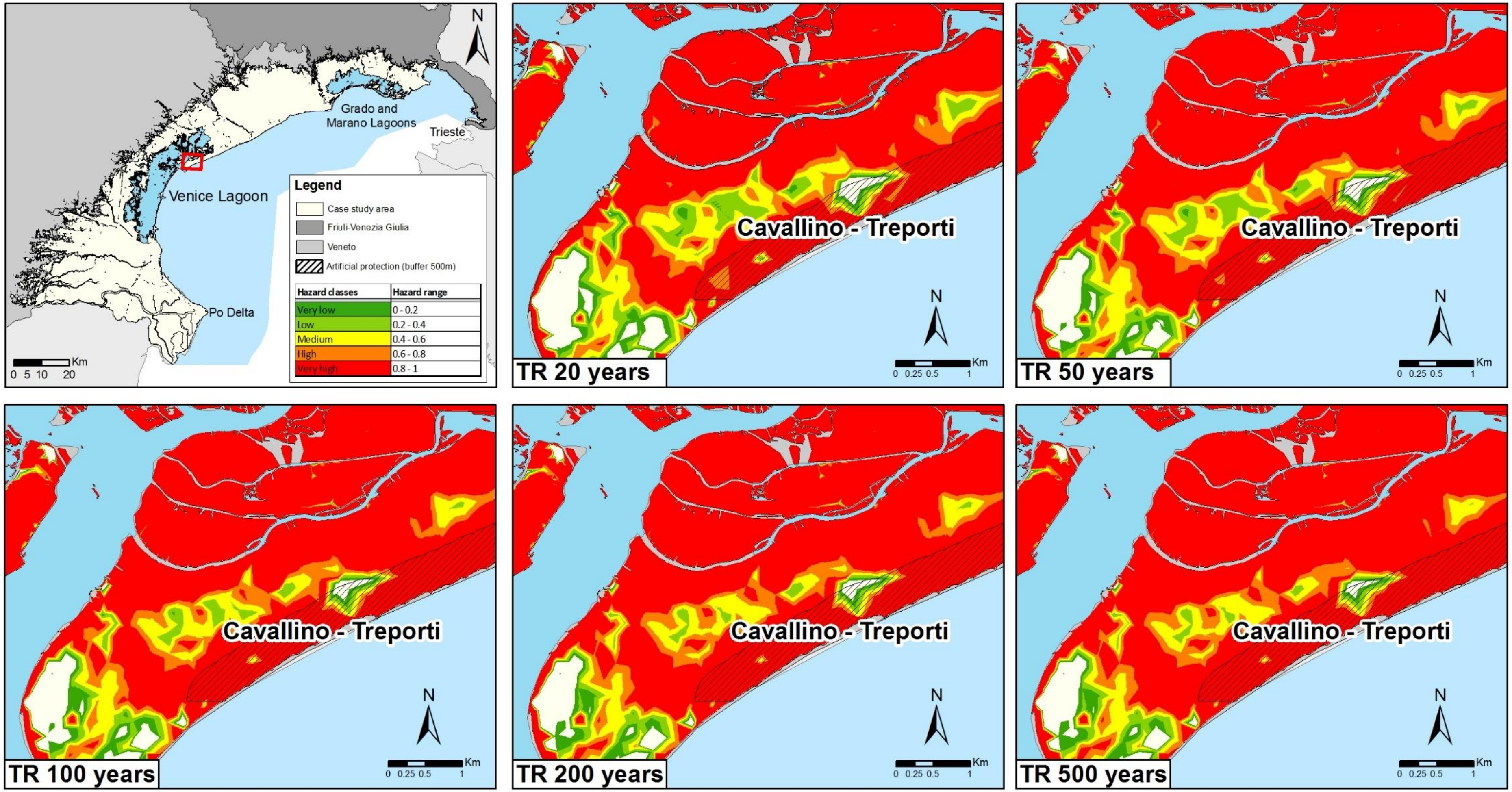


Figure 23. Hazard maps for the different return periods considering the low SLR scenario (i.e., 17 cm).

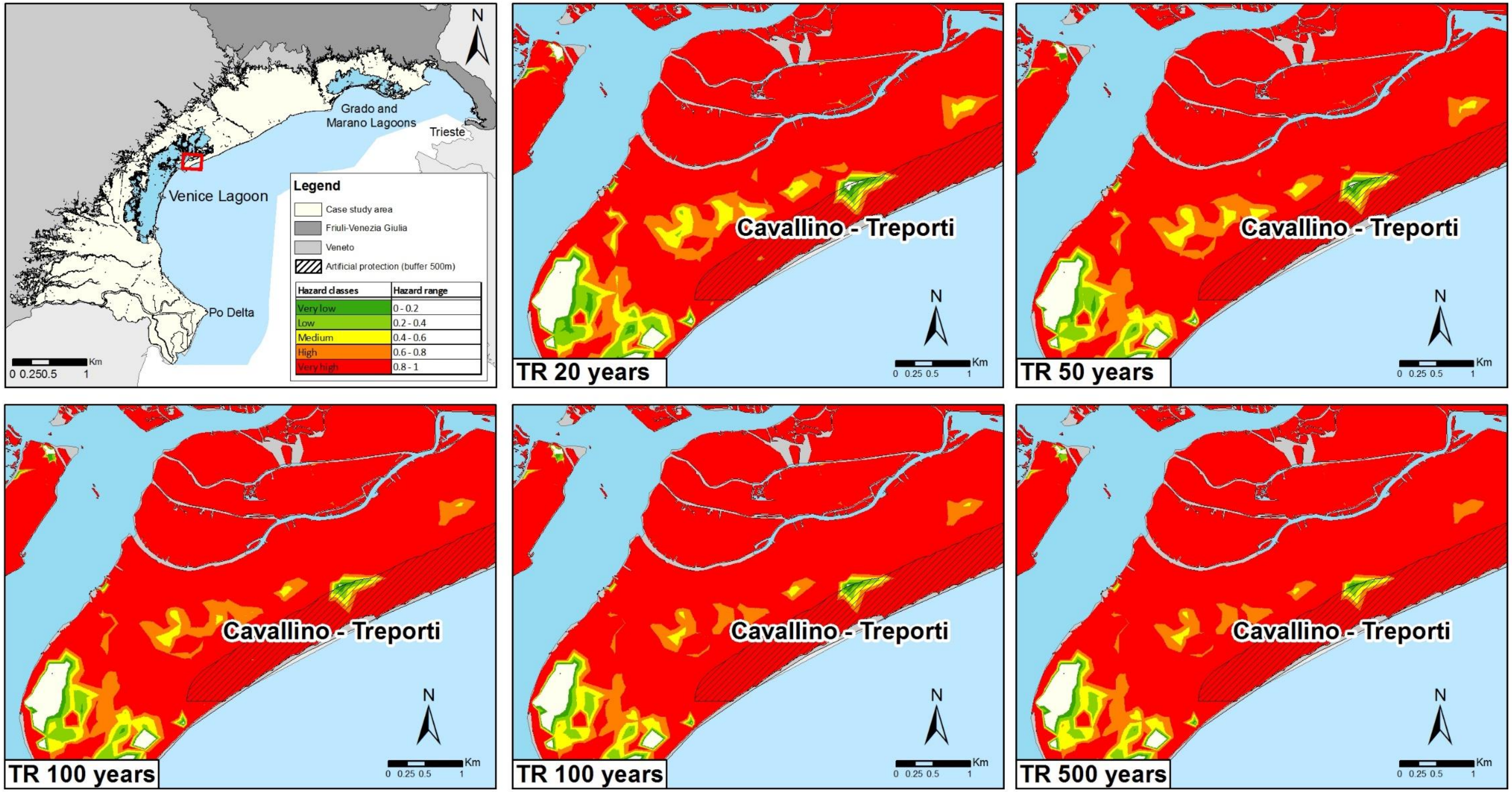


Figure 24. Hazard maps for the different return periods considering the high SLR scenario (i.e., 42 cm).

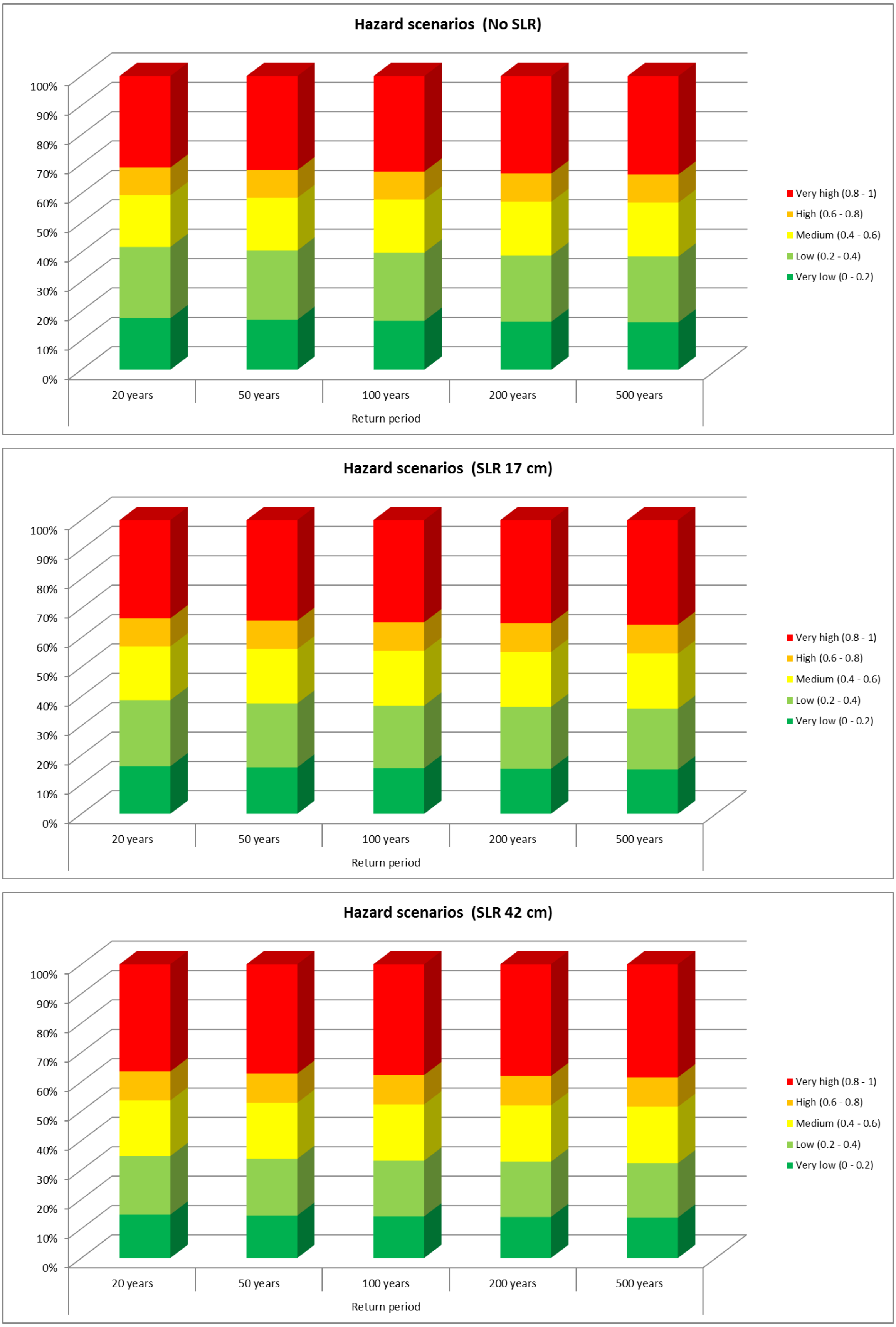


Figure 25. Statistic representing the percentage of the case study area in different hazard classes according to different slr scenarios.

6.2.1. Exposure maps

Based on the selected receptors (Table 9), exposure maps were produced for the different considered targets. Figure 26 show infrastructures, for the whole case study area, representing the different typologies of infrastructures (e.g. highways, railways) with different symbols.

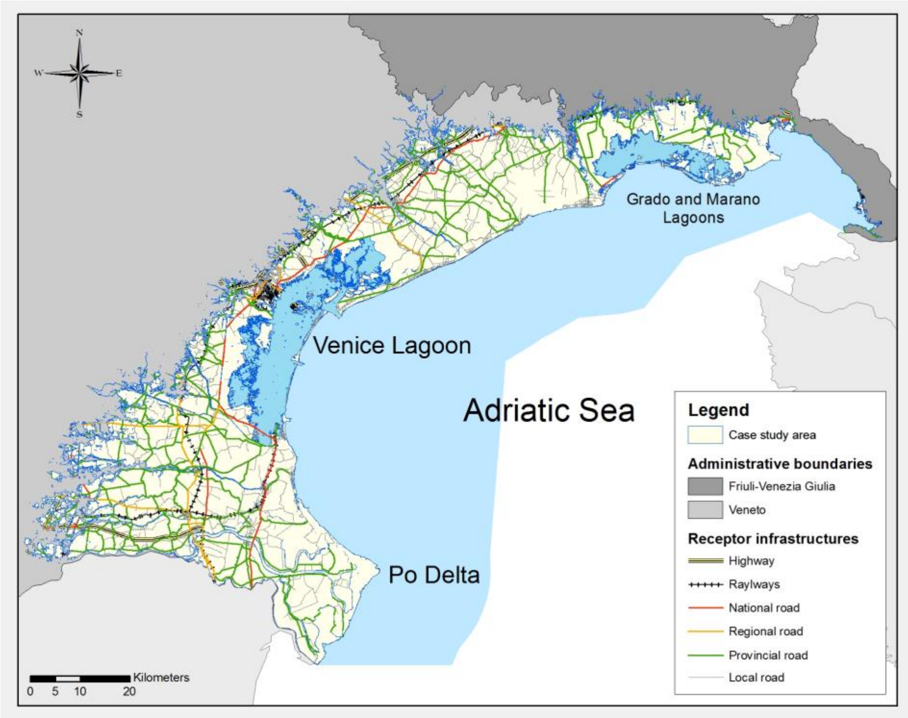
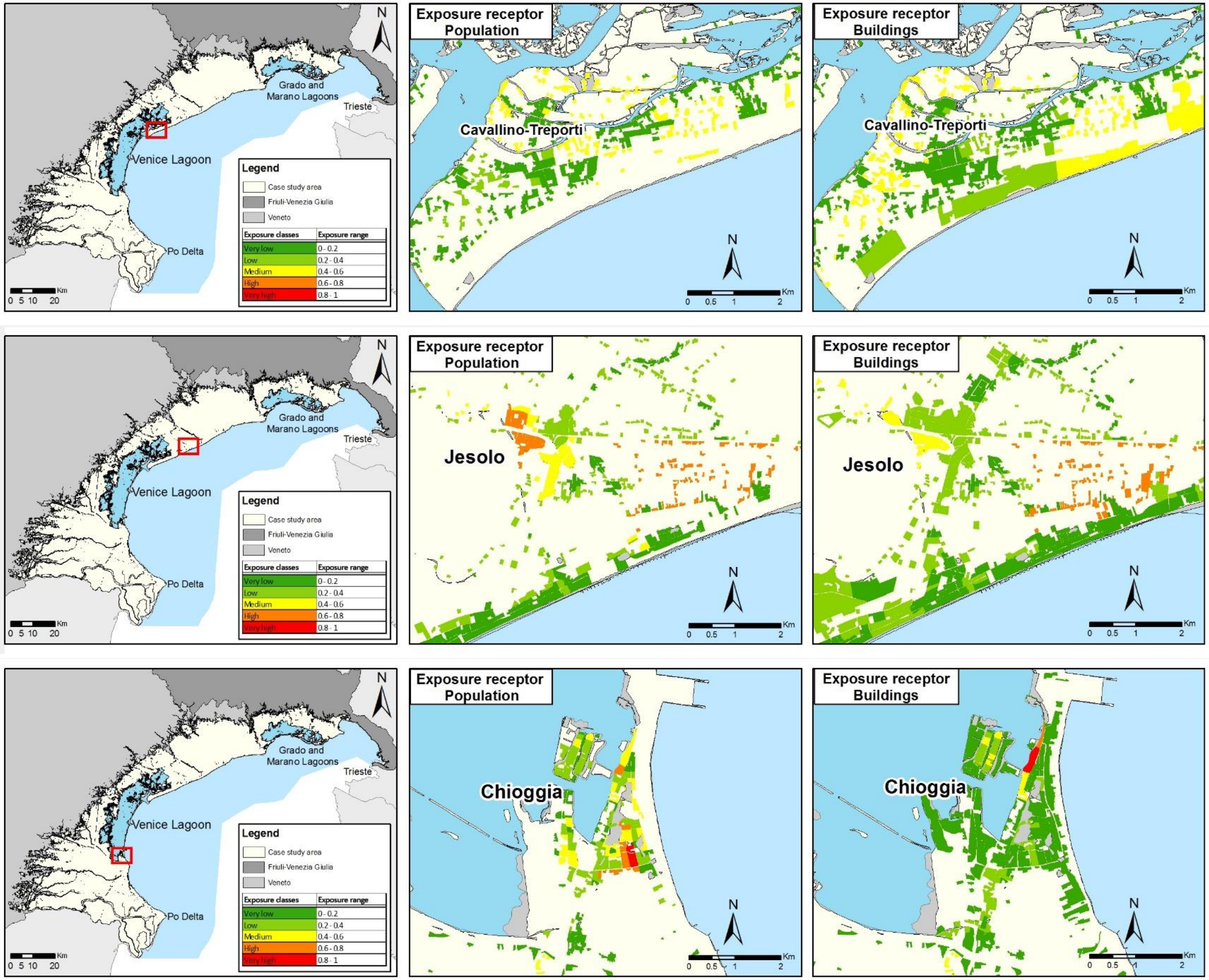


Figure 26. Exposure map of infrastructures.

The other anthropic receptors, i.e. population and buildings, are shown in Figure 27. The localization of population and buildings is based on the land use maps (Table 3) and corresponds to the residential and built-up areas respectively. Exposure map of population is, therefore, a subset of the exposure map of buildings. Moreover, the exposure is represented by the normalised number of inhabitants and buildings in each census zone, and data were retrieve from the population census of 2001 (Figure 27).


Grado and
Marano Lagoons
Trieste
Venice Lagoon
Po Delta
Legend
Case study area
Friuli-Venezia Giulia
Veneto
Exposure classes
Exposure range
Very low
0 - 0.2
Low
0.2 - 0.4
Medium
0.4 - 0.6
High
0.6 - 0.8
Very high
0.8 - 1
0 5 10 20 Km
Exposure receptor
Population
Exposure receptor
Buildings
Cavallino-Treporti
Jesolo
Chioggia
N
0 0.5 1 2 Km

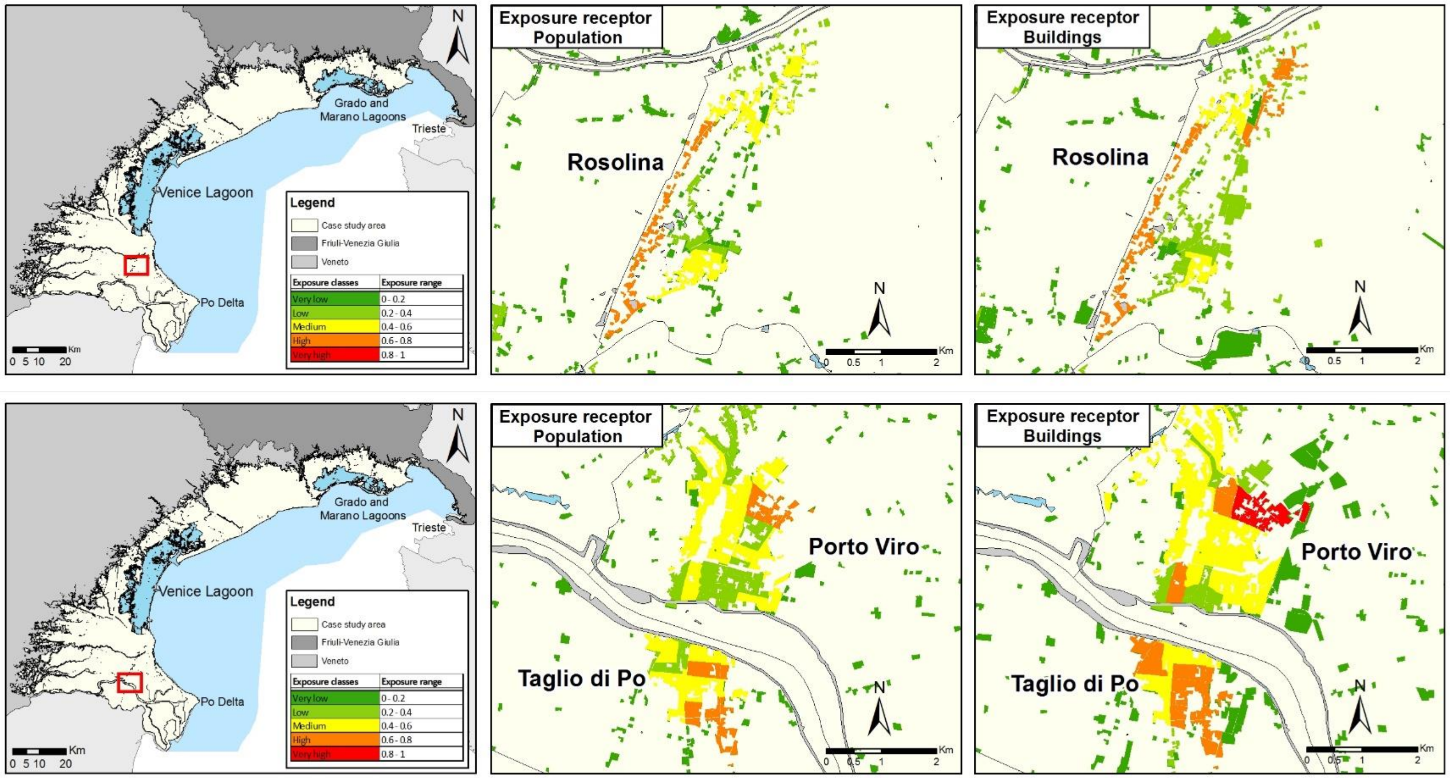


Figure 27. Exposure map of population and buildings.

Figure 28 and Figure 29 show the environmental receptors (i.e. beaches, wetlands, natural and semi-natural environments and agricultural areas) for the whole case study area and for some specific areas.

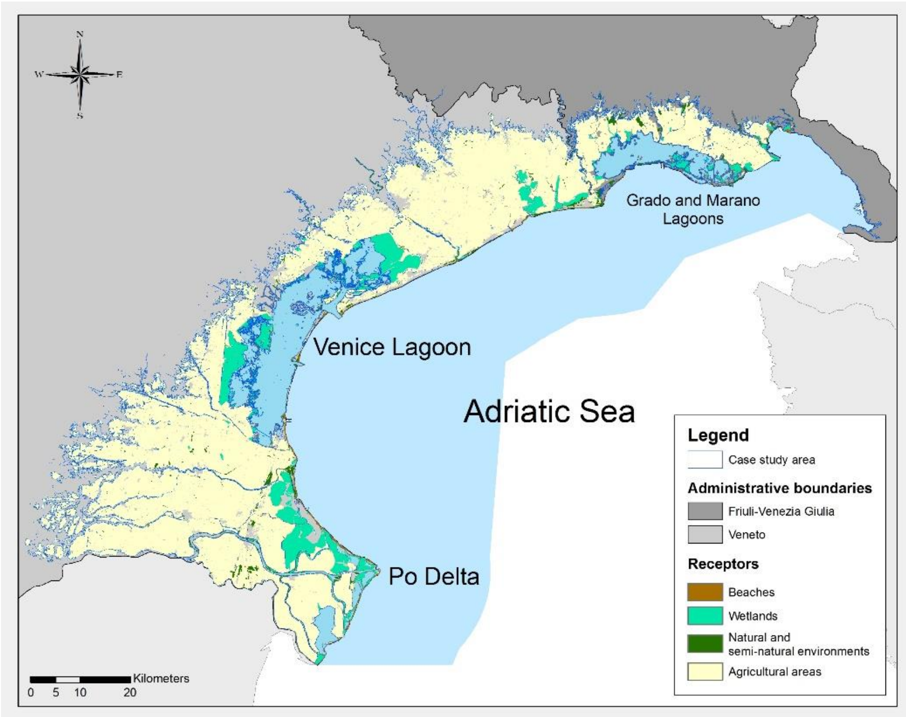


Figure 28. Exposure map of the considered environmental receptors.

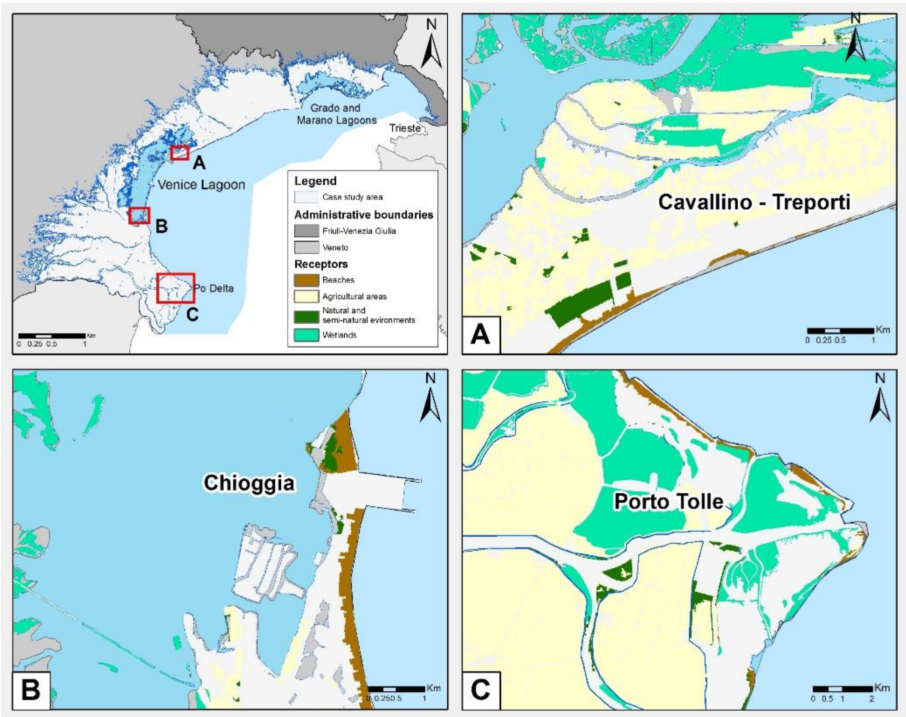


Figure 29. Exposure map of the considered environmental receptors with a focus on the municipalities of Cavallino Treporti (A), Chioggia (B) and Porto Tolle (C).

Finally, Figure 30 shows the exposure related to cultural heritage. This map was produced only for the Veneto region because data were available only for this region. Different colours were used to identify the different typologies of cultural heritage in the region.

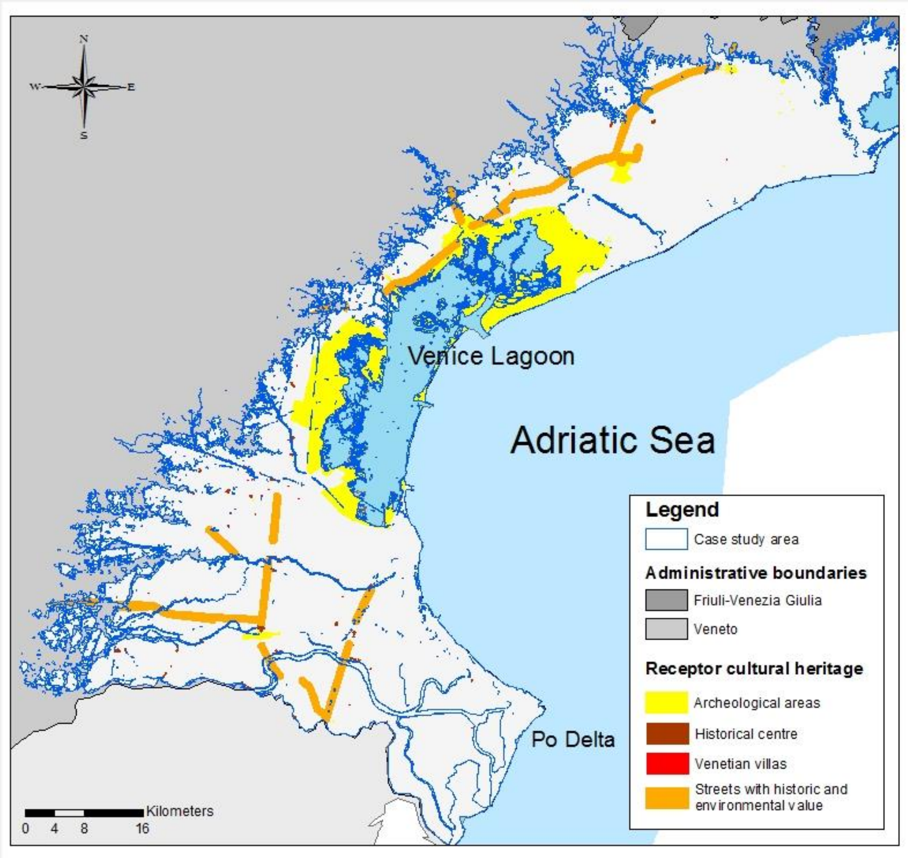


Figure 30. Exposure map of the cultural heritage receptor (only Veneto Region).

6.2.2. Biophysical and Environmental Vulnerability maps

Biophysical and environmental vulnerability maps were produced for five receptors (i.e. population, beaches, wetlands, natural and semi-natural environments and agricultural areas) integrating the factors and scores of Table 10 Table 11. Vulnerability maps were reclassified into 5 vulnerability classes with the equal interval method, from 0 to 1 (i.e. 0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1).

Results showed that the vulnerability is equal to 1 almost over all the considered receptors, except population. This is due the low slope of the case study area which corresponds to the higher class for that factor.

Figure 31 and Figure 32 show the vulnerability of Population over the considered region and for some specific municipalities. The vulnerability was calculated using census data for each census zone and is generally quite low over the entire considered region. Vulnerability is higher in census zones where there is a concentration of children and old people, such as the census zone where there are hospices.

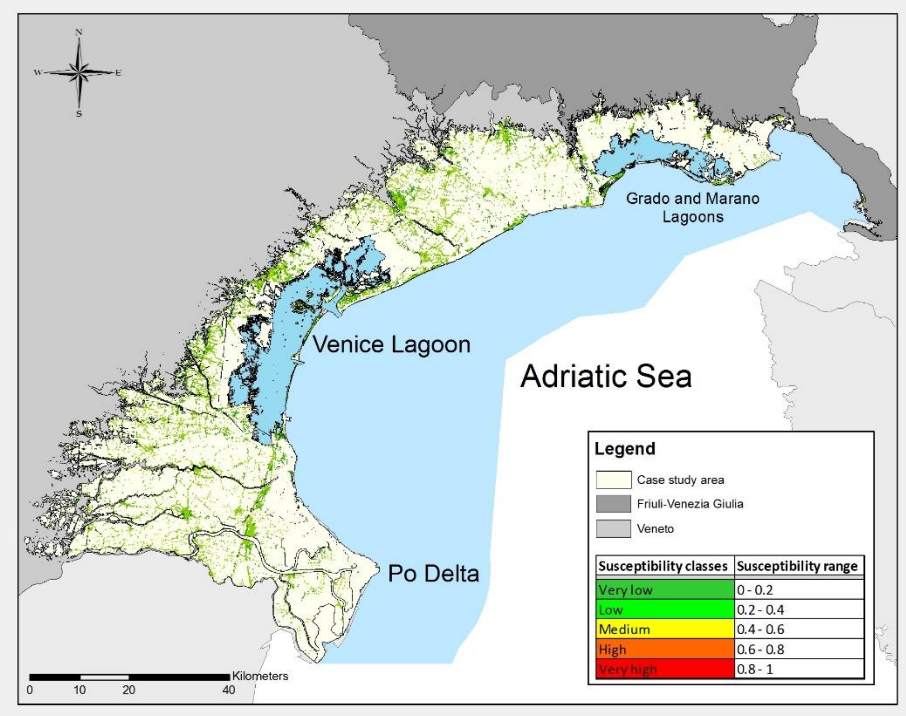


Figure 31. Vulnerability map of population.

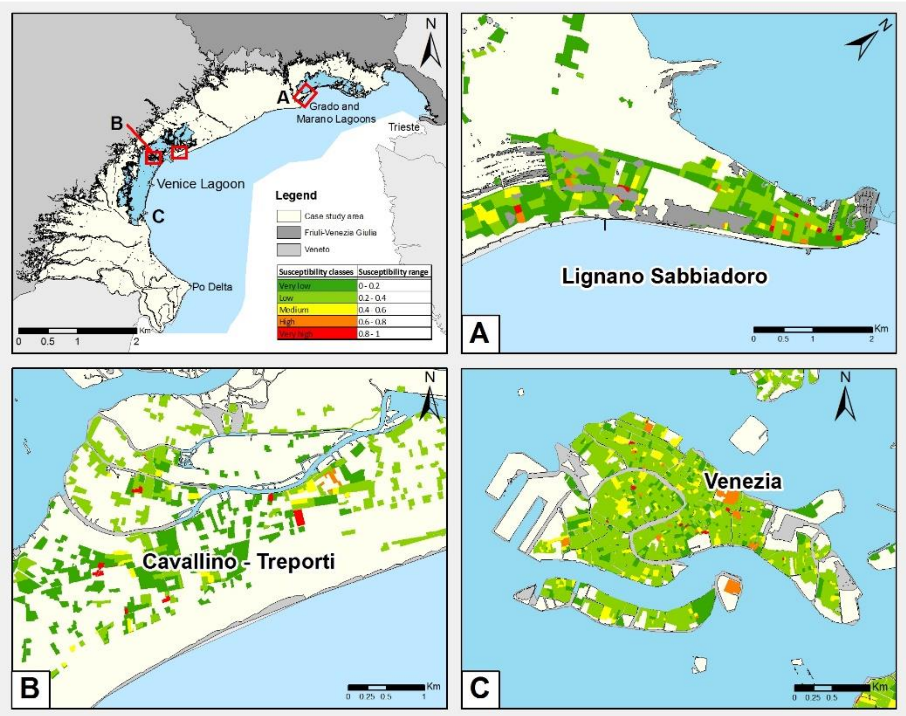


Figure 32. Vulnerability map of population for the municipalities of Lignano Sabbiadoro (A), Cavallino Treporti (B), Venice (C).

Figure 33 and Figure 34 show an example of vulnerability for the beach of Veneto and Friuli venezia Giulia. As anticipated, due to the high score of the slope factor. The vulnerability is 1 over all the considered beaches.

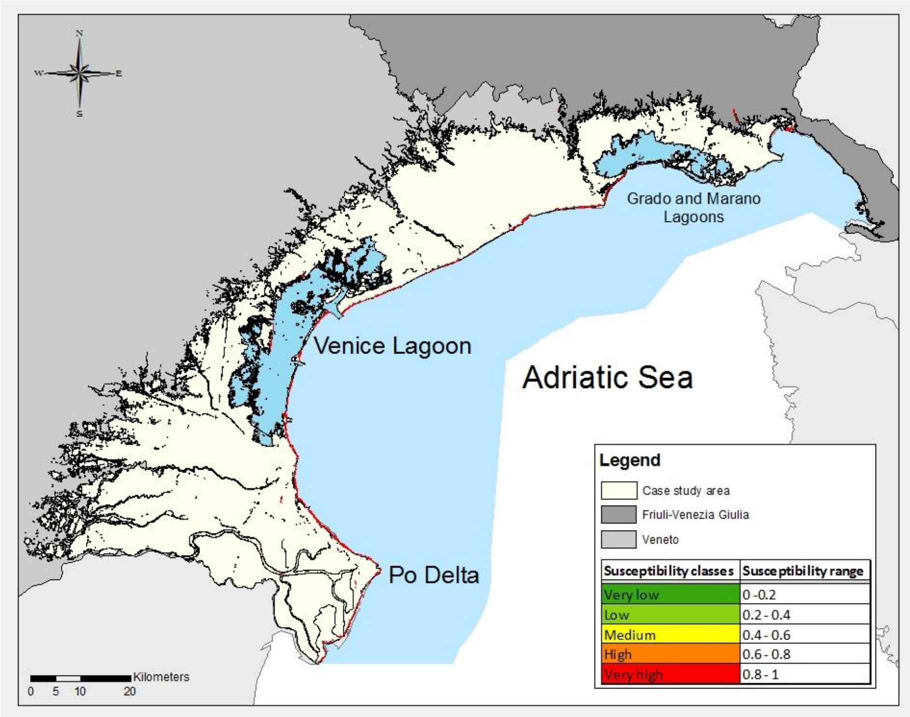


Figure 33. Vulnerability map of beaches.

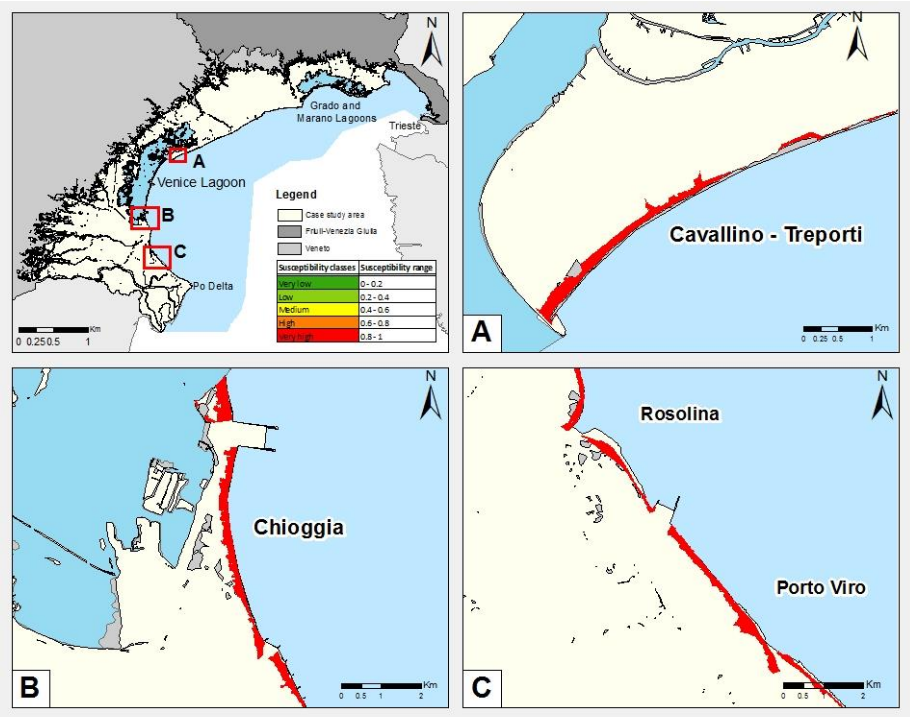


Figure 34. Vulnerability map of beaches in the municipalities of Cavallino-treporti (A), Chioggia (B), Porto Viro and Rosolina (C).

A similar result was obtained also for all the other environmental receptors. In order to evaluate the influence of the other vulnerability factors, bio-physical and environmental vulnerability was also calculated excluding the slope factor. Results are reported in the following figures. Figure 35 and Figure 36 show again the vulnerability of beaches. Without considering the slope, the geomorphology is the factor mainly contributing to the definition of the vulnerability. Wetlands show high vulnerability even without slope (Figure 37), suggesting that vegetation cover and wetlands extension and typology already characterize them with high scores. Natural and semi-natural environments (Figure 38 and Figure 39) have a different situation because the vegetation cover and mainly the soil type characterize some areas with a higher vulnerability and some with medium/low vulnerability. Finally, agricultural areas, mainly represented by arable lands, characterise the majority of the receptor's surface with the higher vulnerability even without slope (Figure 40).

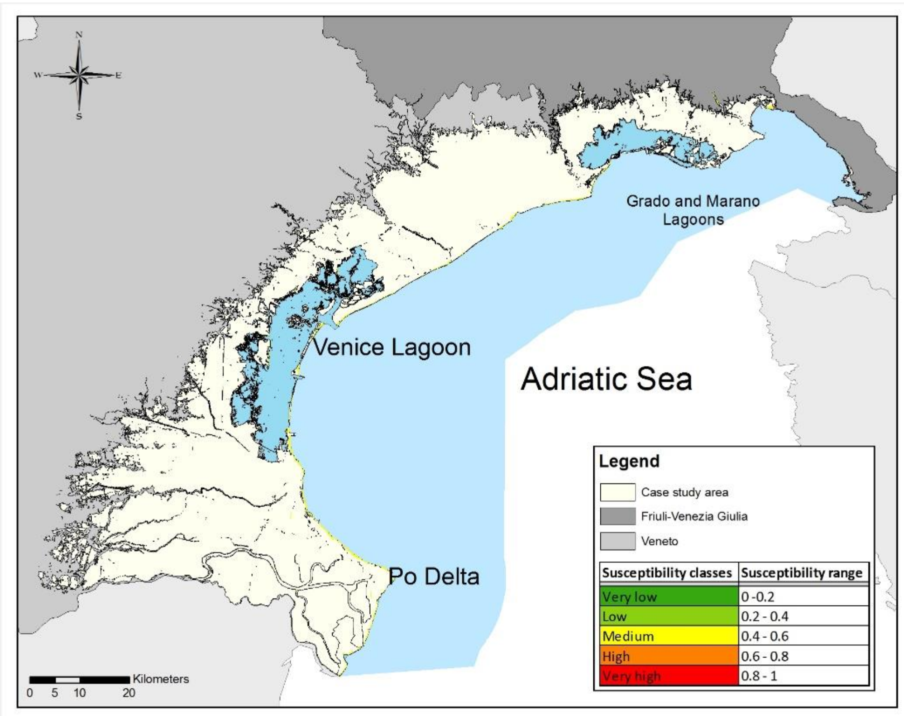


Figure 35. Vulnerability map without slope of beaches.

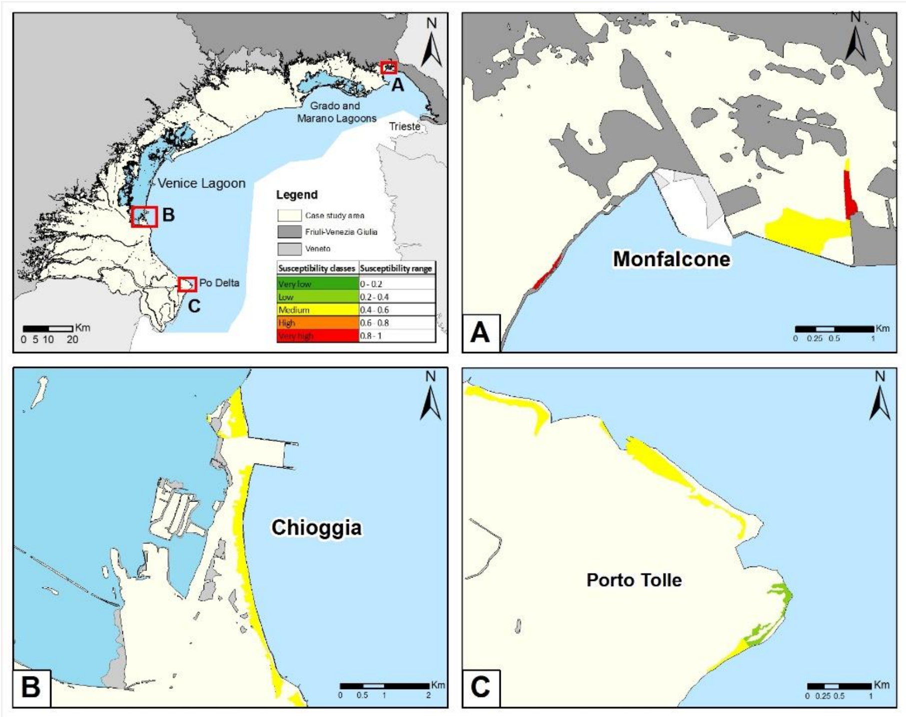


Figure 36. Vulnerability map without slope of beaches in the municipalities of Cavallino-treporti (A), Chioggia (B), Porto Viro and Rosolina (C).

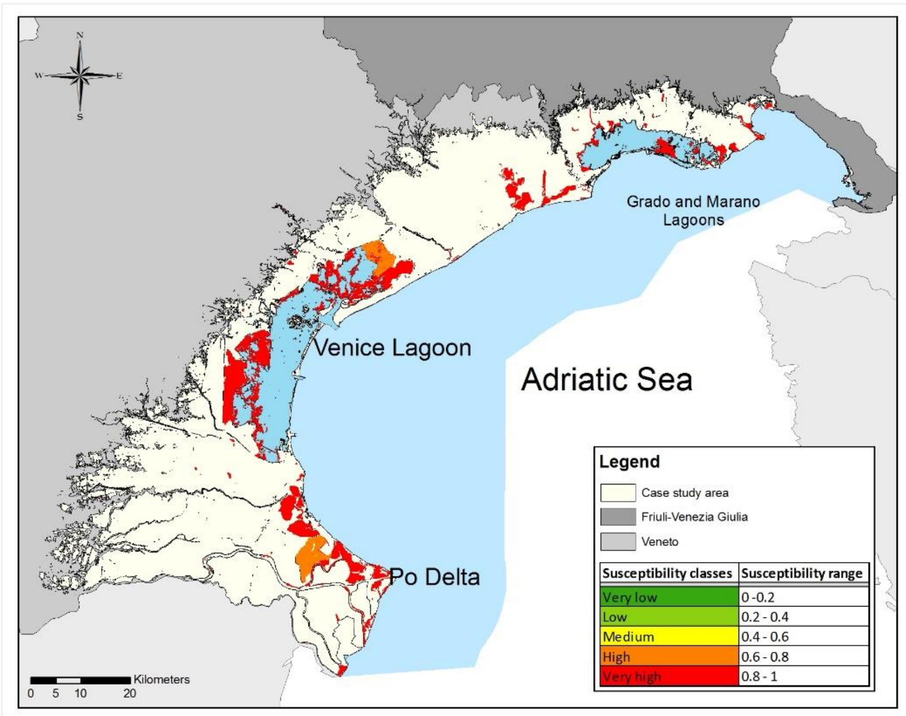


Figure 37. Vulnerability map without slope of wetlands.

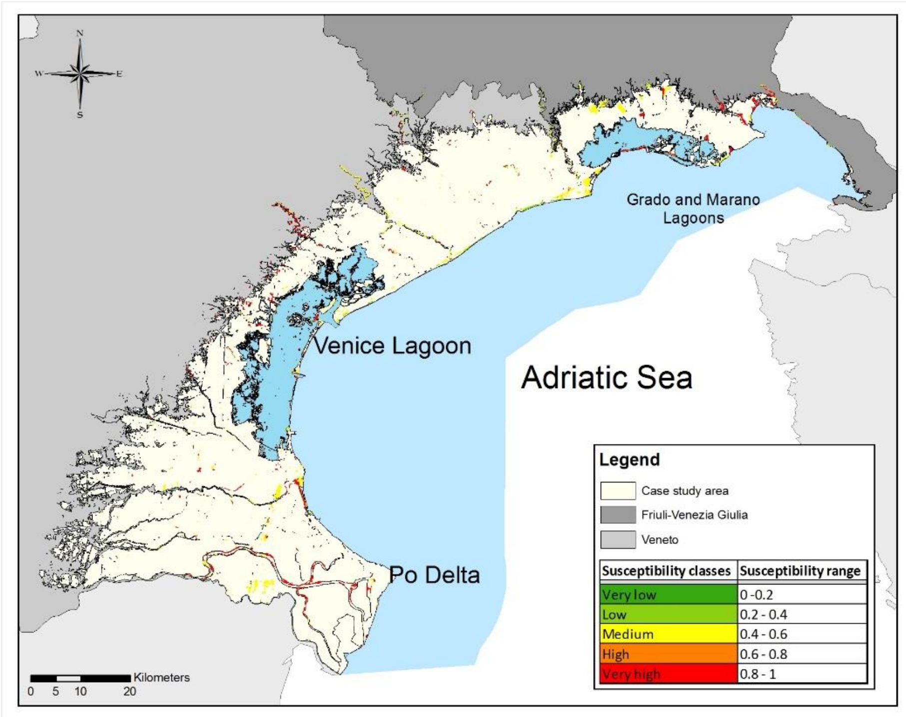


Figure 38. Vulnerability map without slope of natural and semi-natural environments.

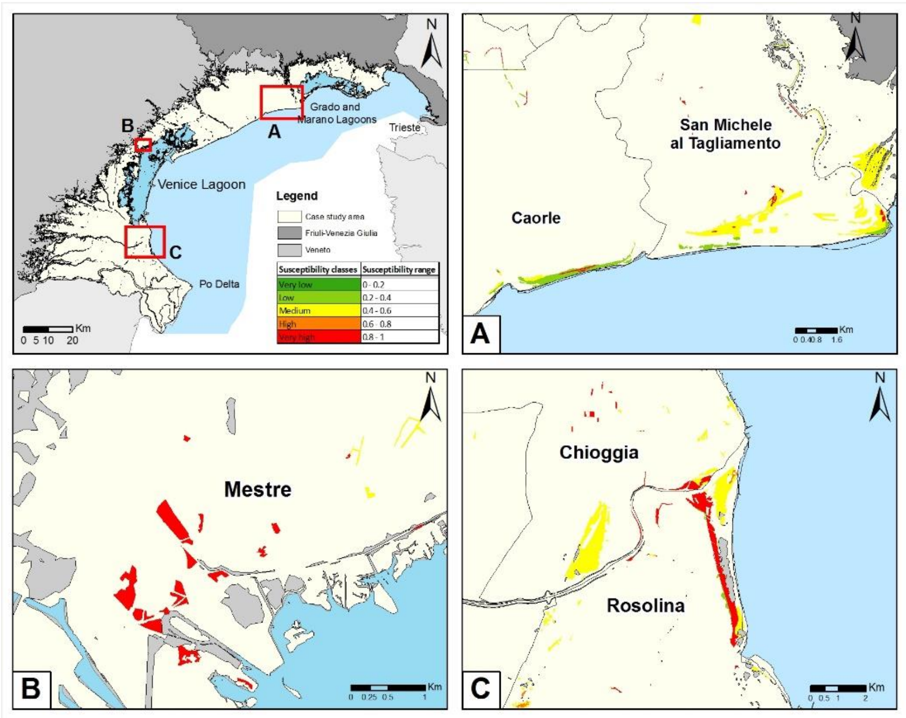


Figure 39. Vulnerability map without slope of natural and semi-natural environments in the municipalities of San Michele al Tagliamento and Lignano Sabbiadoro (A), Punta Sabbioni (B), Chioggia and Rosolina (C).

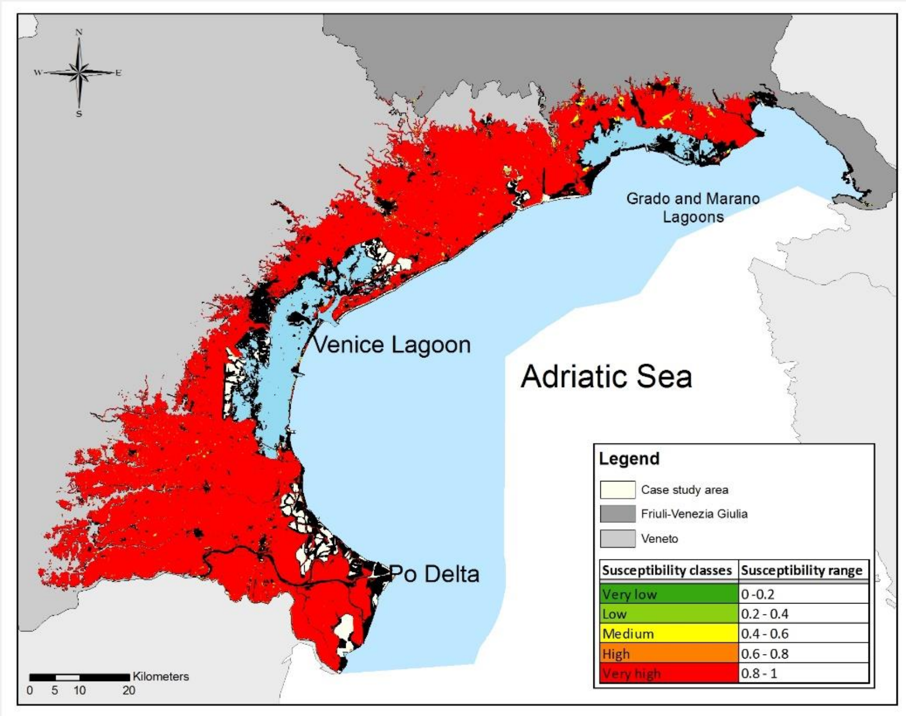


Figure 40. Vulnerability map without slope of agricultural areas.

6.2.3. Risk maps

Based on the hazard, on the exposure and on the vulnerability, risk maps were produced for each considered receptor and scenario. The following figures show the risk calculated for each receptor for best scenario (i.e. return period of 20 years without SLR) and the worst scenario (i.e. return period of 50 the two extreme scenarios: i) the lower return period (i.e. 20 years) with no SLR; ii) the highest return period (i.e. 500 years) with the highest value of SLR (i.e. 42 cm).

Risk maps of infrastructures (Figure 41) and the related statistic (Figure 42 and Figure 43) show that local roads will be the most impacted infrastructures in absolute terms (i.e. the length in km) and in percentage of roads in the highest risk class (40% in the worst scenario). As far as railways are concerned, around the 35 % will be classified in the higher risk class; moreover the total length in the worst scenario will be almost the double of the best scenario (i.e. 95 km and 55 km respectively). As far as highway are concerned, the decrease of percentage in the higher risk class is due to a very high increment of highway at risk in the worst scenario compared to the best scenario; highway at risk only in the worst scenario are almost all classified within the lowest risk class.

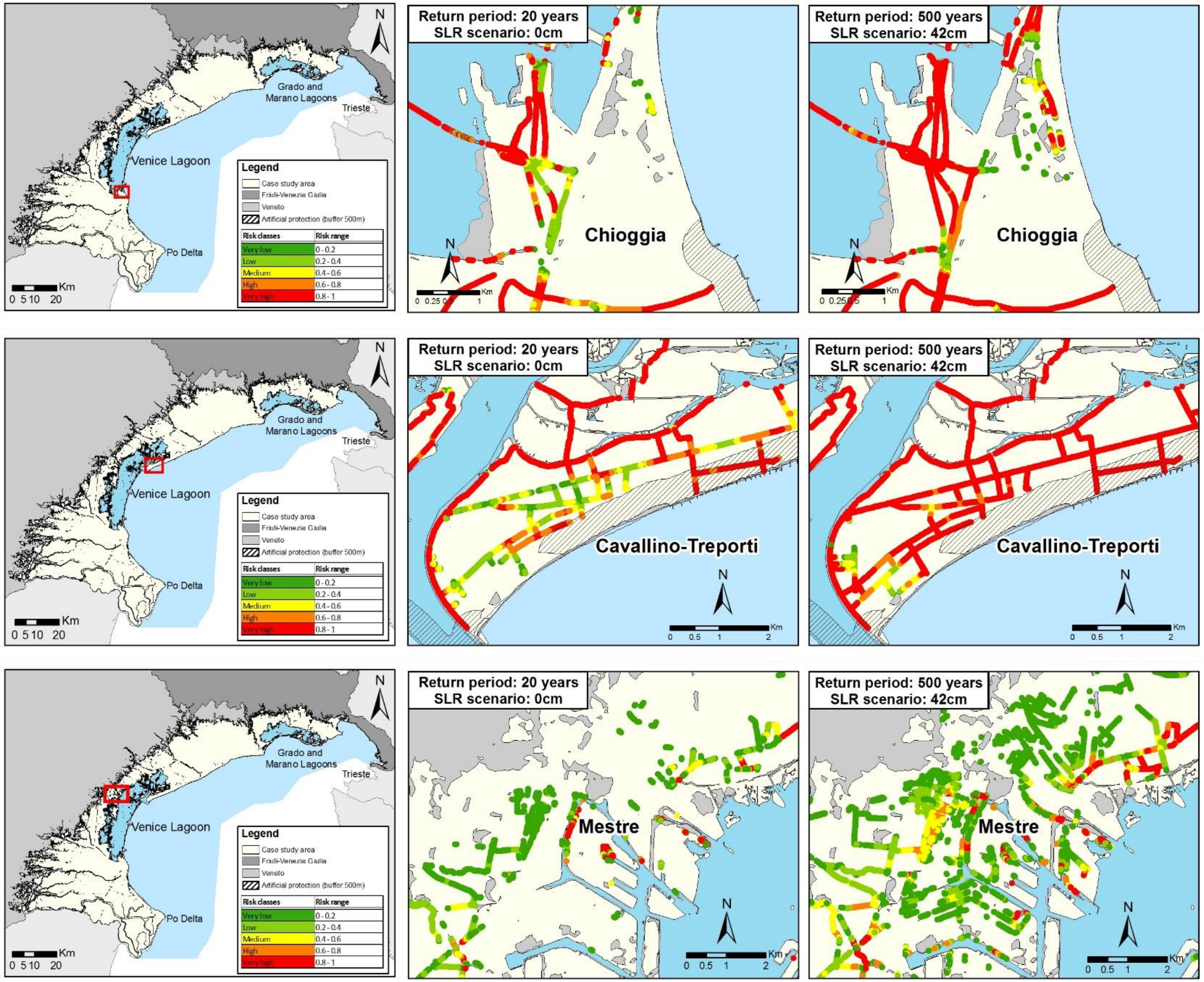


Figure 41. Risk maps of infrastructures.

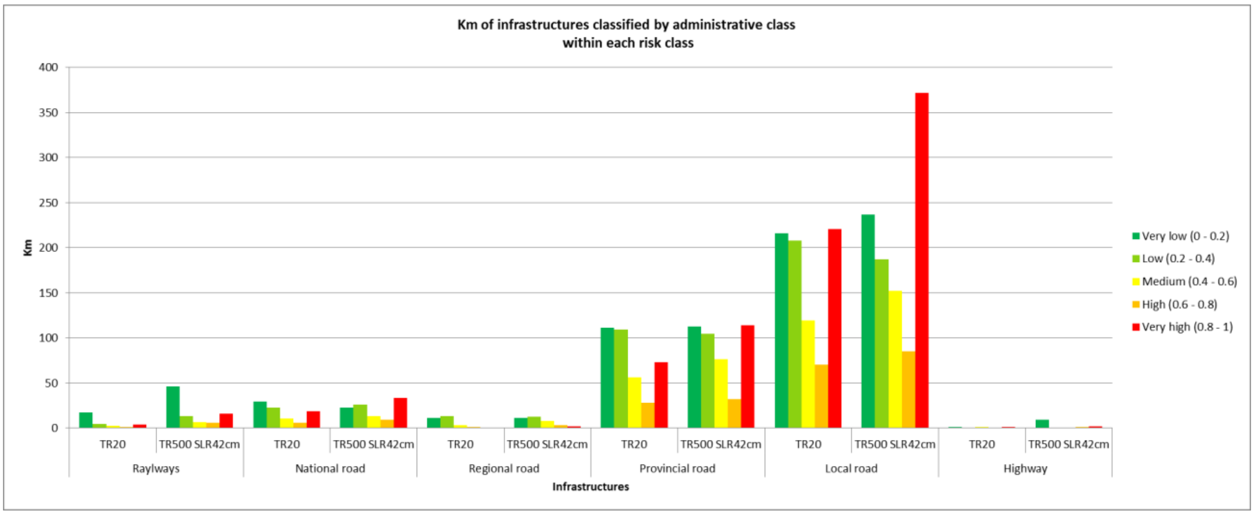


Figure 42. Comparison of the length of infrastructure in the different relative risk classes for the 2 extreme scenarios.

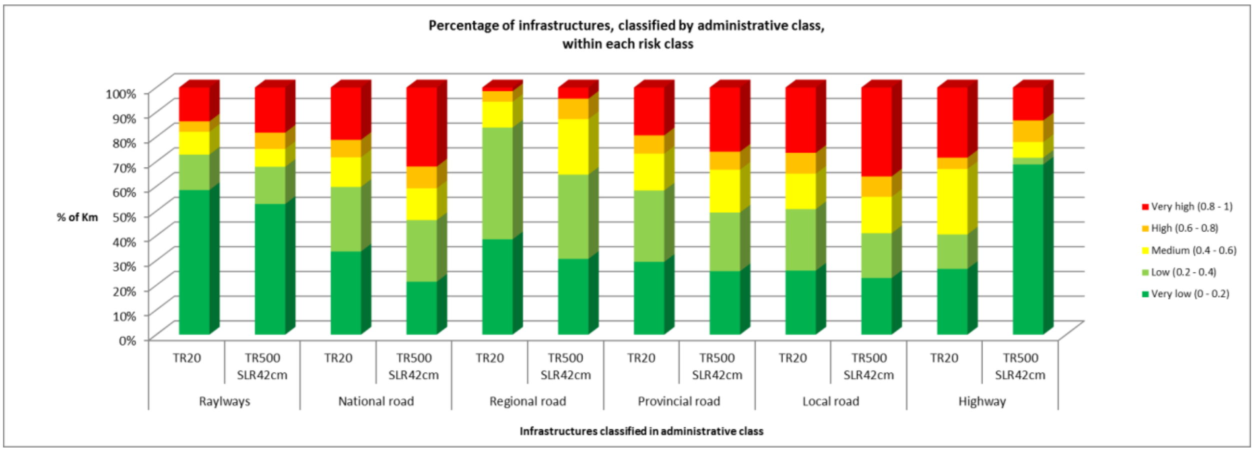


Figure 43. Comparison of the percentage of infrastructure in the different relative risk classes for the 2 extreme scenarios.

Risk maps produced for population (Figure 44 and Figure 45) and buildings (Figure 46 and Figure 47) show that risk is quite low in almost all the considered region. Population will be always classified in the lowest risk classes (i.e. Low and Very low) and buildings will be almost all in the classes from Medium to Very low. The comparison between the best and worst scenarios show that there will be an increase of population and buildings at risk especially in the province of Venice, as highlighted also by the graphs of Figure 48 (e.g. increase of 50.000 people and 7000 buildings at risk in the worst scenario), but also in the worst scenario the highest percentage of population and buildings at risk will be in the lower risk classes.

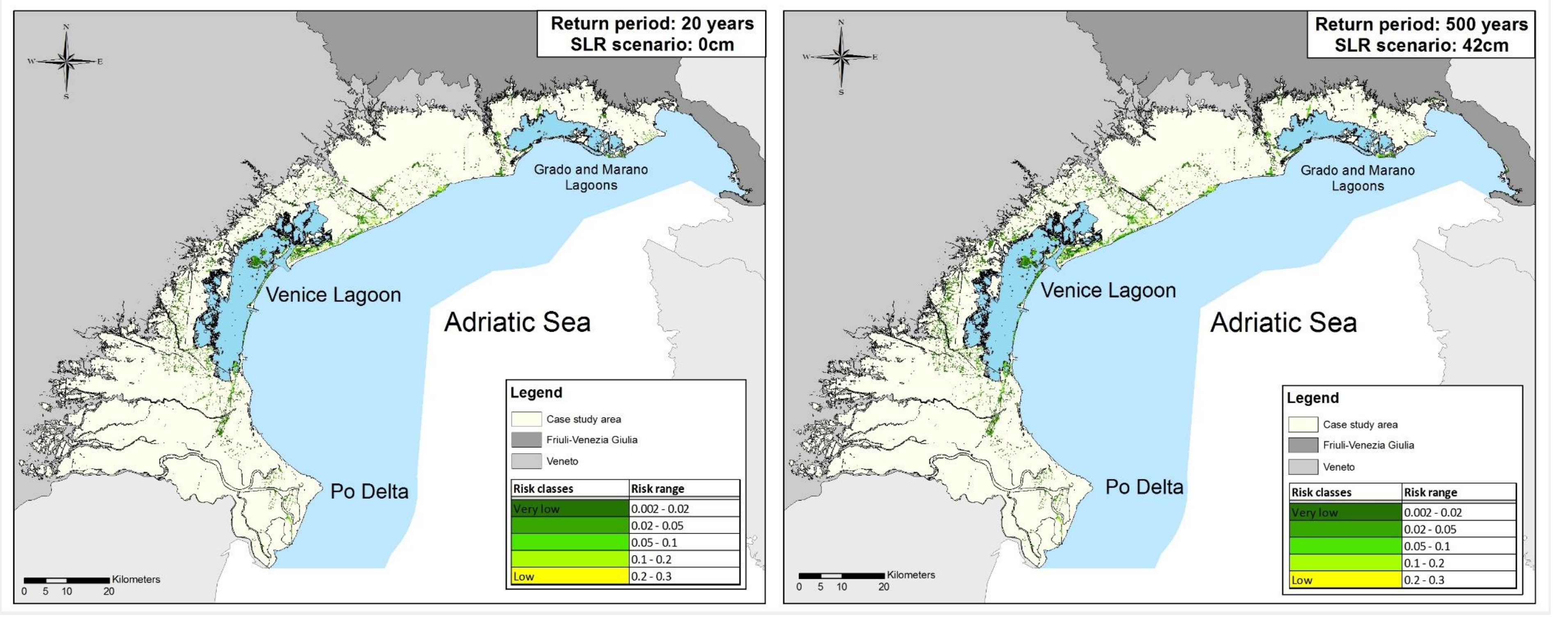


Figure 44. Risk maps of population for the whole case study area.

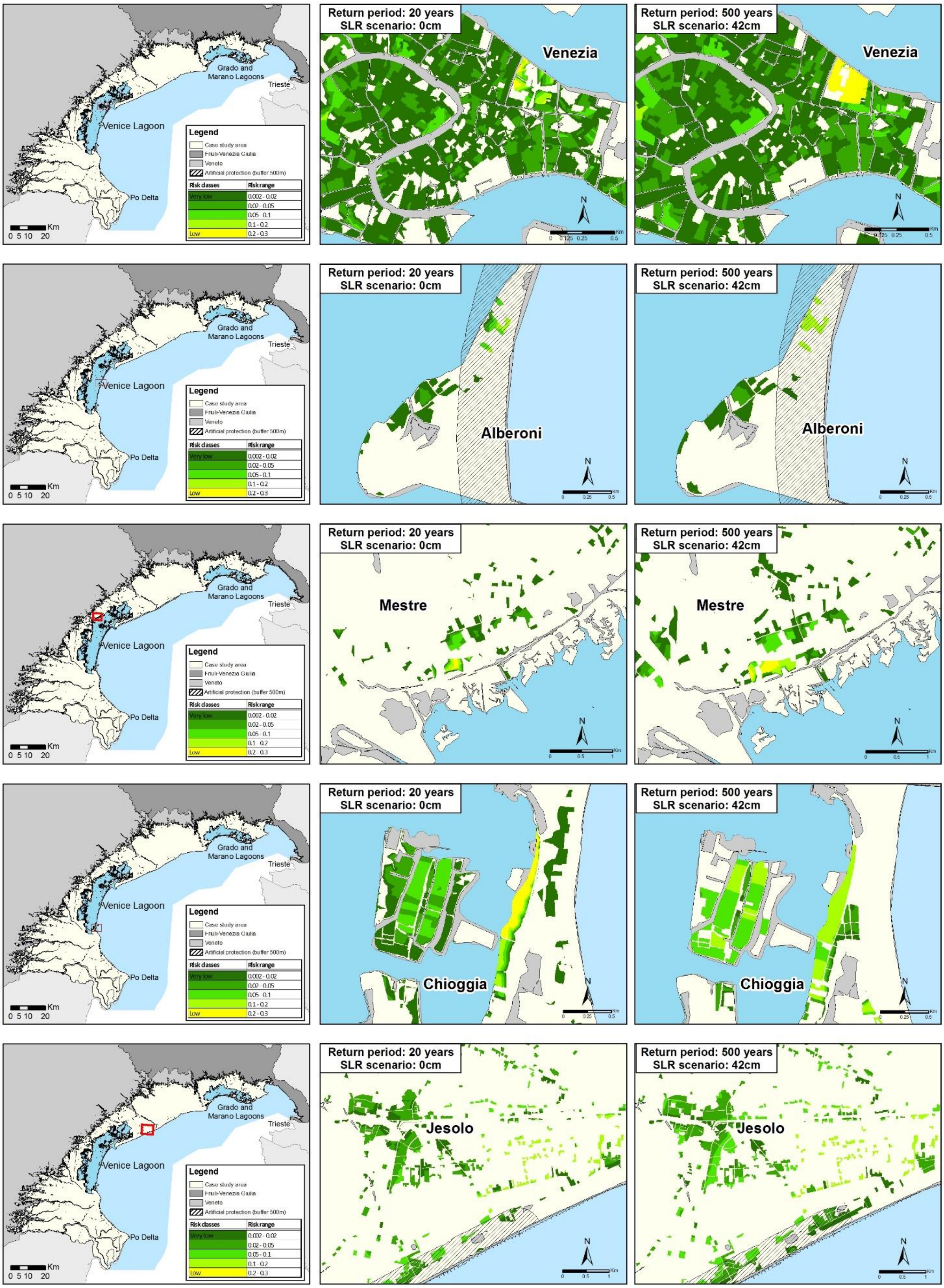


Figure 45. Risk maps of population.

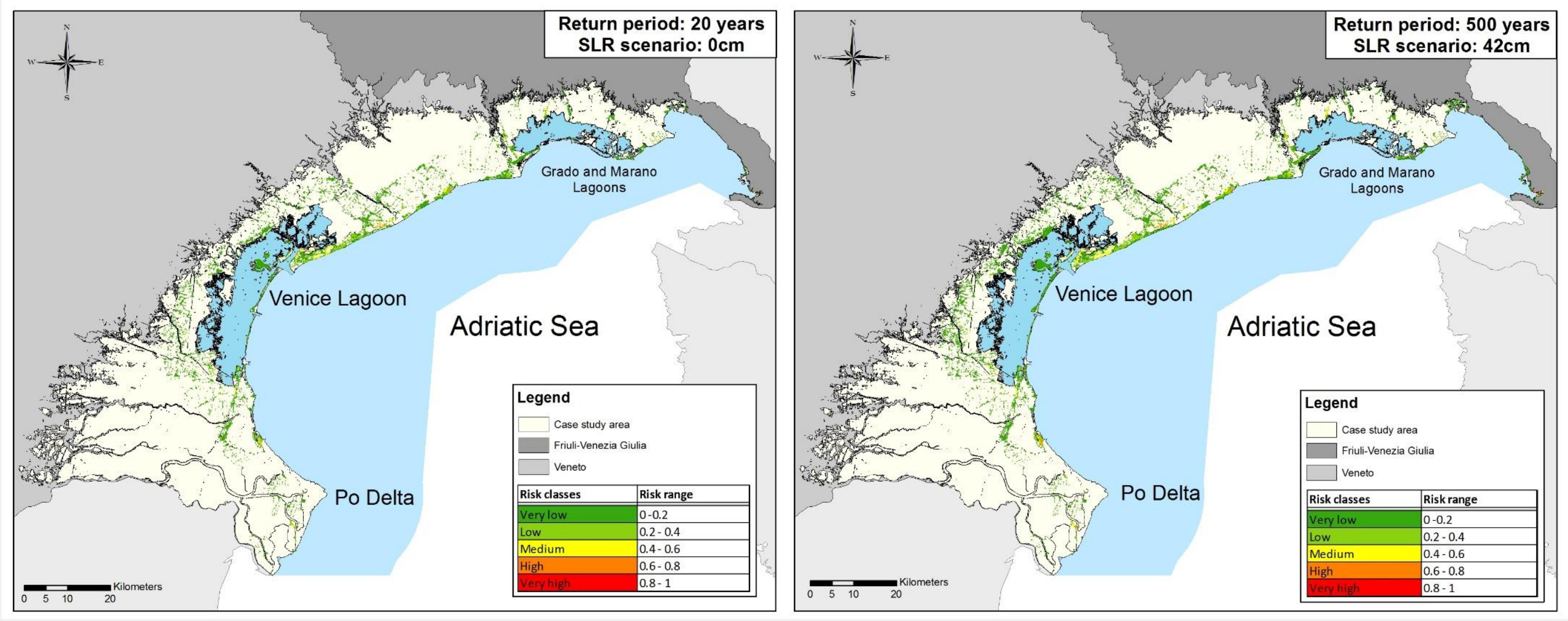


Figure 46. Risk maps of buildings for the whole case study area.

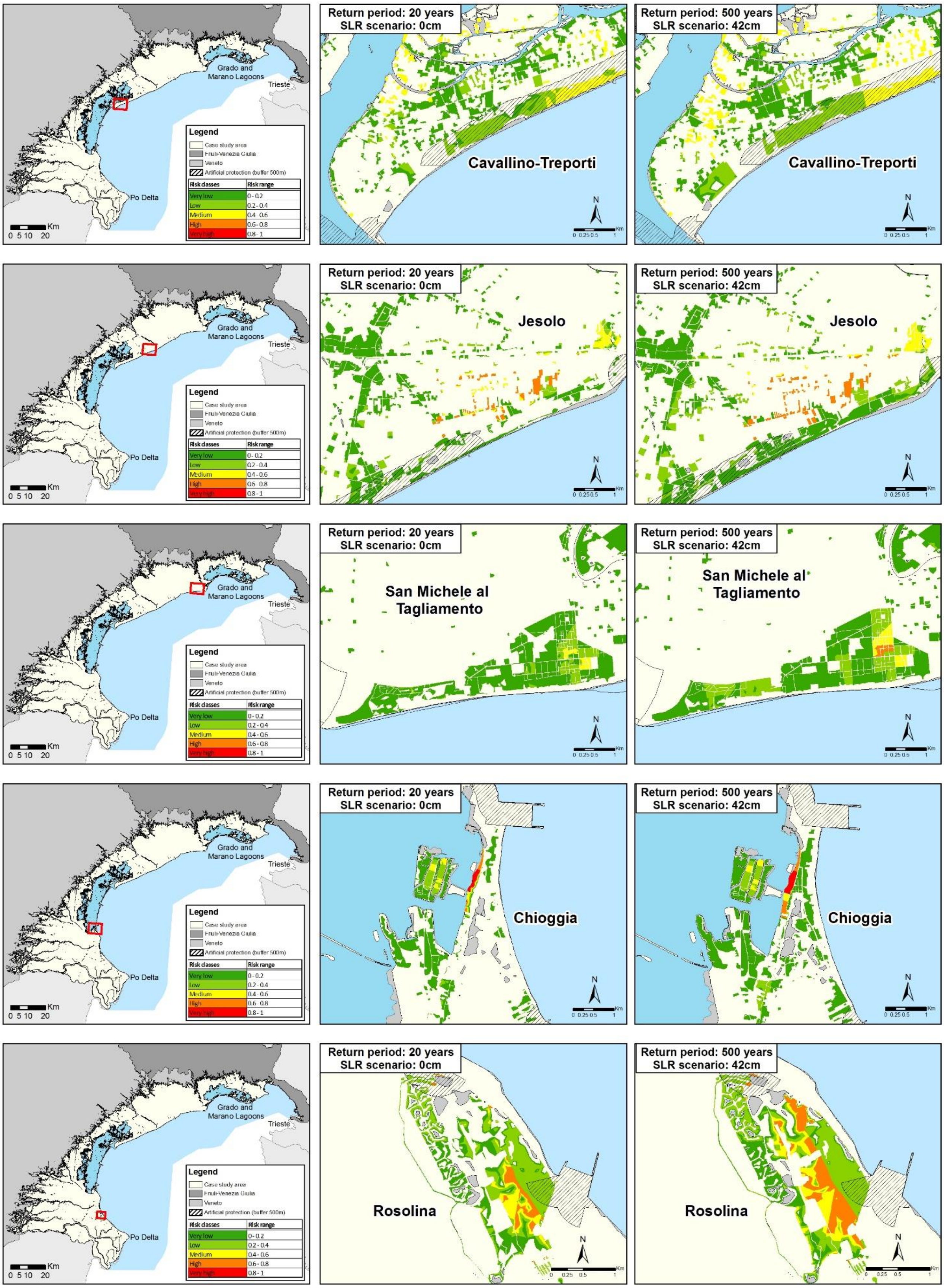


Figure 47. Risk maps of buildings.

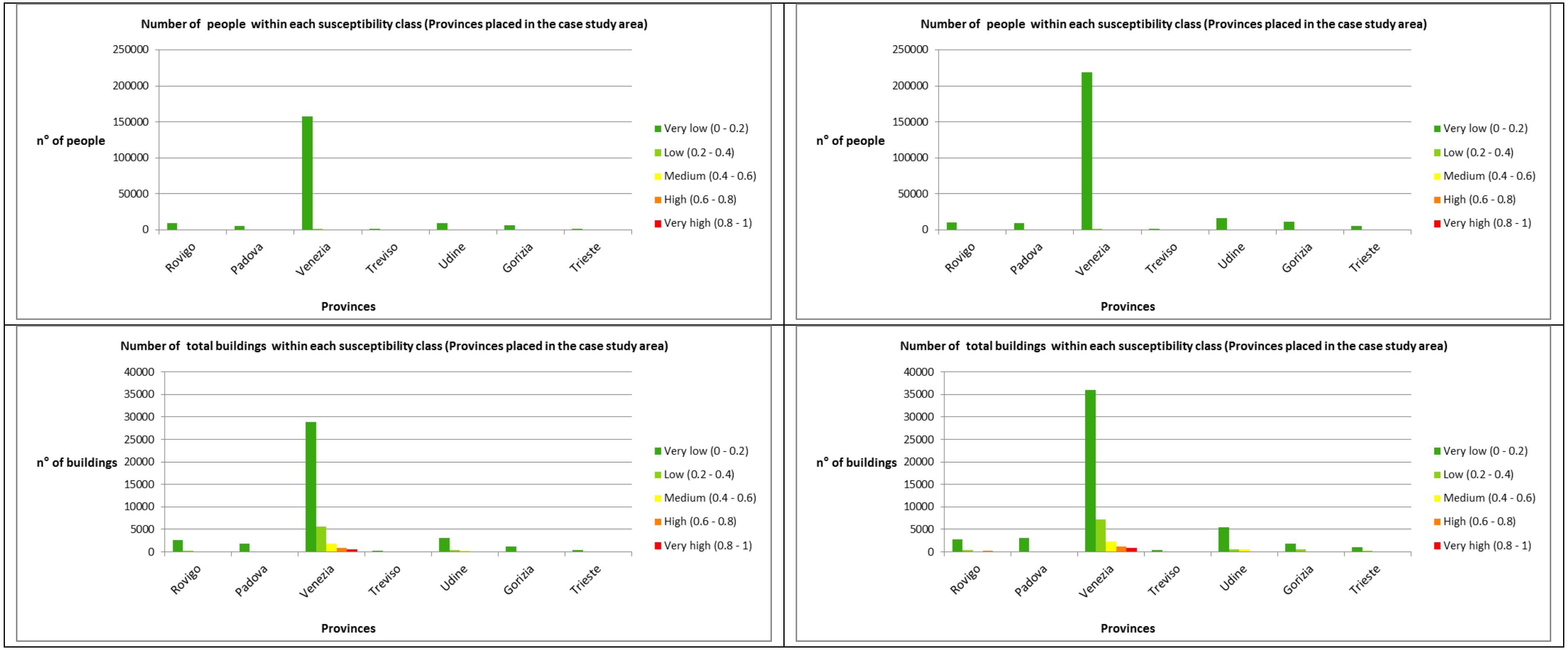


Figure 48. Risk statistics showing the number of people (upper boxes) and buildings (lower boxes) at risk in the 2 considered extreme scenarios, events with return period of 20 years without SLR (left) and with return period of 500 years with 42 cm of SLR (right).

The following figures show the spatial distribution of the risk for the considered environmental receptors (i.e. beaches, wetlands, agricultural areas and natural and semi-natural environments – from Figure 36 to Figure 39) and some related statistics (Figure 40), comparing the best and the work scenarios.

As far as beaches are concerned, they are almost all classified within the highest risk class (Figure 36). This is mainly due to their proximity to the coastline and to their high vulnerability.

Wetlands are classified within the higher risk class for around the 50% of their surface. By the map (Figure 37) it emerge that coastal wetlands, and especially those around the lagoon of Venice and of Marano and Grado, are classified within the higher risk class, while wetlands classified with lower risk classes are those who are more far from the coastline.

The environmental receptor with the lower percentage of surface within the higher risk class is agricultural areas (i.e. less than 25% in the worst scenario). Also in this case the main driver of risk is represented by the distance from the coastline.

Finally, also natural and semi-natural environments, are characterised with very high risk for more than 25% of their surface (40% in the worst scenario), with a level of risk decreasing moving inland from the coastline.

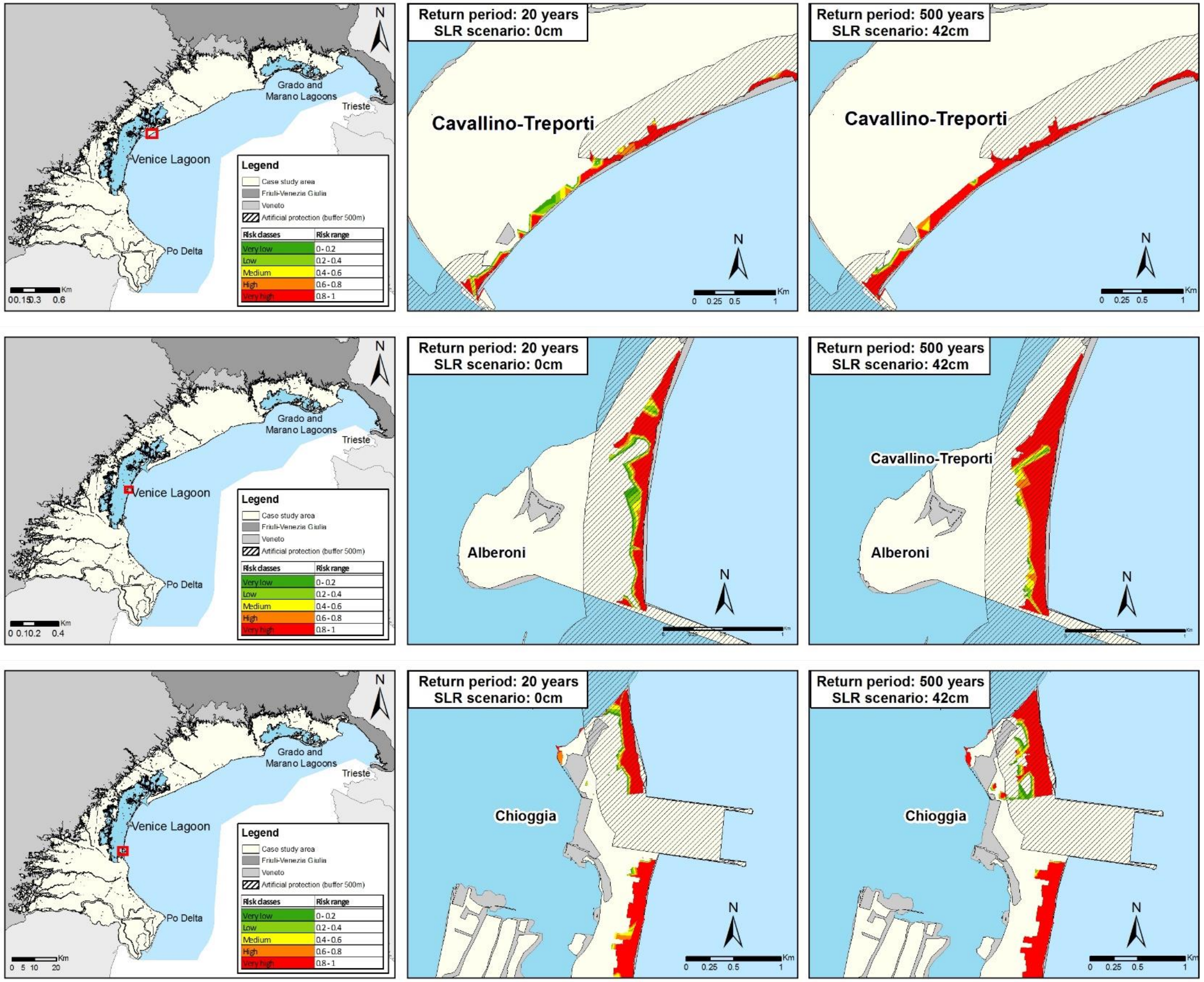


Figure 49. Risk map of beaches.

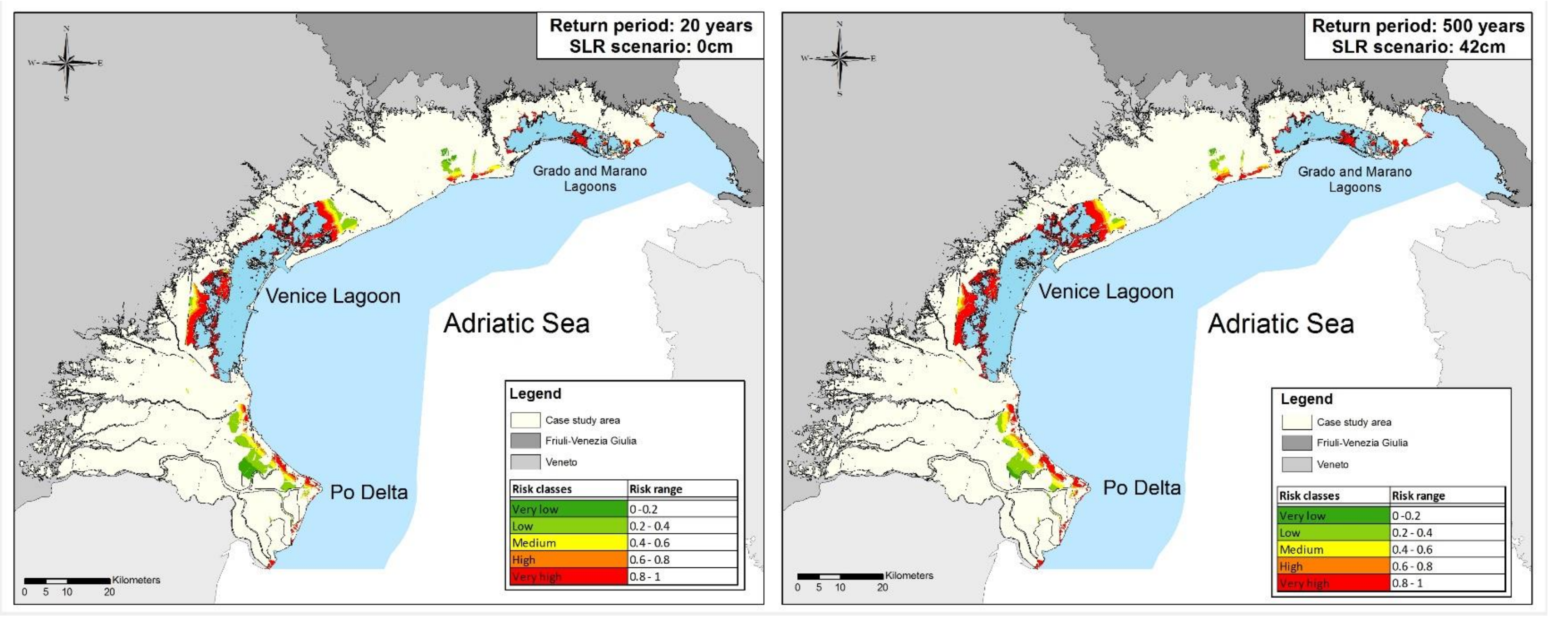


Figure 50. Risk maps of wetlands.

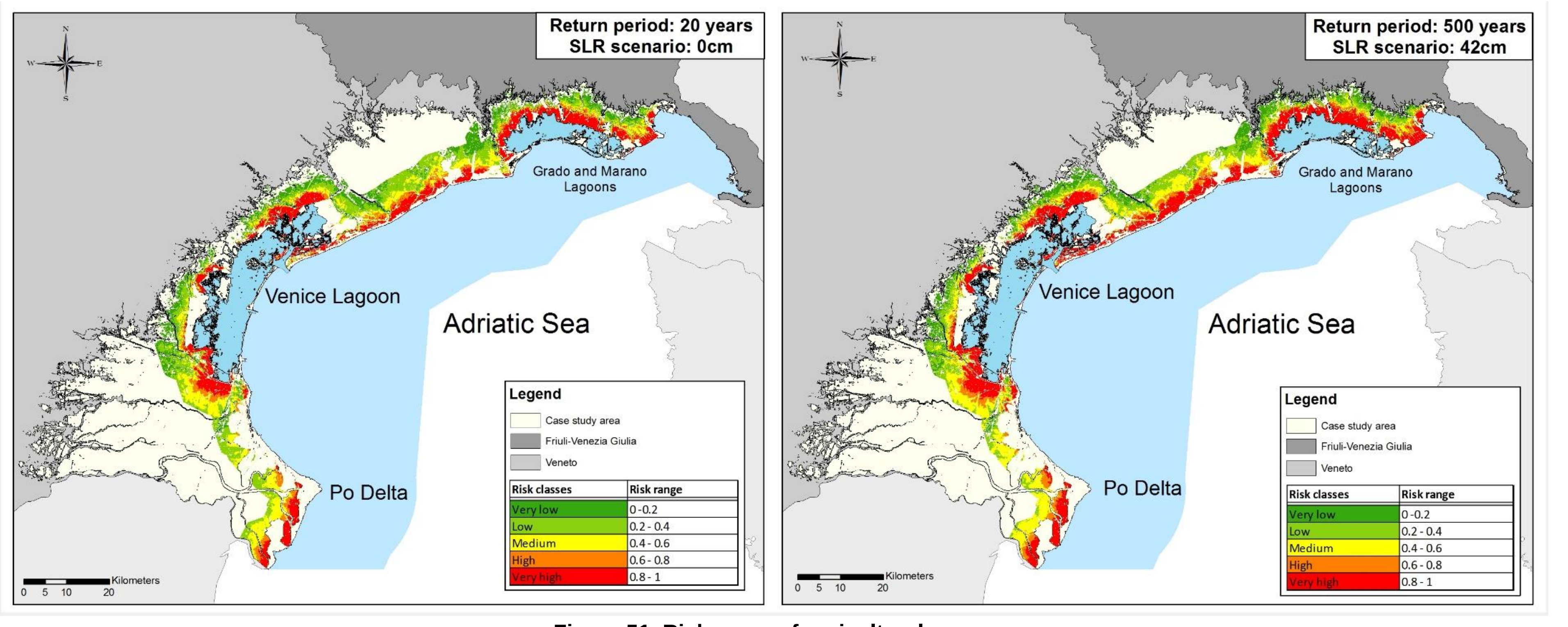
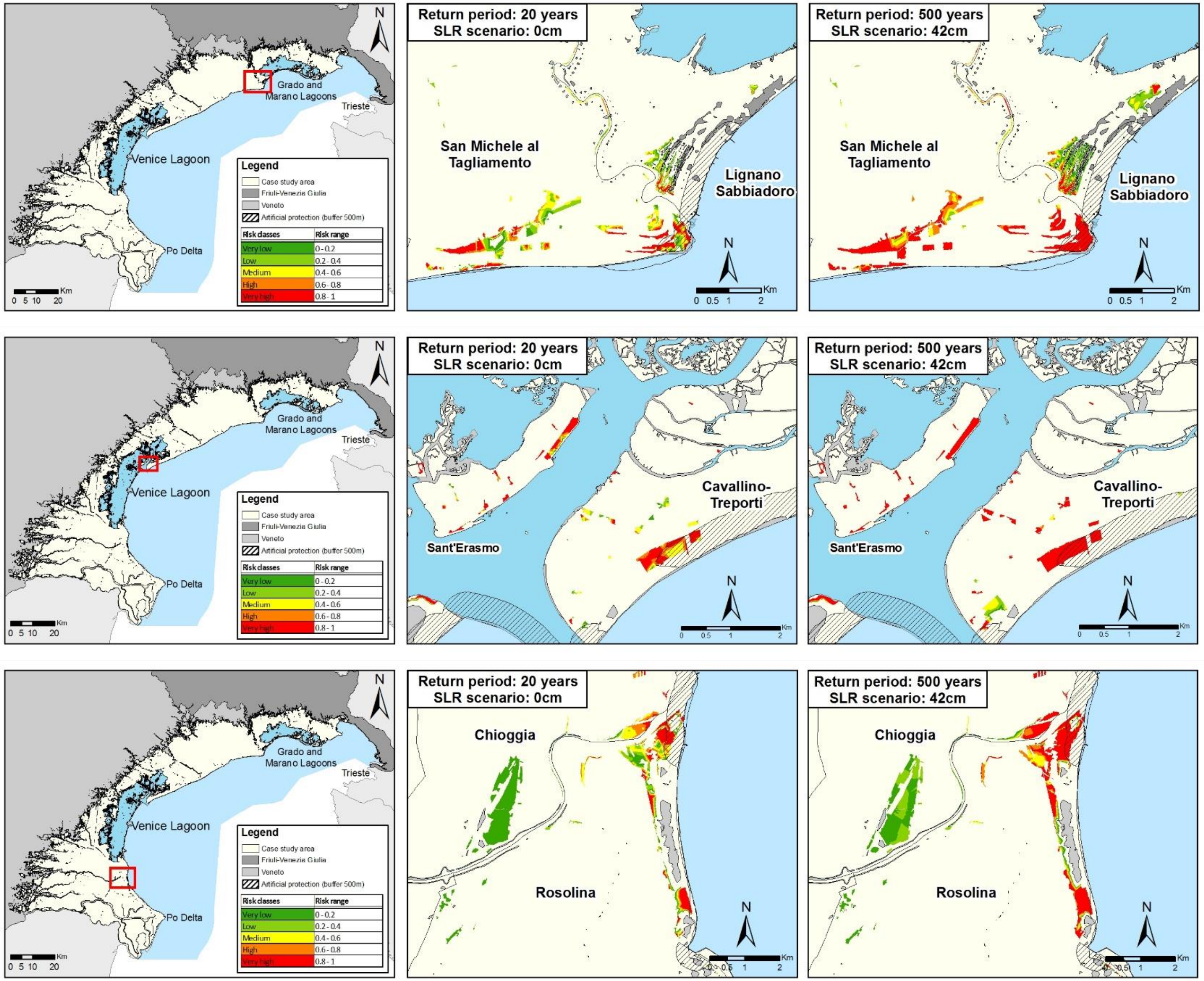


Figure 51. Risk maps of agricultural areas.



N
Grado and Marano Lagoons
Trieste
Venice Lagoon
Po Delta
Legend
Case study area
Friuli-Venezia Giulia
Veneto
Artificial protection (buffer 500m)
Risk classes
Risk range
Very low
0 - 0.2
Low
0.2 - 0.4
Medium
0.4 - 0.6
High
0.6 - 0.8
Very high
0.8 - 1
0 5 10 20 Km
Return period: 20 years
SLR scenario: 0cm
San Michele al Tagliamento
Lignano Sabbiadoro
0 0.5 1 2 Km
Return period: 500 years
SLR scenario: 42cm
San Michele al Tagliamento
Lignano Sabbiadoro
0 0.5 1 2 Km
N
Grado and Marano Lagoons
Trieste
Venice Lagoon
Po Delta
Legend
Case study area
Friuli-Venezia Giulia
Veneto
Artificial protection (buffer 500m)
Risk classes
Risk range
Very low
0 - 0.2
Low
0.2 - 0.4
Medium
0.4 - 0.6
High
0.6 - 0.8
Very high
0.8 - 1
0 5 10 20 Km
Return period: 20 years
SLR scenario: 0cm
Cavallino-Treporti
Sant'Erasmo
0 0.5 1 2 Km
Return period: 500 years
SLR scenario: 42cm
Cavallino-Treporti
Sant'Erasmo
0 0.5 1 2 Km
N
Grado and Marano Lagoons
Trieste
Venice Lagoon
Po Delta
Legend
Case study area
Friuli-Venezia Giulia
Veneto
Artificial protection (buffer 500m)
Risk classes
Risk range
Very low
0 - 0.2
Low
0.2 - 0.4
Medium
0.4 - 0.6
High
0.6 - 0.8
Very high
0.8 - 1
0 5 10 20 Km
Return period: 20 years
SLR scenario: 0cm
Chioggia
Rosolina
0 0.5 1 2 Km
Return period: 500 years
SLR scenario: 42cm
Chioggia
Rosolina
0 0.5 1 2 Km

Figure 52. Risk maps of natural and semi-natural environments.

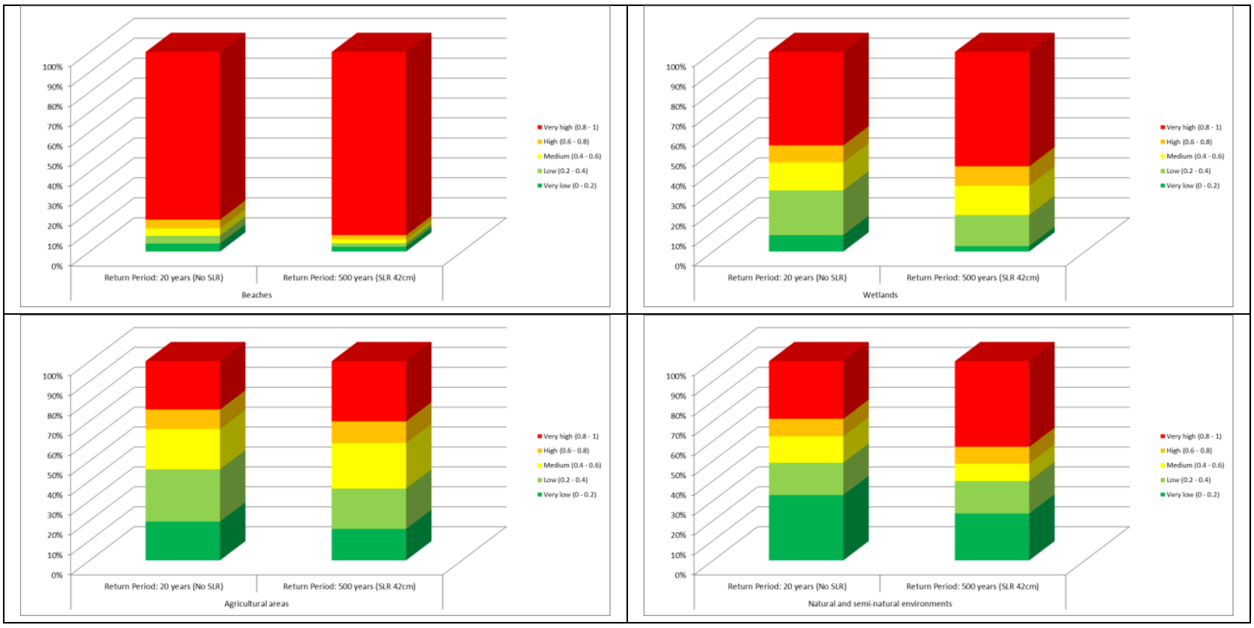


Figure 53. Risk statistics for the environmental receptors: beaches (top left), wetlands (top right), agricultural areas (bottom left), natural and semi-natural environments (bottom right).

Finally, as far as cultural heritage are concerned, it appear that almost the 70% of their surface will be characterized with the very high risk class, and even in the best scenario more than 50% of the surface will be in the higher risk class.

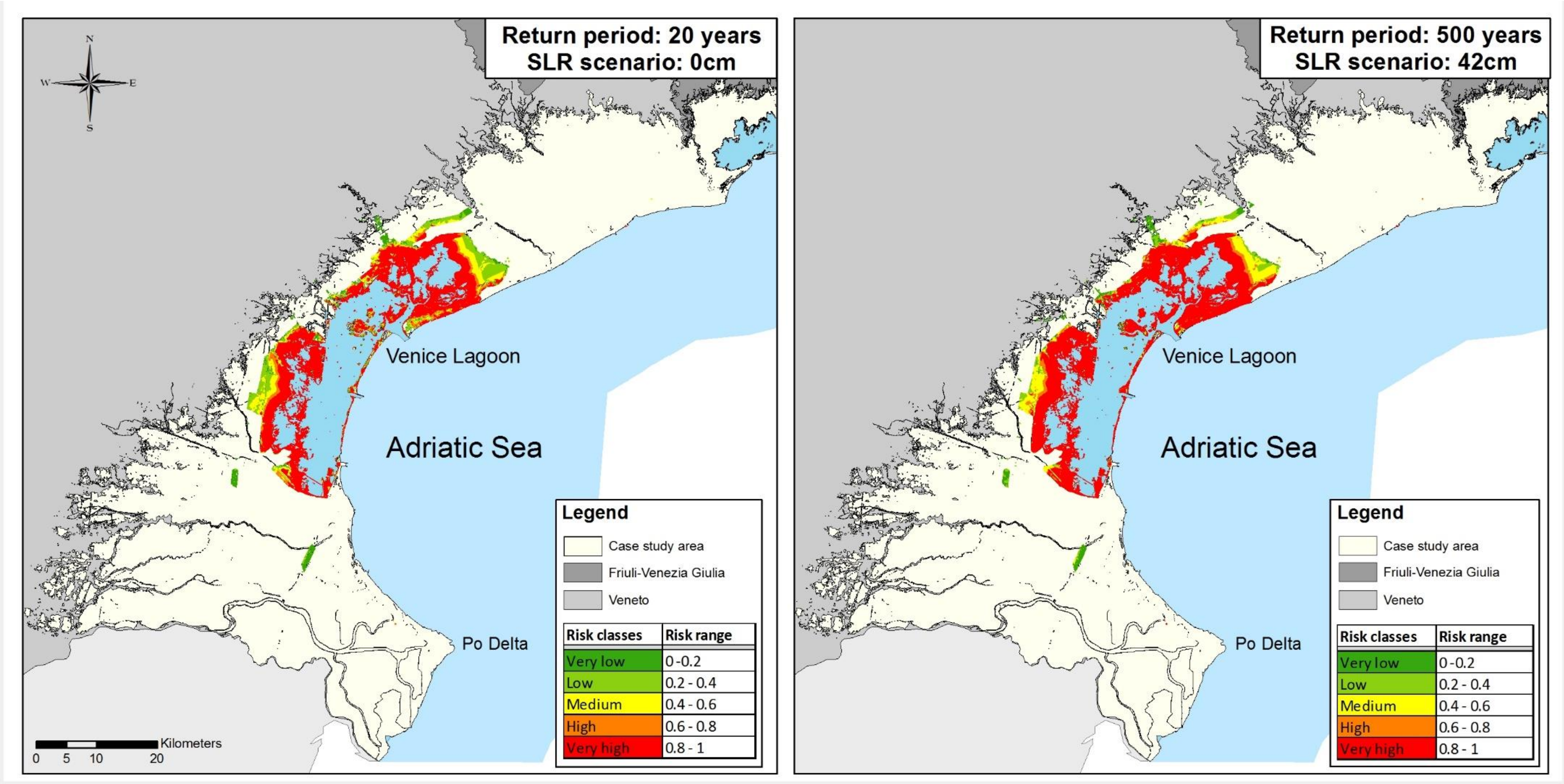


Figure 54. Risk map of cultural heritage.

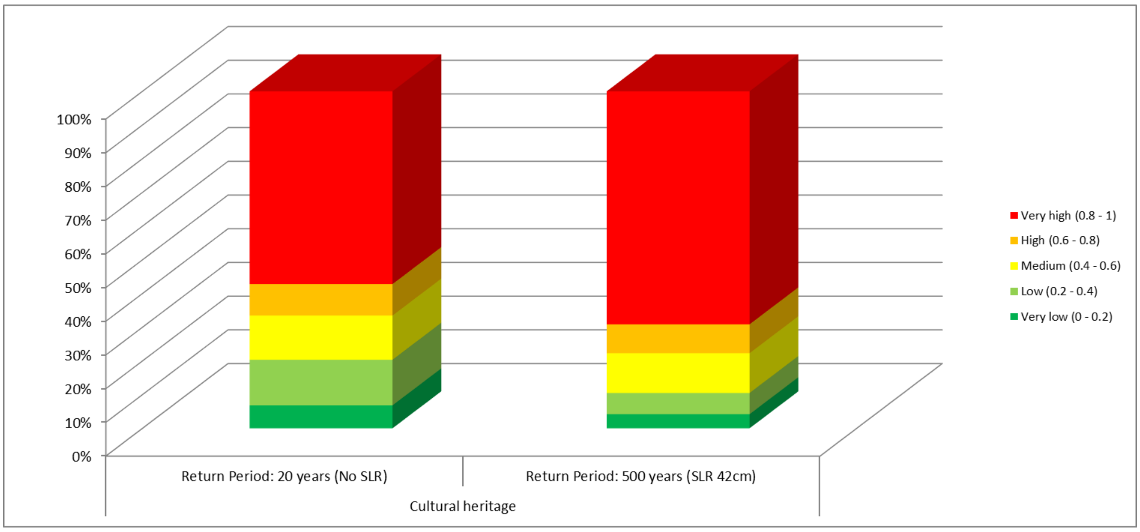


Figure 55. Risk statistics for cultural heritage.

7. Water Quality Variation

Marine ecosystems are very important in the regulation of the climate, and are very sensitive to climate change (Hoegh-Guldberg and Bruno, 2010). In recent years, marine ecosystems are suffering climate change impacts such a loss of habitat forming species (e.g. coral reefs, seagrasses) (Short and Neckles; 1999; Hoegh-Guldberg et al., 2007), decline in the productivity of the oceans (Behrenfeld et al., 2006; Polovina et al., 2008), changes in the geographic distribution of marine organism (Perry et al. 2005; Last et al. 2011). At the global scale, the main drivers of these impacts are represented by the increase of sea surface temperature and the related ice melting in the arctic regions represents (Wang and Overland, 2009) and by changes in the marine currents, which causes changes in other water biogeochemical and physical parameters (e.g. primary production, pH, salinity) that may exceed the thresholds of ecosystem tolerance, and thus lead to marine ecosystems degradation (Hoegh-Guldberg and Bruno 2010, Xia J. et al., 2010).

The European Commission undertook several political actions specifically related to coastal and marine environments, such as the Integrated Maritime Policy (IMP), the Marine Strategy Framework Directive (MSFD), the Water Framework Directive (WFD), the Floods Directive, the Reform of the Common Fisheries Policy (CFP) and the Recommendation for Integrated Coastal Zone Management (ICZM). Among these, the Water Framework Directive (WFD; 2000/60/EC), and the Marine Strategy Framework Directive (MSFD; 2008/56/EC) represents the umbrella used to address the ecological quality of coastal/marine water systems in Europe. Both directives require the comparison of the current quality status of water bodies with the quality status that would be expected under a condition of minimal or sustainable human use (i.e. the best quality condition to be used as reference); moreover, in case of poor quality water bodies must be bring back to the desired good status (Mee et al., 2008). The process of setting achievable environmental targets must also account for highly uncertain changes of the physical and biological environment driven by climate (Roth and O'Higgins, 2010). This aspect has been considered also by the European Commission who published the White Paper on adapting to climate change (EC 2009). The main aim of the White Paper is to provide an overall framework to stimulate and guide national, regional and local adaptation measures and policies, including sector specific dimensions, in order to increase resilience to the impacts of climate change (EC 2009). Emphasis is placed on the need for an integrated approach to increase resilience in coastal and marine environments and interrelated human activities, as well as the need to integrate adaptation into sectoral policies (EC, 2009)

Several recent studies focused on the assessment of the environmental status of marine waters in an integrative manner (e.g.Borja et al., 2011; HELCOM, 2010); despite this several gaps are still existing; in particular is not clear how marine ecosystems respond to human activities, including climate change (Borja et al., 2013). Developed approaches have been applied over several coastal zones which are affected by a dynamical interaction with anthropogenic pressures and climate change, e.g. the Baltic sea, the North sea, the North Adriatic sea and other enclosed basins such as the Black sea, (Melvasalo, 2000). Among these, the North Adriatic sea is one of the most studied basins of the Mediterranean.

Water quality is generally defined based on the final use of the water, but in general terms it can be defined as an overall evaluation based on a suite of measurements and analyses of chemical, physical, and biological characteristics conducted in the field and in laboratory. In order to analyse the potential consequences of climate change on marine water quality and evaluate the related impacts on coastal receptors (e.g. marine biological systems and aquaculture), a Regional Risk Assessment (RRA) methodology was developed and applied to the coastal marine water bodies of the Northern Adriatic coast (Veneto and Friuli Venezia regions, Italy). The analysis is based on the use of regional marine water biogeochemical and physical models and integrate site-specific environmental and socio-economic information. The methodology uses Geographic Information Systems to manage, process, analyse, and visualize data and employs Multi-Criteria Decision Analysis to integrate stakeholders preferences and experts judgments into the analysis, in order to obtain a relative risk index in the considered region. The methodology has been implemented within the DEcision support SYstem for COastal climate change impact assessment (DESYCO) (Torresan et al., 2010).

The main aim of this chapter is to present the RRA methodology adapted for the Water Quality Variation (WQV) impact and its application to coastal marine water bodies of the Northern Adriatic area. The RRA methodology presented in Chapter 2 was adapted for the WQV impact based on the five steps summarized in Figure 56. Accordingly in the next paragraphs, the RRA methodology will be described in detail (Chapter 8.1) and the produced outputs (i.e. hazard, exposure, vulnerability and risk maps) will be presented and discussed (Chapter 8.2).

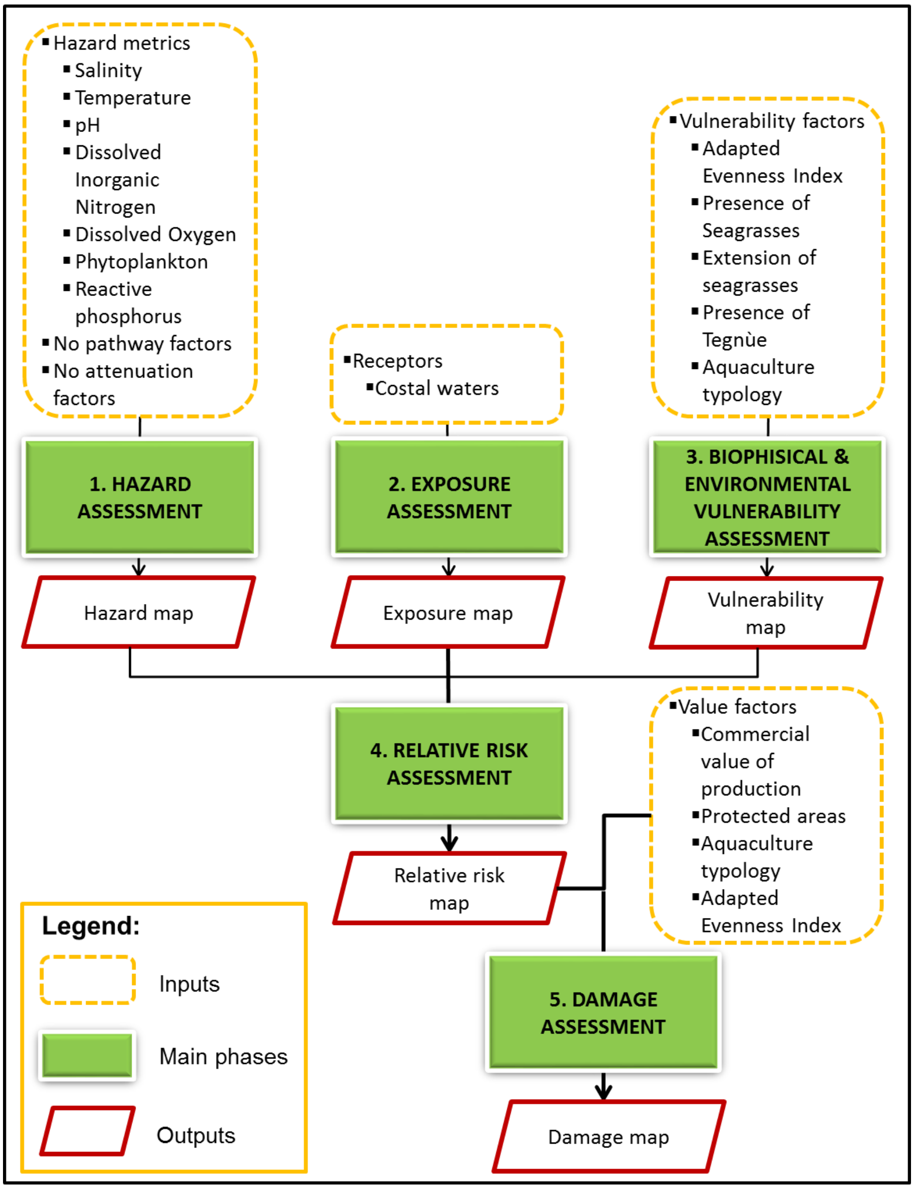


Figure 56. RRA methodology steps for the Water Quality Variation impact.

7.1. RRA for Water Quality Variation

7.1.1. Hazard assessment

The hazard matrix (Table 12) shows the main stressors that drive the water quality variations in relation to climate change. For the considered stressor, several hazard metrics are defined , based on the information provided by numerical models available for the case study area (Table 5).

Stressors	Primary production	Macronutrients	Dissolved oxygen	pH	Sea temperature	Salinity
Hazard metrics	Concentration of C or Clh-a (mg/L)	Concentration of N and P (mg/L)	Concentration (mg/L)	Mean pH	Mean T (°C)	Salinity (PSU)

Table 12. List of hazard stressors and related hazard metrics considered for the construction of climate change hazard scenarios applied to the North Adriatic coasts.

For each hazard metric, data were available on points distributed over irregular grids in the considered region (Table 5; Figure 57). For each point the value is represented by the average of the values of three months (January-March, April-June, July-September, October-December). Data available for the North Adriatic Sea did not included Venice and Grado and Marano Lagoons. Moreover, all data were provided as seasonal average for the simulations of future climate scenarios (i.e. 2070 and 2100) and for the reference scenario (i.e. the year 2005). The year 2005 was selected as reference scenario because data of the considered hazard metrics were available from monitoring campaigns and used as baseline for the implementation of the model chain.

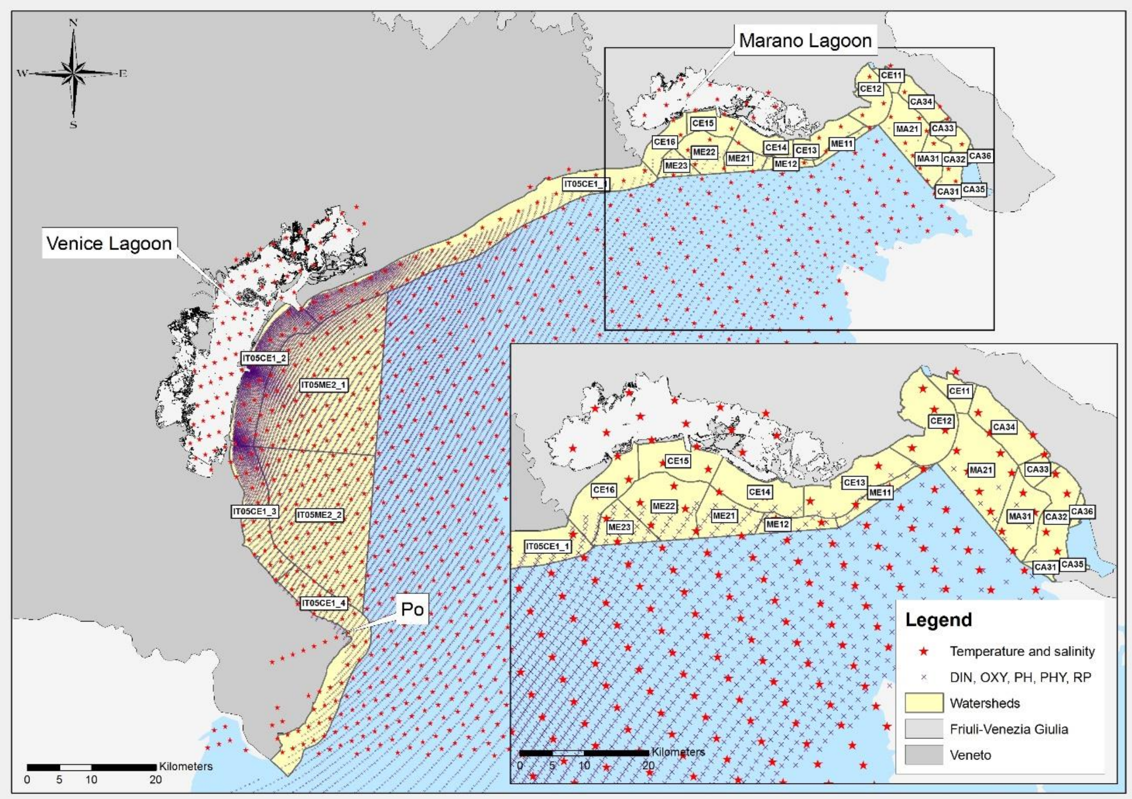


Figure 57. Localization of points used by the different models providing hazard metrics. DIN: Dissolved Inorganic Nitrogen; OXY: Dissolved Oxygen; pH: pH; PHY: Phytoplankton; RP: Reactive Phosphorus.

Based on the considered identified homogeneous areas, the minimum and maximum value were identified. Homogeneous areas will correspond to the water bodies identified by the Veneto and Friuli Venezia Giulia regions in the framework of the implementation of the Water Framework Directive (i.e. 6 water bodies for the Veneto region and 17 water bodies for the Friuli Venezia Giulia region).

The hazard assessment is based on the comparison of future and reference tolerance ranges (i.e. chemical and/or physical thresholds that limit the existence, growth, abundance, or distribution of an organism) that were defined for each hazard metric. If the values of one or more parameters are out of these ranges, many impacts can appear in the ecosystem (e.g. time of reproduction and growth variations, changes in the distribution and abundance of the organisms). Within the North Adriatic case the hazard assessment was performed in homogeneous areas corresponding to the water bodies identified by the Veneto and Friuli Venezia Giulia regions (Figure 5) for the implementation of the Water Framework Directive (i.e. 6 water bodies for the Veneto region and 17 water bodies for the Friuli Venezia Giulia region). Tolerance ranges were identified for each hazard metric, for each period (i.e. each season) for all the considered water bodies using data of the reference year (i.e. 2005).

Hazard metric	**Tolerance range**			
	January - March	**April - June**	**July - September**	**October – December**
Primary production (mg/L)	0.03-0.98	0.09-1.98	0.06-2.35	0.03-0.45
Reactive phosphorous (mg/L)	0.04-1.29	0.02-1.33	0.02-2.06	0.04-1.48
Dissolved inorganic nitrogen (mg/L)	0.07-3.26	0.05-3.79	0.05-5.67	0.08-3.64
Dissolved oxygen (mg/L)	8.48-11.41	7.79-10.84	6.87-10.05	7.97-10.24
pH	8.23-9.90	8.03-9.80	8.04-9.85	8.23-9.67
Temperature (°C)	4.38-7.28	14.44-20.74	20.63-23.91	8.66-14.03
Salinity (PSU)	35.27-37.18	37.01-37.28	35.37-36.80	32.94-36.18

Table 13. Optimal range defined for each hazard metric and season for the North Adriatic coasts.

In order to obtain an overall hazard score for each water body, a hazard function for the water quality variation impact was defined. The function allows the characterisation of the variations of the biogeochemical and physical parameters from the reference to the future climate change scenarios. It is based on the comparison of the range of each hazard metric in the future scenario with the reference range: the greater is the variation in the future, the higher is the hazard. Values obtained for each metric are successively normalized and aggregated in order to obtain an overall hazard score ranging from 0 (no hazard) to 1 (maximum hazard within the considered region for all seasons and scenarios).

Accordingly, the hazard function considers the minimum m and maximum M values of each hazard metric H_i for each water body j in the reference period (i.e. 2005) and in the forecasted periods (i.e. 2070 and 2100). The main aim is to obtain for each water body j and each hazard metric i an indicator $H_{wqv,i,j}$ representing the probability that the forecasted hazard metric variation could affect the considered water body, and then to aggregate all metrics into a single supposed probability.

The defined probability related to the distance from the reference range is not known a priori but, supposing the hazard metric range in the reference period as "safe" and supposing that the probability to get harm effects grows linearly while moving away from that range, the above mentioned index can be calculated by applying the OWA operator (Paragraph 2.4.2), as described below:

$$H_{wqv,i,j} = w_M \cdot \max(\Delta_{i,j}^{m}, \Delta_{i,j}^{M}) + w_m \cdot \min(\Delta_{i,j}^{m}, \Delta_{i,j}^{M})$$

Where:

$H_{wqv,i,j} = \textit{probability that a hazard metric } (i) \textit{ variation affect a water body } (j)$;

$w_M = \textit{importance weights related to the bigger}$;

$w_m = \textit{importance weights related to the smaller differences}$;

$w_M \gg w_m$; $w_M + w_m = 1$ (i.e. $w_M = 0.8$ and $w_m = 0.2$).

Every $H_{wqv,i,j,}$ is characterized by the scale of the related hazard metric and its domain is not known (i.e. these quantities cannot be aggregated without first being normalized in a common scale). To remove scale related issues, $H_{wqv,i,j}$ values can be transformed into percentage of variance of the future value respect to the reference scenario, dividing them by their corresponding reference range defined considering all water bodies $r_i = H_i^M - H_i^m$, and then normalized dividing each obtained value of percentage by the maximum percentage of variation found in the application, taking into account all the parameters and all the seasons.

$$K_{i,j}^{wqv} = \frac{H_{i,j}^{wqv}}{r_i}$$

$$H_{i,j}^{\prime wqv} = \frac{K_{i,j}^{wqv}}{\max_{\forall i,j}(K_{i,j}^{wqv})}$$

Once each $H_{i,j}^{\prime wqv}$ has been calculated, they must be aggregated in order to establish an overall "harm probability" related to the above explained variations. In this case probabilities are aggregated by following the idea that they are in an OR type of relation (i.e. it takes one big probability or many smaller probabilities to higher the overall harm probability), therefore the probabilistic or approach was selected:

$$H_{wqv,j} = \otimes_{i=1}^{n} \left[H_{i,j}^{\prime wqv}\right]$$

The final output of the hazard assessment are hazard maps showing water bodies' hazard score for each considered season and for each scenario. Maps are classified into 5 hazard qualitative classes (i.e. Very low, Low, Medium, High, Very high) using the equal interval method. The produced maps will be presented and discussed in Section 7.1.

7.1.2. Exposure assessment

The second step is the exposure assessment aimed at identifying and selecting the receptors (i.e. elements at risk) that can be subject to potential losses due to changes in water quality. In fact, exposure represents the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected

(UNISDR, 2009a; IPCC, 2012). For the considered impact, exposure includes coastal waters and the related environmental resources (e.g. fish stock, fisheries and aquaculture plant) that could be adversely affected by changes in water quality.

Specifically, the exposure for coastal waters is represented marine water bodies defined by the Veneto and Friuli-Venezia Giulia regions according to the Water Framework Directive (WFD, 2000/60/EC). Water bodies were identified based on the geomorphological and hydrodynamic natural characteristics, using three macrodescriptors: geographical localization, geomorphological descriptors and hydrological descriptors.

The output of this step is represented by an exposure map where 0 indicate absence of exposure and 1 indicate exposure to the considered impact.

7.1.3. Biophysical and Environmental Vulnerability assessment

Vulnerability represents the propensity or predisposition of a community, system, or asset to be adversely affected by a certain hazard (UNISDR, 2009a; IPCC, 2012). Within the RRA methodology, the biophysical and environmental vulnerability assessment is aimed at evaluating the degree to which coastal waters could be affected by water quality variation impacts based on physical/environmental site-specific information (e.g. presence and extension of seagrasses, adapted Evenness index, aquaculture typology).

Specifically, vulnerability is calculated as a function of a set of vulnerability factors that are defined for coastal waters based on available site-specific territorial information. Vulnerability factors identified for the North Adriatic case and related scores are listed in Table 14.

Factor	Source	Legend	Score
Species diversity index for fish -Adapted Evenness index-	AdriBlu, 2006	0.56 - 0.70	0.6
		0.71 - 0.85	0.8
		0.86 - 1	1
Presence of seagrasses	Veneto region, 2009; Friuli Venezia Giulia region, 2009	Absence	0.4
		Presence	1
Extension of seagrasses Km^2	Veneto region, 2009; Friuli Venezia Giulia region, 2009	0 - 6.67	1
		6.68 - 13.34	0.75
		13.35 - 20.01	0.5
		20.02 - 26.68	0.25
Tegnùe	Veneto region, 2009; Friuli Venezia Giulia region, 2009	Absence	0.4
		Presence	1
Aquaculture typology	Veneto region, 2008; Friuli Venezia Giulia region,2008	Mussel culture	1
		Fish farms	0.6

Table 14. Vulnerability factors selected for the water quality variation impact applied to the North Adriatic coastal water bodies and related scores.

The **Adapted Evenness index** is a measure of biodiversity which quantifies how equal the community is numerically (i.e. if there are 40 individuals of species *a*, and 1000 of species *b*, the community is not very even; but if there are 40 *a* and 42 *b*, the community is quite even). This index is an adapted version of the Evenness index because available data included only species relevant for fisheries, and not all species living in the North Adriatic Sea. It is always represented by a number ranging from 0 (less variation in communities between the species) to 1 (high variation in communities between the species). Higher vulnerability scores were attributed to areas with a higher index value, as changes in water biogeochemical and physical parameters can easily modify the existing equilibrium in the abundance of the different species. **Segrassess** are marine flowering plants which are particularly important in coastal zones as they provide several ecosystem goods and ecosystem services (e.g. fishing grounds, wave protection, oxygen production and protection against coastal erosion). The maximum vulnerability score (i.e. 1) was attributed where seagrasses are present. Moreover, segrassess with a greater extension are characterized by a lower susceptibility score as they are assumed to be less vulnerable to external perturbations (i.e. changes in water biogeochemical and physical parameters). **Tegnùe** are biogenic carbonate rocks built by marine organisms. They initially grow on existing hard bottoms formed by cemented sand. They have developed into natural reefs over the last 3-4.000 years. They differ from tropical coral reefs because here the main builder organisms are not corals but calcareous red algae, called "Corallines". Areas where Tegnùe are present are characterized by the highest vulnerability score (i.e. 1). Finally, **Aquaculture typology** indicates whether a plant is devoted to fisheries or mussels cultures: mussel cultures, that are more sensitive to changes in water biogeochemical and physical parameters, are characterized by a higher level of vulnerability than fish farms.

In order to obtain an overall vulnerability score, factors are aggregated using MCDA functions, as shown in Equation 2. This step requires the classification and normalization each vulnerability factor. This activity was supported by a group of experts in environmental risk assessment who defined classes and scores for each vulnerability factor. Normalized factors' scores range from 0 to 1, according to the degree of vulnerability associated to each factors' class: 0 represents no vulnerability and 1 represents the higher vulnerability class for the considered factor.

$$V_{wqv} = \otimes_1^n \, [vf_i'] \qquad \text{Equation 1.}$$

Where:

$V_{wqv} = Biophysical\ and\ Environmental\ Vulnerability\ score$;

$\otimes_1^n = Probabilitic\ or\ operator\ applied\ to\ all\ the\ considered\ vulnerability\ factors$;

$vf_i' = Normalized\ Vulnerability\ factors.$

The final vulnerability score can range from 0 (no vulnerability) to 1 (maximum vulnerability for the considered region). The output is a vulnerability map for North Adriatic coastal waters identifying and prioritizing areas more vulnerable to changes in water quality parameters based on 5 qualitative classes from Very low to Very High vulnerability (i.e. 0-0.25; 0.25-0.5; 0.5-0.75; 0.75-0.99; 0.99-1). Vulnerability maps can support decision makers in the definition of measures aimed at boosting the resilience of receptors in the considered region (e.g. regulating fisheries and other activities in coastal zones in order to preserve seagrasess).

7.1.4. Risk assessment

The Risk assessment phase is aimed at integrating SSF hazard scenarios and vulnerability scores of the different considered receptors to allow the identification and the prioritization of coastal receptors and areas at risk in the considered region. The definition of the risk score is based on the following equation:

$$R_{wqv,s} = H_{wqv,s} \cdot V_{wqv}$$

Where:

$R_{wqv,s} = risk\ score\ related\ to\ the\ scenario\ s$;

$H_{wqv,s} = hazard\ score\ for\ the\ scenario\ s$;

$V_{wqv} = \ vulnerability\ score\ for\ the\ receptor.$

Risk scores range between 0 and 1: 0 means no risk (i.e. there is no exposure or no vulnerability) and 1 means maximum risk for the considered scenario and target/area in the considered region. 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).

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.

7.1.5. Damage assessment

The damage assessment phase aims at providing 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) through the aggregation of the relative risk scores with the environmental and socio-economic value scores of the region under investigation.

The environmental and socio-economic value of coastal waters is estimated by applying a value function based on the aggregation value factors that must be normalized and weighted through the assignation of scores and weights. The value function is aimed at identifying and classifying relevant environmental and socio-economic values of receptors that need to be preserved for the interest of the community (e.g. land use, fishing areas). Value factors identified for the North Adriatic case and related scores are listed in Table 15.

Factor	Source	Legend	Score
Commercial value of production	AdriBlu, 2006	0 - 915764	0.2
		915765 - 2938538	0.4
		2938539 - 4956067	0.6
		4956068 - 7943731	0.8
		7943732 - 18481006	1
Protected areas, ZTB, natural reserves and zones for fish repopulation	Veneto region, 2009; Friuli Venezia Giulia region, 2009	Zones for fish repopulation	1
		ZTB (areas of biological protection) and natural reserves	0.8
		Not protected areas	0.6
Aquaculture typology	Veneto region, 2008; Friuli Venezia Giulia region, 2008	Mussel culture	1
		Fish farms	0.6
Species diversity index for fish -Adapted Evenness index-	AdriBlu, 2006	0.56 - 0.70	0.6
		0.71 - 0.85	0.8
		0.86 - 1	1

Table 15. Value factors selected for the water quality variation impact applied to the North Adriatic coastal water bodies and related scores.

Value scores, representing the relative importance (i.e. the socio-economic or environmental value) of each single class compared to the others, can range between 0 (no value) and 1 (maximum value for the considered region). They are assigned by decision makers or stakeholder; in the presented application they were assigned by a group of expert in environmental sciences based on a consultation of experts. The final value score, assumed that environmental and socio-economic values are additive in determining the total value of a receptor, is calculated by applying the following equation:

$$v_{vqv} = \sum_{i=1}^{n} [vf'_{wqv}]$$

Where:

$v_{vqv} = value\ score\ of\ the\ receptor\ j$;

$vf'_{wqv} = normalized\ value\ factor\ score$;

$n = number\ of\ value\ factors.$

The final value score ranges from 0 to 1. A score of 0 identifies areas without relevant environmental or socio-economic value (i.e. areas where the environmental and socio-economic value associated with all the value factors is null). On the contrary, a score of 1 identifies areas characterized by the higher environmental or socio-economic value in the considered region.

The value score calculate for coastal waters is successively integrated with the relative risk score of the different scenarios in order to calculate the damage score. The damage function allows identifying and prioritizing 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 water quality variations based on the following equation:

$$D_{wqv,s} = R_{wqv,s} \cdot v_{vqv}$$

Where

$D_{wqv,s} = damage\ score\ for\ the\ scenario\ s$

$R_{wqv,s} = risk\ score\ related\ to\ the\ scenario\ s$;

$v_{vqv} = value\ score\ of\ the\ receptor\ j.$

The result of the damage function is a damage score ranging between 0 and 1. If risk and or damage are 0, the final damage score is 0, while if risk and value have the higher score, also damage will be the higher.

7.2. Results

In the following paragraphs the main results of the application (i.e. maps and statistics) of the presented approach will be presented and discussed. All the produced output will be reported in Annex 3.

7.3.1. Hazard maps

Hazard maps show a ranking of water bodies' hazard scores. The higher scores represent water bodies where there is a higher increase/decrease of maximum/minimum hazard metrics' values compared to the reference values. Hazard scores were calculated as described in Section 6.1 within each coastal water body (Figure 60).

Figure 58 and Figure 59 show seasonal hazard maps for the two considered future scenarios (i.e., 2070 and 2100 respectively). The analysis of the produced maps shows that the southern part of the considered region (from Chioggia to the Po river delta) and the part from the Lido's inlet to Bibione is characterized by higher hazard scores in all considered seasons and scenarios. In both the considered scenarios, the season where higher hazard scores are forecasted is from April to June.

A detailed investigation of the hazard metrics contributing to the definition of the final hazard score was performed in order to better understand which metrics contribute more to the result. Metrics that contribute more to the definition of the final hazard score are salinity and temperature.

Moreover, in order to better understand the contribution of the single metrics and their spatial distribution, a histogram showing the reference and future hazard values ranges was produced (Annex 7). Histograms show in the coloured box the reference values ranges, while black lines show the ranges in the two considered reference scenarios (i.e. 2070 and 2100).

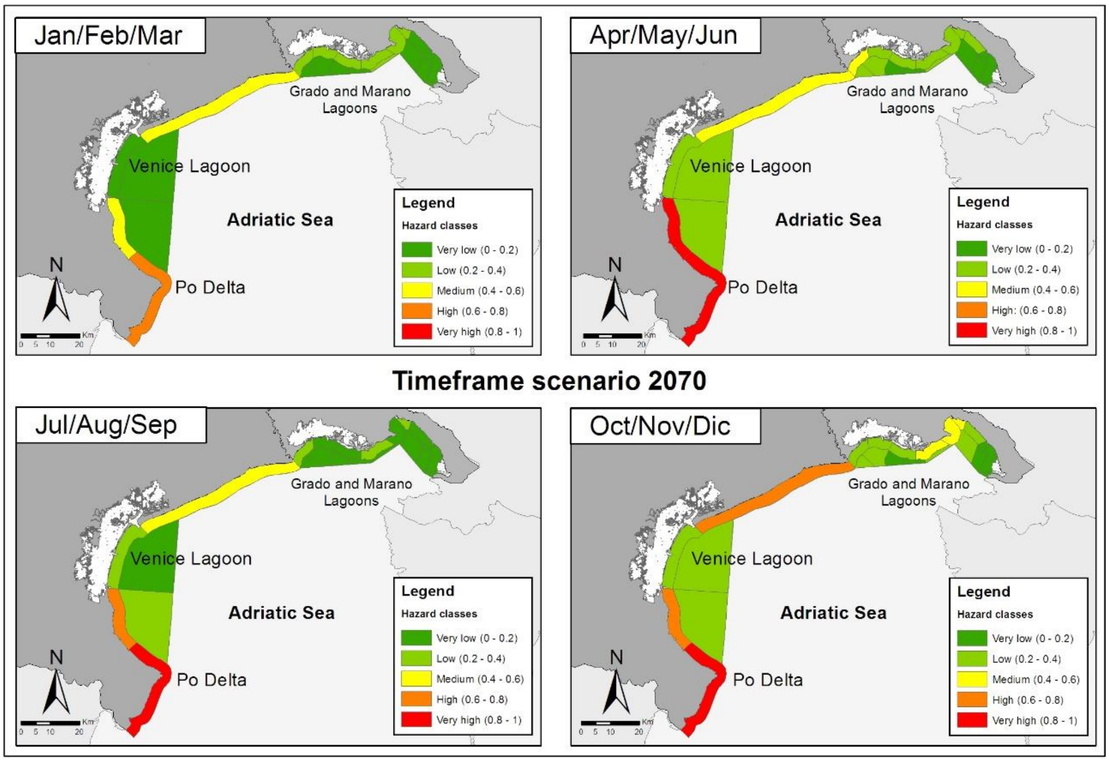


Figure 58. Hazard maps of water quality variations under climate change for the North Adriatic coastal water bodies for the year 2070.

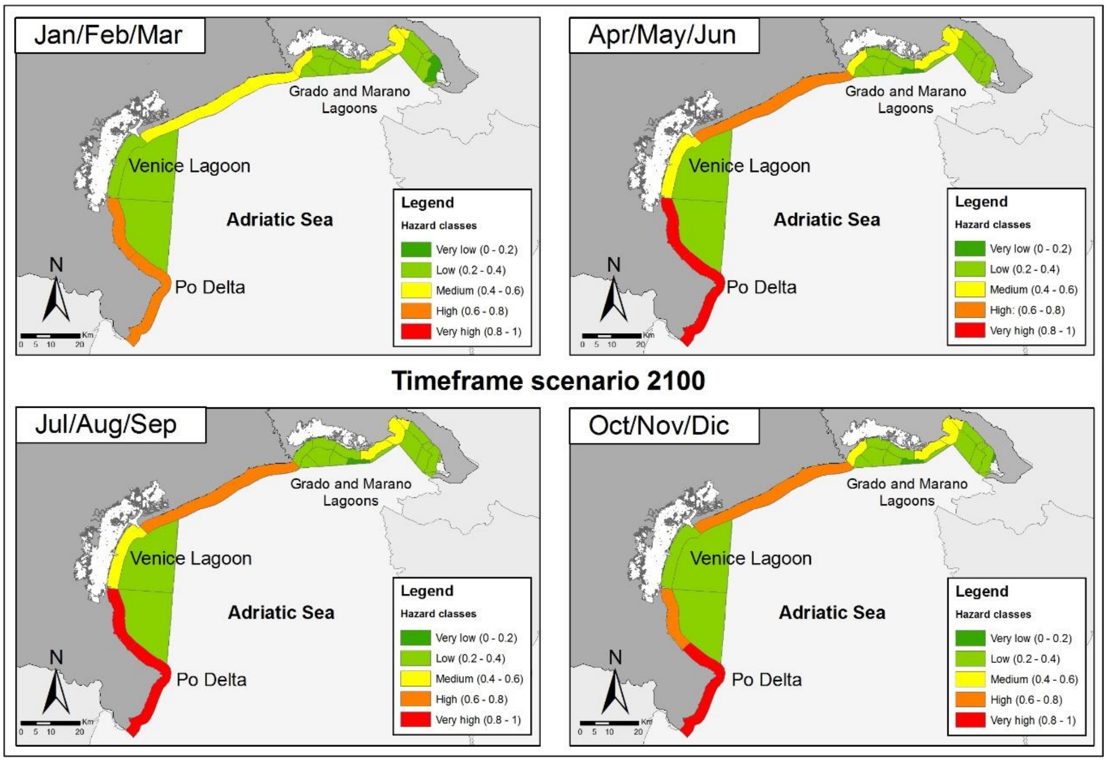


Figure 59. Hazard maps of water quality variations under climate change for the North Adriatic coastal water bodies for the year 2100.

Salinity will decrease in almost all water bodies and seasons. Water bodies close to river mouths have usually a higher decrease of salinity (e.g. IT0SCE_3). The main changes are represented by changes in currents directions and velocities observed in the ocean and sea circulation models included in the model chain (Chapter 6.1).

Temperature will change differently in the considered seasons. It will increase in all water bodies in winter and autumn and changes will be uniform across all the considered region in these seasons. In spring and summer temperature will increase in most of the considered water bodies, but changes will not be uniform. Higher changes are registered in the water bodies in front of the Veneto Region (i.e. IT05CE1_1, IT05CE1_2, IT05CE1_3, IT05CE1_4) located from the Po river delta to the Chioggia’s inlet and from the Lido’s Inlet to Bibione. Winter and autumn will have higher changes than spring and summer.

Dissolved Inorganic Nitrogen (DIN) will generally increase, but changes will be very limited in all considered scenarios, for almost all water bodies, except IT05CE1_1, IT05CE1_3, IT05CE1_4. Winter will be characterized by lower changes while autumn will be characterized by higher changes.

The distribution of other parameters (i.e. Phytoplankton, Reactive Phosphorus, Nitrates and Dissolved Oxygen) are similar as there are connections in the processes determining their values. The concentration of Phytoplankton is strictly connected to the concentrations of Reactive Phosphorus and Nitrates; moreover these parameters have a great influence on the Dissolved Oxygen.

Dissolved Oxygen (OXY) will change in different ways in the different water bodies and seasons. Higher changes will be in the water bodies IT05CE1_1, IT05CE1_3, IT05CE1_4.

Ph will decrease in most water bodies and seasons; higher changes will be in the spring season. Despite the fact that some water bodies will be characterized by a higher variability (i.e. IT05CE1_1, IT05CE1_3, IT05CE1_4) changes will be quite uniform in each season across all water bodies.

Concentration of phytoplankton (PHY) will generally increase in the considered water bodies and seasons. Depending on the season, different bodies will have higher percentage of change. The variability of PHY will be different in the considered water bodies and seasons.

Reactive Phosphorus (RP) will increase in three water bodies, with greatest changes in the autumn season: IT05CE1_1, IT05CE1_3 and IT05CE1_4; other water bodies will not change in future scenarios.

7.3.2. Exposure maps

The exposure map represents the key receptors of the analysis (Figure 60) and include the coastal water bodies of the Veneto and Friuli Venezia Giulia regions, defined according to the criteria listed in Section 6.1. Within the case study area 23 water bodies were considered (6 in the Veneto region's coastline and 17 along the Friuli Venezia Giulia's region's coastline). The considered water bodies include also several aquaculture plants, key hotspots of the analysis, which have been highlighted in red in Figure 60.

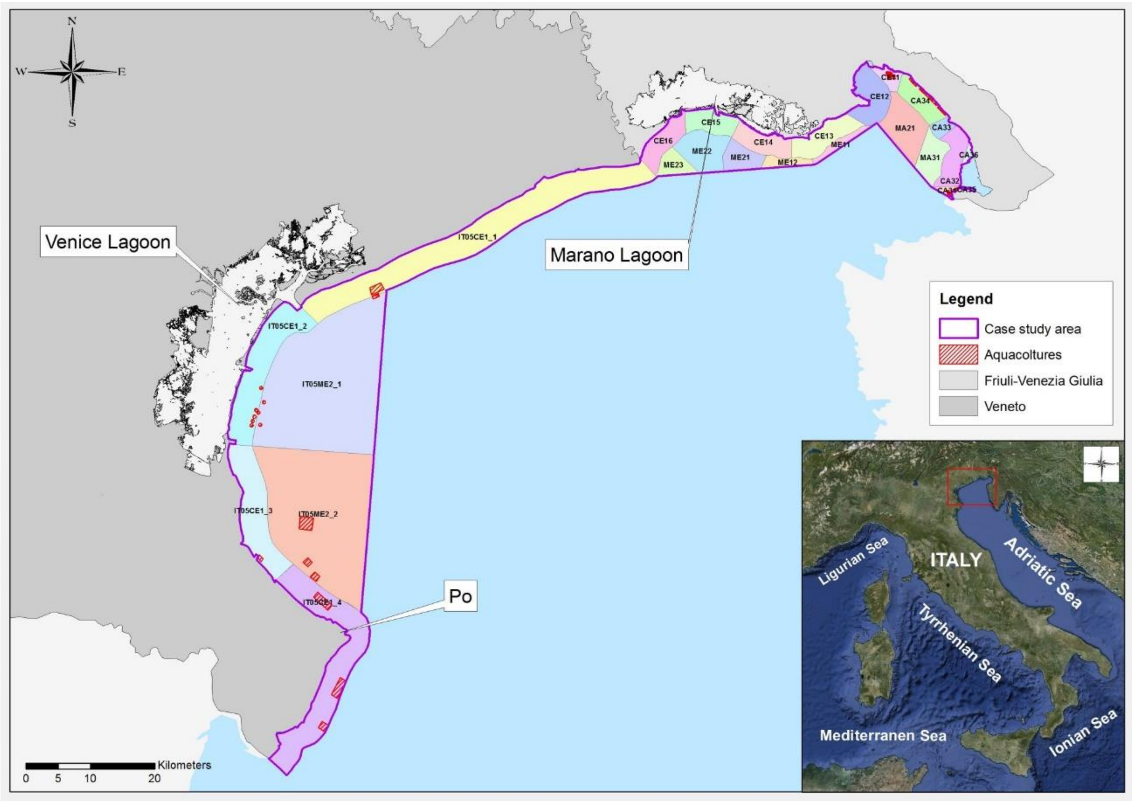


Figure 60. Exposure map showing coastal water bodies of Veneto and Friuli-Venezia Giulia regions and fisheries and aquaculture plants.

7.3.3. Biophysical and Environmental Vulnerability maps

The vulnerability map (Figure 61) highlights and prioritize areas that could be affected more severely that others by climate change impacts on water quality. Within the considered region, coastal water bodies are always characterized by a High or Very high vulnerability score.

Higher vulnerability is identified in the area in front of the Venice lagoon (i.e. Malamocco's and Lido's inlets) and in the northern part of the case study area, from Caorle to Trieste.

Vulnerability factors that mainly contributed to the definition of the vulnerability score are the adapted Evenness index, and those related to the presence of vulnerable targets, i.e. aquaculture plants and tegnùe.

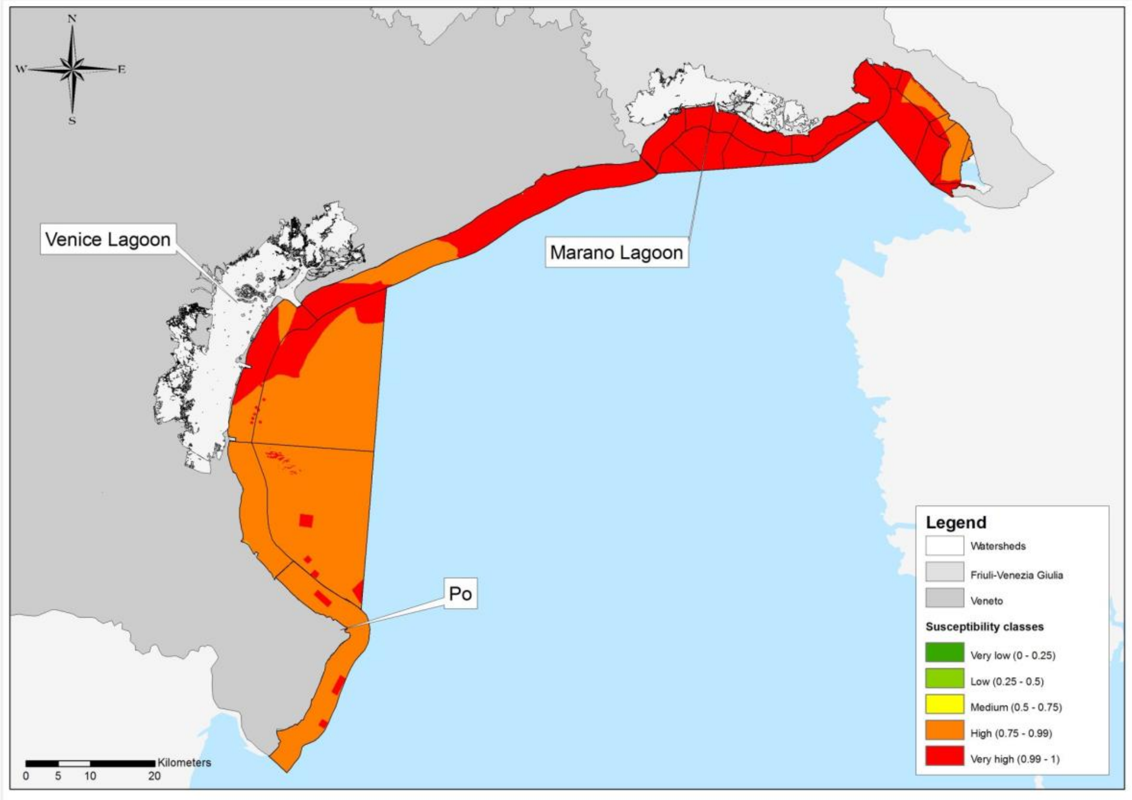


Figure 61. Vulnerability map of Coastal waters to water quality variations under climate change for the North Adriatic sea.

Figure 62 show the percentage of membership of each water bodies to the different vulnerability classes. Result are shown using pie charts and allow understanding how results are homogenous within each water body. Only 18 out of 23 water bodies have more than 15% of their surface within only one vulnerability class.

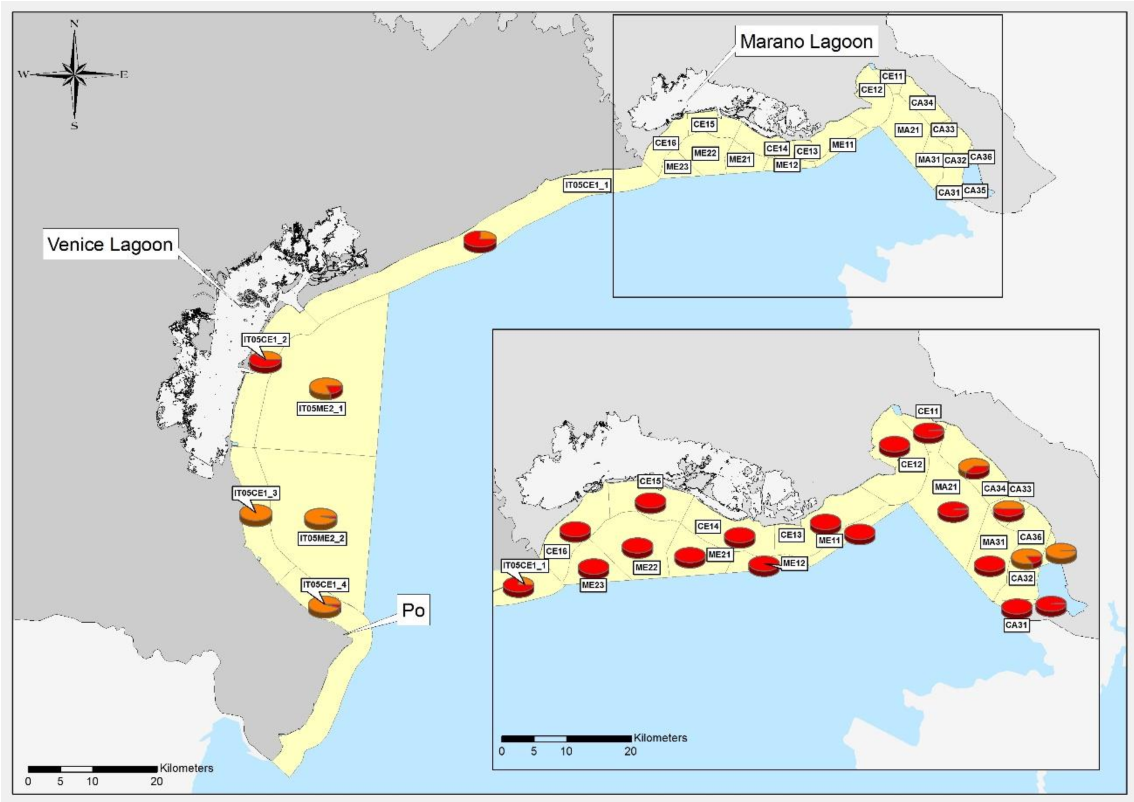


Figure 62. Vulnerability of Coastal waters to water quality variations under climate change for each water body of the North Adriatic sea.

7.3.4. Risk maps

Risk maps identify and rank areas and targets that could be impacted by changes in water quality. The relative risk map produced for the North Adriatic sea for the spring season (Figure 63), which is the worst season, shows scores varying from low to high. Higher relative risk scores are in the area close to the Po river delta and North of the Lido's inlets. The situation in 2100 is always worse than in 2070.

The risk is highly influenced by the hazard assessment. In fact, vulnerability scores are quite homogenous across all the case study area, while hazard scores changes for the different water bodies across the studied region. Moreover water bodies with higher hazard scores have also higher relative risk scores (i.e. from the Po river delta to the Chioggia's inlet and from the Lido's inlet to Bibione, in correspondence to the water bodies IT05CE1_1, IT05CE1_3 and IT05CE1_4).

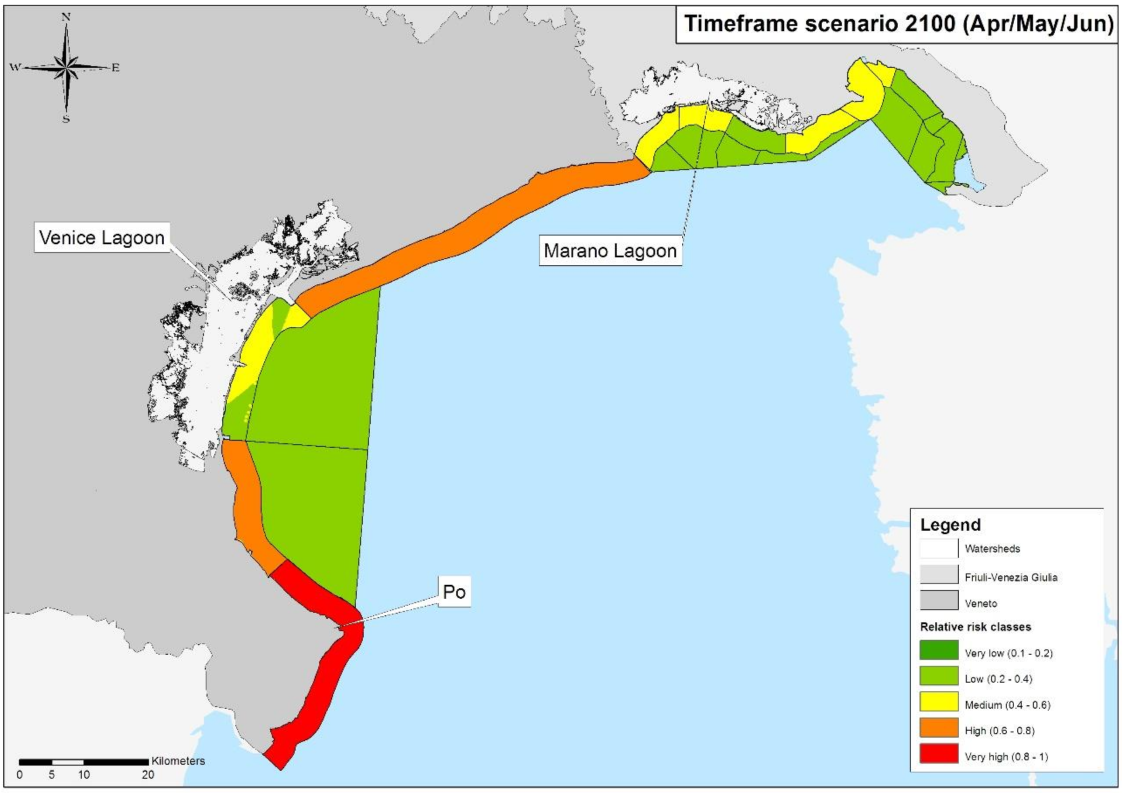


Figure 63. Relative risk map of water quality variations under climate change for the North Adriatic sea.

Statistics were calculate allowing the comparison of the surface in in each relative risk class for the four season and the future scenarios, i.e. 2070 and 2100 (Figure 64).

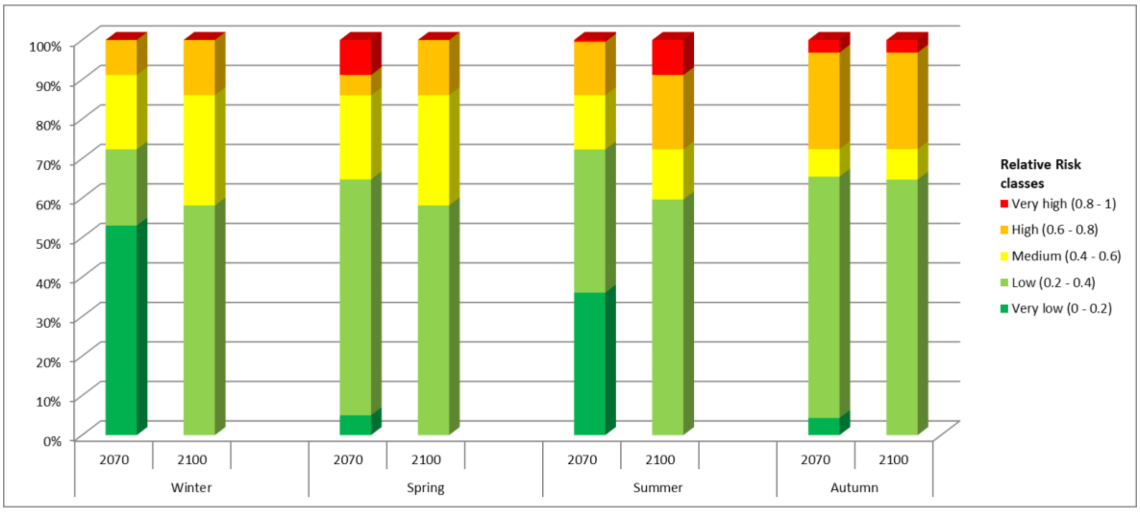


Figure 64. Risk statistics related to water quality variations under climate change for the North Adriatic sea.

7.3.5. Damage maps

Damage maps identify and rank areas and targets where higher loss of environmental and socio-economic values due to water quality variations are expectd. The value map produced for the North Adriatic water bodies (Figure 65) shows that area with higher values are located in front of the Lagoon of Marano and Grando and in front of the Lido's inlet. This in mainly due to the commercial value of production, wich is particularly high in the northern parte of the Adriac Sea. Moreover, a great contribution is given also by the adapted Evenness Index.

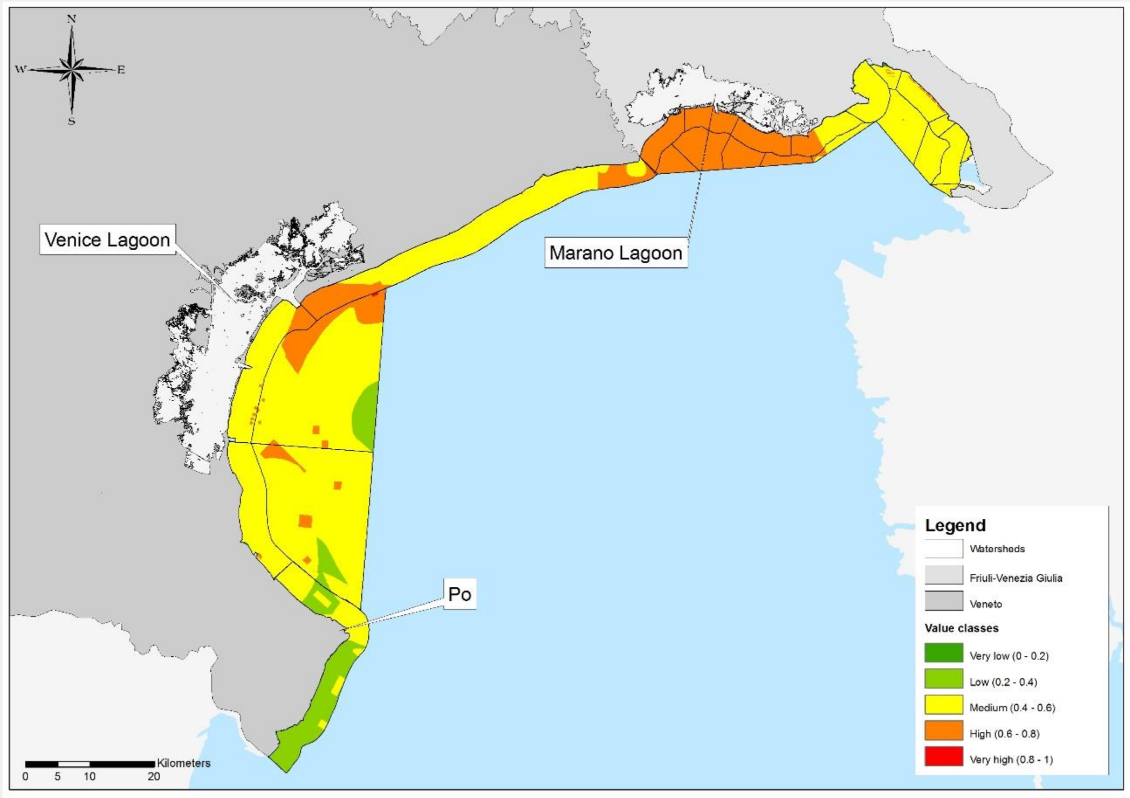


Figure 65. Value map of water quality variations under climate change for the North Adriatic sea.

Figure 66 show the percentage of membership of each water body to the different value classes. All water bodies are classified within 1 or 2 value classes except 2, that are classified within 3 value classes. Moreover, 18 out of the 23 water bodies are classified for more than 75% of their surface within only one value class.

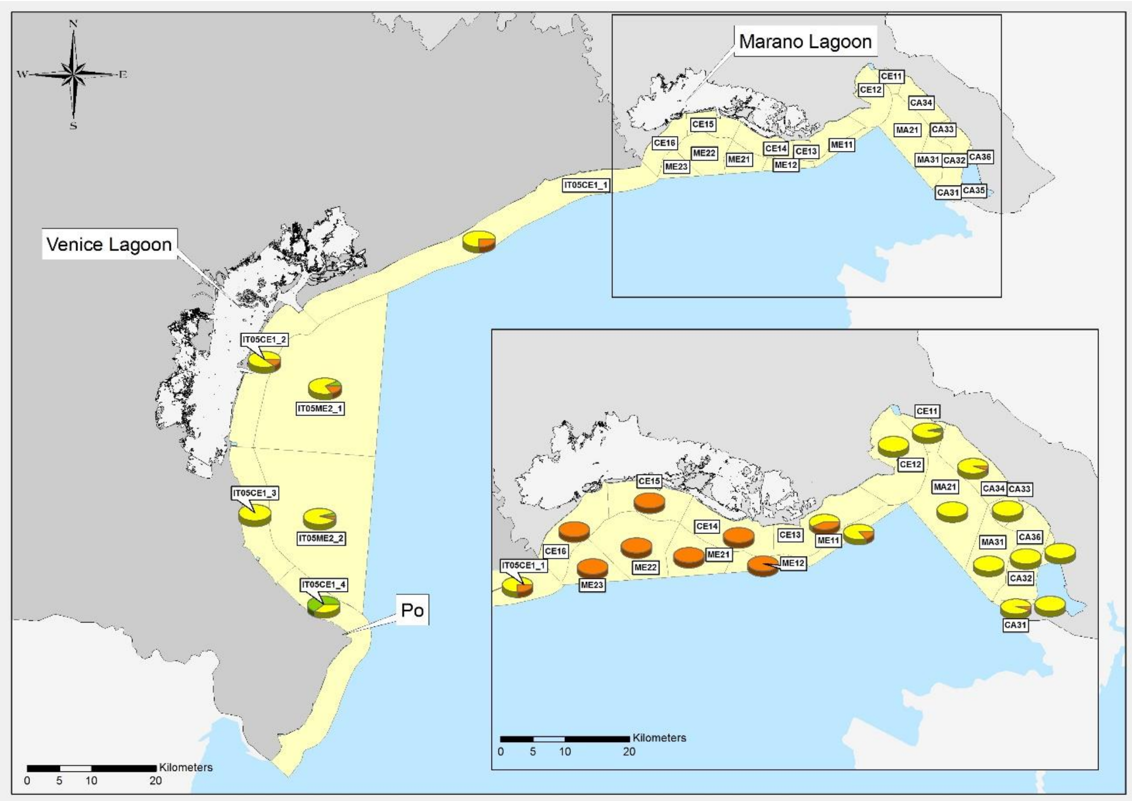


Figure 66. Value of Coastal waters to water quality variations under climate change for each water body of the North Adriatic sea.

The damage map produced for the North Adriatic sea for the spring season (Figure 67), which is the worst season, shows dame scores rangin from the Very low to the Medium class. Based on the produced maps some statistics were calculated (Figure 68). The histogram show the surface in each damage class and allow the comparison between the different season and future scenario. By the graph is clearly evident that in all sesons and scenario (i.e. 2070 and 2100) the percentage of damage in Medium class will be less than 10%.

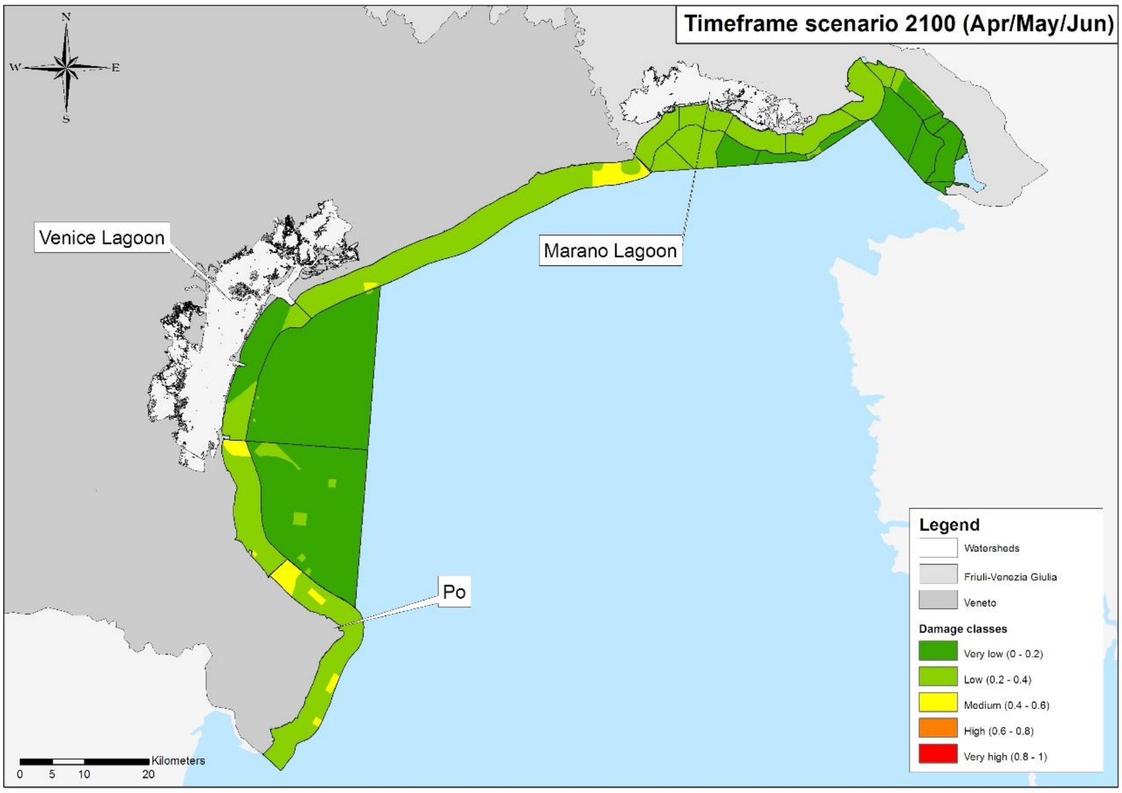


Figure 67. Damage map of water quality variations under climate change for the North Adriatic sea.

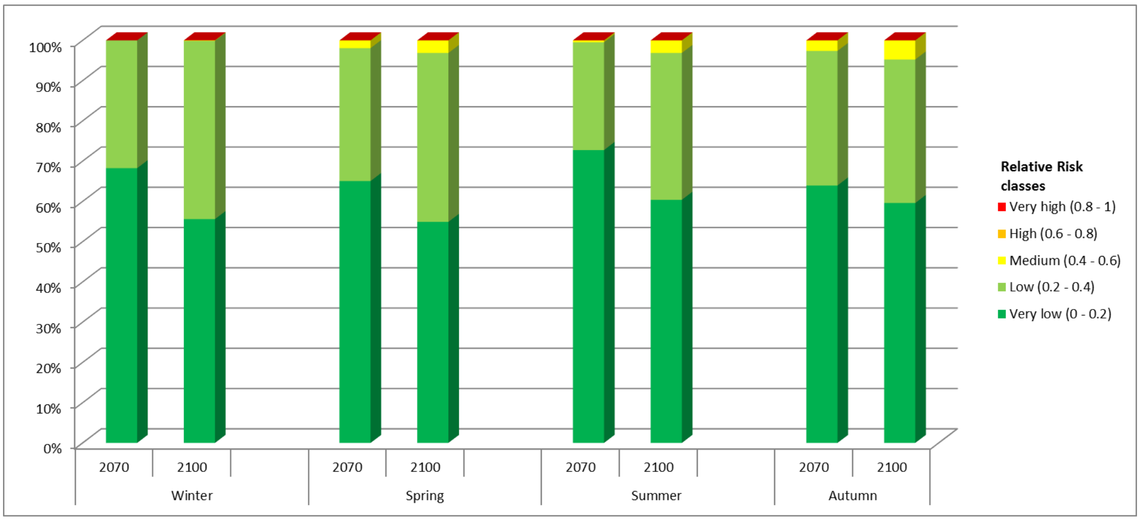


Figure 68. Damage statistics related to water quality variations under climate change for the North Adriatic sea.

Conclusion

A strength of the proposed RRA methodology consists in the use of outputs coming from a chain of models returning information about the spatial and temporal distribution of climate change hazards at the regional scale (i.e. the hazard metrics used as input in the RRA). The same aspect represents a criticality, which is common for all methodologies using data coming from models and chain of models: the difficulties in the estimation of the uncertainty. Every model is characterized by an uncertainty that usually can be quantified by modellers. When integrating or nesting several model this uncertainty increase, but is almost impossible to quantify possible errors. Accordingly, within the proposed RRW approach, the assessment require the selection of several scenarios and the application of the methodology to at least 2 scenarios, including the most optimistic one and the most pessimistic one. This allow evaluating the extreme scenarios, knowing that reality will be between those two extremes.

The originality of the method is represented by the use of MCDA functions and the integration with GIS to produce hazard, risk and damage maps taking into account expert's and stakeholders' judgement. Produced output represent a preliminary ranking at the regional scale of areas and targets who can have higher risk or damages from climate change and can support in the definition of adaptation measures at the regional scale. In particular, hazard, risk and damage maps can support the definition of Plans, Policies and Programs and can be integrated in SEA and EIA processes.

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), used to evaluate the degree of hazard, vulnerability and risk for the considered receptors within the considered region.

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, the results of the application of the proposed methodology and of the DSS highly depends on data availability and on its quality. The availability of larger dataset can allow the inclusion of more factors within the assessment process. Moreover, the higher is the quality of the input data, the higher is the accuracy of the results of the RRA application. On the other side, all data need to be pre-processed in order to homogenise data with different geographic coordinate systems and attribute tables and allow the GIS overlay and calculations within the DSS, thus resulting quite time consuming. Moreover, even if for the application are used the best available geographical information at the regional scale, they can represent potential sources of uncertainty and of geometrical errors in the final risk estimate.

An improvement of the presented work related to the storm surge flooding impact is represented by the use of storm surge models for the simulation of extreme storm surge events (including also information on velocity and directions of extreme events). Moreover within the current application the inundation behind the coastline was estimated with a simplified model based only the water height along the coastline excluding possible riverine floodings. Areas that are currently prone to flooding from catchment based sources (as opposed to sea-level rise) would be at much greater risk than is identified through this analysis. Accordingly, an interesting further development is represented by the investigation of the hazard of coincident events – storm surge floodings with a high rainfall event leading to riverine flooding, for flood prone areas.

The proposed methodology and the DSS DESYCO con be further improved adopting a multi-hazard and multi-risk approach able to take into account the presence of several climate change impacts on the same coastal zones. Moreover, it would important to implement the methodology as a dynamic assessment, taking into account data referred to the same time in all the component of the assessment, Accordingly, modes simulating also vulnerability an value data are necessary to perform the application.

Moreover, it would be important to analyse in a quantitative way errors coming from the model chain and give an estimate of the probability of the different proposed scenario. This would require a stronger cooperation with modellers providing input data for the hazard assessment. In addition, also the uncertainty coming from the contribution to the assessment coming given by experts and stakeholder should be quantified through a sensitivity analysis quantifying how much the output of the assessment are influenced by its input parameters (i.e. scores and weights).

Finally, feedbacks coming from the public authorities who collaborate in the PEGASO project and in the CLIMDAT project related to the application of the RRA methodology and of the DSS DESYCO were recognized to be very useful to support in the definition of Plans, Policies and Programs according to ICZM principles and for the implementation of the Flood directive, taking into account the potential impacts of climate change. The DSS was considered to be use-friendly and easy to use. Moreover, the time required for an application is quite short, suggesting that when data as been prepared is quite simple and fat to prepare several scenarios to be evaluated and compared. The proposed approach allows to understand the main drivers of changes and can support the definition of adaptation measures aimed at reducing consequences of climate changes in the future. The methodology applied to the North Adriatic case can be replicated in any other coastal region of the Mediterranean Sea and Black Sea using set of indicators and dataset customized for each application.

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Annexes

Annex 1 – Comparison of DSS for climate change

Name	Application domain	Regulatory Framework of reference	Objective	Climate change impacts addressed	Climate change scenarios generating impacts
CLIME	• Lakes.	WFD for environmental assessment.	To explore the potential impacts of climate change on European lakes dynamics linked coast.	• Water quality.	• Emission scenarios. • Temperature scenarios.
CORAL	• Coral reef	IWRM and ICZM both for environmental assessment and management.	Sustainable management of coastal ecosystems in particular, coral reef.	• ND	• ND
COSMO	• Coastal zones.	ICZM for environmental management.	To evaluate coastal management options considering anthropic (human) forcing and climate change impacts.	• Sea-level rise.	• Sea-level rise scenarios.
Coastal Simulator	• Coastal zones.	National legislation for environmental assessment and management.	Effects of climate change /management decisions on the future dynamics of the coast.	• Storm surge flooding. • Coastal erosion.	• Emission scenarios. • Sea-level rise scenarios.
CVAT	• Coastal zones.	National legislation for environmental assessment and management.	To assess hazards, vulnerability and risks related to climate change and support hazard mitigation options.	• Storm surge flooding. • Coastal erosion. • Cyclone. • Typhoon. • Extreme events	• Past observations
DESYCO	• Coastal zones. • Coastal Lagoons	ICZM for environmental assessment and management.	To assess risks and impacts related to climate change and support the definition of adaptation measures.	• Sea-level rise. • Relative sea-level rise • Storm surge flooding. • Coastal erosion. • Water quality	• Emission scenarios. • Sea level rise scenarios.
DITTY	• Coastal Lagoons.	IWRM and WFD for environmental management.	To achieve sustainable and rational utilization of resources in the southern European lagoons by taking into account major anthropogenic impacts.	• ND	• ND
DIVA	• Coastal zones.	ICZM for environmental assessment and management.	To explore the effects of climate change impacts on coastal regions.	• Sea-level rise. • Coastal erosion. • Storm surge flooding.	• Emission scenarios. • Sea-level rise scenarios.
ELBE	• River basin. • Catchment.	WFD for environmental management.	To improve the general status of the river basin usage and provide sustainable protection measure within coast.	• Precipitation and temperature variation.	• Emission scenarios.
GVT	• Coastal zones. •	National legislation for environmental assessment.	To describe the vulnerability of groundwater resources to pollution in a particular coastal region.	• Groundwater quality. • Saltwater intrusion.	• Sea-level rise scenarios.
IWRM	• Coastal zones. • River basin •	IWRM for environmental assessment and management.	To explore potential risks on coastal resources due to climate and water management policies.	• Sea-level rise. • Coastal erosion. •	• Sea-level rise scenarios. • Emission scenarios.
KRIM	• Coastal zones.	ICZM for environmental assessment.	To determine how coastal systems reacts to climate change in order to develop	• Sea-level rise. • Extreme events.	• Sea-level rise scenarios.

			modern coastal management strategies.	• Coastal erosion.	• Extreme events scenarios.
MODSIM	• River basin.	IWRM for environmental management.	To improve coordination and management of water resources in a typical river basin.	• ND	• ND
RegIS	• Coastal zones. •	SMP and Habitats regulation (UK) for environmental assessment and management.	To evaluate the impacts of climate change, and adaptation options.	• Coastal and river flooding. • Sea level rise •	• Emission scenarios • Socio-economic scenarios • Sea level rise scenarios
RAMCO	• River basin. • Coastal zones.	WFD and ICZM for environmental assessment and management.	For effective and sustainable management of coastal resources at the regional and local scales.	• ND	• ND
SimLUCIA	• Coastal zones.	National legislation for environmental assessment.	To assess the vulnerability of low lying areas in the coastal zones and island to sea-level rise due to climate change.	• Sea-level rise. • Coastal erosion. • Storm surge flooding.	• Sea-level rise scenarios.
SimCLIM	• Coastal zones.	ICZM for environmental assessment and management.	To explore present and potential risks related to climate change and natural hazards (e.g. erosion, flood).	• Sea-level rise. • Coastal flooding. • Coastal erosion.	• Sea-level rise scenarios.
STREAM	• River basin. • Estuaries.	IWRM and WFD for environmental management.	To integrate the impacts of climate change and land-use on water resources management.	• Water quality variation. • Salt intrusion.	• Emission scenarios.
TaiWAP	• River basin.	IWRM for environmental assessment.	To assess vulnerability of water supply systems to impacts of climate change and water demand.	• Water quality variations.	• Emission scenarios.
WADBOS	• River basin. • Coastal zones.	WFD and ICZM for environmental assessment and management.	To support the design and analysis of policy measures in order to achieve an integrated and sustainable management.	• ND	• ND

Table 16. List of the examined DSSs according to the general technical criteria (ND: Not Defined).

Name	Functionalities	Analytical methodologies	Structural elements
CLIME	• Identification of pressure generated by climatic variables. • Environmental status evaluation. • Water quality evaluation related to climate change. • Socio-economic evaluation. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Probabilistic Bayesian network. • Uncertainty analysis.	• Climatic, hydrological, chemical, geomorphological data. • Climate, ecological and hydrological models. • Web-based user interface
CORAL	• Evaluation of management strategies • Spatial analysis (GIS).	• Scenarios construction and analysis. • Cost-effectiveness analysis. • Ecosystem-based.	• Environmental, socioeconomic, ecological, biological data. • Economic and ecological models. • Desktop user interface.
COSMO	• Problem characterization (e.g. water quality variation, coastal erosion etc.) • Impact evaluation of different development and protection plans. • Indicator production. • Spatial analysis (GIS).	• Scenarios construction and analysis. • MCDA. • Ecosystem-based	• Socio-economic, climatic, environmental, hydrological data. • Ecological, economic and hydrological models. • Desktop user friendly interface
Coastal Simulator	• Environmental status evaluation. • Management strategies identification and evaluation. • Indicator production. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Uncertainty analysis. • Risk analysis. • Ecosystem-based.	• Climatic, socio-economic, environmental, hydrological, geomorphological data. • Ecological, morphological climatic and hydrological models. • Desktop user interface.
CVAT	• Environmental status evaluation. • Hazard identification. • Indicators production.	• Hazard analysis. • Critical facilities analysis. • Society analysis.	• Environmental and socio-economic data. • Hydrological model.

	• Mitigation options identification and evaluation. • Spatial analysis (GIS).	• Economic analysis. • Environmental analysis. • Mitigation options analysis.	• Desktop user friendly interface
DESYCO	• Prioritization of impacts, targets and areas at risk from climate change. • Impacts, vulnerability and risks identification. • Indicators production. • Adaptation options definition • Spatial analysis (GIS).	• Regional Risk Assessment methodology. • Scenarios construction and analysis. • MCDA. • Risk analysis.	• Climatic, biophysical, socio-economic, geomorphological, hydrological data. • Desktop automated user interface.
DITTY	• Management options evaluation • Indicator production. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Uncertainty analysis. • MCDA. • Social cost and benefits analysis. • DPSIR.	• Morphological, social, hydrological, ecological data. • Hydrodynamics, biogeochemical, socio-economic models. • Desktop user interface.
DIVA	• Scenarios generation and analysis. • Environmental status evaluation. • Indicators production. • Adaptation options evaluation. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Cost-benefit analysis. • Ecosystem-based.	• Climatic, socio-economic, geography, morphological data. • Economic, ecological, geomorphological, climate models. • Desktop graphical user interface.
ELBE	• Environmental status evaluation. • Protection measures identification. • End-user involvement. • Spatial analysis (GIS).	• Scenarios construction and analysis.	• Hydrological, ecological, socio-economic, morphological data. • Economic, • Hydrological, models. • Desktop complex user interface.
GVT	• Environmental status evaluation. • Indicators production • Spatial analysis (GIS). • Impact and vulnerability evaluation	• Risks analysis. • Fuzzy logic. • MCDA.	• Data (environmental, climatic, hydrological, socioeconomic). Hydrological, socioeconomic and DEM models. • Desktop user interface.
IWRM	• Environmental status evaluation. • Indicators production. • Adaptation measures evaluation. • Information for non-technical users. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Risk analysis. • Cost-benefit analysis. • Socio-economic analysis.	• Climatic, environmental, socio-economic, geomorphological data. • Hydrodynamic, climate, economic models. • Desktop user interface.
KRIM	• Environmental status evaluation. • Adaptation measures evaluation. • Information for non-technical users. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Impact and risk analysis. • Ecosystem-based.	• Climatic, socio-economic, ecological, environmental, hydrological data. • Economic, ecological, hydrodynamic, geomorphological models. • Desktop user interface.
MODSIM	• Environmental status evaluation. • Management measures evaluation. • Spatial analysis (GIS).	• Statistical analysis. • Analysis of policies.	• Administrative, hydrological, socio-economic, environmental data. • Socio-economic, hydrological models. • Web-based user interface.
RegIS	• Indicators production • Management measures evaluation. • Information for non-technical users. • sectoral evaluation • Spatial analysis (GIS).	• Scenarios construction and analysis. • Impact analysis. • DPSIR. • Integrated assessment.	• Climatic, socio-economic, geomorphological, hydrological data. • Climate and flood metal-models. • Desktop user interface.
RAMCO	• Environmental status evaluation. • Indicators generation. • Management measures evaluation. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Cellular automata. • Ecosystem-based.	• Socio-economic, environmental, climatic data. • Biophysical, socio- economic and environmental models. • Web-based user interface.
SimLUCIA	• Indicators production. • Impact and vulnerability evaluation. • Management and land-use measures evaluation. • Spatial analysis (GIS).	• Cellular Automata. • Scenarios construction and analysis. • Socio-economic analysis. • Bayesian probabilistic networks. • Ecosystem-based.	• Climatic, environmental, socio-economic data. • Land use, social and economic, climate models. • Web-based user interface.
SimCLIM	• Environmental status evaluation. • Impact and vulnerability evaluation. • Adaptation strategies evaluation • Spatial analysis (GIS).	• Scenario construction and analysis. • Statistical analysis. • Risk analysis.	• Climatic, hydrological, socio-economic data. • Climate, hydrological, economic models.

		• Cost/benefit analysis. • Ecosystem-based.	• Desktop user interface.
STREAM	• Environmental status evaluation. • Indicators production. • Management measures evaluation spatial analysis (GIS).	• Scenarios construction and analysis.	• Climatic, socio-economic, ecological, hydrological data. • Climate, hydrological models. • Web-based user interface.
TaiWAP	• Environmental status evaluation.- • Indicators production. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Impact and vulnerability analysis.	• Climatic, socio-economic, hydrological data. • Climate, hydrological, water system dynamic models. • Desktop user interface.
WADBOS	• Management measures identification and evaluation. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Sensitivity analysis. • MCDA.	• Socio-economic, hydrological, environmental, ecological data. • Socio-economic, ecological, landscape models. • Desktop user interface.

Table 17. List of the examined DSSs according to the specific technical criteria.

Name	Scale and area of application	Flexibility	Status and availability last updated version (year)
CLIME	• Supra-National, National, Local. (Northern, western and central part of Europe).	+++ Flexible in structural modification and study area.	Available to the public. Demo. 2010.
CORAL	• Regional, Local. (Coastal areas of Curacao; Jamaica and Maldives).	+++ Flexible in study area.	Not available to the public. Prototype. 1995.
COSMO	• National, Local. (Coast of Netherland).	++ Flexible in study area.	Commercial application. 1998.
Coastal Simulator	• National, Regional, Local. (Coast of Norfolk in East Anglia, UK).	+	Available only to the Tyndall Research Centre. Prototype. 2009
CVAT	• Regional, Local. (New Hanover County, North Carolina).	++ Flexible in study area.	Available to public. Prototype. 2002.
DESYCO	• Regional, Local. (North Adriatic Sea).	++ Flexible in study area.	Not available to the public. Prototype. 2010.
DITTY	• Supranational, National, Regional. (Ria Formosa-Portugal; Mar Menor-Spain; Etang de Thau-France; Sacca di Goro-Italy, Gera-Greece).	+++ Flexible in study area.	Not available to the public. 2006
DIVA	• Global, National.	+++ Flexible in study area.	Available to the public. 2009
ELBE	• Local. (Elbe river basin Germany).	+	Available to the public. 2003
GVT	• Regional, Local. (Eastern Macedonia and Northern Greece).	+	Not available to the public. 2006
IWRM	• Regional, Local. (Halti-Beel, Bangladesh)	++ Flexible in study area.	Not available to the public. Prototype. 2009
KRIM	• Regional. (German North sea Coast, Jade-Weser area in Germany).	+	Not available to the public. Prototype. 2003
MODSIM	• National, Regional. (San Diego Water County, Geum river basin- Korea).	++ Flexible in study area.	Available to the public online. 2006
RegIS	• Regional, Local. (North-West, East Anglia).	++ Flexible in study area.	Available online to stakeholders. Prototype. 2008
RAMCO	• Regional, Local. (South-West Sulawesi coastal zone).	++ Flexible in the used dataset and concepts.	Not available to the public. Prototype. 1999
SimLUCIA	• Local (St Lucia Island, West India)	+	Available online to the public. Demo. 1996
SimCLIM	• National, Regional, Local. (Rarotonga Island, Southeast Queensland).	++ Flexible in structural modification and study area.	Available to the public. Demo. 2009
STREAM	• Regional, Local. (Ganges/Brahmaputra river basin, Rhine river basin, Yangtze river basin and Amudarya river basin).	+++ Flexible in structural modification and study area.	Available online to the public. Demo. 1999
TaiWAP	• Regional, Local. (Touchien river basin).	+	Available to National Taiwan University. Prototype.

			2008
WADBOS	• Regional, Local. (Dutch Wadden sea).	+	Available online to the public. Demo. 2002

Table 18. List of the examined DSSs according to the applicability criteria. (+++, highly flexible; ++, flexible; +: modertly to no-flexible).

Annex 2 – Storm surge output

JPM Outputs

	Return periods (years, months)									
	Adriatic Sea				Venice Lagoon					Marano and Grado Lagoon
Level	Ancona	Ravenna	Piattaforma	Trieste	Chioggia	Lido Diga Sud	Punta della Salute	Burano	Grassabò	Grado
10										
11										
12										
13										
14										
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42										
43										
44										
45										
46	0,01									
47	0,01									
48	0,01									
49	0,01									
50	0,01									
51	0,01									
52	0,01									
53	0,01									
54	0,01									
55	0,01									
56	0,02									
57	0,02									
58	0,02									
59	0,02									
60	0,03									
61	0,03									
62	0,03	0,01								
63	0,03	0,01								
64	0,04	0,01								
65	0,05	0,01								
66	0,05	0,01							0,01	
67	0,06	0,01							0,01	
68	0,07	0,01							0,01	
69	0,08	0,01						0,01	0,01	
70	0,10	0,01						0,01	0,01	
71	0,11	0,01		0,01				0,01	0,01	
72	1,00	0,01		0,01				0,01	0,01	
73	1,02	0,01	0,01	0,01				0,01	0,01	
74	1,03	0,02	0,01	0,01				0,01	0,01	
75	1,05	0,02	0,01	0,01	0,01	0,01		0,01	0,01	
76	1,07	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,01	
77	1,10	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,01	
78	2,00	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,02	
79	2,03	0,03	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,01
80	2,06	0,03	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,01
81	2,10	0,03	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,01
82	3,03	0,04	0,01	0,01	0,01	0,01	0,01	0,02	0,03	0,01
83	3,08	0,04	0,01	0,01	0,01	0,01	0,01	0,03	0,03	0,01
84	4,02	0,05	0,02	0,02	0,01	0,01	0,01	0,03	0,03	0,01
85	4,08	0,05	0,02	0,02	0,01	0,01	0,01	0,03	0,04	0,01
86	5,03	0,06	0,02	0,02	0,01	0,01	0,01	0,03	0,04	0,01
87	5,10	0,06	0,02	0,02	0,02	0,02	0,02	0,03	0,04	0,01
88	7,03	0,06	0,02	0,02	0,02	0,02	0,02	0,04	0,05	0,01
89	9,00	0,07	0,03	0,02	0,02	0,02	0,02	0,04	0,05	0,01
90	11,04	0,07	0,03	0,03	0,02	0,02	0,02	0,04	0,05	0,02
91	14,04	0,08	0,03	0,03	0,02	0,02	0,02	0,05	0,06	0,02
92	18,06	0,09	0,04	0,03	0,02	0,02	0,02	0,05	0,06	0,02
93	24,05	0,09	0,04	0,03	0,03	0,03	0,03	0,06	0,07	0,02
94	33,09	0,10	0,04	0,04	0,03	0,03	0,03	0,06	0,06	0,02
95	49,03	0,11	0,05	0,04	0,03	0,03	0,03	0,07	0,07	0,02
96	77,04	0,11	0,05	0,04	0,03	0,03	0,03	0,07	0,07	0,03
97	133,02	1,00	0,05	0,05	0,04	0,03	0,03	0,08	0,08	0,03
98	269,11	1,01	0,06	0,05	0,04	0,04	0,04	0,08	0,09	0,03
99	669,09	1,02	0,06	0,06	0,05	0,04	0,04	0,09	0,09	0,03
100		1,03	0,07	0,06	0,05	0,04	0,05	0,10	0,10	0,04
101		1,03	0,08	0,07	0,06	0,05	0,05	0,11	0,10	0,04
102		1,05	0,09	0,07	0,07	0,06	0,06	0,11	0,11	0,04
103		1,08	0,09	0,08	0,07	0,05	0,05	1,01	1,00	0,04
104		1,11	0,10	0,09	0,08	0,06	0,05	1,01	1,00	0,05
105		2,02	0,11	0,09	0,08	0,06	0,06	1,02	1,01	0,05
106		2,06	0,11	0,09	0,09	0,06	0,07	1,03	1,01	0,06
107		2,10	1,00	0,11	0,10	0,06	0,07	1,03	1,02	0,06
108		3,04	1,01	0,11	0,10	0,07	0,07	1,04	1,02	0,07
109		3,10	1,01	1,00	0,11	0,07	0,08	1,05	1,03	0,07
110		4,05	1,02	1,01	0,11	0,07	0,08	1,06	1,04	0,07
111		5,01	1,03	1,03	1,00	0,08	0,08	1,06	1,04	0,08
112		5,11	1,03	1,05	1,01	0,08	0,09	1,07	1,05	0,08
113		6,11	1,04	1,06	1,02	0,09	0,09	1,08	1,06	0,09
114		8,01	1,05	1,05	1,02	0,09	0,09	1,08	1,07	0,10
115		9,05	1,06	1,06	1,03	0,10	0,10	1,09	1,07	0,10
116		11,01	1,07	1,08	1,04	0,11	0,10	1,10	1,08	0,11
117		13,02	1,07	1,10	1,05	0,11	0,10	1,10	1,09	1,00
118		15,08	1,08	1,11	1,06	1,00	0,11	1,11	1,10	1,00
119		18,09	1,09	1,11	1,07	1,01	0,11	1,11	1,11	1,01
120		22,08	1,10	2,02	1,07	1,02	0,11	2,00	2,01	1,02
121		27,06	1,10	2,04	1,08	1,02	0,11	2,00	2,02	1,03
122		33,10	1,11	2,07	1,09	1,03	0,11	2,00	2,03	1,04
123		42,00	1,11	2,10	1,10	1,04	1,00	2,03	2,04	1,05
124		52,09	2,00	3,01	1,11	1,05	1,00	2,06	2,06	1,06
125		66,02	2,00	3,03	2,00	1,07	1,01	2,09	2,07	1,07
126		83,10	2,02	3,06	2,01	1,08	1,02	3,01	2,09	1,09
127		106,04	2,05	3,09	2,02	1,09	1,03	3,05	3,01	1,10
128		136,05	2,07	4,00	2,03	1,10	1,05	3,10	3,05	1,11
129		177,00	2,10	4,04	2,04	2,00	1,06	4,03	3,10	2,01
130		231,03	3,02	4,07	2,05	2,02	1,08	4,10	4,04	2,02
131		305,10	3,05	4,11	2,06	2,04	1,10	5,05	4,11	2,04
132		409,09	3,09	5,03	2,07	2,05	2,01	6,01	5,07	2,05
133		581,11	4,02	5,07	2,08	2,08	2,03	6,10	6,05	2,07
134		854,04	4,07	5,11	2,09	2,10	2,07	7,08	7,04	2,09
135		1293,01	5,01	6,04	2,10	3,00	2,10	8,08	8,05	3,00
136		2066,11	5,07	6,08	2,11	3,03	3,02	9,10	9,08	3,04
137		3659,06	6,02	7,01	3,00	3,06	3,07	11,01	11,02	3,08
138		7257,05	6,11	7,06	3,01	3,11	4,00	12,07	13,00	4,01
139		15564,00	7,08	7,11	3,02	4,04	4,06	14,03	15,02	4,06
140		64590,09	8,07	8,05	3,03	4,11	5,01	16,01	17,08	5,00
141		645907,01	9,08	8,10	3,03	5,06	5,09	18,02	20,09	5,06
142			10,10	9,04	3,04	6,02	6,06	20,06	24,06	6,02
143			12,03	9,10	3,05	7,00	7,05	23,02	29,01	6,10
144			13,11	10,04	3,08	7,11	8,07	26,01	34,10	7,08
145			15,10	10,10	3,11	8,11	9,10	29,05	41,10	8,06
146			18,01	11,05	4,03	10,02	11,05	33,01	50,10	9,07
147			20,10	11,11	4,07	11,08	13,03	37,04	62,02	10,09
148			24,00	12,05	5,00	13,04	15,06	42,01	76,11	12,02
149			27,11	13,00	5,05	15,05	18,02	47,10	95,02	13,09
150			32,07	13,06	5,11	17,10	21,06	54,10	119,00	15,08
151			38,04	14,00	6,05	20,08	25,08	62,11	149,06	17,11
152			45,05	14,07	6,11	24,03	30,09	72,08	190,00	20,07
153			54,01	15,05	7,07	28,05	37,03	84,06	244,02	23,09
154			64,07	16,03	8,03	33,08	45,04	99,06	319,04	27,05
155			77,11	17,02	9,01	40,01	55,08	117,11	430,00	31,11
156			94,07	18,02	10,00	48,02	68,11	140,05	597,06	37,04
157			115,07	19,02	11,00	58,04	86,08	167,05	818,11	44,02
158			143,01	20,02	12,01	71,03	109,09	204,06		52,06
159			178,07	21,03	13,04	87,11	141,09	251,07		62,09
160			224,10	22,04	14,09	110,01	185,00	310,06		75,08
161			286,00	23,06	16,05	140,02	247,04	390,01		92,09
162			368,11	24,09	18,03	180,07	336,08	511,03		114,04
163			478,06	26,00	20,04	237,00	466,07	677,04		143,04
164			642,04	27,03	22,09	315,05	671,10	919,01		179,11
165			896,05	28,08	25,06	428,04	983,04			232,05
166				30,01	28,07	585,05				302,10
167				31,08	32,03	822,05				398,05
168				33,03	36,05					533,03
169				34,11	41,04					731,02
170				36,08	47,00					
171				38,07	53,08					
172				40,07	61,09					
173				42,09	71,06					
174				45,00	83,04					
175				47,05	97,07					
176				50,00	115,08					
177				52,10	138,06					
178				55,09	167,01					
179				58,10	205,02					
180				62,02	254,07					
181				65,08	322,09					
182				69,06	414,02					
183				73,06	535,09					
184				77,10	728,10					
185				82,05						
186				87,05						
187				92,08						
188				98,04						
189				104,05						
190				111,00						
191				118,00						
192				125,09						
193				134,00						
194				143,00						
195				152,10						
196				163,06						
197				174,09						
198				187,03						
199				201,00						
200				215,07						
201				232,00						
202				250,00						
203				269,10						
204				291,05						
205				316,02						
206				343,11						
207				374,09						
208				410,03						
209				450,08						
210				496,11						
211				549,11						
212				612,01						
213				685,01						
214				772,09						
215				876,08						

Table 19. Return periods for the considered tide gauge stations.

Exposure statistics

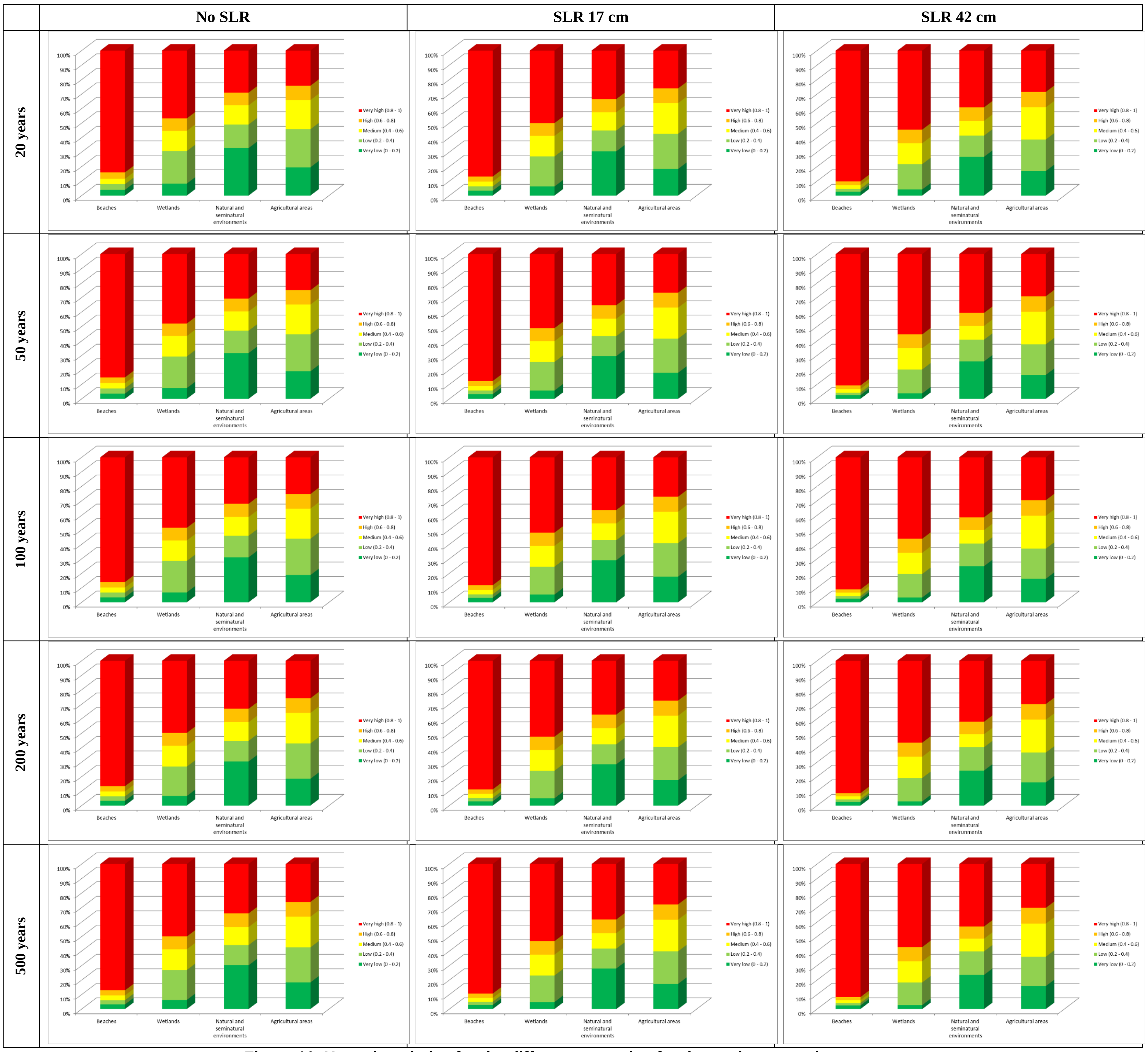


Figure 69. Hazard statistics for the different scenarios for the environmental receptors.

Figure 70. Hazard statistics related to infrastructures.

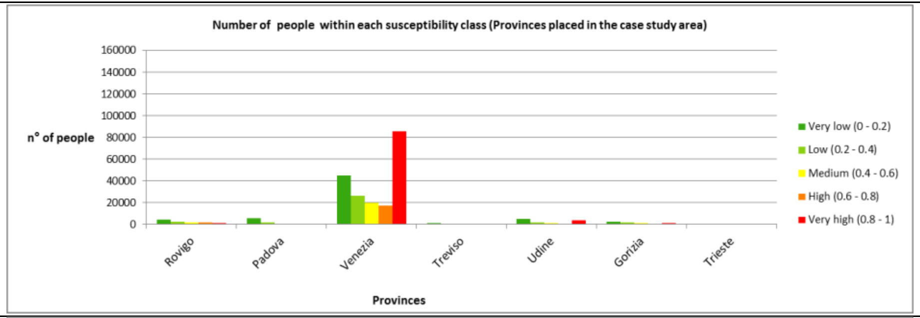
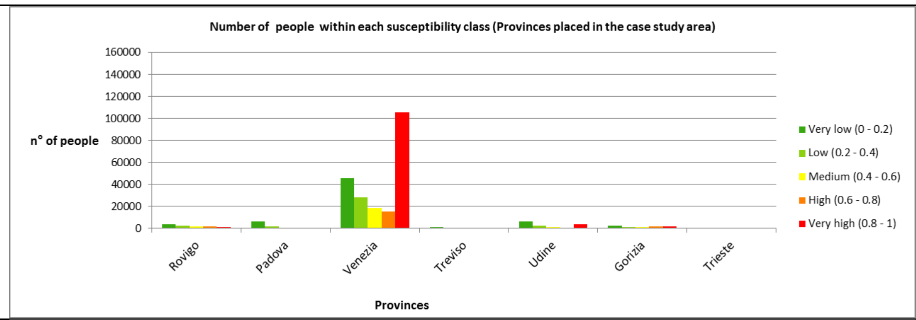
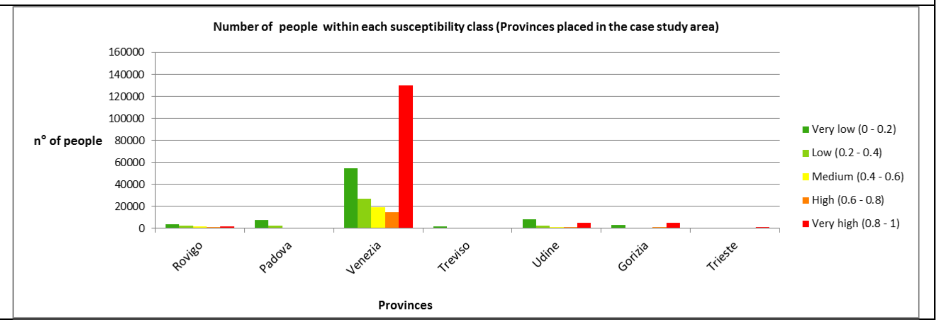
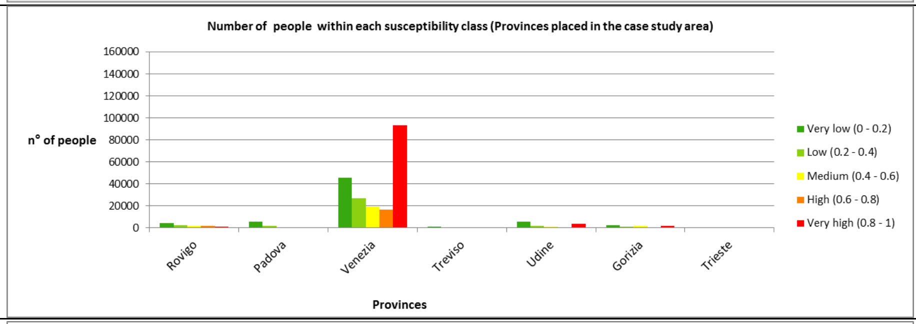
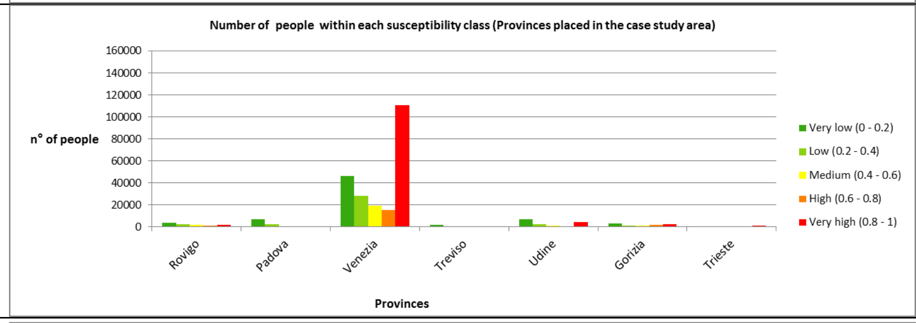
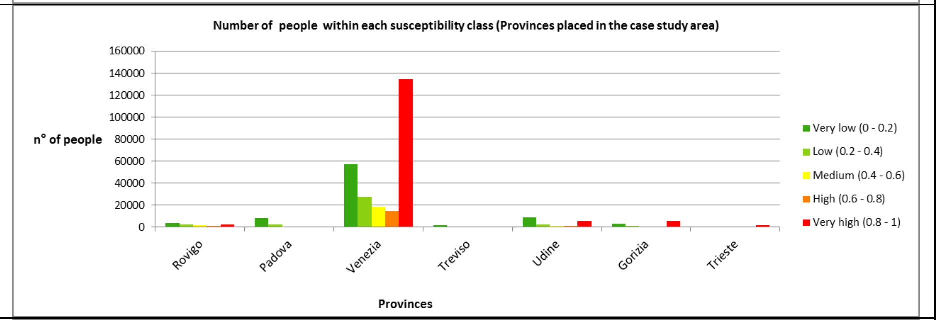
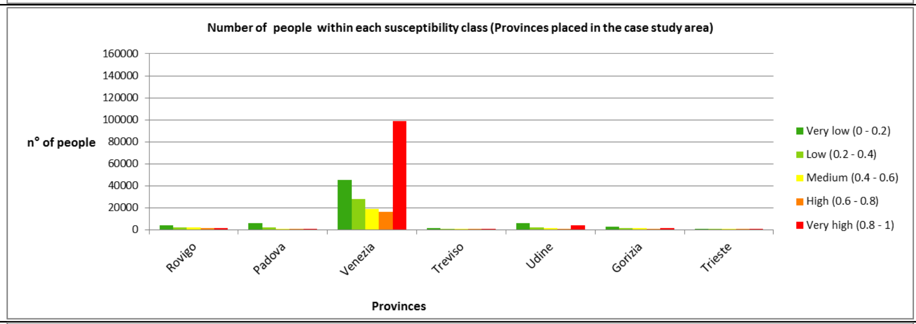
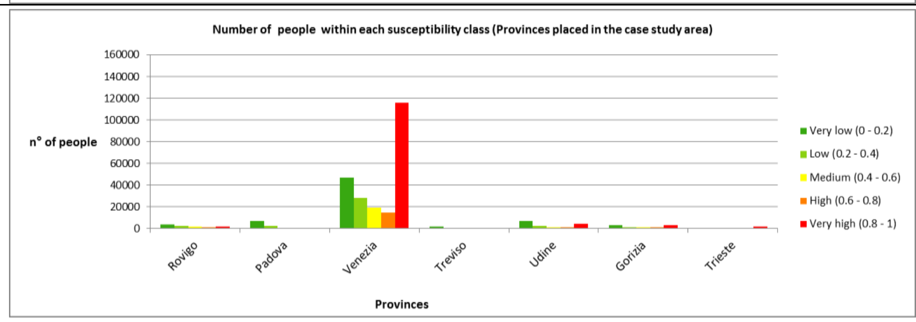
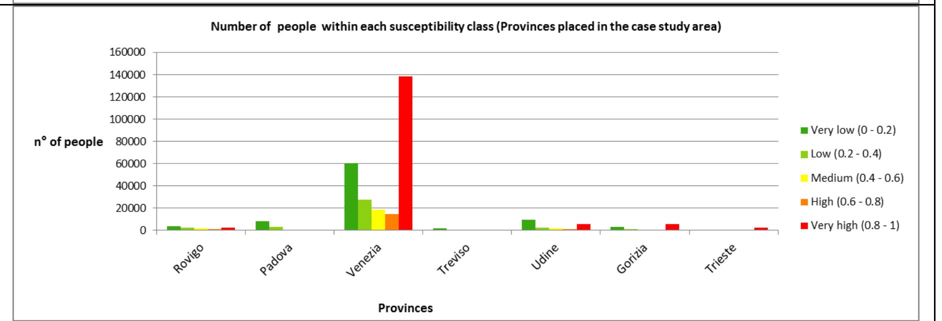
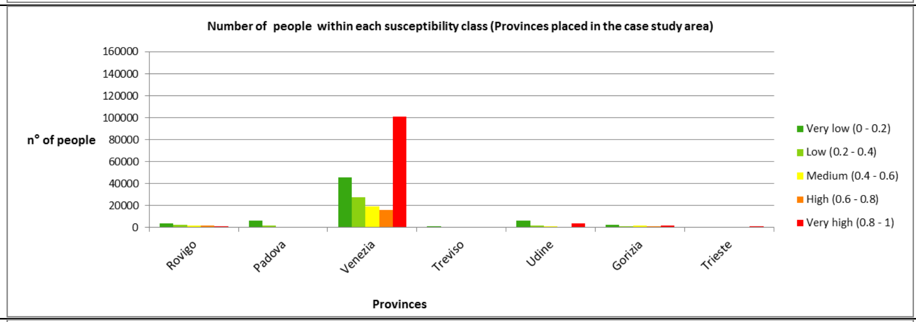
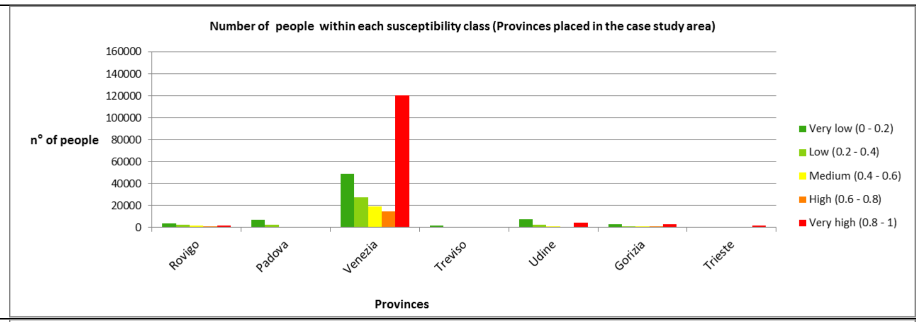
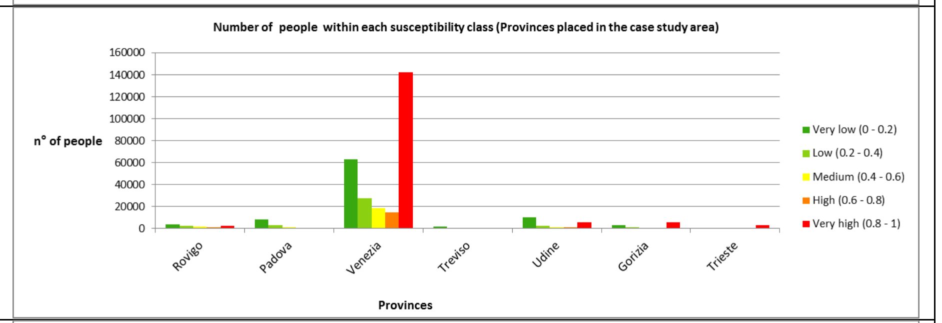
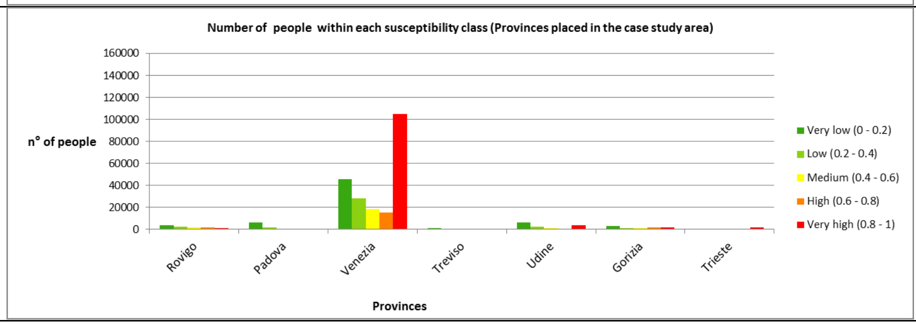
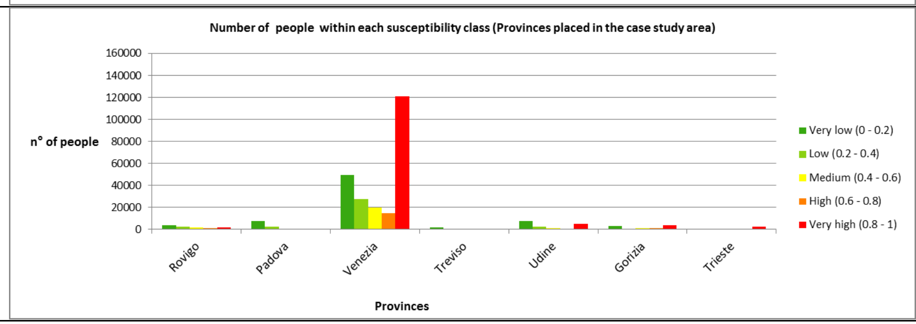
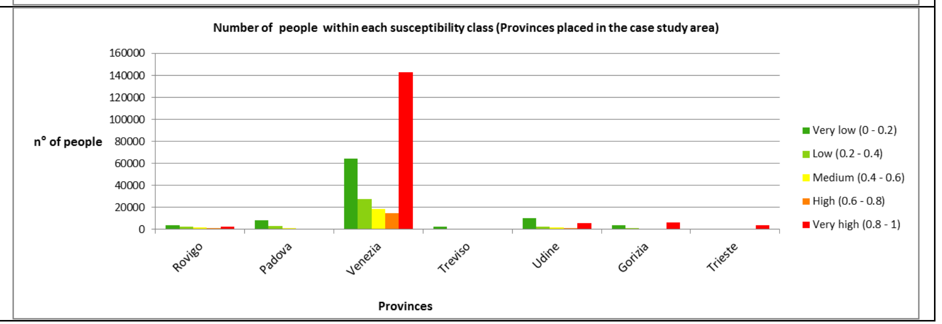
	No SLR	SLR 17 cm	SLR 42 cm
20 years			
50 years			
100 years			
200 years			
500 years			

Figure 71. Hazard statistics related to population.

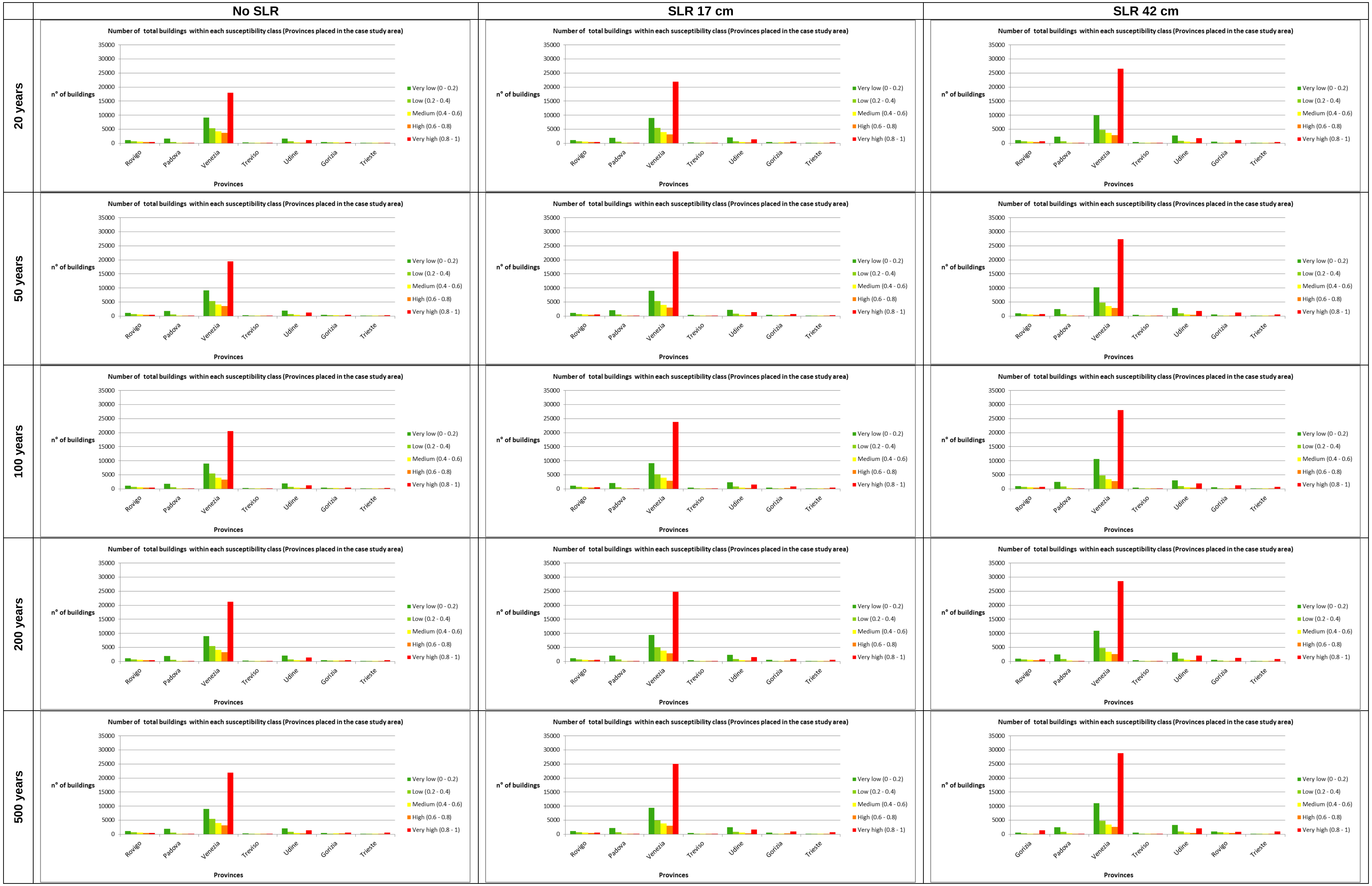


Figure 72. Hazard statistics related to building

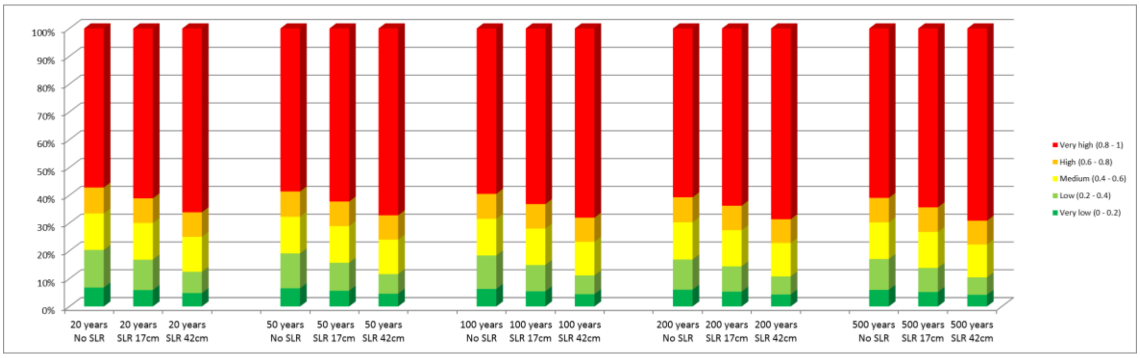
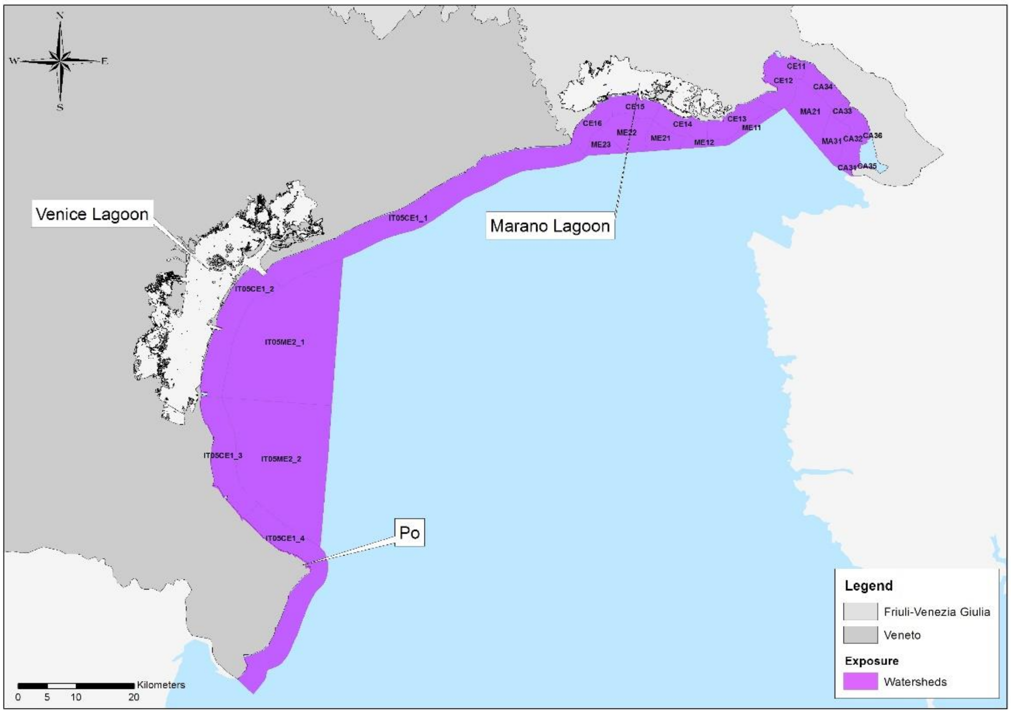


Figure 73. Hazard statistics related to cultural heritage.

Annex 3 – Water quality output

Exposure map



Vulnerability factors maps

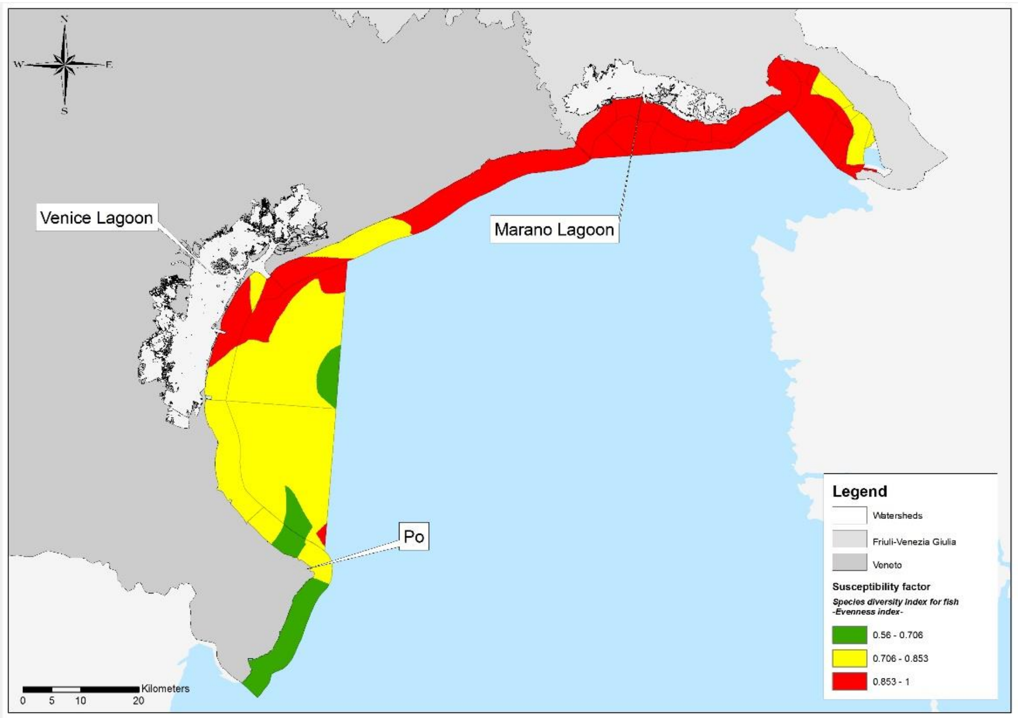


Figure 74. Adapted Evenness index.

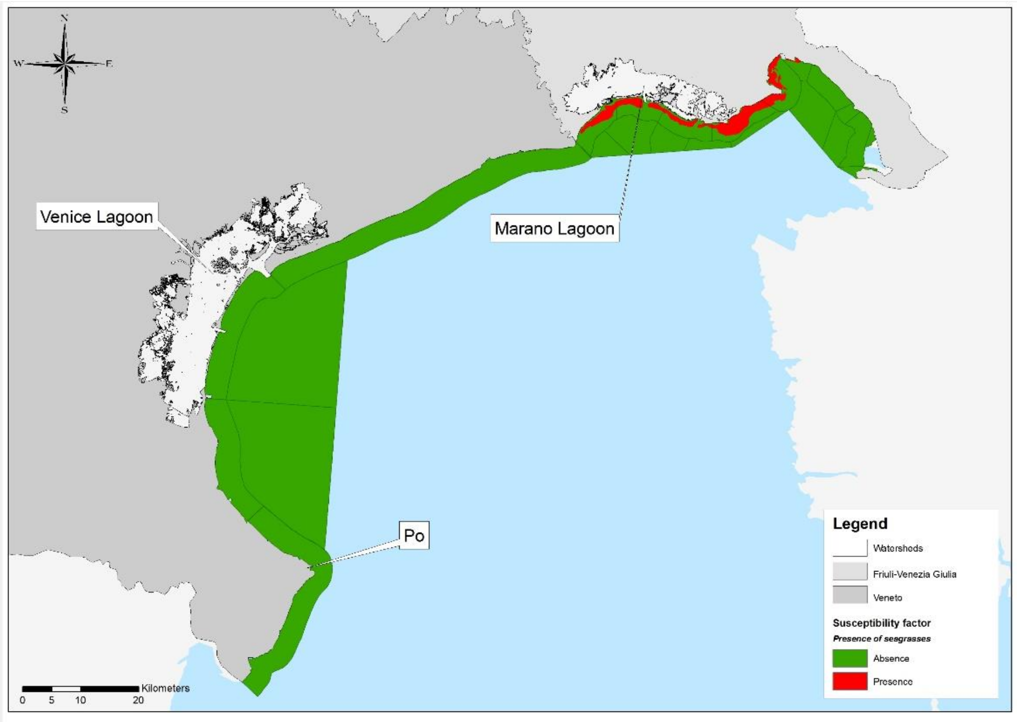


Figure 75. Presence of seagrasses.

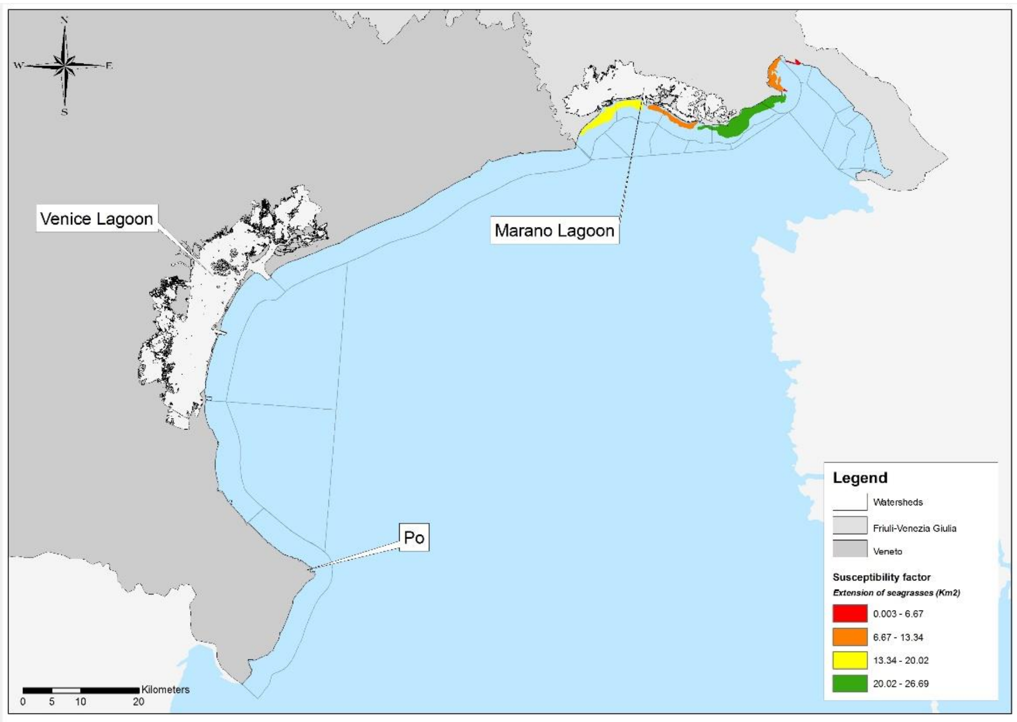


Figure 76. Extension of seagrasses.

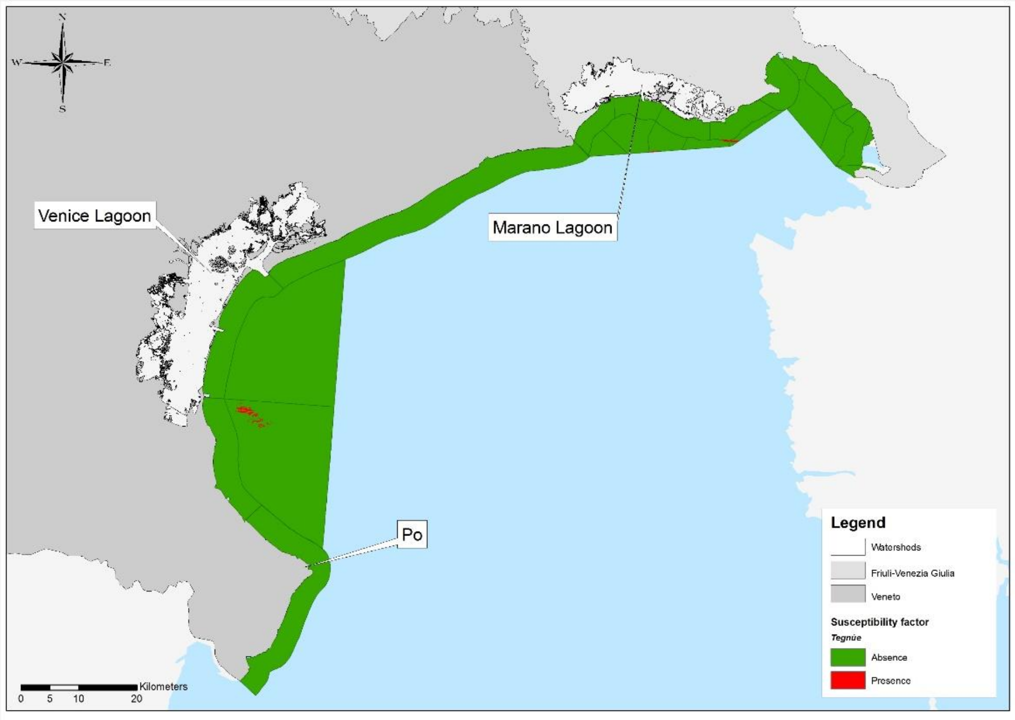


Figure 77. Presence of Tegnùe.

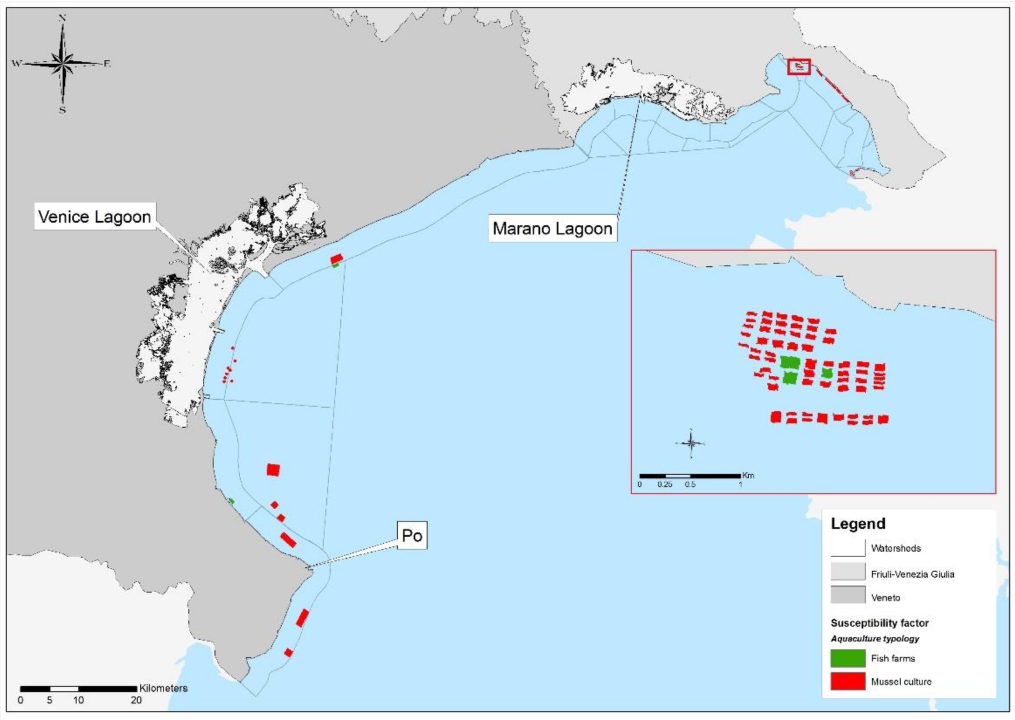


Figure 78. Aquaculture typology.

Risk maps

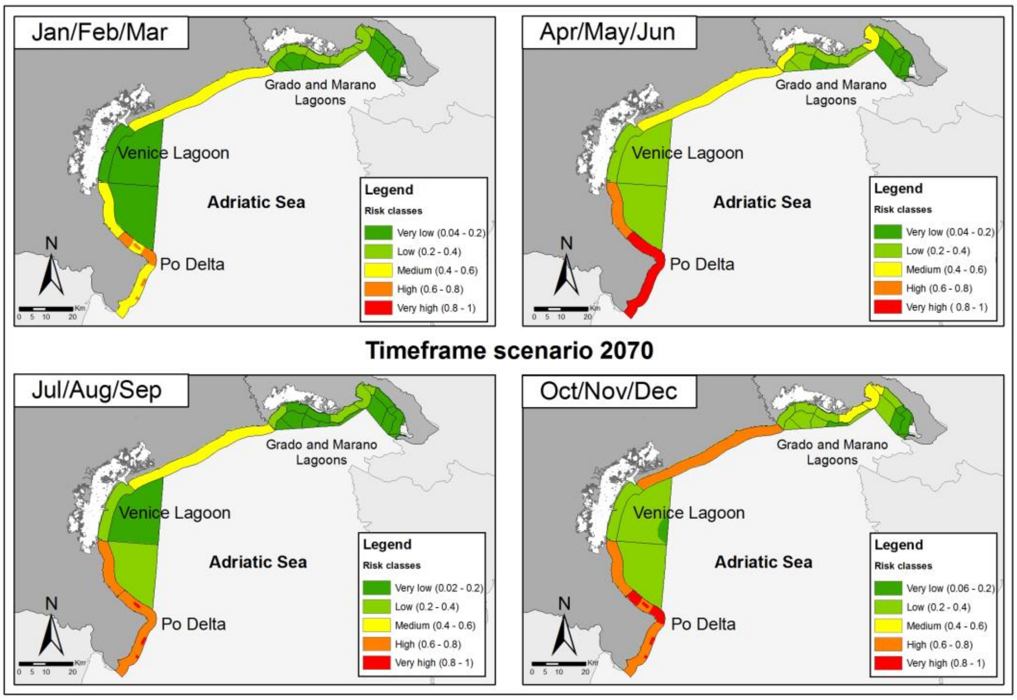


Figure 79. Risk maps of water quality variations under climate change for the North Adriatic coastal water bodies for the year 2070.

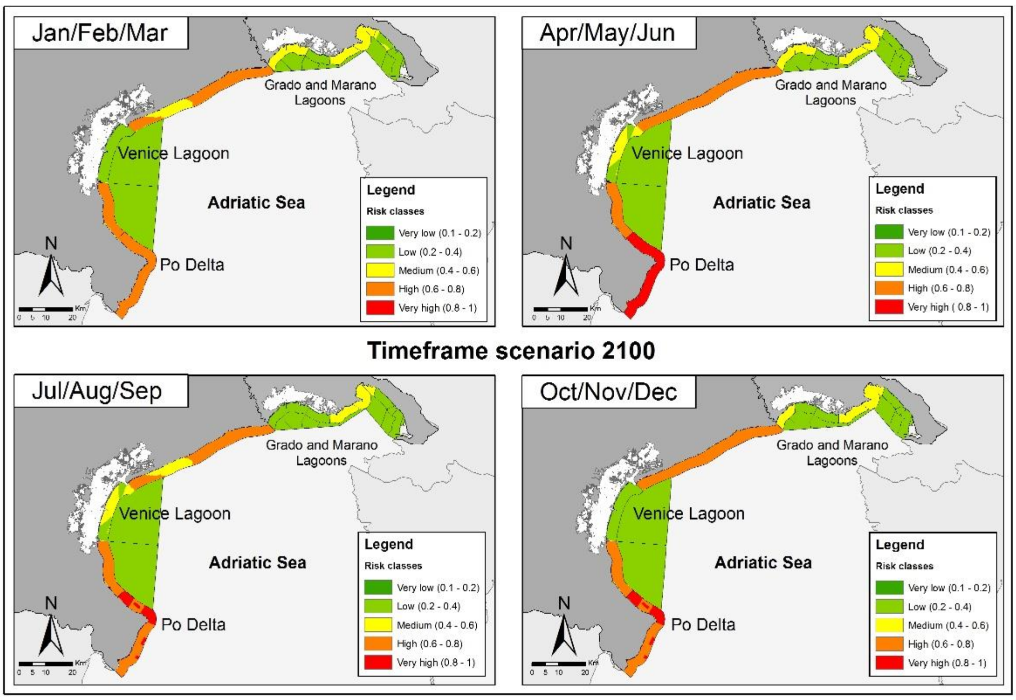


Figure 80. Hazard map of water quality variations under climate change for the North Adriatic coastal water bodies for the year 2100.

Value factors maps

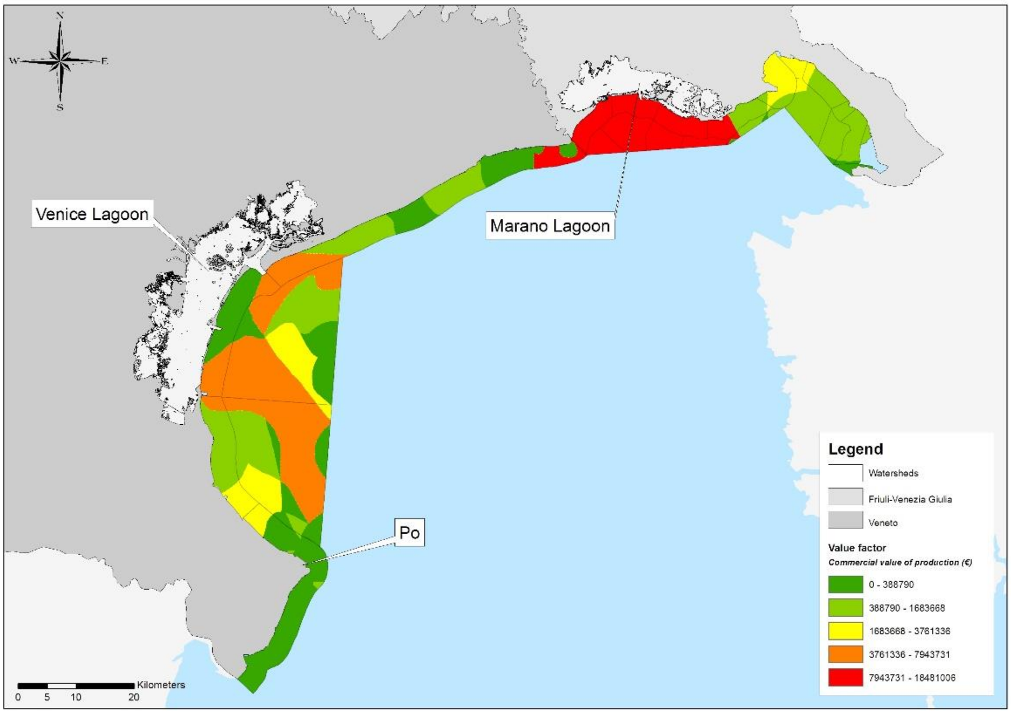


Figure 81. Commercial value of production.

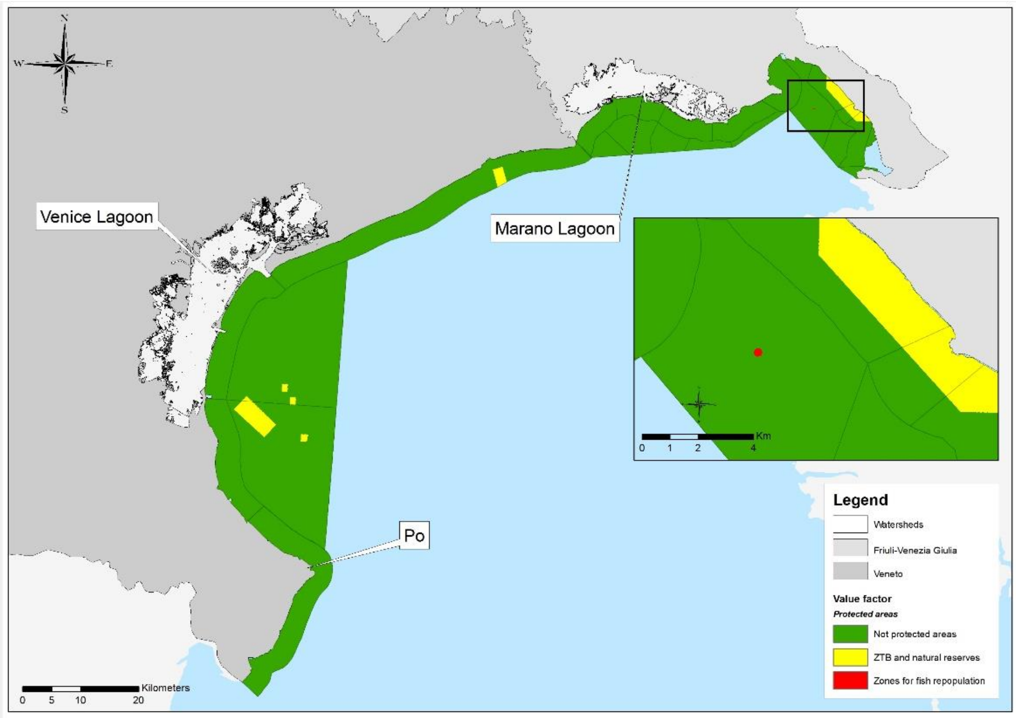


Figure 82. Protected areas, ZTB, natural reserves and zones for fish repopulation.

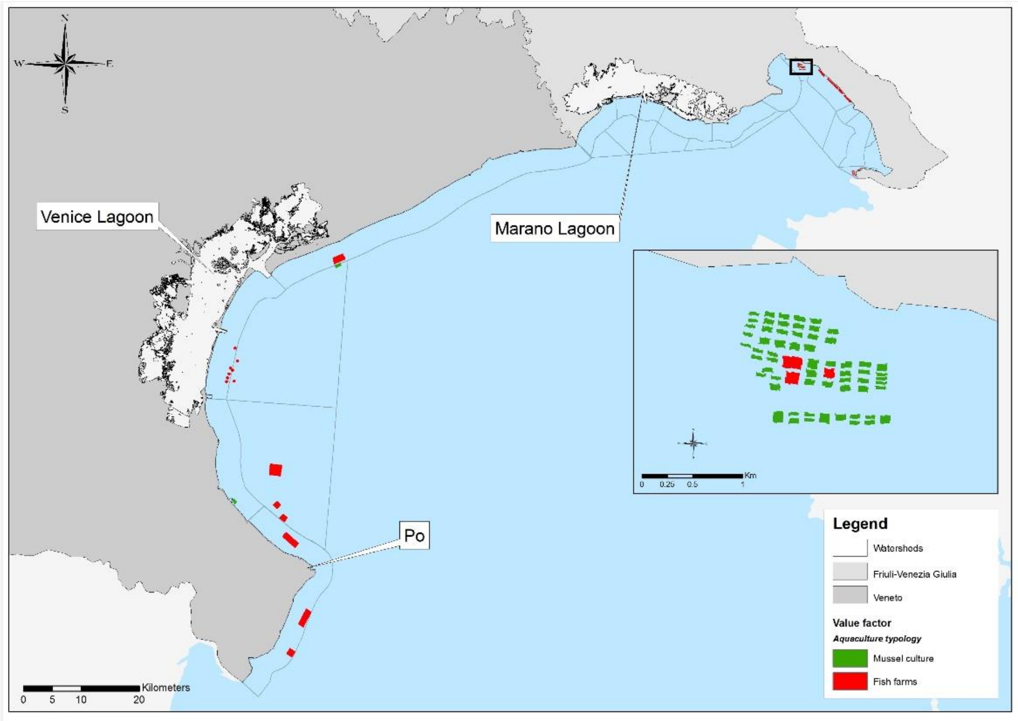


Figure 83. Aquaculture typology.

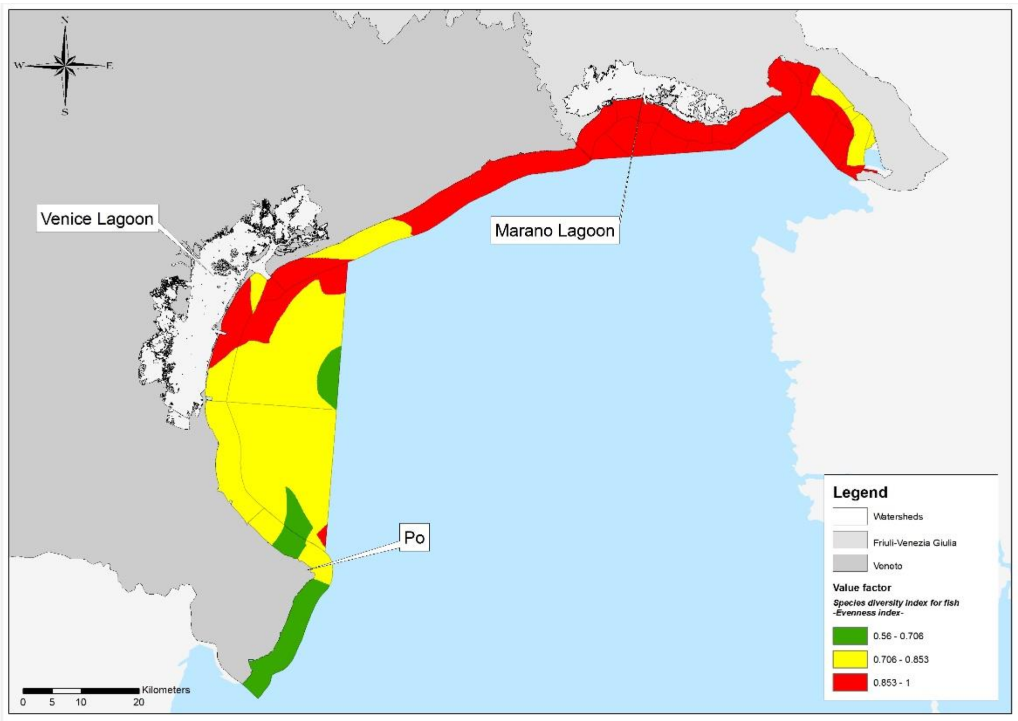


Figure 84. Adapted Evenness Index.

Damage maps

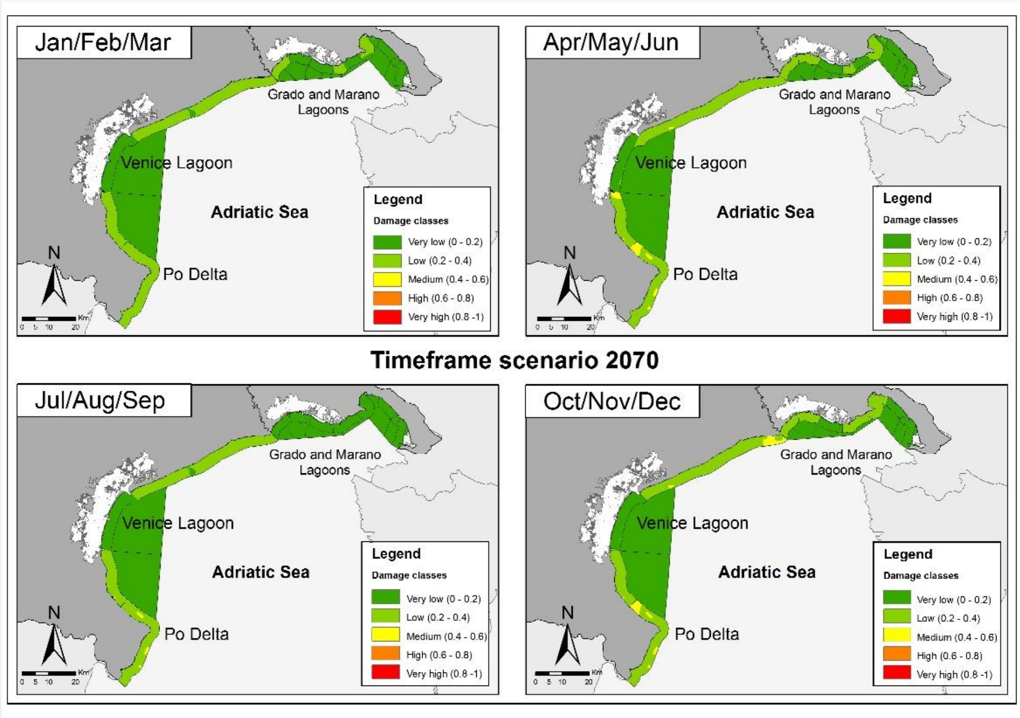


Figure 85. Damage maps of water quality variations under climate change for the North Adriatic coastal water bodies for the year 2070.

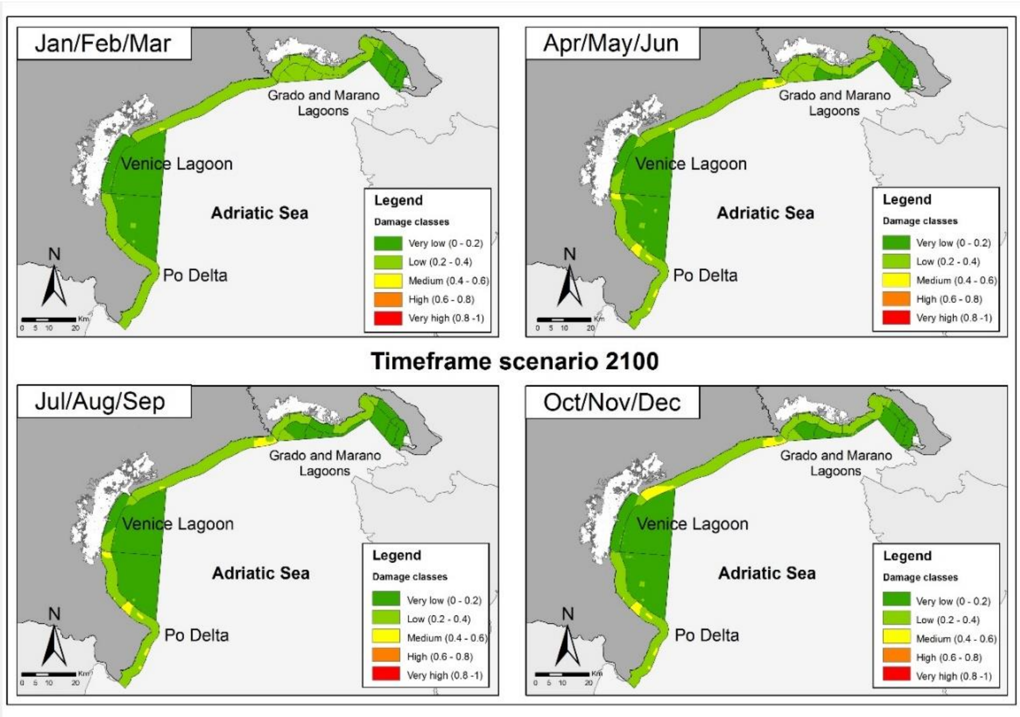


Figure 86. Damage maps of water quality variations under climate change for the North Adriatic coastal water bodies for the year 2100.