Università
Ca'Foscari
Venezia

Scuola Dottorale di Ateneo
Graduate School

Dottorato di ricerca
in Scienze ambientali
Ciclo 27°
Anno di discussione 2015

An advanced methodology for the multi-risk assessment.
An application for climate change impacts in the North Adriatic case study (Italy).

SETTORE SCIENTIFICO DISCIPLINARE DI AFFERENZA: CHIM/12
Tesi di Dottorato di Valentina Gallina, matricola 824026

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Summary

Climate change will pose multiple impacts on natural and human systems worldwide, increasing risks from long-term climate trends and disasters triggered by weather extremes. Until now, a hazard by hazard approach was considered in risk assessment for evaluating the consequences of individual natural and climate-related hazards (e.g. heavy precipitation events, droughts, floods, debris flows, landslides, storm surges) on vulnerable systems, without any consideration of an integrated assessment of multiple risks triggered by different forces.

Starting from an initial review of existing multi-risk assessment concepts and tools applied by international organisations and projects, the main aim of the thesis was to develop and apply an advanced and interdisciplinary multi-risk methodology, allowing a sound assessment and communication of the multi-faceted threats posed by a variety of climate-related hazards across regions and sectors. A multi-hazard assessment was developed to analyze the relationships of multiple hazards (e.g. sea-level rise, coastal erosion, storm surge) happening in the same spatial and temporal area, using an influence matrix and the disjoint probability. Then, the multi-vulnerability of different exposed receptors (e.g. natural systems, beaches, agricultural and urban areas) was estimated through a variety of vulnerability indicators (e.g. vegetation cover, sediment budget, % of urbanization) associated to different hazards. Finally, the multi-risk assessment was performed by integrating the multi-hazard with the multi-vulnerability index for the exposed receptors, thus supporting the development of information useful to stakeholders in the definition of adaptation strategies. The methodology was tested in the North Adriatic coast producing GIS-based multi-hazard, exposure, multi-vulnerability and multi-risk maps. The results of the analysis showed that the areas affected by higher multi-hazard scores are located close to the coastline where all the investigated hazards are present. Multi-vulnerability assumes relatively high scores in the whole case study, showing that beaches, wetlands, protected areas and river mouths are the more sensitive targets. Finally, the multi-risk map presents a similar trend - of the multi-hazard map, highlighting beaches as the receptor more affected by multi-risk with a relevant percentage of surface (i.e. 60%) in the very high and high multi-risk classes. The final estimate of multi-risk for coastal municipalities provides useful information for local public authorities to set future priorities for adaptation and define future plans for shoreline and coastal management in view of climate change.

In conclusion, the proposed multi-risk methodology is a step forward to traditional single risk assessments, providing a more comprehensive – even if relative - assessment of the multiple impacts and risks affecting the same area. Moreover, moving from the multi-risk methodologies generally developed for natural hazards, the presented methodology considers also future scenarios of climate-related hazards, providing a generic guideline for its application to different case studies, scale of analysis and contexts. The proposed multi-risk methodology can be applied adopting a bottom-up approach considering stakeholder needs in order to obtain tailored risk-based adaptation services suitable to mainstream adaptation in the development of plans, policies and programmes.

Sommario

I cambiamenti climatici causeranno molteplici impatti sia sui sistemi naturali che umani a livello globale, aumentando i rischi legati agli andamenti climatici al lungo termine e ai disastri causati da eventi estremi. Finora, per l'analisi del rischio era stato considerato un approccio di valutazione sui singoli pericoli al fine di valutare le conseguenze dei pericoli naturali e associati ai cambiamenti climatici (ad es. eventi di precipitazione estrema, siccità, inondazioni, colate di debris flow, frane, mareggiate) su sistemi vulnerabili, senza tuttavia alcuna analisi integrata dei molteplici rischi innescati da diverse forzanti

Partendo da un'analisi iniziale di concetti, strumenti, organizzazioni e progetti esistenti riguardo l'analisi multi-rischio applicati a livello internazionale, l'obiettivo principale della tesi è stato quello di sviluppare e applicare una metodologia avanzata e interdisciplinare di analisi multi-rischio, al fine di permettere una valutazione e comunicazione affidabile delle diverse minacce causate dai diversi pericoli legati ai cambiamenti climatici, in differenti regioni e settori.

La valutazione dei multi-pericolo permette di analizzare le relazioni tra i molteplici pericoli (ad es. innalzamento del livello del mare, erosione costiera, mareggiate) che possono verificarsi nella stessa finestra spazio-temporale utilizzando una matrice di influenza e l'analisi delle probabilità disgiunte. Successivamente, la multi-vulnerabilità di recettori esposti (ad es. sistemi naturali, spiagge, aree agricole e urbane) è stata stimata attraverso indicatori di vulnerabilità (ad es. copertura vegetale, budget sedimentale, % di urbanizzazione) associati ai diversi pericoli. Infine, la valutazione di multi-rischio è stata svolta integrando l'indice di multi-pericolo con la multi-vulnerabilità degli elementi esposti, al fine di supportare lo sviluppo di informazioni multi-rischio che siano utili per gli utenti finali nella definizione di strategie di adattamento.

La metodologia è stata applicata alle coste del Nord Adriatico, fornendo delle mappe su base GIS di multi-pericolo, esposizione, multi-vulnerabilità e multi-rischio.

I risultati mostrano che le aree colpite da i più alti punteggi di multi-pericolo sono localizzate vicino alla linea di costa dove sono presenti tutti i pericoli analizzati. La multi-vulnerabilità assume punteggi relativamente alti in tutta l'area studio, evidenziando che le spiagge, le aree umide, le aree protette e le bocche di fiume sono i recettori più sensibili.

Infine, la mappa di multi-rischio presenta un andamento simile rispetto alla mappa di multi-pericolo, sottolineando che le spiagge rappresentano il recettore più colpito dai molteplici rischi con una percentuale superficiale rilevante (i.e. 60%) nelle classi di multi-rischio alta e molto alta.

La stima finale di multi-rischio per i comuni costieri fornisce delle informazioni utili per le autorità locali al fine di definire priorità future di adattamento e piani per la gestione costiera in un'ottica di cambiamento climatico.

In conclusione, la metodologia multi-rischio proposta permette di fare un passo avanti rispetto alla tradizionale valutazione dei singoli rischi, fornendo un'analisi più completa – anche se relativa – dei molteplici impatti e rischi che colpiscono la stessa area. Inoltre, partendo dalle metodologie multi-rischio generalmente sviluppate per i pericoli naturali, la presente metodologia considera anche gli scenari futuri per i pericoli derivanti dai cambiamenti climatici, fornendo delle linee guida utili per la sua applicazione a diversi casi studio, scale di analisi e contesti. La metodologia di multi-rischio può essere applicata adottando un approccio bottom-up considerando le necessità degli utenti finali al fine di ottenere degli strumenti efficaci per lo sviluppo di piani, politiche e programmi.

List of Contributions

Published papers and book chapters:

Iyalomhe F. Rizzi J. Torresan S., **Gallina V.** Critto A. Marcomini A., 2011. Inventory of GIS-based Decision Support Systems addressing climate change impacts on coastal waters and related inland watersheds. In Singh B. R. (Ed.). Climate Change - Realities, Impacts Over Ice Cap, Sea Level and Risks. Chapter 10, pp. 251-272. Intech, ISBN 980-953-307-389-2.

Ronco P., **Gallina V.**, Torresan S., Zabeo A., Semenzin E., Critto A., Marcomini A., 2014. The KULTURisk Regional Risk Assessment methodology for water-related natural hazards – Part 1: Physical-environmental assessment, Hydrol. Earth Syst. Sci. Discuss., 11, 7827-7874, doi:10.5194/hessd-11-7827-2014.

Manuscripts under review:

Rizzi J., **Gallina V.**, Torresan S., Gana S., Critto A., Marcomini A., 2014. Application of a Regional Risk Assessment addressing the impacts of climate change on the coastal area of the Gulf of Gabès (Tunisia). Regional Environmental Changes.

Gallina V., Torresan S., Critto A., Glade T., Marcomini A., 2014. A review of multi-risk methodologies for natural hazards: challenges for a climate change impact assessment. Journal of Environmental Management. It refers to Chapter 2 of the thesis.

Torresan S., **Gallina V.**, Gualdi S., Bellafiore D., Umgiesser G., Sclavo M., Carniel S., Giubilato E., Critto A., 2014. Assessment of climate change impacts in the North Adriatic coastal area. Part I: A multi-model chain for the definition of climate change hazard scenarios. Climate Research.

Gallina V., Torresan S., Zabeo A., Rizzi J., Sclavo M., Carniel S., Pizzol L., Critto A., Assessment of climate change impacts in the North Adriatic coastal area. Part II: Coastal erosion impacts at the regional scale. Climate Research.

Gallina V., S. Torresan, A. Critto, D. Brombal, J. Xue, J. Zhao, A. Marcomini. Review of regulatory frameworks, approaches and methodologies for environmental risk assessment and management related to climate change, 2014. In P. Farah (Editor) "Sustainable energy and environmental risk analysis: the scientific support to decision making in Europe and Asia".

Isigonis P, Torresan S, Sperotto A., **Gallina V.**, Zabeo A, Critto A, Marcomini A. Review of organisations, methods and tools for the provision of relevant climate services for different sectors of society, 2014. In P. Farah (Editor) "Sustainable energy and environmental risk analysis: the scientific support to decision making in Europe and Asia".

Manuscripts in preparation:

Gallina V., Torresan S., Zabeo A., Critto A., Glade T., Marcomini A. A multi-risk methodology for the assessment of climate change impacts: the case study of the North Adriatic coast (Italy).

Torresan S., **Gallina V.**, Rizzi J., Critto A., Marcomini A. Regional Risk Assessment applied to study Sea Level Rise impacts on the North Adriatic Sea.

Sperotto A., Torresan S., **Gallina V.**, Critto A., Coppola E., Marcomini A. Development of risk-based adaptation services for pluvial floods under climate change scenarios in the urban territory of the municipality of Venice.

Ronco P., Bullo M., **Gallina V.**, Torresan S., Critto A., Zabeo A., Semenzin E., Olschewski R., Marcomini A. Assessing flood risk in Zurich, Switzerland: the KR-RRA approach. In: Planning the Adaptation to Climate Change for the Cities of the Tropical and Sub Tropical Regions, Tiepolo & Pezzoli Editors, De Gruyter Versita Open Access, 2014.

Working papers:

Giannini V., Torresan S., **Gallina V.**, Critto A., Marcomini A., 2013. Deliverable 8.2 - Workshop report: context and objectives, confrontation of data supply. Integrated case study: Veneto and Friuli Venezia Giulia, Northern Adriatic Sea, Italy. CLIM-RUN - Project No. 265192.

Torresan S., Sperotto A., Giannini V., **Gallina V.**, Critto A., Marcomini A., 2013. Deliverable 8.4 Cross-cutting conclusions. CLIM-RUN - Project No. 265192.

Gallina V., Torresan S., Critto A., Zabeo A., Semenzin E., Marcomini A., 2012. Deliverable 1.7 Part A. Development of a risk assessment methodology to estimate risk levels. FP7-ENV-2010 KULTURISK Project 265280.

Giannini V., Torresan S., **Gallina V**., Critto A., Giupponi C., Marcomini A., 2012. Deliverable 8.1 - Workshop report: context and objectives, comparison of data supply and demand, simulation results, feedback and discussion. Integrated case study: Veneto and Friuli Venezia Giulia, Northern Adriatic Sea, Italy. CLIM-RUN - Project No. 265192.

Branković Č., Torresan S., **Gallina V**., Giannini V., 2012. Deliverable 8.3 Protocol definition. CLIM-RUN - Project No. 265192.

Balbi S., Giupponi C., Gain A., Mojtahed V., **Gallina V.**, Torresan S., Marcomini A., 2012. Deliverable 1.6 The KULTURisk Framework (KR-FWK): A conceptual framework for comprehensive assessment of risk prevention measures. FP7-ENV-2010 KULTURISK Project 265280.

Proceedings of national and international conferences (extended abstracts):

Torresan S., J. Rizzi, A. Zabeo, A. Critto, **V. Gallina**, E. Furlan, A. Marcomini, Assessing environmental impacts of climate change at the regional scale to provide adaptation services: the DEcision support SYstem for COastal climate change impact assessment (DESYCO), in “Proceedings of the first annual conference SISC on climate change and its implications on ecosystem and society”, Lecce, Italy, pp. 468-476, ISBN 978 – 88 – 97666 – 08 – 0.

Ronco P., **V. Gallina**, S. Torresan, A. Critto, A. Zabeo, E. Semenzin, A. Marcomini, Towards flood risk assessment in a climate change perspective in “Proceedings of the first annual conference SISC on climate change and its implications on ecosystem and society”, Lecce, Italy, pp. 468-476, ISBN 978 – 88 – 97666 – 08 – 0.

Torresan S., Rizzi J., Zabeo A., Pasini S., **Gallina V.**, Critto A., Marcomini A., 2011. Climate change impacts on coastal areas: results from the SALT, TRUST, CANTICO and PEGASO projects. Proceedings of the Tenth International Conference on the Mediterranean Coastal Environment MEDCOAST, 25-29 October 2011, Rhodes, Greece, Mediterranean Coastal Foundation, Dalyan, Mugla, Turkey, vol.1, p. 401-410.

Abstracts at conferences:

Gallina V., Torresan S., Sperotto A., Furlan E., Critto A., Marcomini A., 2014. Development of climate risk services under climate change scenarios in the North Adriatic coast (Italy), Accepted to European Geosciences Union General Assembly 2014 Vienna Austria 27 April – 2 May 2014.

Gallina V., Torresan S., Critto A., Marcomini A., 2014. Multi-risk assessment: from natural hazards to climate change. , Accepted to European Geosciences Union General Assembly 2014 Vienna Austria 27 April – 2 May 2014.

Gallina V., Torresan S., Critto A., Zabeo A., Sperotto A., Marcomini A., 2014. Assessing multiple climate change impacts in coastal zones: the North Adriatic case study (Italy). Accepted to Società Italiana per le Scienze del Clima. Seconda conferenza annuale Venezia 29-30 September 2014.

Torresan S., Sperotto A., **Gallina V.**, Furlan E., Critto A., Marcomini A., 2014. Developing climate risk and adaptation services in coastal zones: an integrated bottom-up approach applied in the North Adriatic coast. Accepted to Società Italiana per le Scienze del Clima. Seconda conferenza annuale Venezia 29-30 September 2014.

Gallina V., Torresan S., Critto A., Zabeo A., Semenzin E., Marcomini A. A methodology for the assessment of flood hazards at the regional scale, Accepted to European Geosciences Union General Assembly 2013 Vienna Austria 7 – 12 April 2013.

Gallina V., Torresan S., Giannini V., Rizzi J., Zabeo A., Gualdi S., Bellucci A., Giorgi F., Critto A., Marcomini A. Climate services for the assessment of climate change impacts and risks in coastal areas at the regional scale: the North Adriatic case study (Italy), Accepted to European Geosciences Union General Assembly 2013 Vienna Austria 7 – 12 April 2013.

Rizzi J., Torresan S., **Gallina V.**, Critto A., Zabeo A., Marcomini A. Regional Risk Assessment for the analysis of the risks related to storm surge extreme events in the coastal area of the North Adriatic Sea, Accepted to European Geosciences Union General Assembly 2013 Vienna Austria 7 – 12 April 2013.

Gallina V., Torresan S., Zabeo A., Isigonis P., Rizzi J., Critto A., Semenzin E., Marcomini A., 2012. A risk-based methodology for assessing water-related hazards at the regional scale. EGU Leonardo 2012, 'HYDROLOGY AND SOCIETY', November 14th – November 16th,Torino, Italy.

Critto A., **Gallina V**., Torresan S., Rizzi J., Zabeo A., Carniel S., Sclavo M., Marcomini A. Coastal erosion impacts under climate change scenarios at the regional scale in the North Adriatic Sea, Accepted to European Geosciences Union General Assembly 2012 Vienna Austria 22 – 27 April 2012.

Torresan S., **Gallina V**., Giannini V., Rizzi J., Zabeo A., Critto A., Marcomini A. DESYCO: a Decision Support System to provide climate services for coastal stakeholders dealing with climate change impacts, Accepted to European Geosciences Union General Assembly 2012 Vienna Austria 22 – 27 April 2012.

Rizzi J., Torresan S., Zabeo A., Pasini S., **Gallina V.**, Critto A., Marcomini A., 2011. A GIS-based Decision Support System for the Assessment and Sustainable Management of Climate Change Impacts on Coastal Areas and Groundwater Resources at the Regional Scale. SuWaMa Conference, Istambul, Turkey, September 2011.

1.1. Motivations and objectives

According to the report of the World Bank on the main hotspots of natural hazards (Dilley et al. 2005), about 3.8 million km^2 and 790 million people in the world are relatively highly exposed to at least two hazards, while about 0.5 million km^2 and 105 million people to three or more hazards. In this context, the relevance for adopting a multi-risk assessment approach emerges from international organizations (e.g. Dilley et al. 2005; IPCC 2012) at a range of spatial scales, including the European level (EC 2010). Also in the special report of extreme events and disasters (IPCC 2012), the IPCC points out the relevance of adopting a multi-hazard approach in order to allow adaptation and reduction measures more effective, in the present and particularly in the future. Moreover, multi-risk approaches should be considered and applied in all geographical areas affected by several hazard types for a spatially oriented risk management and for the development of Environmental Impact Assessment and Strategic Environmental Assessment (Greiving et al. 2006; Carpignano et al. 2009; EC 2011).

At the global and European level, the interest about the multi-risk assessment increased in the last decade. This concept is generally used in applications and initiatives aimed at the assessment of risks derived from different natural and man-made hazardous events (e.g. Schmidt-Thomè 2006; FEMA 2011; Farrokh and Zhongqiang 2013).

However, usually a hazard by hazard approach is considered for evaluating the consequences of individual natural and climate-related hazards (e.g. heavy precipitation events, droughts, floods, debris flows, landslides, storm surges) on vulnerable systems (EC 2004; DEFRA 2006; Kappes et al. 2010; Santini et al. 2010; Feyen et al. 2011; Hinkel et al. 2011). Specifically, single-risk analysis allows a determination of the individual risk arising from one particular hazard and process occurring in a specific geographic area during a given period of time (Bell and Glade 2004a; EC 2010), while it does not provide an integrated assessment of multiple risks triggered by different forces (natural and anthropogenic) (Glade and von Elverfeldt 2005; IPCC 2007; World Bank 2010; Marzocchi et al. 2012).

For instance, coastal zones will be exposed to different climate change impacts and consequences, such as storms, coastal erosion, sea-level rise and saltwater intrusion (IPCC 2007; Nicholls and Cazenave 2010; Torresan et al. 2012). This highlights the importance to consider all these hazards simultaneously in order to approximate their dependencies and to provide a useful overview of the total risk arising from climate change (IPCC 2012) for that particular coast. Therefore, a comprehensive approach should be applied to the assessment of natural and specifically climate-related disaster risks in order to consider the whole aspects contributing to the increase of hazards, exposure and vulnerability in a multi-risk perspective (Del Monaco et al. 2007; Garcia-Aristizabal and Marzocchi 2011). Moreover, future changes in exposure and vulnerability should be considered as key determinants of loss and should be analysed together with natural climate variability and anthropogenic climate change for the assessment of disaster risks and impacts (IPCC 2012).

The objective of this thesis is to develop a multi-risk assessment of potential natural and climate change impacts on multiple natural ecosystems and human sectors (e.g. beaches, wetlands, urban and agricultural areas), in order to support the development of risk management strategies and the definition of adaptation measures.

The methodology was developed with the aim to be flexible and applicable to different case studies and spatial scales (i.e. from local to national) and for different hazards (i.e. natural and climate-related hazards). This innovative assessment should provide a useful spatial tool for territorial authorities to improve risk assessment and management decision making including all the risks affecting the analysed area (Greiving et al. 2006; Kappes 2011). The final goal is to provide improved scientific-based and local knowledge about the different impacts and risks posed by natural and climate-related hazards, in order to aid decision making processes and spatial planning.

Moving beyond the traditional single hazard analysis (Torresan 2008; Torresan et al. 2012; Gallina et al. 2014 b; Rizzi 2014), the proposed methodology integrates information from multi- models and climate scenarios (e.g. regional climate models, hydrodynamic models) in a multi-hazard perspective; and a multi-vulnerability assessment which considers the physical and environmental characteristics of the elements at risk affected by multiple hazards.

The methodology applies Multi Criteria Decision Analysis (MCDA) which enables the evaluation and ranking of different decision making alternatives and the involvement of many users (decision makers as well as experts) (Giove et al. 2009). Specifically, the integration of expert judgments and stakeholder preferences allows the aggregation of quantitative and qualitative physical and environmental indicators for hazard, exposure and vulnerability characterization.

The final result is a semi-quantitative assessment of areas and targets affected by multiple risks related to natural hazards and climate change and includes the identification of homogeneous multi-risk units allowing the establishment of priority multi-risk areas where detailed analysis and interventions should be defined. In this approach, the socio-economic sphere is not taken into account. The separate analysis of the physical/environmental and the socio-economic spheres was also applied in other contexts (e.g. Ronco et al. 2014) even if is easily possible to join the two aspects in order to provide a composite evaluation of risks and impacts. Also in this PhD work, the multi-risk methodology provides an estimation of the physical/environmental multi-risk that can be used as input for the social and economic evaluation.

The multi-risk methodology was developed within the Euro-Mediterranean Centre on Climate Change (CMCC, www.cmcc.it) in the frame of the GEMINA project (2011-2015) funded by the Italian Special Integrative Fund for Research (FISR). The North Adriatic coastal area was selected as case study to test the multi-risk methodology and the main results of the analysis are presented and discussed in this thesis.

1.2. Thesis structure

This thesis is organised in three main sections: Section A illustrates the theoretical background of this PhD work; Section B describes the multi-risk methodology developed within the thesis; finally, Section C presents the application of the methodology to the case study area of the North Adriatic coast.

Section A presents the state of the art concerning multi-risk approaches and methods for natural hazards and climate change, providing a general overview of the main definitions used in literature (i.e. multi-hazard, multi-vulnerability, multi-hazard risk and multi-risk); a critical analysis of the relevant organisations, tools, projects and methodologies developed at the international level; and finally illustrating the main challenges and issues concerning the development of a multi-risk methodology in a climate change perspective. This part highlights the major research objectives that the climate change community should handle when considering the assessment of multiple impacts and risks for adaptation and prevention purposes in order to provide a more comprehensive and advanced methodology for multi-risk assessment.

Section B concerns the methodological development of the multi-risk assessment. After a brief presentation of the methodological framework, each step of the methodology (i.e. multi-hazard, exposure, multi-vulnerability and multi-risk) is described considering the input data, the aggregation equations and the outputs of each phase.

Finally, Section C is related to the application of the multi-risk methodology presented in Section B for the North Adriatic coastal case study. After an introduction to the case study area, the main input data, assumption and results of each step of the multi-risk methodology are presented and critically analysed.

Conclusions are aimed to provide a summary of main findings and possible further investigations and recommendations for the improvements of the proposed multi-risk methodology.

SECTION A: THEORETHICAL BACKGROUND

2. A review of multi-risk methodologies for natural hazards: challenges for a climate change impact assessment

The present Section A (Chapter 2) is aimed to present the state of the art concerning multi-risk approaches and methods in order to provide a solid scientific support for the development of a multi-risk methodology addressing cumulative natural hazards and climate change impacts on different natural and human systems. Particular emphasis is given to the analysis of natural climate variability and biophysical and environmental aspects of vulnerability, while the socio-economic dimension as well as any coping capacity of the exposed elements at risk is not considered in this phase of analysis.

Following the review of the relevant key definitions used in the literature (Section 2.1), Section 2.2 and 2.3 provide a critical analysis and discussion about organisations, tools, projects and methodologies applied at the international level and specifically in Europe. Finally, Section 2.4 aims to discuss the main consequences and challenges for the development of a multi-risk assessment approach related to climate change hazards.

2.1. Terminology of multi-risk

Within the general development of the International Decade of Natural Disaster Reduction (IDNDR) and the following permanently installed International Strategy for Disaster Reduction (ISDR) (Zentel and Glade 2013), the interest and reference to the concept of multi-hazard has been first made in the Agenda 21 Conference in Rio de Janeiro (UNEP 1992) and then in the Johannesburg Plan (UN 2002) in which a complete multi-hazard approach was proposed for disaster management and risk reduction. Afterwards, the initiatives of analysing the multiple risks arising from different hazards and affecting many exposed elements at risk are constantly increasing during the last years (e.g. Bell and Glade 2004b; Glade and von Elverfeldt 2005; Kappes et al. 2010; EC 2011; Garcia-Aristizabal and Marzocchi 2012a, 2012b; Kappes et al. 2012a).

A major difficulty in a new emerging discipline, such as multi-risk, is the lack of a precise definition of terms generally agreed by all different communities. However, a unified glossary is essential to minimize misunderstanding and to provide a rigorous basis for the scientific knowledge (Garcia-Aristizabal and Marzocchi 2012a; Thywissen 2006).

In order to avoid any confusion, Table 2.1.1 summarises the main concepts and references within the multi-risk context. These are the basis for the discussion of the analysed initiatives and methodologies.

Concept	Definition	References
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 2009; IPCC 2012, 2014
Exposure (i.e. elements potentially at risk)	It 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 2009; IPCC 2012, 2014
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 2009; IPCC, 2012, 2014
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.	IPCC 2012, 2014
Disaster risk	The potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period.	UNISDR 2009
Multi-hazard	It refers to: – different hazardous events threatening the same exposed elements (with or without temporal coincidence); – hazardous events occurring at the same time or shortly following each other (cascade effects).	Carpignano et al. 2009; EC, 2011; Garcia-Aristizabal and Marzocchi 2012a, 2012b
	It refers to the totality of relevant hazards in a defined administrative area.	Kappes et al. 2010, 2011
Multi-vulnerability	It refers to: – a variety of exposed sensitive targets (e.g. population, infrastructure, cultural heritage, etc.) with possible different vulnerability degree against the various hazards; – time-dependent vulnerabilities, in which the vulnerability of a specific class of exposed elements may change with time as consequence of different factors (e.g. the occurrence of other hazardous events).	Carpignano et al. 2009; Garcia-Aristizabal and Marzocchi 2012a, 2012b
Multi-hazard risk	It refers to the risk arising from multiple hazards.	Kappes et al. 2012a
Multi-risk	It is related to multiple risks such as economic, ecological, social, etc.	Kappes et al. 2012a
	It determines the whole risk from several hazards, taking into account possible hazards and vulnerability interactions entailing both a multi-hazard and multi-vulnerability perspective.	Carpignano et al. 2009; Garcia-Aristizabal and Marzocchi 2012a, 2012b

Table 2.1.1. Concepts and definitions of the multi-risk approaches.

As defined by UNISDR (2009) and IPCC (2012, 2014), the basic components that should be considered in the multi-risk assessment are: hazard, elements at risk including their exposure and vulnerability. Specifically, hazard refers to the physical phenomenon that has the potential to cause damages and losses to human and natural systems (UNISDR 2009; IPCC 2012, 2014). While exposure represents the presence of the elements at risk (e.g. buildings, infrastructure, environments) that could be adversely affected, these elements at risk are characterized by their intrinsic vulnerability towards a given hazard intensity. In a broad sense vulnerability should include economic, social, geographic, demographic, cultural, institutional, governance, and environmental factors (IPCC 2012, 2014). However, several authors strictly refer to the physical and environmental vulnerability (e.g., Glade 2003; Papathoma-Köhle et al. 2011; Kappes et al. 2012b; Pasini et al. 2012; Torresan et al. 2012), while others are focused on the socio-economic characteristics and damages (e.g., Holman et al. 2002; Fuchs et al. 2007; Fekete 2009; Hufschmidt and Glade 2010). In this paper the term vulnerability is considered in the physical and environmental sense, especially in Section 2.4 where no considerations were provided for the socioeconomic characteristics. The afore-mentioned concepts (i.e. hazard, exposure and vulnerability) contribute to the definition of risk that should allow a quantification of the consequences derived from different hazards (i.e. relative risk, Table 2.1.1). Moreover, disaster risk is considered by UNISDR (2009) as the potential disaster losses, in lives, health status, livelihoods, assets and services that could occur to a particular community or a society over some specified future time period.

However, for the understanding of the multi-risk concept, the two most important pillars are multi-hazard (Glade and von Elverfeldt 2005; Carpignano et al. 2009; Kappes et al. 2010; EC 2011; Kappes et al. 2011; Garcia-Aristizabal and Marzocchi 2012a, 2012b) and multi-vulnerability (Carpignano et al. 2009; Hufschmidt and Glade 2010; Garcia-Aristizabal and Marzocchi 2012a, 2012b; Ciurean et al. 2013) which may consider all the hazards, exposed sensitive targets and their time-dependent vulnerability in the analysed area (e.g. administrative unit, case study).

Specifically, the multi-hazard concept is related to the analysis of different relevant hazards, triggering and cascade effects threatening the same exposed elements with or without temporal concurrence (Komendantova et al. 2014).

Multi-vulnerability may consider different exposed elements (i.e. ecosystem approach) with possible different vulnerability, changing according to different types of hazards and over time.

In the cited definitions it is not clearly specified that hazards and vulnerability should be considered simultaneously, allowing an open interpretation and application of these concepts. For instance, it is possible to find different multi-hazard tools that provide single hazard analysis without any consideration about cascade effects or the aggregation in a total hazard index highlighting areas most affected by hazards than others (e.g., the HAZUS concept of FEMA, http://www.hazus.org).

It is possible to summarise two main approaches that consider both hazards and vulnerability: the multi-hazard risk assessment (Kappes et al. 2012a) and the multi-risk assessment (Carpignano et al. 2009; Garcia-Aristizabal and Marzocchi 2012a, 2012b; Kappes et al. 2012a).

The first approach provide an analysis of different hazards - aggregating them in a multi-hazard index - and the assessment of a total territorial vulnerability (i.e. no hazard-dependent vulnerability) allowing a multi-hazard risk assessment. These steps can be summarised as follows:

1. Hazard assessment;
2. Multi-hazard assessment;
3. Exposure assessment of elements at risk;
4. Vulnerability assessment;
4. Multi-hazard risk assessment.

The multi-risk assessment, is more complex and it comprises both multi-hazard and multi-vulnerability concepts taking into account possible hazards and vulnerability interactions (Carpignano et al. 2009; Garcia-Aristizabal and Marzocchi 2012a, 2012b). In this approach risks are analysed separately (i.e. considering for each hazard a specific analysis of exposure and vulnerability) and then the aggregation allows a multi-risk index evaluation. The steps that should be adopted are the following:

1. Hazard assessment;
2. Exposure assessment of elements at risk;
3. Vulnerability assessment;
4. Single-risk assessment;
5. Multi-risk assessment.

Moreover, the analysed concepts have different connotations according to the expertise involved (e.g. natural scientists, engineers, economists) and to the aim of the analysis, requiring a holistic assessment of risks and consequences (Garcia-Aristizabal and Marzocchi 2011).

This thesis will present multi-hazard, multi-hazard risk and multi-risk methodologies. The approaches dealing with the analysis of multi-vulnerability are not investigated in further detail. The focus of this work is related only to the biophysical and environmental characteristics. Moreover, the methodologies and approaches will be outlined in the following chapters (2.2 and 2.3) specifically for the natural hazards, while climate change consequences will be investigated in Chapter 2.4.

2.2. An overview of multi-risk assessment

In the light of the presented definitions on multi-hazard, multi-hazard risk and multi-risk, different organisations and institutions are involved in the development of services and tools for global, national and local applications. Table 2.2.1 provides a list of the main organisations and tools including the main references.

Organisation	Tool ad services	Web-site, references
World Bank	Global hotspot maps of natural disasters	www.worldbank.org; Dilley et al. 2005
Munich Re	Global maps of natural hazards	www.munichre.com
FEMA	Hazus software	www.fema.gov; FEMA 2011
RiskScape	RiskScape	www.riskscape.org.nz; Reese et al. 2007; GNS and NIWA 2010
Central American Coordination Centre for Disaster Prevention	CAPRA software	www.ecapra.org; Bernal 2010
AMRA	Development of quantitative multi-risk approaches.	www.amracenter.com; AMRA 2013

Table 2.2.1. Organizations, tools and services dealing with the multi-risk concept.

At the global level, the World Bank (Dilley et al. 2005) and Munich Re (Touch Natural Hazards, www.munichre.com) provide a large-scale analysis of natural hazards allowing a spatial visualization of hotpots by the use of simple risk indexes (e.g. potential losses, mortality) in which different hazards occur (e.g., floods, droughts, cyclones, earthquakes) . These representations are useful for addressing global policies even if they cannot provide a coherent risk assessment at a more detailed level, which requires a deeper analysis of causes and effects of the considered hazards.

The Federal Emergency Management Agency of United States (www.fema.gov) developed the HAZUS GIS-based tool (FEMA 2011) which allows the estimation of potential losses from several individual hazards (i.e. floods, hurricanes, and earthquakes) in order to support mitigation planning efforts. The estimated losses in HAZUS are related to physical damages to buildings (residential and commercial) and infrastructure; economic losses (lost jobs, business interruptions and reconstruction costs) and social impacts (shelter requirements, displaced households, and population exposed to hazard scenarios). However, this tool neither allows a simultaneous assessment of multiple hazards and damages nor their interactions and cascading effects, but provides different outputs for different hazards applicable for comparisons.

Moreover, in New Zealand RiskScape has been developed by GNS Science (www.gns.cri.nz) and NIWA (www.niwa.co.nz) for the quantification of direct and indirect losses due to river floods, earthquakes, volcanic activity (ash), tsunamis, and wind storms on people's lives. The methodology allows the comparison among different hazards considering the information arising from hazard exposure (i.e. the magnitude of the hazard), assets (i.e. human- or socially-valued elements that are threatened by a hazard) and vulnerability by means of fragility functions that specify a relation between hazard, asset characteristics, and the potential damages (GNS and NIWA 2010; Schmidt et al. 2011; www.riskscape.org.nz).

A GIS-based tool freely available is CAPRA (www.ecapra.org) developed by Central American Coordination Centre for Disaster Prevention (CEPREDENAC), in collaboration with Central American Governments, the

United Nation's International Strategy for Disaster Reduction (ISDR), the Inter-American Development Bank and the World Bank. The software allows a probabilistic analysis of earthquakes, hurricanes, volcanic activity, floods, tsunamis, landslides and related losses in the Central America. Moreover, it allows the comparison of different hazards considering also the secondary hazards arising from earthquakes, rainfall and hurricanes (i.e. tsunami, landslides and floods) (Bernal 2010).

Robust analyses and monitoring of environmental risks are the main tools provided by AMRA center (www.amracenter.com) for the development of quantitative multi-risk approaches in different EU funded projects (NaRAs, MATRIX, CLUVA and ByMur, e.g., Komendantova et al. 2014).

The analysed tools provide an overview of the multi-risk approaches from the global to the local scale. It emerges that most of the initiatives have developed multi-risk methodologies that partially consider the definitions listed in Table 2.1.1, providing only a detailed analysis of single hazards without considering their interactions and cascading effects. Moreover, the developed tools are generally based on the scale of analysis: at a broad scale the methodology is performed using simple risk indices, while the more detailed scale allows a more deep assessment of hazards, exposure and vulnerabilities.

In addition to multi-risk assessment tools, in the last decade different European projects have been funded for the analysis of multi-risk and for the development of a generalised methodology for its assessment. Table 2.2.2 summarises the objective, the scale of analysis, the investigated hazards, the approach used and the references for each analysed project.

Project	Objective	Scale of analysis	Investigated hazards	Approach	Reference
NaRAs	To promote the development of education actions and early warning methods for seismic risk mitigation and to stimulate the development of quantitative probabilistic methodologies for risk evaluation and different emergency scenarios using stochastic methods.	Local/ Casalnuovo municipality (Campania, Italy)	Volcanic, Seismic, Flooding, Landslide, Industrial	Probabilistic	Marzocchi et al. 2012
ESPON-HAZARD 1.3.1	To represent the spatial patterns of natural and technological hazards in administrative regions of the ESPON space, on NUTS 3 level.	European, regional and local/Dresden (Germany); Centre Region of Portugal; Itä Uusimaa (Finland); Ruhr District (Germany); Europe	River floods, Forest fires, Earthquakes, Winter storms, Volcanic eruptions, Droughts, Extreme precipitations and temperatures, Oil transport, Major accident hazards (e.g. nuclear power plants, waste deposit, dams)	Delphi method Weighted sum	Greiving 2006; Greiving et al. 2006; Olfert et al. 2006; Schmidt Thomè 2006
ARMONIA	To produce a methodology that combines multiple risks aggregating hazards, exposure and vulnerability.	National and local/ Arno River basin (Italy); England and Wales	Flooding, Earthquakes, Forest fires, Landslides, Volcanic eruptions	Generic framework and specific application to different case studies	Del Monaco et al. 2007
MATRIX	To develop methods and tools to tackle multiple natural hazards within a common framework.	Regional, local	Earthquakes, Landslides, Volcanic eruptions, Tsunamis, Wildfires, Winter storms, Fluvial floods, Coastal floods	Three level of analysis: qualitative, semi-quantitative, quantitative.	Farrokh and Zhongqiang 2013; matrix.gpi.kit.edu
CLUVA	To develop methods and knowledge to be applied to African cities to manage climate risks, to reduce vulnerabilities and to improve their coping capacity and resilience towards climate changes.	Regional, local/ African case studies	Sea-level rise, Flood, Drought, Intense rainfall, Erosion, Water scarcity, Desertification	Probabilistic	Garcia-Aristizabal and Marzocchi 2012a, 2012b, 2012c; www.cluva.eu
ByMur	To provide a quantitative and objective new Bayesian Multi-Risk method for comprehensively analyzing the complex of risks threatening a given area.	Local/ Naples (Campania, Italy)	Eruptions, Tsunami, Earthquakes	Bayesian	bymur.bo.ingv.it

Table 2.2.2. European funded projects dealing with the multi-risk concept.

The analysed European projects are mostly focused on the assessment of natural (e.g. droughts, avalanches, earthquakes, floods, landslides) and technological hazards (e.g. air traffic hazards, hazards from nuclear power plants). In fact, the hazards influenced by climate change (e.g. sea-level rise, drought, flood, erosion, desertification) are considered only in the CLUVA project (Garcia-Aristizabal and Marzocchi 2012b).

The investigated projects encompass different approaches, from the qualitative one, which is the most simple but does not allow a numerical evaluation of the hazards, to the quantitative estimates of the hazards and risks that provides a robust assessment of the elements characterizing the risks. As far as the qualitative approaches are concerned, the ESPON HAZARD 1.3.1 and MATRIX projects have developed a Delphi method based on the administration of questionnaires and allowing a subjective estimate of the hazard starting from the end-user level (Farrokh and Zhongqiang 2013). Specifically, in the ESPON project, the questionnaire has been proposed to the experts involved in the application in order to rank and aggregate the analyzed hazards based on a set of weights representing the importance of each hazard in the integrated hazard map (Greiving 2006; Greiving et al. 2006; Olfert et al. 2006; Schmidt-Thomè 2006). Moreover, in the MATRIX project the qualitative method is used as first step analysis to integrate end-users' knowledge for the identification of hazards and vulnerable targets to be considered in the multi-risk process (Farrokh and Zhongqiang 2013; Komendantova et al. 2014).

Moving to a more detailed analysis, the semi-quantitative methods (e.g. cause-effects matrixes) provide an evaluation of the relationships between agents and processes (Farrokh and Zhongqiang 2013) and the respective exposures of given elements at risk (Kappes et al., 2012c), while quantitative methods (e.g. weighted sum, Bayesian networks, probabilistic approaches) for the multi-risk assessment allow a robust analysis of the risk components (Greiving 2006; Greiving et al. 2006; Olfert et al. 2006; Schmidt-Thomè 2006; Garcia-Aristizabal and Marzocchi 2012c; Marzocchi et al. 2012; Farrokh and Zhongqiang 2013).

Analysing the flexibility of application, most of the investigated projects are focused on the multi-risk assessment of natural and technological hazards in specific case studies, while only ARMONIA and MATRIX projects are aimed at the development of general methodologies that can be applied in different case studies and for several hazards. The strength of these approaches is the development of general guidelines that could be adopted and improved by experts dealing with the multi-risk problems.

2.3. State of the art of existing methodologies

In order to facilitate a comparative analysis and discussion, the reviewed methodologies were categorized in multi-hazard, multi-hazard risk and multi-risk approaches (Table 2.1.1). Moreover, the methodologies were resumed in Table 2.3.1, according to the following fields: reference (i.e. name of the project or reference), objective, scale of analysis and case study, investigated hazards, multi-hazard aggregation, vulnerability, outputs.

Reference	Objective	Scale of analysis/case study	Investigated hazards	Multi-hazard aggregation	Vulnerability	Outputs
Multi-hazard						
Mahendra et al. 2010	Assessment and mapping of multi-hazards using the historical data to measure trends and future projections.	Regional/the coast of Nellore District, Andhra Pradesh East Coast of India.	–Sea-level rise; –Storm surge; –Coastal erosion.	GIS and remote sensing techniques.	/	–Multi-hazard map of the studied region; –Statistics related to the surface of the case study area affected by multi-hazard.
Kappes et al. 2010, 2012c; Frigerio et al. 2012	Modelling different hazards on a similar data bases, but based on different medelling approaches	Regional scale	–Floods –Rock falls –Debris flows –Shallow landslides –Snow avalanches	Single hazard modelling Overlay of the spatial extend of single hazards	Exposure analysis only	–Maps of single and multi-hazards –Map of number of hazards for given locations –Exposure maps –Validation maps for all single hazards
De Pippo et al. 2008	To present a semi-quantitative method to quantify, rank and map the distribution of hazard along the Northern Campania coastal zone.	Local/Northern Campania coastal zone (Naples), Italy	–Shoreline erosion; –Riverine flooding; –Storms; –Landslides; –Seismicity and volcanism; –Man-made structures.	–Geomorphologic indicators; –Cause/effect matrix; –Aggregation equation.	/	Multi-hazard maps of the studied region or of a particular area.
Multi-hazard risk						
ESPON Hazard 1.3.1	to present the Integrated Risk Assessment of Multi-Hazards as a new approach to serve as a basis for a spatial	European, regional and local/Dresden (Germany); Centre Region of Portugal; Itä Uusimaa (Finland); Ruhr	–Natural hazards (e.g. avalanches, drought, earthquakes, floods, tsunami); –Technological hazards (e.g. air traffic and	–Selection of the hazard indicators (e.g. hazard frequency); –Weighting of the hazard indicators by means of the Delphi method;	–Selection of the vulnerability indicators (e.g. GDP, per capita, population density); –Aggregation of the vulnerability indicators	– Integrated hazard map; – Vulnerability map; – Integrated risk map obtained aggregating the hazard score with

Reference	Objective	Scale of analysis/case study	Investigated hazards	Multi-hazard aggregation	Vulnerability	Outputs
	risk management process in administrative regions on NUTS3 level.	District (Germany); Europe	major accident hazards, nuclear power plants)	–Weighted sum of the hazard indicators.	by means of weighted sum.	the vulnerability score by means of a correlation matrix.
Wipulanusat et al. 2009	To develop the application of GIS and remote sensing in multi-hazard risk assessment.	Local/Pak Phanang Basin, southern east coast of Thailand	–Drought; –Floods.	–Selection of the hazard indicators based on quotation frequencies and authors' experience (e.g. rainfall, channel density, drainage) and their sub-factors; –Weighting of the hazard factors according to their relative priority and expected significance in causing the hazard; –Aggregation and classification of the hazard factors by means of weighted sum obtaining qualitative hazard classes (low, moderate, high).	– Selection of the vulnerability factors (population density and land use type) and their sub-factors; – Aggregation of the vulnerability factors by means of weighted sum.	– Risk map related to the single hazard; – Multi-risk created by overlaying the drought risk map with the flood risk map; – Statistics related to the surface of the case study area affected by the different risk/multi-risk classes. Risk is classified in qualitative classes (low, moderate, high).
Multi-risk						
van Westen et al. 2002	To support the local authorities with basic information for disaster management at the municipal level with a multi-risk assessment.	Local/Turrialba, Cartago, Costa Rica, Central America	– Seismic; – Flooding; – Landslides.	–Selection of the hazard indicators (Modified Mercalli index, Flood hazard maps, Landslide hazard based on historical landslide inventory);	– Quantification of the direct tangible cost for building for each investigated hazard by means of vulnerability functions correlating the cost with the intensity of the hazard;	–Specific risk curve for each hazard type and each return period representing the expected degree of loss; –Total risk curve from the combination of the investigated hazard

Reference	Objective	Scale of analysis/case study	Investigated hazards	Multi-hazard aggregation	Vulnerability	Outputs
				– Creation of hazard maps of each investigated hazard.	– Vulnerability data are used in GIS creating a vulnerability map.	representing the annual expected losses to buildings and contents of buildings for all the investigated hazards.
Bell and Glade 2004b	To develop a general methodology to analyse natural risk for multiple processes	Local/ Bíldudalur, NW-Iceland	– Debris flow; – Rock fall; – Snow avalanche.	– Hazards are classified according to the probability of spatial impact of each process dependant on its magnitude or hazard.	– Vulnerability is classified based on the hazard and for different exposed elements (i.e. power lines, roads and infrastructure, properties, people, people in buildings).	– Risk map posed by each process is calculated representing individual risk, object risk to life, economic risk; – Multi- risk map obtained by the combination of the single risk maps (qualitative classes: very low, low, medium, high).
ARMONIA	To produce a general methodology that combines multiple risks aggregating hazards, exposure and vulnerability.	National and local/ Arno River basin (Italy); England and Wales	– Flooding; – Earthquakes; – Forest fires; – Landslides; – Volcanic eruptions.	– Selection of the hazard indicators (e.g. flood depth, approximate flame length, volcanic explosive index); – Classification of the hazard by means of a correlation matrix considering the intensity and the probability of the hazard.	– Selection of the vulnerability indicators based on the hazard and for different exposed elements (i.e. people, buildings, road networks, agriculture, environment, other buildings); – Computation and normalization of the vulnerability by means of vulnerability functions or indices;	– Risk maps for different hazards and exposed elements; – Multi-risk map obtained from the aggregation of the single risk maps (summed and normalized risk scores).

Reference	Objective	Scale of analysis/case study	Investigated hazards	Multi-hazard aggregation	Vulnerability	Outputs
					– Computation of the consequence indices for each exposed element.	
NaRAs	To provide principles for the multi-risk assessment to be applied to case studies in which different hazards should be compared.	Local/ Casalnuovo municipality (Campania, Italy)	–Volcanic; –Seismic; –Flooding; –Landslide; –Industrial.	– Identification of hazard/risk sources considering triggering or simultaneous hazards; – Identification of the hazard scenarios and their probabilistic assessment.	– Computation of the vulnerability functions for each hazard and exposed elements (i.e. man-made structures, infrastructure and buildings; cultural heritage; life-lines; humans and animals; agricultural and forest areas; and ecosystems).	– Computation of the investigated risks providing a quantification of the human life loss per year for each hazard obtaining comparable scores.
MATRIX	To develop methods and tools to tackle multiple natural hazards within a common framework.	Regional, local	–Earthquakes; –Landslides; –Volcanic eruptions; –Tsunamis; –Wildfires; –Winter storms; –Fluvial floods; –Coastal floods.	– Qualitative analysis questionnaire to consider or not a multi-type assessment approach, which explicitly accounts for cascading hazards; – Semi-quantitative analysis of the hazards: cause-effect matrix; – Quantitative analysis of the hazards and their interactions by means of event tree; Bayesian networks; time stepping Monte Carlo simulation	–Qualitative analysis questionnaire to consider or not a dynamic vulnerability; –Semi-quantitative analysis to consider interactions among the different vulnerabilities: cause-effect matrix; –Quantitative analysis: fragility curves.	–Computation of the investigated risks providing a quantification of the potential losses for each hazard obtaining comparable scores.

Table 2.3.1. Multi-risk methodologies analysed considering the investigated hazards, the scale of analysis and the case studies, how multi-hazard and vulnerability are computed and the final outputs.

The analysed methodologies will be presented in the next paragraphs considering the following concepts: application context (objective and scale of analysis), multi-hazard, exposure and vulnerability, outputs (multi-hazard risk and multi-risk).

2.3.1. Application context

In the application context, the objective, the scale of analysis and the input data used in the different methodologies are investigated.

In order to provide useful tools for stakeholders and decision makers in the management of risks, the objectives of the analysed methodologies are focused on the development of a composite visualisation of the different hazards affecting the same area (Schmidt-Thomè 2006; Frigerio et al. 2012; Kappes et al. 2012a). However, only the ESPON-HAZARD project considers the expert involvement in the assessment which allows the integration of expert knowledge in its implementation, while the qualitative level of MATRIX project requires the participation of the end-users in order to answer to the questions related to the relevance of hazards and vulnerabilities in the interested area (Komendantova et al. 2014).

Moving to the scale of analysis, most of the reviewed methodologies are focused on the assessment at the sub-national, regional or local scale and their applications require a huge amount of data that have to be used for the analysis. Therefore, the methodologies are focused on a specific case study both for the definition of the problem and for the data availability (Kappes et al., 2012a). Specifically, for the hazard assessment, data that usually are used for the application are historical information of previous events (e.g., ESPON-HAZARD project, van Westen et al. 2002, Kappes et al. 2012c; Marzocchi et al. 2012) and cartographic data of the elements potentially at risk and their characteristics (e.g. van Westen et al. 2002; Wipulanusat et al. 2009; Marzocchi et al. 2012). Moreover, the temporal scale is related to the static analysis of present data, while the future scenarios are not considered.

ARMONIA and MATRIX projects are aimed at the development of a general methodology to be implemented at the local scale but an application is not yet available (for the ARMONIA project the application was conducted until the quantification of the single risks). In ESPON-HAZARD project the multi-risk analysis is performed at the European level providing a classification of the different regions. Nevertheless, different organizations (e.g. Munich Re, World Bank) provide a global assessment for the identification of hotspots where natural hazard impacts may be largest.

Finally, it was observed that most of the investigated projects and methodologies presented in Table 2.2.2 and Table 2.3.1 (e.g. Bell and Glade 2004; Frigerio et al. 2012; Marzocchi et al. 2012; NaRAs, CLUVA, MATRIX and ARMONIA project) are focused on the multi-risk assessment, providing a composite visualisation of different risks affecting the same area, as useful tool for spatial risk management process and disaster management.

Specifically, the methodologies are dealing with problems related to the multi-hazard aggregation and the identification and quantification of vulnerability providing different approaches and methods.

2.3.2. Multi-hazard

Most of the analysed methodologies (e.g. Bell and Glade 2004b; Kappes et al. 2012c; Marzocchi et al. 2012; NaRAs, MATRIX and ARMONIA project) are dealing with the assessment of natural hazards (e.g. landslides, floods, seismicity), two consider coastal hazards (De Pippo et al. 2008; Mahendra et al. 2010), and one is focused on natural and technological hazards (ESPON-HAZARD 1.3.1 project).

Specifically, for the multi-hazard assessment most of the methodologies consider hazards as independent events (e.g. ARMONIA and ESPON-HAZARD project, van Westen et al. 2002; Bell and Glade 2004b; Wipulanusat et al. 2009). While potential interactions are analysed by means of cause-effects matrix (De Pippo et al. 2008; Garcia-Aristizabal and Marzocchi 2012c; Kappes et al. 2012c) that allows a semi-quantitative estimate of the relationships between agents and processes in the evolution of a system.

Moreover, hazard interactions can be considered from the probabilistic analysis of historical databases that already take into account triggering and cascade events (e.g. tsunami databases that already included the possibility of an earthquake triggered tsunami. For details, please refer to Marzocchi et al. (2012) and in particular to the NaRAs project).

The consideration of interactions among hazards is more demanding than the hazard-by-hazard approach both for the data requirement and for the time that should be given in the analysis of the interactions that are not the simple sum of the single hazards that affect the same area (Kappes et al., 2012a).

Although the methodologies are focused on the development of maps and tools useful for spatial risk and disaster management, commonly no future hazard scenarios are considered. However, Mahendra et al. (2010) proposed in their approach the adaptation and spatial planning capacities for a future scenario of a 50 year sea-level trend. Concerning the methodologies that are focused only in the multi-hazard assessment they provide a total multi-hazard map and related statistics (e.g. surface of the affected areas) of the studied region (De Pippo et al. 2008; Mahendra et al. 2010).

2.3.3. Exposure and vulnerability

The elements potentially at risk are identified in the exposure phase that allows the representation of different features of the territory. In the present review the exposure refers to the same elements for all the investigated methodologies: population, socioeconomic and cultural assets, infrastructure and environment. However the characterization of the vulnerability for the exposed elements differs among the methodologies.

A generalized agreement on the use of vulnerability functions (fragility curves) has been reached (e.g., van Westen et al. 2002; Papathoma-Köhle et al. 2011; Kappes et al. 2012b; MATRIX and ARMONIA project; Marzocchi et al. 2012), which facilitates the application of the multi-risk analysis. Also the identification of vulnerability indicators through the use of cartographical data (e.g., Wipulanusat et al. 2009) is widely used for the characterization of different elements at risk (e.g. population, land-use). However, keeping in mind the definition of multi-vulnerability proposed in Table 2.1.1, it emerges that the analysis of the dynamic (i.e. time-dependent) exposure and vulnerability with the assessment of potential future scenarios is not considered in the reviewed methodologies. Moreover, the vulnerability derived from hazard interactions (e.g. vulnerability of a system to both seismicity and volcanism) is commonly not considered in the methodologies. One exception is the MATRIX project, in which the qualitative step, the semi-quantitative analysis (cause-effect matrix) and the more detailed quantitative assessment consider both hazard and vulnerability interactions.

A more accurate and comprehensive approach strongly depends on both the scale of the study and the availability of information (for both hazard and vulnerability assessments).

2.3.4. Multi-hazard risk and multi-risk outputs

Multi-hazard risk and multi-risk methodologies require the aggregation of hazard, exposure and vulnerability (Table 2.2.1) in order to provide outputs (e.g. maps, web-based applications, statistics and indices) that can be easily consulted and used by different end-users. Accordingly, the investigated methodologies consider qualitative, semi-quantitative or quantitative approaches for the aggregation of the intermediate steps (i.e. multi-hazard, exposure and vulnerability).

Specifically, the multi-hazard risk methodologies perform a qualitative aggregation of hazards and vulnerability by means of questionnaires (Greiving 2006; Greiving et al. 2006; Olfert et al. 2006; Schmidt-Thomè 2006) or a semi-quantitative assessment assigning scores and weights to the identified classes (Wipulanusat et al. 2009). However, the results allow a classification of the multi-hazard risk in qualitative terms (e.g. low, medium, high).

With respect to the multi-risk methodologies, the approaches are more focused on the quantitative assessment of the multi-risk, allowing a more detailed analysis of hazard and vulnerability correlations. In the MATRIX project (Farrokh and Zhongqiang 2013), three different methods are suggested for the description and quantification of the interactions: event tree, Bayesian networks and time stepping Monte Carlo simulations.

Moreover, the single risks within a multi-risk assessment are computed using a common unit of measure (e.g. loss of lives, economic losses, 0-1 normalization) (e.g., van Westen et al. 2002; Marzocchi et al. 2012; MATRIX project). This allows a direct comparison and aggregation among different kind of risks.

The final results, for both approaches multi-hazard risk and multi-risk highlights areas affected by different classes of the total risk (e.g., Bell and Glade 2004b; Wipulanusat et al. 2009) providing a classification of the different areas more affected than other to the investigated hazards. The spatial-oriented maps can be used by different end-users to know specific information in the form of quantifiable risk metrics for the implementation of adaptation measures and planning.

2.4. Climate change multi-risk assessment: consequences and challenges

Considering the most important past projects and methodologies on multi-risk assessment presented in Section 2.2 and 2.3, it emerges that most of the initiatives on multi-risk have developed methodological approaches for the assessment of natural and technological hazards and respective consequences with a varying degree of detail. However, climate change is going to pose a variety of impacts caused by extreme natural events on natural and human systems worldwide (EC 2012). This emerging issue highlights the need to include the analysis of climate change impacts on the planning of adaptation and land-use management measures that would be comprehensive of the interactions among different climate-related hazards (EC 2010; Marzocchi et al. 2012).

In this context, a major challenge for climate impact research is to develop new methods and tools for the aggregation of cumulative effects expected from multiple climate impacts across different regions and sectors. This perspective necessarily leads to a variety of issues that should be taken into account (e.g. scale of analysis, methods of aggregation), in particular in the context of multi-hazard, multi-hazard risk and multi-risk analysis. Therefore, the next paragraphs are aiming to present the main consequences and challenges dealing with the multi-risk assessment for climate change impacts. Moreover, Table 2.4.1 provides a summary of the review results.

	Climate change related issued and challenges within multi-risk assessment
Application context	– Identify the objective of the analysis; – Define the time frame; – Distinguish the scale of analysis; – Detect the most appropriate resolution; – Review the available data sources for multi-hazards and associated risks; – Define the approach to be used (multi-hazard, multi-hazard risk, multi-risk); – Consider the involved uncertainties of input information.
Multi-hazard	– Improve climate models and analysis; – Define the temporal window to be considered; – Assess cumulative effects of hazards; – Consider cascade and triggering effects in different scenarios; – Provide climate change scenarios with an associated probability and uncertainty; – Differentiate between short-term triggers and long-term changes.
Exposure	– Identify the elements potentially at risk (e.g. population, agriculture, infrastructure, buildings); – Consider the spatiotemporal dimensions for each element at risk (e.g. night-/daytime population); – Provide an ecosystem approach in order to integrated different sectors and their interrelationships; – Provide future scenarios of the elements potentially at risk.
Vulnerability	– Identify vulnerability factors for the characterization of the exposure; – Calculate vulnerability functions for each element at risk and the corresponding hazards; – Consider herein also a changing resilience towards a given impact may increase or decrease; – Provide future scenarios of the vulnerability factors that should be considered to be dynamic (e.g. vegetation cover, population density); – Provide a coupling model land-use/climate model; – Provide a common scale of comparison for a suitable aggregation of the vulnerability factors.
Multi-risk	– Identify a common scale of comparison; – Consider the different data requirements for the variety of processes and elements at risk; – Identify the most suitable aggregation method: qualitative, semi-quantitative and quantitative approach;
Facing the challenges	– Identify the final users; – Increase the awareness of the stakeholders; – Involve stakeholders and final users at an early stage in the multi-risk process; – Managing the huge amount of data with different, hazard and elements at risk dependent units of measurements; – Aggregate these different unit of measurements; – Communicate the uncertainty of the assessment due to the uncertainty associated to climate models and to the error propagation; – Explain openly the assumptions and limitations of each assessment in order to avoid misjudgement; – Provide an easy-visualization of the outputs in a climate service perspective for management purposes.

Table 2.4.1. Climate change related issued and challenges within multi-risk assessment.

2.4.1. Application context

The first step towards the development of a multi-risk assessment methodology for climate change impacts is the identification of the application context. After the specification of the objectives, this phase requires the choice of the scale of analysis and the problems to be tackled.

The preliminary decision is related to the main objective of the study that could be focused on a scientific analysis of multi-risk, or could be related to the provision of useful results (e.g. maps, statistics, graphs) for different stakeholders and sectors of society (e.g. policymakers, planners, citizens).

The identification of the scale of analysis depends on the objective to achieve but also on the target area that should be analysed (e.g. an administrative unit, a country, a region).

Dealing with the timeframe a climate change perspective requires a strong effort in term of climate models to be used and exposure and vulnerability indicators that should provide information for future scenarios (e.g. 2050, 2100). Moreover, the timeframe will reflect the identification of the hazards that should be investigated in the multi-hazard phase, the time lag of any cascading effects and the evolution of vulnerability factors to be assessed in the vulnerability phase in order to estimate a reliable multi-hazard risk and multi-risk scenario.

Therefore, the first major decision is related to the definition of the focus of the analysis: multi-hazard, multi-hazard risk or multi-risk. In a multi-hazard perspective, the major effort will concern climate models and their outputs (e.g. wind fields, precipitation intensities and distributions, drought) but no information related to exposure and vulnerability will be provided. The multi-hazard risk will consider multi-hazard scenarios to be integrated with an overall analysis of exposure and vulnerability of the elements at risk in the analysed territory. The most complex approach is the multi-risk assessment where it is possible to analyse the risk arising from different elements at risk - in the same geographical area - evaluating their vulnerability to different typologies of hazards. The selection of the approach to be used depends not only on the research objective, but is also a question of data availability and scale of analysis. The most complex and comprehensive framework should consider the multi-risk assessment (i.e. multi-hazard, multi-vulnerability and their interactions, Table 2.1.1) to be applied at different scale of analysis (i.e. from the global to the local scale).

2.4.2. Multi-hazard

The first step of an analysis is related to the assessment of multi-hazards related to climate change. This requires the improvement of climate models and their analysis in order to identify the possibility to assess cumulative effects of hazards (happening with or without temporal consequences) and to consider triggering and cascading effects as explicitly defined in Table 2.1.1. Current climate models do commonly not provide an analysis of the hazard interactions, while they support the hazard by hazard assessment allowing a single-risk assessment of the investigated area. Climate models should be improved in their inputs and outputs considering the need to analyse the effects of different climate-related hazards that are caused by the same stressors, and to define the cascade effect starting from a specific hazard (e.g. flooding) that causes secondary hazards (e.g. landslides caused by fluvial undercutting of the slope toe). Moreover, different scenarios should be provided in order to analyse all the potential triggers and hazard cascades, as effectively there is no detailed knowledge about the sequence of the hazards in the future. If at all, these future hazards can only be approximated.

In order to provide a probabilistic assessment of the hazards the availability of future climate change scenarios with an associated probability and uncertainty is essential. Effectively, global and regional climate models are not useful for a detailed analysis, providing low resolution outputs that are not relevant for planners to study climate change impacts locally (UKCIP 2003; Maraun et al., 2010 Ramieri et al. 2011). Therefore, a strong effort should be done for the improvement of climate models or statistical methods (e.g. downscaling) in order to provide high resolution outputs that might be used for a multi-hazard assessment at a national, regional or local scale.

The initial selection of the time frame poses an additional effort in the multi-hazard phase, asking for the identification of short-term triggers (e.g. extreme events) or long-term changes (e.g. sea-level rise) and if their relations can be investigated.

2.4.3. Exposure and vulnerability

Moving to exposure and vulnerability of given elements at risk, a multi-risk methodology requires a multidimensional and integrated approach (Table 2.1.1) in which different exposed elements (e.g. population, agriculture, infrastructure, buildings) and their vulnerability towards a given hazard intensity should be considered. After the selection of the potentially exposed elements at risk, this phase poses an additional challenge in a multi-risk setting as it requires, in addition to the changing hazards, the need to provide future scenarios of elements at risk including their exposure and vulnerability, identifying vulnerability factors that can be considered static (e.g. slope, height) or dynamic (e.g. factors related to land-use and population) in the future. Moreover, IPCC (2012) describes vulnerability as a result of different conditions and processes that should be taken into account in the identification of vulnerability factors, from social and cultural (also addressing adaptive and coping capacity) to environmental and biophysical (e.g. geomorphology, vegetation cover) ones. The inclusion of adaptive and coping capacity can be used to prepare for and undertake actions to reduce adverse impacts, moderate harm, or exploit beneficial opportunities (Mojtahed et al. 2012). However, the scope of this work is strictly focused on the environmental and biophysical characteristics of vulnerability that allow the assessment of those aspects that are not explicitly related to the future development of society and economy.

Most of the work, until now, was focused on the static assessment of exposure and vulnerability (e.g., Papathoma-Köhle et al. 2011; Kappes et al. 2012b). However, the information provided by coupled land-use/climate models (Santini and Valentini 2011) can be integrated in the multi-risk process in order to evaluate future scenarios of exposure and vulnerability.

2.4.4. Multi-risk

The multi-risk approach refers to a complex combination of hazards, exposures and vulnerability of elements at risk and consequent risks that should also be analysed in a climate change perspective taking into account interrelations and interconnections under consideration of the different unit of measures. Therefore the aggregation poses the challenge to define common scales of comparison (e.g. normalized indicators, Torresan et al. 2012).

At the international level risk is considered as the product of hazard, vulnerability and exposure (IPCC 2012). This leads to the questions about the aggregation of the risk that could be developed considering qualitative, semi-quantitative or quantitative approaches for addressing climate change driven multi-risks. A valuable quantitative approach is the assessment of risks by means of Multi-Criteria Decision Analysis (MCDA) functions that allow the estimate of the relative risks in the considered region, the comparison of different impacts and stressors and the ranking of targets and exposure units at risk (Giove et al. 2009; Torresan et al. 2011). Moreover, the MCDA allows the involvement of the end users in the aggregation phase. This approach has the advantage to be transparent in the construction of results and to aggregate different end users' considerations. Nevertheless, it imposes a subjective assessment of the multi-risk and the problem of the integration of different expertise (e.g. technical features, decision-making aspects) in the analysis (Giove et al. 2009).

2.4.5. Facing the challenges

The most important challenge for the application of the aforementioned steps (i.e. application context, multi-hazard, exposure and vulnerability of elements at risk, multi-hazard risk and multi-risk) is to provide a useful and applicable result that could be adopted for the development of adaptation measures, for instance in a spatial planning context. The successful implementation of a comprehensive climate change multi-risk assessment into management strategies should require the identification of the final users and stakeholders (e.g. researches, public local administrations, national institutions) and their awareness in order to produce an effective need of multi-risk information. Therefore, the early involvement of stakeholders in the process could help the identification of their needs and the adequate communication of the results (Greiving and Glade 2013). However, dealing with the multi-risk implies different issues related to the amount of data that should be used, the probabilities, uncertainty and error propagation (Kappes et al, 2012a). Specifically, the multi-risk assessment requires a huge amount of data to be collected, analysed and aggregated in order to provide a rigorous multi-risk information. All this information characterized by different units of measurement should be therefore used in order to provide a dimensional multi-risk index. Moreover, the identification and communication of the information related to the probability, uncertainty and error propagation should be well communicated to stakeholders and end-users as a range of possibilities of what the future could be (IPCC 2012). The appropriate communication of what is certain and what is uncertain is crucial when the results have to be used by different stakeholders and end users. Commonly stakeholders are adverse to uncertainty and to take action in response to this kind of information (Morton et al. 2011). However, the scientific approach requires the analysis and the clarification of these aspects in a way that can be easily understood by a non-scientific community in order to avoid any decision based on misjudged information.

In order to provide climate services useful for the development of adaptation measures to different stakeholders and end-users, an easy visualisation of the synthetic index of multi-risk is needed. The climate services should be related to targeted information about multi-hazard, exposure and vulnerability, in a specific time horizon and will include high quality information about multi-risk. Specifically, there is the need to understand how to aggregate and map the multi-risk results in a usable, comprehensive and easy way to stakeholders and no expert users for assessment and management purposes (e.g. aggregated multi-risk index, different colours and symbols for different risks as presented by Frigerio et al. 2012, to name one example only).

2.5. Remarks from the literature review

This Section presents a selection of important initiatives published in the international literature dealing with multi-hazard, multi-hazard risk and multi-risk assessment.

The lack of a precise terminology was discussed and as a solution, common definitions in the multi-risk context were provided as a starting basis for this analysis. Moreover, three main approaches were identified in the literature: multi-hazard, multi-hazard risk and multi-risk. At the international level there are different projects addressing these approaches (e.g. HAZUS, RiskScape, CAPRA). The respective institutions maintaining these projects provide services and tools for global, national and local applications, however none of them are related to climate change aspects. The literature review allows the identification of different methodologies dealing with multi-hazard, multi-hazard risk and multi-risk that were analysed considering the application context, how multi-hazard, exposure and vulnerability of elements at risk, the multi-hazard risk and multi-risk results were implemented in the analysed works.

It can be concluded that most of the methodologies assessed risks related to natural hazards (e.g. floods, landslides, avalanches), focussing their efforts on the multi-hazard assessment and on the static vulnerability (i.e. neither changes in time nor in space).

The lack of methodologies focused on climate-related hazards highlights that the multi-risk approach should be taken into account in this emerging field considering its increasing relevance on the consequences that could affect both natural and anthropogenic systems (IPCC 2012).

In this context, the paper was also aimed to present an overview of challenges and consequences of the multi-risk assessment in a climate change perspective. The challenging perspective for impact assessors is therefore to make a quantitative synthesis of information about multiple-climate impacts at different spatial and temporal scales including consistent estimates of uncertainties, taking into account the special view of spatial planning on hazards and risks.

In order to achieve this objective, strong cross-sectoral interactions and collaborations with different experts should be developed to take advantage from the information of the consolidated research on climate scenarios and sector by sector analysis (e.g. agriculture, economy, natural hazards such as landslides, wind or coastal erosion, social science).

However, in order to include all the aspects dealing with climate change, a major effort should be addressed in the light of the socio-economic development and the anthropogenic influence.

SECTION B: METHODOLOGICAL DEVELOPMENT

3. Multi-risk methodology for the assessment of natural and climate-related impacts

The main aim of the multi-risk methodology is to estimate cumulative impacts related to natural hazards and climate change in order to provide a rapid assessment method to scan areas and targets at risk from different hazards and to advance current management approaches to risk reduction and climate change adaptation.

Specifically, the multi-risk methodology pursues the following key objectives:

- to identify suitable risk and vulnerability indicators for the assessment of multiple natural and climate-related impacts;
- to provide a semi-quantitative multi-risk assessment for the relative ranking of areas and targets affected by multiple risks related to natural hazards and climate change by means of Multi-Criteria Decision Analysis;
- to provide a quick assessment tool to scan multiple threats in the considered region and to assist local communities and stakeholder (e.g. water, soil, coastal management authorities) in the definition of adaptation strategies.

According to Table 2.1.1, risk is considered as the potential adverse consequences for natural and human systems resulting from the interactions of climate-related hazards with vulnerabilities of the exposed systems (i.e. elements at risk) (IPCC 2012, 2014). Moreover, going beyond the traditional hazard by hazard approach proposed by the climate change adaptation community, the risk framework proposed in this work adopts a multi-risk perspective, considering that different hazards can potentially affect a variety of receptors (i.e. elements at risk) in the analysed case study area. Figure 3.1 summarises the four main steps of the multi-risk methodology: multi-hazards, exposure, multi-vulnerability and multi-risk assessment.

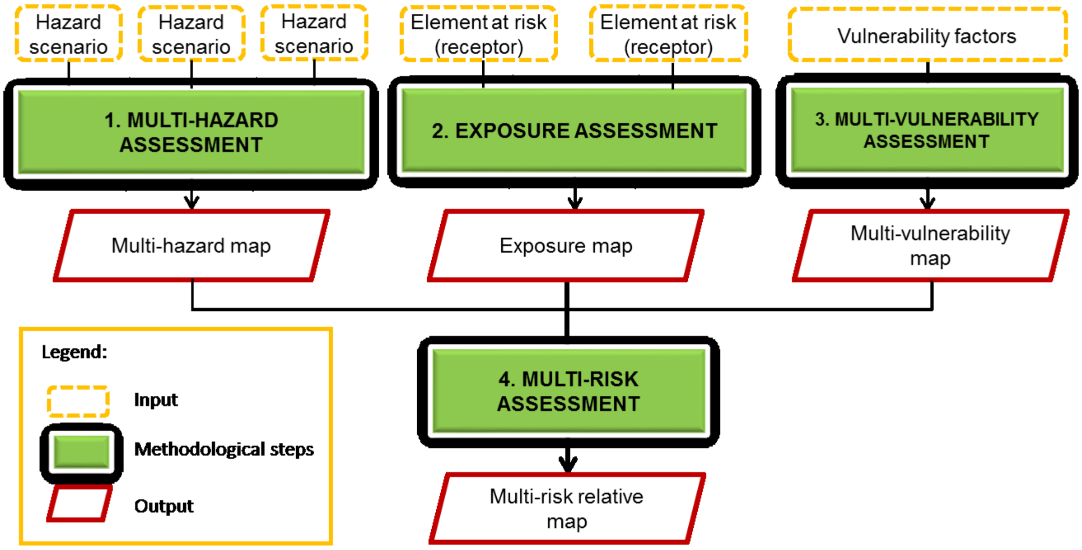


Figure 3.1. The multi-risk framework.

Each step requires the management of a huge amount of heterogeneous input data with different units of measures (e.g. output coming from climate and hydrodynamic models to characterize hazard scenarios, spatial data of land-use for the identification of the receptors and their vulnerabilities) that are normalized and aggregated through Multi-Criteria Decision Analysis (MCDA) in order to provide spatial information useful for the public authorities responsible for the protection of environment and human health (Figure 3.1).

The main steps, the input data and their results will be illustrated in the next paragraphs, while the application to the North Adriatic case study will be presented in Section C (Application to the case study area).

3.1. Multi-hazard assessment

The first step towards the application of the multi-risk methodology is the multi-hazard assessment that is aimed at providing a multi-hazard scenario considering the potential influences among different single hazard scenarios and, if available, their probabilities of occurrence in the timeframe of analysis.

Therefore, the multi-hazard assessment is performed through the following procedure:

1) Selection of the hazards and timeframe to be considered;
2) Assessment of hazard interactions;
3) Analysis of hazard probabilities;
4) Aggregation and normalization of the multi-hazard score.

Single hazard scenarios to be considered could be created based on the outputs of climate models (e.g. temperature or precipitation projections) and physical impact models (e.g. sea-level rise, currents velocity, bottom stress) (Torresan et al. 2014), or by reviewing single-hazard scenarios available from previous projects in the considered region. These maps are useful for the visualization of a physical event or trend (e.g. sea-level rise, coastal erosion, flood) that may cause losses or damages for people, properties, infrastructure, ecosystems and environmental resources (IPCC 2014). Moreover, the future timeframe of analysis (e.g. 2050-2100) should be identified based on the objectives of the analysis and the available data for the case study.

Once the single hazard scenarios have been created or selected, the multi-hazard assessment requires the semi-quantitative analysis of the relationships among the analysed hazards (e.g. how a hazard could be negatively affected by another operating in the same area and in the same temporal window) by means of the hazard influence matrix as presented in Table 3.1.1.

h_1	$w_{1,2}$	$w_{1,3}$
$w_{2,1}$	**h_2**	$w_{2,3}$
$w_{3,1}$	$w_{3,2}$	**h_3**

Table 3.1.1. Example of hazard influence matrix. Hazard scores are placed in the grey cells. Weights used to measure hazard interactions (e.g. influence of sea-level rise (h_1) on coastal erosion (h_2)) are placed in the white cells.

The hazard influence matrix is aimed at providing the weights representing how much the different hazards influence each other (i.e. the synergies among the hazards) and can be read in a clockwise scheme of interaction (e.g. h_1 influences h_2 with a magnitude represented by $w_{1,2}$ and h_2 influences h_1 with a magnitude of $w_{2,1}$).

For the assignation of weights, experts should be consulted in order to fulfil the white cells of Table 3.1.1 following the linguistic evaluation reported in Table 3.1.2.

Linguistic Evaluation	**Scores**
Most important class/weight	1
Weakly less important class/weight	0.8
Rather less important class/weight	0.6
Strongly less important class/weight	0.4
Demonstratively less important class/weight	0.2
Absolutely not important class/weight (i.e. no vulnerability)	0

Table 3.1.2. Linguistic evaluation supporting the expert in the assignation of relative scores and weights (adapted from Pasini et al. 2012).

Function 1 of Table 3.1.3 allows the calculation of the weighted single hazard scores considering the hazard influence matrix (Table 3.1.1) that should be aggregated in order to obtain a cumulative multi-hazard weighted score (Function 2, Table 3.1.3).

Function	Description
1) $h_i' = h_i \cdot [1 + \frac{\sum_{j=1,j\neq i}^{n} w_{j,i}\cdot\bar{\emptyset}(h_j)}{\sum_{j=1,j\neq i}^{n}\bar{\emptyset}(h_j)}]$ $h_i' =$ hazard score associated to the *ith* hazard weighted according to the influence of other hazards in the investigated cell. The score ranges in [0,2]; $h_i =$ hazard score associated to the *ith* hazard for the investigated cell; $h_j =$ hazard score associated to the *jth* hazard for the investigated cell; $w_{j,i} =$ weight assigned to the influence of h_j to h_i using the hazard influence matrix (Table 3.1.1); $\bar{\emptyset}(h_j) =$ "not empty function" which assumes the value equal to 1 when the hazard j is present in the investigated cell and 0 otherwise; $n =$ number of hazards in the system.	Function 1 is aimed at calculating the weighted score of each hazard affecting the investigated cell considering all the interactions with other hazards. If in the investigated cell a hazard (e.g. H$_1$) is not influenced by another, it will maintain its score (i.e. the score that it has on the analysed cell, h_1). Otherwise the score of h_i is multiplied by $1 + \frac{\sum_{j=1,j\neq i}^{n} w_{j,i}\cdot\bar{\emptyset}(h_j)}{\sum_{j=1,j\neq i}^{n}\bar{\emptyset}(h_j)}$ representing synergic influence of all the hazards affecting the investigated cell. The synergic influence is increased by 1 in order to better visualise the increasing score of the considered *ith* hazard due to the hazard interactions. If there are no hazard relationships, synergic influence will turn to the indeterminate form of 0/0 which for simplification is assumed as 0.
2) $h = \frac{\sum_{i=1}^{n} h_i'}{2n}$ $h =$ multi-hazard score associated to the investigated cell weighed and normalized in [0,1]; $h_1', \ldots, h_n' =$ single hazard scores associated the investigated cell weighted according to the hazard influences (calculated by Function 1); $n =$ number of the investigated hazards in the case study.	The final result of Function 2 allows the normalization of the multi-hazard score in [0,1], considering that if in a cell a single hazard is located with a score of 1 (i.e. the maximum hazard score) with no other influencing hazards, than the multi-hazard score of that cell will be lower than the initial single hazard score h_i calculated with Function 1.
3) $p = P_n^V(H) = P_{n-1}^{\vee}(H) + p(h_n) - P_{n-1}^{\vee}(H) \cdot p(h_n)$ $p =$ probability of the *n* hazards affecting the investigated cell in the same timeframe ranging in [0,1]; $P^V =$ disjunctive probability function; H = vector of hazard scenarios for the investigated cell; $n =$ number of the investigated hazards in the case study.	If the investigated cell is interested by a single hazard (e.g. H$_1$) only the probability of the hazard should be considered (e.g. $p(h_1)$). If the investigated cell is interested by 2 or more hazards (e.g. H$_1$, H$_2$), the disjoint probability of the hazards affecting the cell should be considered. Function 3 allows providing a probability to each cell considering that the hazards affecting the cell could happen individually (i.e. probability of the single hazard: for instance, it happens h_1 or h_2) or simultaneously (e.g. h_1 happens together with h_2).

Table 3.1.3. Multi-hazard functions and their description applied in the multi-hazard assessment.

Then, the expert should define the probabilities of single hazards happening in the same timeframe (not necessary simultaneously), based on the available hazard data. Probabilities can be derived from numerical modelling or from the analysis of past events happened with the intensity of concern: the more are the events, the higher is the probability of the related hazard. If the return period is provided, its invers should be considered as the probability of the hazard event. However, if no probabilities can be defined for each hazard, a probability score equal to 1 should be assigned, assuming the investigated hazard as certain event in the timeframe, as a conservative estimate. Accordingly, the disjoint probability function (Function 3, Table 3.1.3) should be applied to each cell considering the probabilities of all hazards (hazards not present in the cell have 0 probability) and obtaining a total multi-hazard probability value p. The higher is the number of the hazards affecting the cell, the higher is the total probability.

The last step of the multi-hazard assessment is aimed at the aggregation of the weighted scores and the probabilities related to the investigated hazards. Therefore, the final score in a specific cell is comprehensive of the multi-hazard weighted score (h) and the probability of occurrence of the hazards affecting the cell. The result of Equation 1 ranges in [0,1].

The final multi-hazard score is provided applying the following equation:

$$h^p = h \cdot p \qquad \text{Equation 1}$$

Where:

$h^p =$ multi-hazard score with the associated probability;

$h =$ multi-hazard score associated to the investigated cell weighed and normalized in $[0,1]$ according to Function 2;

$p =$ probability in the investigated cell according to the disjunctive probability function (Function 3).

The multi-hazard assessment phase provides a relative multi-hazard map for the whole case study area representing the spatial distribution of areas potentially exposed to multiple hazard (an example is provided in Paragraph 5.1.2). The result ranges in [0,1], where 0 means no hazards will affect the cell, 1 represents the cells where the number, weights, intensities and probabilities of hazards are the higher for the case study area.

3.2. Exposure assessment

The main aim of the exposure assessment is to identify the elements at risk (i.e. receptors) of interest for the multi-risk assessment considering their presence and their spatial localization using land-use maps or models. Specifically, this step allows the identification of all the receptors (i.e. r_1, r_2, r_3,…, r_n) that can be affected by the analysed hazards and the union of their geographic areas.

The exposure score is therefore evaluated as follows:

$$e = \begin{cases} 0 & \text{if no receptor is present in the investigated cell} \\ 1 & \text{else} \end{cases} \qquad \text{Equation 2}$$

Where:

$e =$ exposure score related to the union of the geographical area of the investigated receptors.

Equation 2 provides a value of 0 in the cell where no receptors are located, and 1 where there is the presence of one or more receptors.

Moreover, a useful analysis could be developed considering the identification of the potential overlapping of receptors in each cell. This analysis highlights areas where more than one receptor are located and therefore more socio-ecological values should be preserved.

The result of this step is a map showing the localization and the geographic extent of all the investigated receptors.

3.3. Multi-vulnerability assessment

The main aim of this step is to provide a physical and environmental assessment of the multiple vulnerabilities of the case study area. It considers the presence of different receptors and of their predisposition to be adversely affected by multiple natural and climate-related hazards in the territory of the analysis (IPCC 2014).

The multi-vulnerability score is determined by the selection and aggregation of vulnerability factors (*vf*) that should be identified considering the couple hazard/receptor in order to identify all the physical and environmental characteristics representing the sensitivity of the receptor to the different investigated hazards.

According to Torresan et al. (2012), this step is carried out through the development of a vulnerability matrix in which the main row is an inventory of the main potential natural and climate-related hazards affecting the analysed area (defined in the multi-hazard assessment) and the main column lists the investigated receptors (defined in the exposure assessment). The white cells (in the intersection between a hazard and a receptor) should represent the identified *vf* (e.g. slope, vegetation cover, wetland extension, % of urbanization). An applied example of a vulnerability matrix for the case study of the North Adriatic coastal area will be presented in Paragraph 5.3.

The aggregation of the *vf* should be provided for each cell of the analysed case study. Specifically, if a cell is characterized by one receptor (e.g. r_1) that is affected by one hazard (e.g. H_1) the biophysical and environmental vulnerability factors that should be aggregated are listed in the vulnerability matrix in the intersection between H_1 and r_1. While, if a cell is characterized by two or more receptors and two or more hazards, the aggregation should consider all the *vf* identified for those receptors and hazards taken only once.

Moreover, individual vulnerability factors can be weighted to represent their relative importance in the estimation of multi-vulnerability associated with the investigated natural and climate-related impacts.

The assignation of scores and weights can follow the linguistic evaluations reported in Table 3.1.2. Given a bidimensional matrix $W_{h,vf}$ which contains the weights related to the importance of a vulnerability factor *vf* in respect to the hazard (*h*), the final weight for a vulnerability factor vf, possibly part of several receptors and affected by several hazards, should be defined as the maximum of the weights preventively evaluated.

The aggregation of the vulnerability factors is then performed by applying the "probabilistic or" function (Kalbfleisch J. G. 1985), defined as follows:

$$vf = \otimes_{|VW_c|}(VW_c) \qquad \text{Equation 3}$$

Where:

vf = physical and environmental multi-vulnerability score of the investigated cell to the investigated impact(s);

$\otimes$ = "probabilistic or" function (Kalbfleisch J. G. 1985);

VW_c = set of physical and vulnerability factors weighted by the corresponding $w_{f,c}$. They are related to all impact(s) and receptors present in the investigated cell c, i.e. $VW_c = \{vf_c \cdot w_{vf,c} | vf_c \text{ is a vulnerability factor present in cell c}\}$.

Applying the "probabilistic or" function (Equation 3), if just a vulnerability factor (*vf*) assumes the maximum value (i.e. 1) then the multi-vulnerability score will be 1. On the other side, many *vf* with low scores contribute in increasing the final multi-vulnerability score: the more is the number of low vulnerability factor scores, the greater is the final multi-vulnerability.

The result of the multi-vulnerability assessment is a map for the whole case study highlighting the areas more vulnerable to multiple natural and climate-related hazards according to the intrinsic characteristics of the investigated territory.

3.4. Multi-risk assessment

The main aim of the multi-risk assessment is to provide a relative evaluation of the cumulative risk in the investigated case study area taking into account correlation and probabilities of the analysed hazards, the presence and localization of the receptors of interest and vulnerability to the different hazards.

According to IPCC (2014), the aggregation of hazard, exposure and vulnerability scores allows the evaluation of the multi-risk in the case study, as showed in Equation 4:

$$r = h^p \cdot e \cdot vf \qquad \text{Equation 8}$$

Where:

$r =$ multi-risk score;

$h^p =$ multi-hazard score with the associated probability, according to Equation 1;

$e =$ exposure score related to the union of the geographical area of the investigated receptors, according to Equation 2;

$vf =$ physical and environmental multi-vulnerability score of the investigated cell to the investigated impact(s), according to Equation 3.

The result is a multi-risk map for the whole case study which highlights areas more affected by different natural and climate-related risks considering the different hazards affecting the territory and the vulnerability arising from the combined hazards.

C: APPLICATION TO THE CASE STUDY AREA

4. Description and characterization of the case study area

This section introduces the case study area of the North Adriatic coast (Paragraph 4.1) and the dataset used for the application of the multi-risk methodology including data for the characterization of hazards, exposure and vulnerability (Paragraph 4.2).

4.1. The North Adriatic coastal area

The North Adriatic coastal area (Figure 4.1.1) represents a unique and fragile ecosystem in which several socio-economic and environmental locations coexist (e.g. Po river delta, Venice and its lagoon, Grado and Marano lagoon, the Gulf of Trieste).

Figure 4.1.1. Case study area of the North Adriatic coast.

The case study area comprises the area between the national border connecting Italy and Slovenia, and the mouth of the southern tributary of the Po Delta system (i.e. Po di Goro), reaching an overall length of about 290 km and encompassing Veneto and Friuli Venezia Giulia regions along the Adriatic Sea (Torresan et al. 2012).

For its particular position and structure, this case study was affected in the past by different pressures deriving from natural and anthropogenic sources (e.g. the catastrophic inundation of the coastal areas in Veneto and Friuli Venezia Giulia in 1966, the pluvial flood event of Mestre in 2007).

High tides are particularly relevant due to local subsidence phenomena, which increase the importance of inundations causing severe damages to affected population and economic activities located in low-lying areas (Pirazzoli 2005; www.comune.venezia.it) and coastal erosion is a considerable issue from the 17th century and especially after 1960 (Bondesan et al. 1995; Ferretti et al. 2003). Moreover, the frequency and intensity of inundations (e.g. high tides) and coastal erosion will increase in the future due to the effects of climate change and sea-level rise (www.comune.venezia.it; Tomasin and Pirazzoli 2008; Umgiesser et al. 2011).

Several protection measures were developed in the North Adriatic region with the aim to cope with single hazards (e.g. high tides and coastal erosion processes). The MOSE project (www.mosevenezia.eu), today about 80% completed, consists of mobile barriers located at the lagoon' inlets with the aim to protect Venice and its lagoon from high tides events. Other types of natural and semi-natural coastal protections (e.g. beach and sandbanks nourishment, dune restoration, creation of new dunes with the use of natural vegetation) were implemented along the shoreline to protect it against coastal erosion (Cecconi 1997; Cecconi and Ardone 1998; Caniglia et al. 1998; CVN 2000; Cecconi and Ardone 2000; Visintini et al. 2000; Regione FVG 2008).

However, sustainable and integrated coastal planning should consider cumulative effects and impacts that could amplify one another in the coastal development and consider a balance between the economic development and the preservation of natural systems (UNEP-MAP-RAC/SPA 2010).

A series of single risk assessments were implemented in the case study area (e.g. Bondesan et al. 1998; Gonella et al. 1998; Gambolati and Teatini 2002; Lionello 2008; Torresan et al. 2012; Gallina et al. 2014; Rizzi 2014; Torresan et al. 2014) in order to provide a first regional screening of the impacts arising from single climate-related hazards. Specifically, the DESYCO Decision Support System was applied for the analysis of sea-level rise, storm surge and coastal erosion considered as single threats in the North Adriatic area in order to provide useful tools for the implementation of coastal adaptation measures. Sharing the results with local stakeholders, within PEGASO and CLIM-RUN EU-projects, allowed the identification of an additional need related to a comprehensive multi-risk index combining the single risk results (Giannini et al. 2012; UNIVE Team 2013).

Differently from recent studies, to my knowledge, this is the first attempt to adopt a multi-risk approach to study the cumulative impacts of climate change in the North Adriatic coast considering a multi-disciplinary perspective.

4.2. North Adriatic dataset for multi-risk assessment

Several data in graphic format or database were requested and retrieved from previous research projects and from local public authorities (mainly Veneto and Friuli-Venezia Giulia region) in order to characterize climate related hazards, the elements potentially at risk (i.e. targets) and their vulnerability.

Single hazard scenarios necessary to apply the multi-hazard approach in the North Adriatic coastal zone were selected from recent risk assessment studies developed for the North Adriatic coast (Torresan 2012; Gallina et al. 2014; Rizzi 2014; Torresan et al. 2014). Table 4.2.1 summarizes the main features of the single-hazard maps retrieved for sea-level rise, storm surge and coastal erosion hazards. The table shows the emission scenarios used as climate forcing, the model(s)/method to produce hazard metrics, timeframe or return period considered in the assessment, as well as the spatial resolution and the reference in which the maps were reported.

Single hazard map	Description	Technical features	Reference
Sea-level rise	Maps of inundated areas (cm) according to projected sea-level rise scenarios for the year 2100 (spatial resolution 25 m).	- Emission scenario: A1B SRES; - Climate-forcing model: EBU-POM (spatial resolution 28 km). - Impact Model: SHYFEM high resolution ocean and sea circulation model (Spatial resolution: 2.5 km-50 metres); - Reference period: 1960-1990 - Time scenario: 2070-2100; - Hazard metric: projected sea-level at 2100 (low 17 cm, high 42 cm).	Umgiesser et al. 2004; Torresan et al. 2014
Storm surge	Maps of inundated areas (cm) according to different storm surge return periods and sea-level rise scenarios (spatial resolution 25 m).	- Method: Joint Probability Method (JPM, Pugh and Vassie 1979); - Storm surge return period: 20, 50, 100, 200, 500 years; - Spatial resolution: 28 tide gauge stations; - Hazard metrics: projected sea-level at 2100 (low 17 cm, high 42 cm, from the impact model SHYFEM), mean sea-level, astronomical and meteorological tide (from the JPM).	Rizzi 2014
Coastal erosion	Maps of seasonal coastal erosion hazard for the thirty year period 2070-2100 (spatial domain: 1km from the shoreline, spatial resolution 25 m).	- Emission scenario: A1B SRES; - Climate-forcing model: COSMO-CLM Regional Climate Model (spatial resolution 14 km); - Impact model: coupled wave-ocean ROMS-SWAN model (spatial resolution: 5-2 km); - Reference period: 1960-1990 - Time scenario: 2070-2100; - Hazard metrics: wave height, bottom stress.	Carniel et al. 2007; Torresan et al. 2014

Table 4.2.1. Summary and technical description of single hazard maps selected to test the multi-hazard approach in the coastal area of the North Adriatic Sea.

The single hazard maps described in Table 4.2.1 were obtained following the Regional Risk Assessment approach implemented by the DEcision support SYstem for COastal climate change impact assessment (DESYCO) (Torresan 2012; Torresan et al. 2013; Santoro et al. 2013; Gallina et al. 2014; Rizzi 2014) which allows the integration of the hazard metrics produced by impact models (e.g. projected sea-level rise scenarios, wave height) with pathway (e.g. elevation of the territory) and attenuation factors (e.g. artificial protections), in order to evaluate the potential areas affected by coastal hazards (Appendix I). Specifically, as summarized in the column “technical features”, the maps were obtain by integrating quantitative information from different types of numerical models (including climate, hydrodynamic and statistical models) running at different spatial scales provided within the CMCC-FISR (2005-2010) and CLIMDAT (2012-2013) projects. More specific information about the models and the model chain used for the single hazard assessment could be found in Umgiesser et al. (2004), Carniel et al. (2007) and Torresan et al. (2014).

The sea-level rise hazard maps produced for the North Adriatic area allow the visualization of the amount of water above each spatial unit (i.e. cell) for the year 2100, considering the topography of the territory represented by a Digital Elevation Model (DEM) (Torresan 2012). Even if subsidence, is a relevant phenomenon, especially for the low-lying coastal plains of the Venice lagoon and the Po River Delta (with values of 1-2 mm/year, Carminati and Martinelli 2002; Carbognin et al. 2009), there is a lack of homogeneous data to map and detect this phenomenon for the overall coast of Veneto and Friuli-Venezia Giulia, and consequently it was not possible to include this factor in the analysis.

The storm surge maps provide the spatial representation of the extent of coastal flooding for the year 2100, combining the potential sea-level rise with mean sea-level, astronomical and meteorological tides and considering different return periods (e.g. 20, 50, 100, 200, 500), the topography of the territory and the distance from the coastline (Rizzi 2014).

Finally, the seasonal coastal erosion maps (i.e. spring, summer, autumn, winter) were produced in order to identify coastal areas that could be exposed to coastal erosion due to two relevant hazard metrics influenced by climate change (i.e. wave height and bottom stress), the presence of artificial protections and the distance from the sea in the future scenario 2070-2100 (Gallina et al. 2014).

The information gained from the single hazard assessment and summarized in Table 4.2.1 will be used for the application of the multi-hazard assessment (Paragraph 5.1.1).

All single hazard maps were produced considering the A1B scenario, representing an intermediate case compared to the more intense A2 and the weaker B1 storyline families (IPCC 2007). Moreover, the A1B projections are equally plausibile and comparable with the more recent simulations of the RCP6 (IPCC 2013), an intermediate forcing pathways between RCP4.5 and RCP8.5. No detailed projections at the Mediterranean scale are available and the scenario comparison can be conducted only at the global level, showing similar values of mean global temperature for the CMIP5 ensemble (IPCC 2013) and the older CMIP3 (IPCC 2007) which range in 1.7-4.4 °C for the A1B and 1.8-3.7 °C for RCPs (Cattiaux et al. 2013; Knutti and Sedláček 2013). Also the projected sea-level rise used in this application (i.e. 42 cm) renders a medium value compared to the SRES scenarios (ranging between 18 and 52 cm, from IPCC 2007) and to the more recent RCPs (i.e. 26-98 cm from IPCC 2014).

As far as sea-level rise is concerned, there is a high uncertainty on future projections due both to the greenhouse gas emissions considered and to the assumptions done about the dynamics of terrestrial ice melting (Umgiesser et al. 2011). The present application employs sea-level rise projections produced by a dedicated model chain composed of climate and high-resolution ocean/sea circulation models for the North Adriatic Sea (Torresan et al. 2014), that allow to properly evaluate the consequences associated to sea-level rise, storm surge and coastal erosion.

A variety of physical and environmental data are needed to characterise the spatial pattern and distribution of targets (e.g. beaches, wetlands, agricultural areas) and define appropriate indicators of multi-vulnerability (e.g. vegetation cover, percentage of urbanisation, presence of protected areas) to cumulative climate change impacts in the studied area. The available dataset for the application of the exposure and multi-vulnerability assessment to the case study area of the North Adriatic coast is summarized in Table 4.2.2.

Dataset	Spatial Domain	Reference
Land cover Map (1:10000)	VE	VE Region, 2009
Monitoring Land Use/Cover Dynamics (MOLAND) (1:25000)	FVG	FVG Region, 2000
Digital Elevation Model (DEM) (5 m)	VE	VE Region, 2007
Digital Elevation Model (DEM) (10 m)	FVG	FVG Region, 2006a
Natural reserves, Regional Parks, Sites of Community Importance (SIC)/ Special Protection Areas (ZPS) (1:150.000)	VE	VE Region, 2005
	VE	VE Region, 2008
	VE	VE Region, 2006
	FVG	FVG Region, 2007
	FVG	FVG Region, 2008
Soil type, Geologic map (1:100.000)	VE	VE Region, 2009
Soil type, Geologic map (1:150.000)	FVG	FVG Region, 2006b
Population and Housing Census	VE	ISTAT, 2001
	FVG	ISTAT, 2001

Table 4.2.2. Available dataset for the characterization of exposure and vulnerability in the North Adriatic coast (VE= Veneto, FVG= Friuli Venezia Giulia).

5. Application of the multi-risk methodology for the assessment of multi-risks related to climate change impacts in the North Adriatic coastal area

This section presents the sub-sequential implementation of each step of the multi-risk methodology (Chapter 3), focusing on three climate-related hazards affecting the North Adriatic case study: sea-level rise, storm surge and coastal erosion.

5.1. Multi-hazard

5.1.1. Assessment

The single hazard scenarios for the application of the multi-risk methodology for 2070-2100 were selected considering the available data presented in Paragraph 4.2 using a precautionary approach, in which the worst scenarios were considered: sea-level rise inundation corresponding to the higher sea-level rise projection (i.e. 42 cm); storm surge associated to the more intense extreme event with a return period of 500 years and with the higher sea-level rise projection (i.e. 42 cm); winter coastal erosion scenario representing the worst season for the coastal erosion stressors (i.e. bottom stress and wave height).

In this application, a team of environmental experts performed the assignation of the influence weights that are listed in Table 5.1.1.1.

Sea-level rise	0,8	0,5
0	**Storm surge**	0,8
0	0	**Coastal erosion**

Table 5.1.1.1. Hazard influence matrix applied to the North Adriatic case study. In the white cells the influence weights are listed.

The weights were assigned considering a qualitative evaluation of the hazard relationships starting from international literature and according to the linguistic evaluations of Table 3.1.2.

Table 5.1.1.1 highlights that sea-level rise is not interested by the influence of storm surge and coastal erosion (i.e. influence weight equal to 0), as, considering the hydrodynamic model SHYFEM used for this application (Paragraph 4.2), it is mainly forced by regional climate variables related to atmospheric pressure and winds (Torresan et al. 2014). Therefore, the investigated hazard influences concern sea-level rise affecting storm surge and coastal erosion, and storm surge affecting coastal erosion. Specifically, an influence weight equal to 0.8 was assigned to the influence of the sea-level rise to storm surge events due to the strong effects that sea-level rise could have on tidal range and the evolution of storm surges, exacerbating the intensity of flood events (Tebaldi et al. 2012; IPCC 2012).

Sea-level rise will also affect coastal erosion, however, in literature there are still controversial studies for what concerns the nature of their relationship (e.g. Tebaldi et al. 2012; Woodroffe and Murray-Wallace 2012; IPCC 2014). Therefore, an influence weight equal to 0.5 was assigned to the relationship between sea-level rise and coastal erosion which provides a certain but intermediate importance to the synergy that the two investigated hazards have.

Finally, looking at the relation between storm surge and coastal erosion, an influence weight equal to 0.8 was provided. Effectively, the effects that storm surges will have on coastal erosion are quite certain: they will increase the probability and the rate of the beach removal (e.g. IPCC 2014).

The assignation of the aforementioned influence weights allowed the implementation of Functions 1 and 2 (Table 3.1.3) to the case study providing a weighted multi-hazard normalized score for each cell as intermediate result of the multi-hazard assessment.

In this phase, experts were also asked to define the probabilities for each single hazard assigning a probability equal to 1 to sea-level rise and coastal erosion as it was no possible to reconstruct probabilities from historical data for these phenomena and not probabilistic information was provided by numerical models, while for the storm surge extreme event, the inverse of the return period considered in the assessment (i.e. 1/500= 0.002) was identified as value of probability.

5.1.2. Results

The final result of the multi-hazard assessment is the map represented in Figure 5.1.2.1 in which the whole case study and some specific zooms are depicted, highlighting that 75% circa of the investigated territory will be affected by multiple hazards. The multi-hazard map was classified using the equal interval method allowing the division of the scores into 5 equal sized classes (i.e. very low, low, medium, high, very high) (Zald et al. 2006).

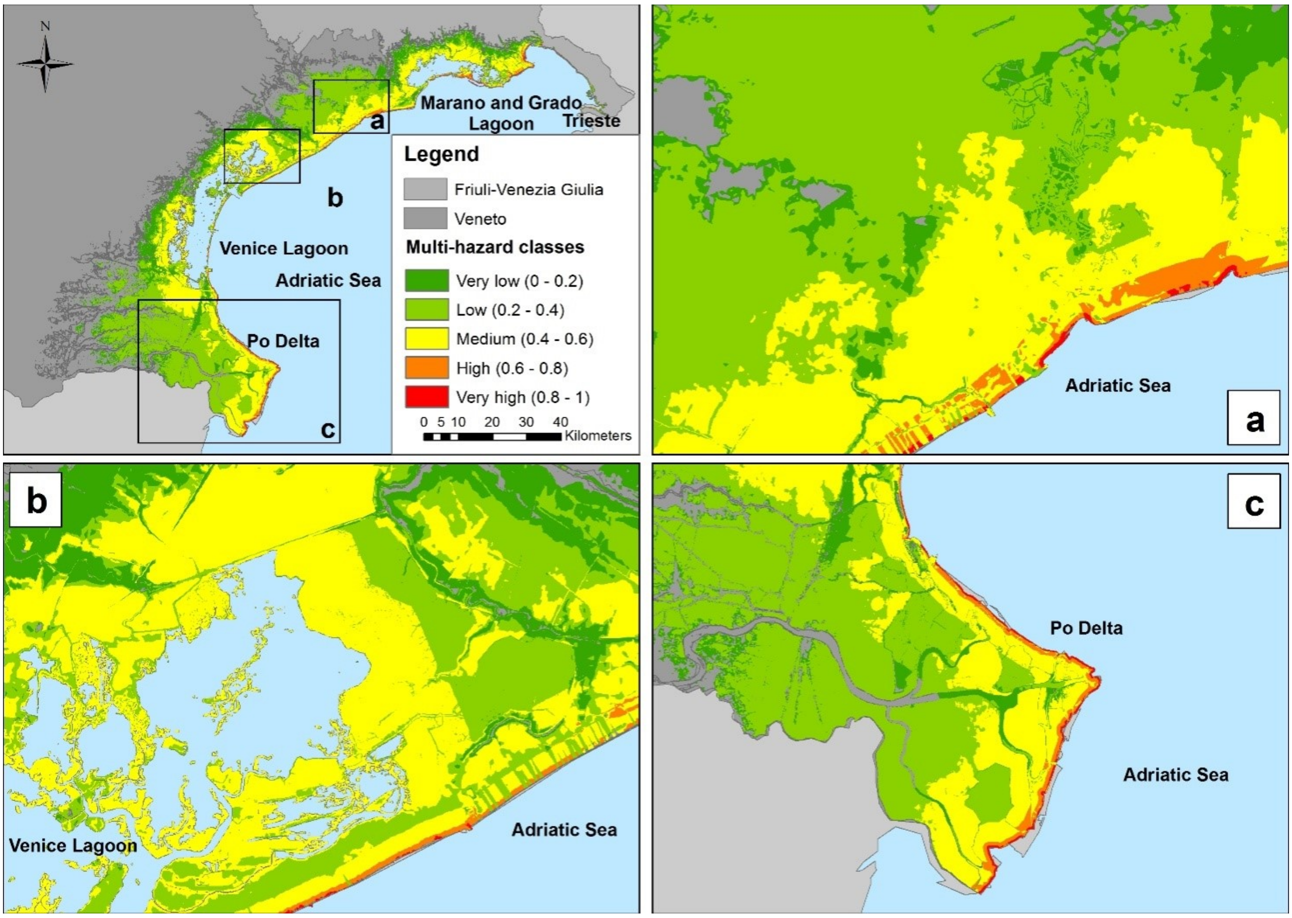


Figure 5.1.2.1. Multi-hazard map of the whole case study and three selected areas (a, b, c) in the North Adriatic coast.

The higher multi-hazard classes are located in the proximity of the coastline where there is an overlapping of the considered hazards (i.e. sea-level rise, storm surge and coastal erosion). About 66 % of the beach surface will be affected by the higher multi-hazard classes (i.e. by the three analysed hazards).

Generally, the multi-hazard score decreases going inland following the trend of the single hazard maps (Annex I). In Figure 5.1.2.1a the presence of artificial protections attenuate the effect of coastal erosion, while sea-level rise and storm surge inundation continues inland and decreases with the distance from the coastline. Figure 5.1.2.1b refers to the northern part of the Venice lagoon in which the contribution of coastal erosion (close to the Adriatic Sea) and sea-level rise is highlighted. Also in the fragile area of the Po Delta, the area near the shoreline is affected by multiple hazards (Figure 5.1.2.1c).

The case study area will be affected by different hazards for almost 75 % of the territory (i.e. 2.635 km^2). Specifically, the 72% will be affected by one or two hazards (i.e. lower multi-hazard scores) and the 3% (i.e. higher multi-hazard scores) by all the three hazards (Table 5.1.2.1).

Hazards	Case study surface (Km^2)	Case study percentage (%)
Sea-level rise	811,77	22,95
Storm surge	454,60	12,86
Coastal erosion	7.69	0.22
Sea-level rise, storm surge	1.207,26	34,14
Coastal erosion, storm surge	65,86	1,86
Coastal erosion, storm surge, sea-level rise	88,13	2,49
No hazards	901,04	25,48

Table 5.1.2.1. Surface and percentage of the case study area affected by one, two or three hazards. The last row highlights the surface of the case study not affected by hazards.

This information, together with the spatial geographical localization of the multi-hazard classes, could help the local Civil protection in achieving a higher level of protection and resilience against disasters, by considering the likely impacts of climate change and the need for appropriate adaptation action, as explicitly requested by the European Parliament (EU 2013). The multi-hazard assessment allows the identification of those coastal areas that could be affected by multiple hazards. This information can be primarily used for future building regulation in order to avoid the zoning of residential or commercial/industrial areas in hazard prone areas. After the identification of single and multi-hazards, a comprehensive assessment of risks should also consider the exposure of targets and their potential vulnerabilities to the investigated hazards, as described in the next paragraphs.

5.2. Exposure

5.2.1. Assessment

The exposure assessment required the selection of the elements (i.e. receptors) that could be potentially affected by multiple risks in the North Adriatic coast. According to the main characteristics of the territory and the available data (Chapter 4), the following elements at risk were considered:

- Beaches;
- River mouths;

- Wetlands;
- Protected areas;
- Agricultural areas;
- Urban areas (including infrastructure);
- Natural and semi-natural systems.

5.2.2. Results

The exposure map (Figure 5.2.2.1) allows the spatial visualization of the investigated elements at risk and their overlapping in the North Adriatic case study.

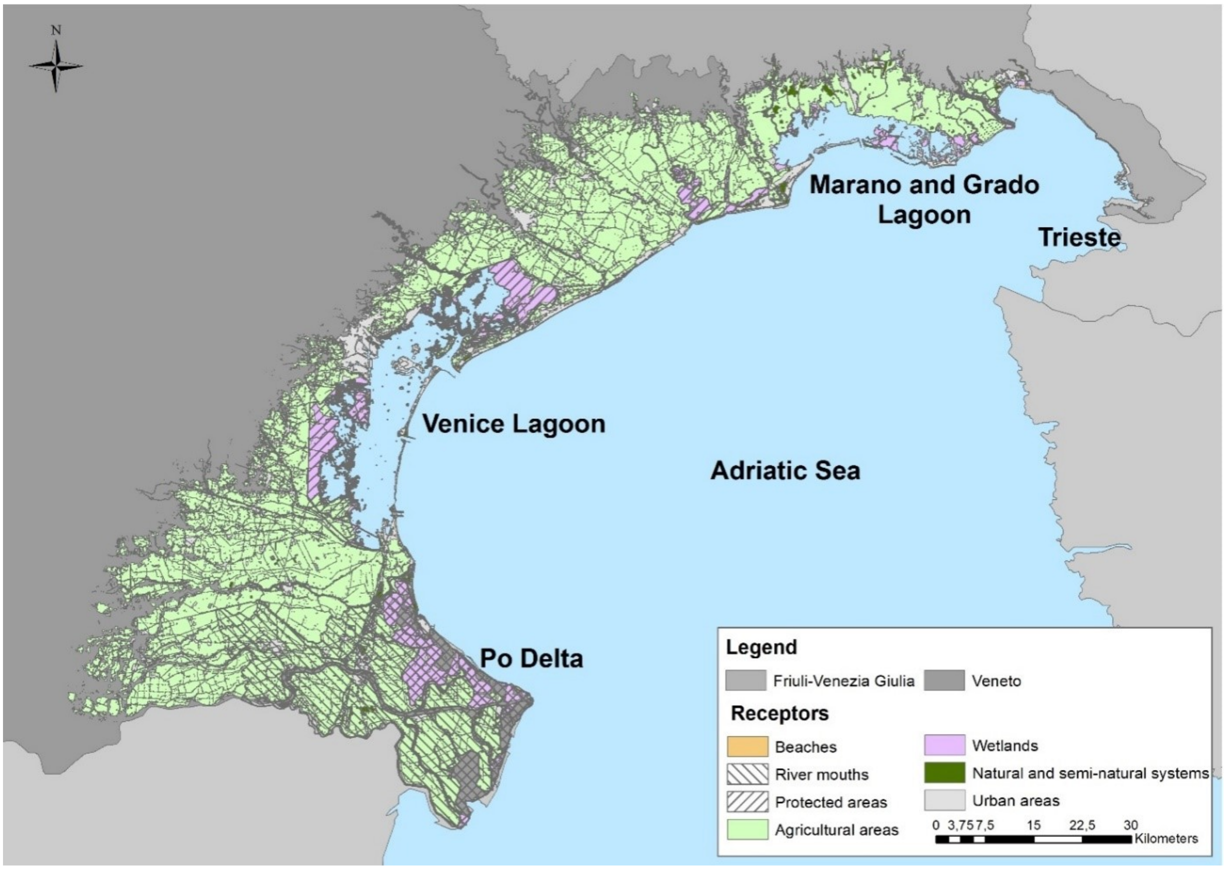


Figure 5.2.2.1. Exposure map for the multi-risk assessment in the North Adriatic coast.

The most of the case study is characterized by agricultural areas (ca. 70% in light green) which, in some areas, overlaps with protected areas and river mouths (e.g. the Natural reserve of the Po river delta) highlighting complex and fragile ecosystems that should be preserved. Moreover, the 11% of the North Adriatic area is represented by urban areas (e.g. Venice municipality, and around Grado and Marano lagoon) which could be affected by multiple-risks causing damages to people, economic activities and the environment. Other small receptors which are relevant at the local level are analysed (i.e. beaches, natural and semi-natural systems, and wetlands) as they represent important features for the North Adriatic coastal area, increasing the socio-ecological and economic importance of this region.

5.3. Multi-vulnerability

5.3.1. Assessment

According to the multi-risk methodology introduced in Chapter 3, this phase concerns the development of a vulnerability matrix in which the vulnerability factors introduced in Chapter 4 are assigned to each couple receptor/hazard.

Table 5.3.1.1 is the resultant multi-vulnerability matrix that was applied to the North Adriatic coast.

Multi-vulnerability matrix							
	Beaches	**River mouths**	**Wetlands**	**Protected areas**	**Natural and semi-natural systems**	**Agricultural areas**	**Urban areas**
Storm surge	- Vegetation cover	- Vegetation cover	- Vegetation cover	- Vegetation cover	- Vegetation cover	- Agricultural tipology	- Coastal slope
	- Coastal slope	- Coastal slope	- Coastal slope	- Coastal slope	- Coastal slope	- Coastal slope	
	- Geomorphology		- Wetland extension				
			- Wetland typology				
Coastal Erosion	- Vegetation cover	- Vegetation cover	- Vegetation cover	- Vegetation cover	- Vegetation cover	- Agricultural tipology	- Coastal slope
	- Coastal slope	- Coastal slope	- Sediment budget	- Coastal slope	- Coastal slope	- Coastal slope	- % of urbanization
	- Geomorphology	- Sediment budget	- Wetland extension	- Sediment budget			
	- Sediment budget	- Mouth typology					
	- Dunes						

Table 5.3.1.1. Multi-vulnerability matrix applied to the case study of the North Adriatic coast.

Vulnerability factors were identified considering only storm surge and coastal erosion hazards, this is why a sea-level rise inundation event was assumed to affect all the receptors in the same way, causing a permanent loss of all submerged receptors, based only on the elevation of the cells. Therefore, each cell of the territory was considered to have the same vulnerability (i.e. equal to 1) to sea-level rise.

In order to apply Equation 3, the classification and scoring of vulnerability factors was provided by the experts involved in the implementation of the methodology also considering previous studies (Torresan et al. 2012; Gallina et al. 2014; Rizzi 2014) and the opinion from relevant stakeholders interviewed in several previous workshops in the North Adriatic region (Giannini et al. 2012; UNIVE Team 2013).

The classification, scoring and the description of the correlations with the vulnerability of the investigated receptors are listed in Table 5.3.1.2.

Vulnerability factor	Vulnerability class	Storm surge score	Coastal erosion score	Description of the vulnerability classes
Agricultural typology	Arable land	1	NA	Arable lands (i.e. lands under a rotation system or fallow lands) are more vulnerable as they are less defensive for the affected territory to storm surge than other identified classes (French 2001; Torresan et al. 2008; 2012).
	Stable meadow-Pastures	0,6	NA	
	Permanent crops	0.2	NA	
Slope (degrees)	Plains: 0°-6°	1	1	Low-lying areas are more vulnerable to flooding movements inland and should retreat faster than steeper regions (Sharples 2006; Pendleton et al. 2010; Torresan et al. 2008; 2012).
	Gentle to moderate slope terrain: 6°-20°	0,6	0,6	
	Steep slope terrain: >20°	0,2	0,2	
Vegetation cover	Natural grassland and meadow	1	1	Natural grassland and meadow do not provide enough cover to the territory increasing its vulnerability to coastal erosion and storm surge (UNESCO 1998; Torresan et al. 2008; 2012).
	Vegetation with shrubbery	0,6	0,6	
	Forest	0,2	0,2	
Wetland extension (Km^2)	0 – 8.56	1	1	Small wetlands are considered to have higher vulnerability as they could be more sensitive to coastal erosion and storm surge pressures than wider ones (Torresan et al. 2008; 2012).
	8.57 – 17.12	0,8	0,8	
	17.13 – 25.68	0,6	0,6	
	25.69 – 34.24	0,4	0,4	
	34.25 – 42.80	0,2	0,2	
Geomorphology	Muddy coast	1	1	Muddy and sandy beaches are the most vulnerable geomorphic themes that could be affected by storm surges and coastal erosion (Sharples 2006; Torresan 2012).
	Sandy coast	0,6	0,6	
	Rocky coast	0,2	0,2	
Wetland typology	Inland welands (marshes, peatbogs)	1	NA	Inland freshwater wetlands can be affected more severely by the investigated impacts and they are considered more vulnerable (i.e. more sensible to salt water), respect to coastal wetlands (Rizzi et al. 2014).
	Coastal wetlands (salt masrhes, salines, intertidal flats)	0,6	NA	
% of urbanization	> 10% of the land occupied by urban and industrial areas (per municipality)	NA	1	Areas in which more than 10% of the land is urbanised are considered more vulnerable to coastal erosion, as they cannot cope with erosion processes such as urban areas less urbanised (EU 2004; Torresan et al. 2008; 2012).
	5% and 10% of the land occupied by urban and industrial areas (per municipality)	NA	0,6	
	< 5% of the land occupied by urban and industrial areas (per municipality)	NA	0.2	
Sediment budget	Coast in erosion	NA	1	Retreating coasts are more vulnerable to coastal erosion, compared to stable or advancing ones (Torresan 2008; 2012; Abuodha and Woodroffe 2006).
	Stable coast	NA	0,6	
	Advancing coast	NA	0.2	
Dunes	Absence	NA	1	The absence of natural dunes can aggravate the vulnerability to coastal erosion as they cannot protect the surrounding area from the impact (McLaughlin and Cooper 2010; Torresan et al. 2008; 2012)
	Presence	NA	0.2	
Mouth typology	Estuary	NA	1	Estuaries are considered more vulnerable than deltas to erosion as they are less prone to sedimentation processes (Sharples 2006; Torresan 2008; 2012).
	Delta	NA	0,2	

Table 5.3.1.2. Vulnerability factors, classes and scores for the receptors analysed in the North Adriatic case study. NA means Not Applied and concerns the vulnerability classes that are not relevant for the considered hazards.

In order define the importance of each vulnerability factor in determining the multi-vulnerability of coastal areas, weights were assigned to each of them (Table 5.3.1.3).

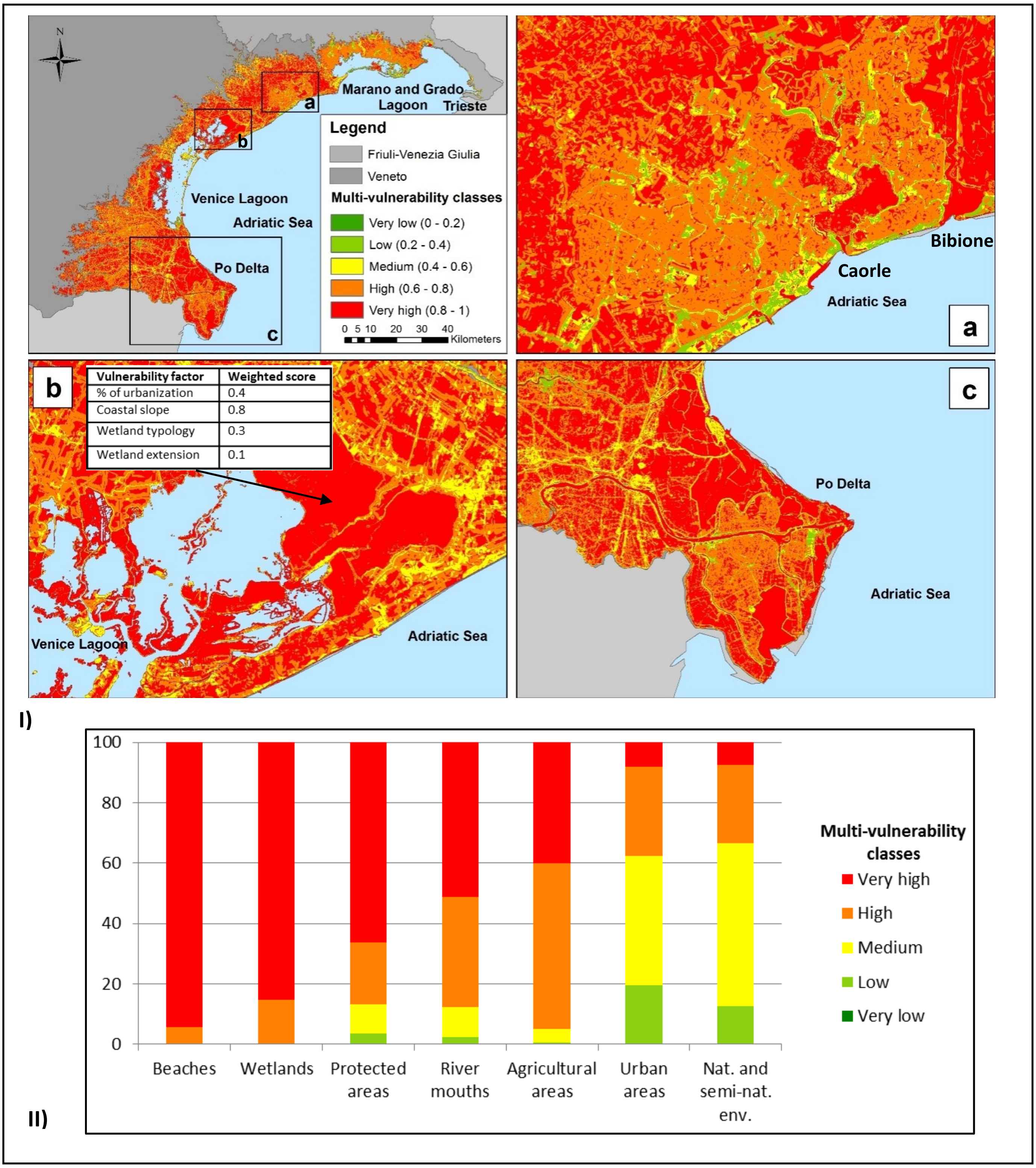
VULNERABILITY FACTOR	WEIGHT
Coastal slope (degrees)	0,8
Geomorphology	0,8
Sediment budget	0,8
Vegetation cover	0,6
Dunes	0,6
River mouth typology	0,5
Agricultural typology	0,5
Wetland typology	0,5
Wetland extension (km^2)	0,5
% of urbanization	0,4

Table 5.3.1.3. Weights assigned to the vulnerability factors in the North Adriatic case study.

Geomorphology, coastal slope and sediment budget gained the higher weights (i.e. 0.8) in the present assessment as they represent geo-physical characteristics very important for the assessment of receptor vulnerability, compared to other vulnerability factors; vegetation cover and dunes were considered to have medium-high weight (i.e. 0.6); finally, medium and low weights (i.e. 0.5 and 0.4) were assigned to the vulnerability factors most related to ecological characteristics (i.e. wetland extension, river mouth, agricultural and wetland typology) and to the percentage of urbanization.

5.3.2. Results

The multi-vulnerability map (Figure 5.3.2.1I) provides the spatial assessment of physical and environmental vulnerabilities of elements at risk (Paragraph 5.2) to the multiple hazards investigated in the case study (Paragraph 5.1). The multi-vulnerability map was classified using the equal interval method allowing the division of the scores into 5 equal sized classes (i.e. very low, low, medium, high, very high) (Zald et al. 2006).



Vulnerability factor	Weighted score
% of urbanization	0.4
Coastal slope	0.8
Wetland typology	0.3
Wetland extension	0.1

Figure 5.3.2.1. Multi-vulnerability map of the whole case study three selected areas (a, b c) for the multi-risk assessment **(I)**; and distribution of the percentage of surface associated with each multi-vulnerability class for the investigated receptors in the North Adriatic coast **(II)**.

Figure 5.3.2.1I highlights that generally multi-vulnerability is high or very high in most of the analysed receptors (Figure 5.3.2.1II) due to the plain trend of the case study and the predominant presence of arable lands which are responsible of the higher multi-vulnerability score (e.g. between Caorle and Bibione, Figure 5.3.2.1Ia, the Venice lagoon, Figure 5.3.2.1Ib). Specifically, beaches, wetlands, protected areas and river mouths show a very high multi-vulnerability score with a surface percentage ranging from 95% for beaches (13 km^2 circa) to 52% for river mouths (422 km^2 circa), while agricultural areas are subjected to the high multi-vulnerability class for the 54% (Figure 5.3.2.1II). Also the percentage of urbanization plays an important role in increasing the multi-vulnerability score where it is higher than 10 % (e.g. the inland of the Venice municipality).

Moreover, urban areas are characterized by the medium multi-vulnerability class for about 43% (Figure 5.3.2.1II) especially due to the slightly high slope of infrastructure; similarly natural and semi-natural systems are interested by the medium multi-vulnerability class for about 54 % (Figure 5.3.2.1II) for the presence of shrubberies and forests (i.e. the medium and low classes of vulnerability for vegetation cover).

The low and very low multi-vulnerability classes are not very represented in the North Adriatic area, with a percentage ranging from less than 1 % (for protected and urban areas in the very low class) to 20% circa (urban areas in the low class, e.g. Trieste) due to the steep shape of those areas and the lower percentage of urbanization.

Comparing the results with the exposure map (Figure 5.2.2.1), it is possible to see that the hotspots of multi-vulnerability are located in the Po Delta and in the Venice lagoon where there is an overlay of sensitive receptors, such as protected areas, river mouths and wetlands. Protected areas are highly vulnerable due to their ecological and biodiversity relevance for different European directives (e.g. Nature 2000 network, Habitat and Bird Directives) and, especially in the analysed case study, these areas should be taken in higher consideration in the Territorial Plan of Provincial Coordination. The multi-vulnerability map is useful for local and regional authorities to identify vulnerable hotspots where the resilience from multiple hazards (i.e. permanent/temporary inundation and coastal erosion) should be increased in the future. Examples of adaptation measures aimed at increasing the resilience (or reducing the vulnerability) of coastal communities and ecosystems to climate-related impacts are the planting of more robust arboreal communities in areas susceptible to flooding; the identification of special preservation measures for the protection of small wetlands highly vulnerable to sea-level rise and erosion; the protection of vegetation useful for the stabilization of natural dunes. Finally, the multi-vulnerability map can help decision-makers in a first screening of infrastructure and buildings more susceptible to coastal flooding (e.g. roads and houses located in gentle sloping and low-lying areas in the North part of the Venice lagoon) where the vulnerability can be reduced with improved drainage systems (e.g. water pums).

5.4. Multi-risk

5.4.1. Assessment

The last step of the multi-risk methodology presented in Chapter 3 requires the aggregation of the model-based information provided by the multi-hazard step (Paragraph 3.1) with the site-specific exposure and multi- vulnerability assessment (Paragraph 3.2 and 3.3). This step allows a ranking of coastal areas and targets potentially affected by multiple climate-related risks useful to have an overall view of the causes and consequences of these complex phenomena in the case study and to mainstream adaptation planning and risk reduction strategies in coastal zone management.

5.4.2. Results

The multi-risk map (Figure 5.4.2.1I) is the final result provided by Equation 4 (Paragraph 4.4) and is classified using the equal interval method allowing the division of the scores into 5 equal sized classes (i.e. very low, low, medium, high, very high) (Zald et al. 2006).

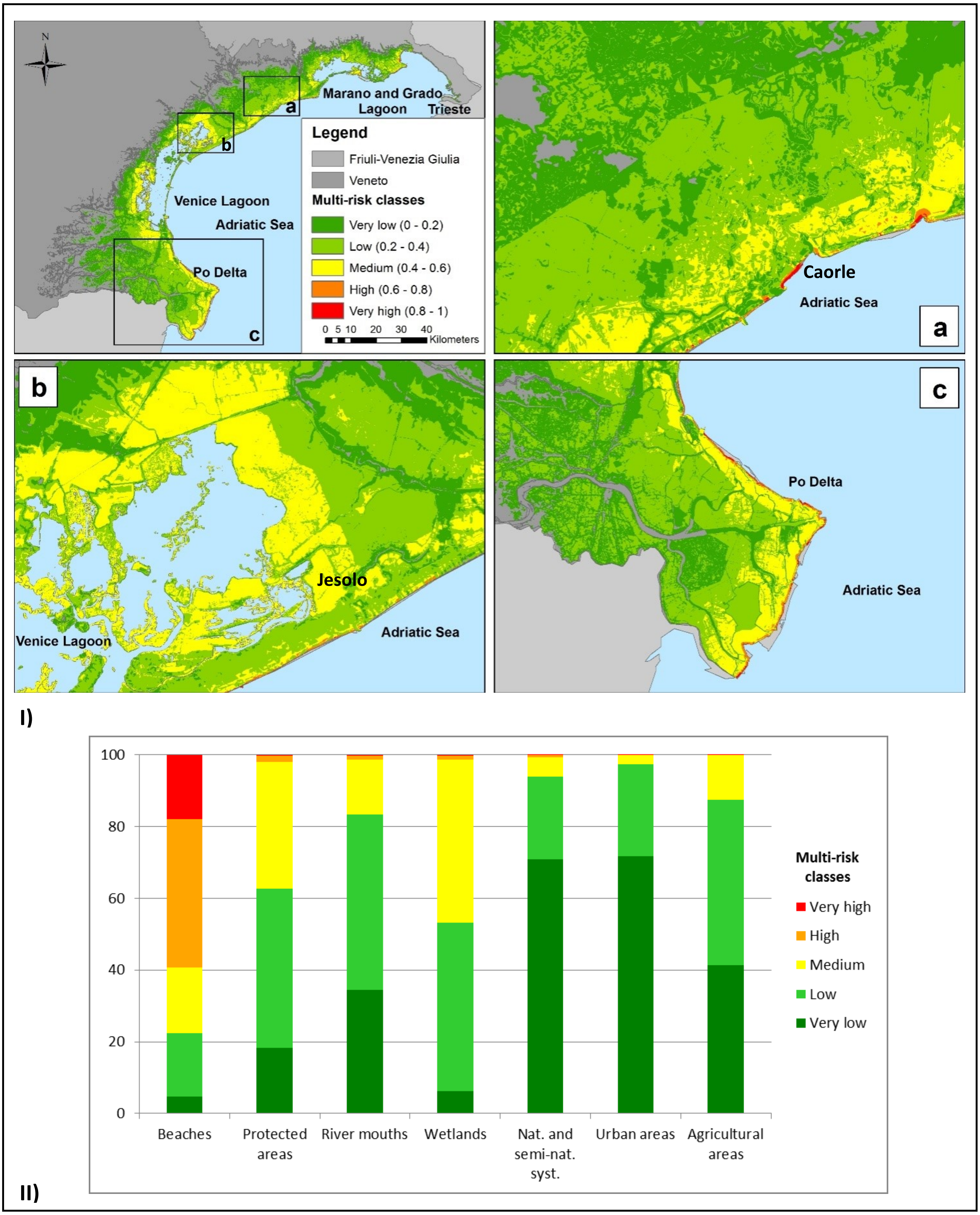


Figure 5.4.2.1. Multi-risk map for the whole case study and three selected areas (a, b, c) **(I)**; distribution of the percentage of surface associated with each multi-risk class for the investigated receptors in the North Adriatic coast **(II)**.

Generally multi-risk scores are lower than the multi-hazard ones as they are multiplied by multi-vulnerability (i.e. scores ranging in 0-1), however in Figure 5.4.2.1I the same trend of multi-hazard is visible. Specifically, Figure 5.4.2.1Ia represents an example of beach (Caorle municipality) that is the receptor more affected by multiple risks with a surface percentage of 60 % circa in the very high and high multi-risk classes (Figure 5.4.2.1II). The inland of Figure 5.4.2.1Ia and Figure 5.4.2.1Ib (i.e. Caorle and Venice lagoon) is mostly interested by the medium multi-risk class which will affect wetlands and protected areas of the Caorle and Venice lagoons due to medium class of the multi-hazard. Finally, the Figure 5.4.2.1Ic represents the Delta Po which will be affected by the higher multi-risk classes close to the North Adriatic sea while the multi-risk scores decrease going inland according to the multi-hazard trend. Moreover, Figure 5.4.2.1II allows the identification of the receptors most affected by the different multi-risk classes (i.e. beaches, protected areas, river mouths and wetlands) and, together with Figure 5.4.2.2, support the identification of intervention priorities in the affected municipalities of the case study area (e.g. Staranzano, Porto Tolle, Grado, Cavallino-Treporti, Caorle, Venice).

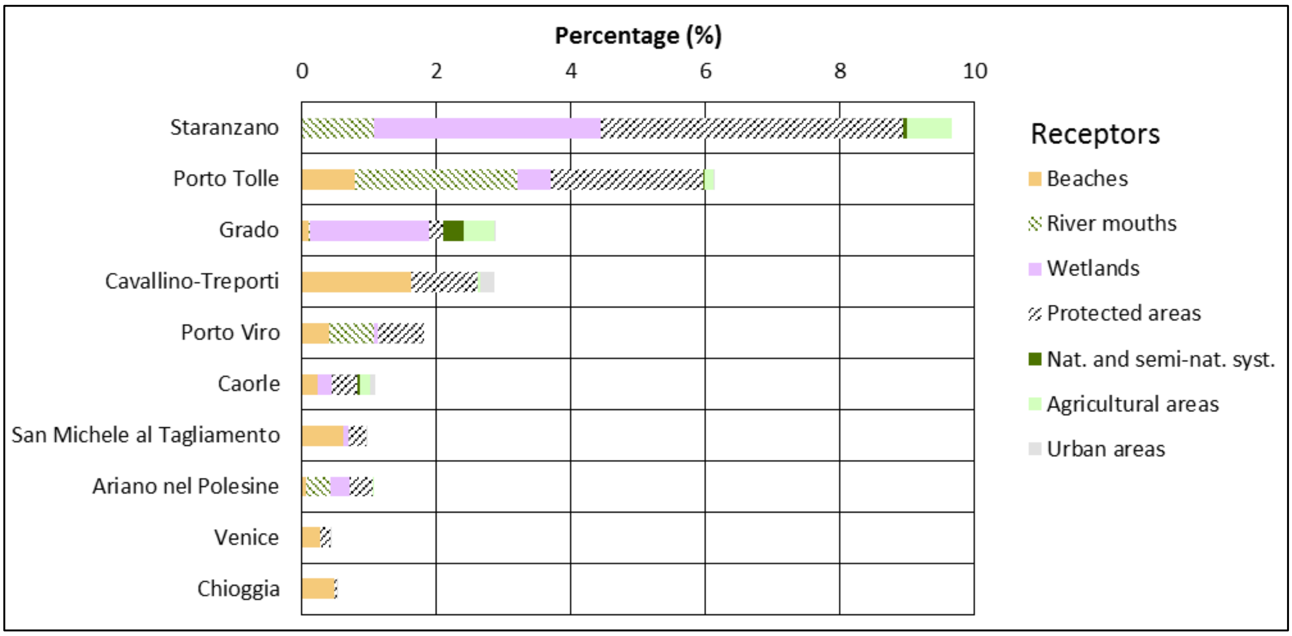


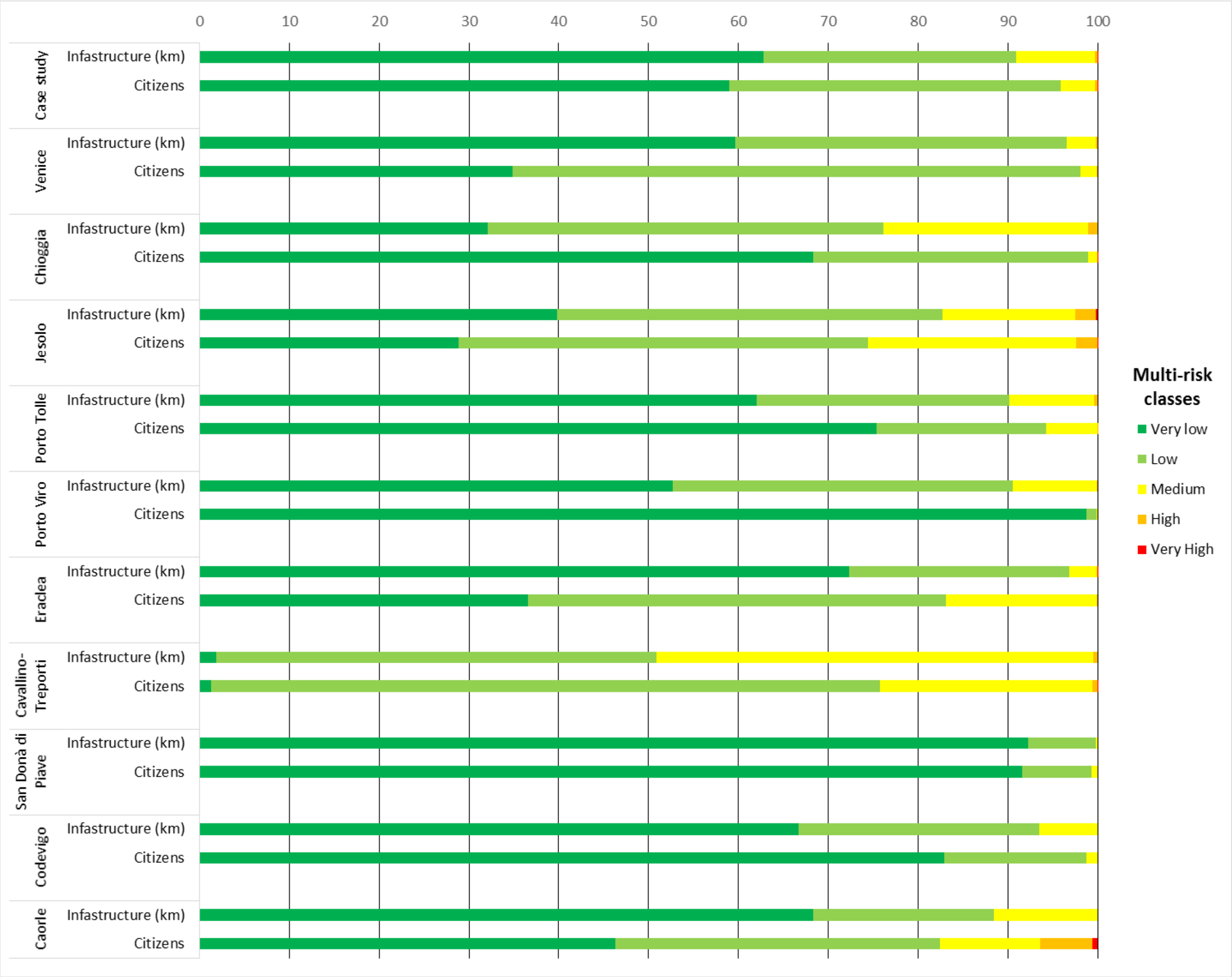
Figure 5.4.2.2. Percentage of surface associated with the very high and high multi-risk classes for the investigated receptors in the ten coastal municipality most affected by multi-risk in the North Adriatic coast.

The multi-risk assessment highlights hotspots for future foreshore planning (e.g. priority areas for beach erosion and sea-level defences) in an Integrated Coastal Zone Management perspective that should focus on the preservation of beaches and protected areas (including river mouths and wetlands) in compliance with the environmental restrictions (e.g. Nature 2000) and the river mouth navigability ensuring the navigability of fishing ships and pleasure boats (Veneto Region 2012). This information could help the authorities in charge to implement adaptation measures in planning future coastal preservation and protection considering multiple climate change impacts in order to reduce the likelihood that risk reduction efforts targeting one type of impact will increase exposure and vulnerability to other impacts (IPCC 2012; Veneto Region 2012).

Useful information for coastal management can be obtained also from the statistics presented in Figure 5.4.2.3 concerning the infrastructure and the citizens that could be affected by multiple risks in the analysed urban areas of the case study.

	Very low		Low		Medium		High		Very High	
	Infrastructure (km)	Population (citizens)	Infrastructure (km)	Population (citizens)	Infrastructure (km)	Population (citizens)	Infrastructure (km)	Population (citizens)	Infrastructure (km)	Population (citizens)
Case study	1.532	247.985	686	154.984	214	15.840	7	1.279	0	60
Venice	124	49.686	77	90.178	7	2.651	1	140	0	0
Chioggia	65	32.170	47	14.383	12	505	0	5	0	0
Jesolo	44	6.074	60	9.591	31	4.861	2	510	0	0
Porto Tolle	80	8.876	36	2.229	12	672	0	2	0	0
Porto Viro	70	11.587	21	128	12	18	0	0	0	0
Eraclea	65	7.457	29	2.523	6	318	0	12	0	1
Cavallino-Treporti	1	121	34	7.213	34	2.294	0	53	0	1
San Donà di Piave	60	8.806	5	744	0	62	0	0	0	0
Codevigo	41	7.639	16	1.451	4	119	0	0	0	0
Caorle	53	3.936	57	3.078	20	947	3	493	0	54

I)



II)

Figure 5.4.2.3. Length of infrastructure (km) and number of citizens in urban areas of coastal municipalities in the North Adriatic area affected by different classes of multi-risk I); and their percentage distribution II).

Considering the urban areas of the North Adriatic coast as key hotspots for the future development of territorial and emergency plans, the statistics can be useful to identify the length of infrastructure (km) and the number of citizens at higher risk from multiple climate related hazards.

In almost all the municipalities there are higher percentages of infrastructure and population in the lower multi-risk classes (i.e. the infrastructure of the whole case study will be affected by very low multi-risk class for the 63% while population for the 59%). While higher multi-risk classes are located in highly urbanised municipalities affected by multiple risks (e.g. Jesolo and Caorle in which 500 citizens and 3 km of infrastructure circa will be affected by the higher multi-risk classes respectively). This information can help regional authorities to identify and rank the municipalities threatened by higher multi-risk scores and therefore improve the allocation of funds for adaptation and/or mitigation measures. Moreover, multi-risk map could help to guide future land-use planning and to investigate if the adaptation measures should focus on reducing the climate-related hazards (e.g. through the construction of natural and artificial coastal defences), on avoiding exposure (e.g. retreating the assets from the coastline) or on decreasing vulnerabilities (e.g. increasing the resilience of the different receptors) to the potential investigated impacts. Even if multiple risks cannot be eliminated, these actions could help in reducing their effects to the environment, society and economic activities.

6. Conclusions

The work described a multi-risk methodology for the integrated assessment of natural and climate-related hazards and risks and its application for the assessment of climate change impacts to the coastal area of the North Adriatic Sea in Italy.

The strength of the proposed methodology is the Multi-Criteria Decision Analysis (MCDA) procedure allowing the aggregation of cumulative risks affecting the same area. This aspect represents a step forward to traditional single risk assessments, providing a common procedure to consider potential interactions among different hazards (happening on different spatial scales and timeframes) and to investigate and compare the heterogeneous vulnerabilities (of different receptors to different types of hazards).

The proposed methodology should be considered as a quick scan tool allowing the semi-quantitative evaluation of the relationships among different hazards (and vulnerabilities) of the same area. A more quantitative assessment should consider the intensities of the hazards – and how vulnerability changes according to different hazard thresholds - and the joint probabilities of each single hazard (e.g. using probabilistic models or by means of expert judgement).

The proposed multi-risk methodology is flexible and applicable in a wide range of conditions and geographical regions, including scarce and abundant data availability. It can be adapted for the analysis of different natural hazards, climate change impacts and vulnerable sectors.

A more detailed exposure assessment can be reached for assessments at the local scales, considering linear and point receptors as sensitive risk targets (e.g. schools, hospitals).

The multi-vulnerability assessment, now focused on the physical and environmental dimensions of vulnerability, can be improved by integrating adaptive and coping capacity indicators (e.g. income level, education, safety network). Moreover, parameters and algorithms for the economic assessment should be included in the multi-risk model in order to allow the measurement of consequences in terms of direct and indirect costs.

Then, a future ambitious improvement should consider an estimate of cascading uncertainties in space and time of the whole assessment in order to provide robust science-based outputs for decision-making in a multi-risk perspective.

An important avenue of further research would be to study the practical application of the multi-risk methodology by decision-makers in different institutions in order to provide an integrated assessment of the territory. Finally, it is important to underline that the multi-risk methodology allows a relative ranking of the cumulative investigated impacts and risks and should be applied every time that improved input information and data (e.g. new models, more accurate site-specific indicators) are available.

Acknowledgments

I want to thank Dr. Andrea Critto, Dr. Silvia Torresan and Prof. Antonio Marcomini who supervised my PhD work and gave me the opportunity to carry out the University studies in the field of climate change and multi-risk assessment.

I want to sincerely thank Prof. Thomas Glade and Prof. Nick Harvey for inspiring discussions and proof-reading of my PhD work.

I want to cordially thank all co-authors who have contributed to the publications that form the basis of this thesis.

Finally, I thank all the public institutions that provided territorial data for the application of the multi-risk methodology in the North Adriatic case study.

My gratitude goes to all colleagues that I met on my way. I am especially very grateful to Alex Zabeo and Jonathan Rizzi for all the scientific and non-scientific discussions, feedback and much more.

Un ringraziamento particolare va ad Anna Sperotto ed Elisa Furlan per la collaborazione e l'amicizia che siamo riuscite ad instaurare in questi anni. Voglio anche ringraziare Sara Alba, Elisa Giubilato, Panagiotis Isigonis, Francesco Rianna, Lara Lamon, Elena Semenzin, Paolo Ronco, Lisa Pizzol, Sara Pasini, Angela Moriggi, Marco Pesce e Daniele Brombal che mi hanno dato un sincero supporto dal punto di vista scientifico, ma soprattutto morale e con cui ho trascorso momenti piacevoli e innumerevoli pause caffè a Venezia e a Pechino ^_^

Voglio ringraziare anche: Ele, Christian e Carlo (Leo ancora non lo conosco), Fra, Anna, Cri, Elisa, Fabio e Lorenzo (e il piccolo Sebastiano), Zuk, Ste e Mavi per la loro amicizia e supporto anche nei momenti più impegnativi. Di sicuro dimentico qualcuno ma anche a questi va il mio grazie.

Un ringraziamento di tutto cuore lo devo ai miei familiari, mamma e papà, mia sorella Erika e tutta la sua famiglia (specialmente Tommy ed Ale!), i miei parenti tutti per avermi sostenuto in questo percorso così impegnativo!

Sono profondamente grata a Gabriele che ha creduto in me sin dall'inizio e che mi ha sempre sostenuta, sorretta, e accompagnata in questo percorso e nelle scelte della mia vita! Così lontani a volte ma sempre molto vicini!

Bibliography

AMRA (2012) Multirisk. AMRA Analysis and monitoring of environmental risk. http://www.amracenter.com/doc/brochure/AMRA_brochure_5_MR.pdf, access 19 March 2013

Bell R, Glade T (2004a). Quantitative risk analysis for landslides - Examples from Bíldudalur, NW-Iceland.- Natural Hazard and Earth System Science 4(1): 117-131

Bell R, Glade T (2004b). Multi-Hazard Analysis in Natural Risk Assessments. In: Brebbia C.A. (ed) International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation, Rhodes, Greece, 197–206

Bernal G (2010). CAPRA: Multi-hazard approach. Conference presentation in the Understanding Risk Forum. http://www.understandrisk.org/ur/node/4573, access 19 March 2014

Bondesan A, Castiglioni GB, Elmi C, Gabbianelli G, Marocco R, Pirazzoli PA, Tomasin A (1995). Coastal areas at risk from storm surges and sea-level rise in northeastern Italy. Journal of Coastal Research: 11(4): 1354-1379

Caniglia G, Casetta D, Nascimbeni P, Pizzinato C (1998) Aspetti del dinamismo della vegetazione nell'edificazione di un sistema dunoso artificiale (Venezia - Cavallino), in La progettazione ambientale nei sistemi costieri, a cura di M. Pietrobelli, Atti del X Seminario, Roma, 10 luglio 1998, International Association for Environmental Design (IAED, Quaderno 12), 42-47

Carbognin L, Teatini P, Tomasin A, Tosi L (2009). Global change and relative sea level rise at Venice: what impact in term of flooding. Clim Dyn DOI 10.1007/s00382-009-0617-5

Carminati E., Martinelli G. (2002). Subsidence rates in the Po Plain, northern Italy: the relative impact of natural and anthropogenic causation. Engineering Geology 66 (2002) 241–255

Carniel S, Warner JC, Chiggiato J, Sclavo M (2009) Investigating the impact of surface wave breaking on modelling the trajectories of drifters in the Northern Adriatic Sea during a wind-storm event. Ocean Modelling, 30, 225-239. doi: 10.1016/j.ocemod.2009.07.001

Carpignano A, Golia E, Di Mauro C, Bouchon S, Nordvik J-P (2009). A methodological approach for the definition of multi-risk maps at regional level: first application. Journal of Risk Research 12(3–4): 513–534. DOI 10.1080/13669870903050269

Cecconi G (1997) The Venice Lagoon mobile barriers. Sea level rise and impact of barrier closures, in Italian Days of Coastal Engineering, Venice, May 16th, International Debate-PIC 97

Cecconi G and Ardone V (1998) La protezione dei litorali con ripascimento delle spiagge. L'esperienza dei litorali di Cavallino e Pellestrina, in La progettazione ambientale nei sistemi costieri, a cura di M. Pietrobelli, Atti del X Seminario, Roma, 10 luglio 1998, International Association for Environmental Design (IAED, Quaderno 12), 11-31

Cecconi G and Ardone V (2000) La fonte di approvvigionamento della sabbia nel ripascimento dei litorali veneti, Intervento alla Presentazione della Costa ligure, Regione Liguria, Genova, 2-4 febbraio 2000

Ciurean RL, Schröter D, Glade T (2013). Conceptual Frameworks of Vulnerability Assessments for Natural Disasters Reduction. In: Tiefenbacher J. (ed) Approaches to Disaster Management - Examining the Implications of Hazards, Emergencies and Disasters. InTech 3-32. http://dx.doi.org/10.5772/55538

De Pippo T, Donadio C, Pennetta M, Petrosino C, Terlizzi F, Valente A (2008). Coastal hazard assessment and mapping in Northern Campania, Italy. Geomorphology 97: 451–466. http://dx.doi.org/10.1016/j.geomorph.2007.08.015

DEFRA (2006). Flood Risk to People Phase 2. Environment Agency Flood and Coastal Defence R&D Programme (London, UK). FD2321/TR2 Guidance Document

Del Monaco G, Margottini C, Spizzichino D (2007). ARMONIA methodology for multi-risk assessment and the harmonisation of different natural risk map. Deliverable 3.1.1. ARMONIA project (Contract n 511208)

Dilley M, Chen U, Deichmann RS, Lerner-Lam A, Arnold M (2005). Natural disaster hotspots: a global risk analysis. In: Disaster Risk Management Series, 5, The World Bank

EC (2004). Living with coastal erosion in Europe: Sediment and Space for Sustainability. PART I – Major findings and Policy Recommendations of the EUROSION project

EC (2011). Council of European Union, Risk assessment and mapping guidelines for disaster management; Brussels, 2010

EC (2012). EU research Natural Hazards and Disasters. Luxembourg: Publications Office of the European Union

EU (2013). DECISION No 1313/2013/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 December 2013 on a Union Civil Protection Mechanism. L 347/924

Farrokh N, Zhongqiang L (2013). Framework for multi-risk assessment. Deliverable 5.2. MATRIX project (Contract n 265138)

Fekete A (2009). Validation of a social vulnerability index in context to river-floods in Germany. Nat. Hazards Earth Syst. Sci. 9: 393–403. doi:10.5194/nhess-9-393-2009

FEMA (2011). Getting started with HAZUS-MH 2.1. Tech. rep. U.S. Department of Homeland Security, Federal Emergency Management Agency

Ferretti O, Delbono I, Furia S (2003). Elementi di gestione costiera Parte prima. Tipi morfo-sedimentologici dei litorali italiani. ENEA ISSN/0393-3016

Feyen L, Dankers R, Bódis K, Salamon P, Barredo J (2012). Fluvial flood risk in Europe in present and future climates. Climatic Change, 112(1): 47-62. DOI 10.1007/s10584-011-0339-7

Frigerio S, Kappes MS, Glade T, Malet J-P (2012). MultiRISK: a platform for Multi-Hazard Risk Modelling and Visualisation - Rend. Online Volume of Italian Geological Society 19: 32-35

Fuchs S, Heiss K, Hübl J (2007). Towards an empirical vulnerability function for use in debris flow risk assessment. Nat. Hazards Earth Syst. Sci. 7: 495–506. doi:10.5194/nhess-7-495-2007

FVG Region (2000). Monitoring Land Use/Cover Dynamics (MOLAND) map for the Friuli Venezia Giulia Region, Geographic Information System and Cartography Unit. Available at: http://irdat.regione.fvg.it/consultatore-dati-ambientali-territoriali/ (In Italian)

FVG Region (2006a). Digital Elevation Model (DEM) for the Friuli Venezia Giulia Region, Geographic Information System and Cartography Unit. Available at: http://irdat.regione.fvg.it/consultatore-dati-ambientali-territoriali/ (In Italian)

FVG Region (2006b). Regional geologic map, Cartography and hydrogeological protection Unit. Available at: http://irdat.regione.fvg.it/consultatore-dati-ambientali-territoriali/ (In Italian)

FVG Region (2007), Natura 2000 network -Site of Community Importance and Special Area of Conservation-, Rural resources, Hunt and Biodiversity Unit. Available at: http://irdat.regione.fvg.it/consultatore-dati-ambientali-territoriali/ (In Italian)

FVG Region (2008) Piano di gestione del SIC IT3320037 Laguna di Grado e Marano. Carta delle aree di tutela e di intervento scala 1:50000

Gallina V, Torresan S, Zabeo A, Carniel S, Sclavo M, Rizzi J, Pizzol L, Critto A (2014). Assessment of climate change impacts in the North Adriatic coastal area. Part II: Coastal erosion impacts at the regional scale. Submitted to Climate Research

Gambolati G and Teatini P (2002). GIS Simulations of the Inundation Risk in the Coastal Lowlands of the Northern Adriatic Sea, Mathematical and Computer Modelling, 35, 963–972

Garcia-Aristizabal A, Marzocchi W (2011). State-of-the-art in multi-risk assessment. Deliverable 5.1. MATRIX project (Contract n 265138)

Garcia-Aristizabal A, Marzocchi W (2012a). Dictionary of the terminology adopted. Deliverable 3.2. MATRIX project (Contract n 265138)

Garcia-Aristizabal A, Marzocchi W (2012b). Bayesian multi-risk model: demonstration for test city researchers. Deliverable 2.13. CLUVA project (Contract n 265137). http://www.cluva.eu/deliverables/CLUVA_D2.13.pdf

Garcia-Aristizabal A, Marzocchi W (2012c). Framework for multi-risk assessment. Deliverable 5.2. MATRIX project (Contract n 265138)

Giannini V, Torresan S, Gallina V, Critto A, Giupponi C, Marcomini A (2012). Deliverable 8.1 - Workshop report: context and objectives, comparison of data supply and demand, simulation results, feedback and discussion. Integrated case study: Veneto and Friuli Venezia Giulia, Northern Adriatic Sea, Italy. CLIM-RUN - Project No. 265192

Giove S, Brancia A, Satterstrom FK, Linkov I (2009). Decision Support Systems and Environment: Role of MCDA In: Marcomini A, Suter GW, Critto A (eds.) Decision Support Systems for Risk-Based Management of Contaminated Sites, Springer Science Business Media,US 53–73 DOI 10.1007/978-0-387-09722-0_3

Glade T (2003). Vulnerability assessment in landslide risk analysis - Die Erde 134: 121-138

Glade T, von Elverfeldt K (2005). MultiRISK: An innovative Concept to model Natural Risks.- In: Oldrich H, Fell R, Coulture R, Eberhardt E (eds) International Conference on Landslide Risk Management - 31. May - 03. June 2005, Vancouver (CND), Balkemaa: 551-556

GNS, NIWA (2010). RiskScape—user manual. Version 0.2.30. http://riskscape.niwa.co.nz/documents/usermanual, access 19 March 2014

Gonella M, Teatini P, Tomasi L, Gambolati G (1998). Flood risk analysis in the Upper Adriatic Sea due to storm surge, tide, waves, and natural and anthropic land subsidence, In “CENAS-Coastline Evolution of the upper Adriatic Sea due to Sea Level Rise and Natural and Anthropogenic Land Subsidence”. Gambolati G. (Ed.). Kluver Academic Publisher Dordrecht, the Netherlands, 313-324

Greiving S (2006). Integrated risk assessment of multi-hazards: a new methodology. In: Schmidt-Thomé P. (ed) Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions. Geological Survey of Finland, Special Paper 42: 75–82

Greiving S, Fleischhauer M, Lückenkötter M (2006). A Methodology for an Integrated Risk Assessment of Spatially Relevant Hazards. Journal of Environmental Planning and Management 49(1): 1-19. DOI 10.1080/09640560500372800

Greiving S, Glade T (2013). Risk Governance. In: Bobrowsky PT (ed.) Encyclopedia of Natural Hazards. Springer-Verlag Dordrecht, 863 – 870

Hinkel J, Brown S, Exner L, Nicholls RJ, Vafeidis AT, Kebede AS (2011). Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. Reg Environ Change 12:207–224. DOI 10.1007/s10113-011-0249-2

Holman IP, Loveland PJ, Nicholls RJ, Shackley S, Berry PM, Rounsevell MDA, Audsley E, Harrison PA, Wood R (2002). REGIS - Regional Climate Change Impact Response Studies in East Anglia and North West England

Hufschmidt G, Glade T (2010). Vulnerability analysis in geomorphic risk assessment - In: Alcántara-Ayala I, Goudie AS (eds) Geomorphological Hazards and Disaster Prevention, Cambridge University Press 233-243

IPCC (2007). Climate Change 2007: Impacts, Adaptation and Vulnerability. Summary for Policymakers. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva

IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds). Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp

IPCC (2014). Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32

ISTAT (Italian National Institute of Statistics) (2001). Population density extracted from Population and Housing Census of 2001. Available at: http://www.istat.it/it/archivio/104317#GIS (In Italian)

Kalbfleisch J G (1985). Probability and Statistical Inference: Volume 1: Probability. Springer Texts in Statistics-Sep 9, 1985

Kappes M (2011). Multi-hazard risk analyses: a concept and its implementation. PhD thesis, University of Vienna http://othes.univie.ac.at/15973/1/2011-08-03_0848032.pdf, access 19 March 2014

Kappes M, Keiler M, Glade T (2010). From single- to multi-hazard risk analyses: a concept addressing emerging challenges. In: Malet JP, Glade T, Casagli N (eds) Mountain risks: bringing science to society. Proceedings of the international conference, Florence, CERG Editions, Strasbourg, 351–356

Kappes MS, Gruber K, Frigerio S, Bell R, Keiler M, Glade T (2012c). The MultiRISK platform: The technical concept and application of a regional-scale multi hazard exposure analysis tool - Geomorphology 151-152: 139-155. DOI 10.1007/s11069-012-0294-2

Kappes MS, Keiler M, von Elverfeldt K, Glade T (2012a). Challenges of analyzing multi-hazard risk: a review. Nat Hazards 64(2): 1925-1958. DOI 10.1007/s11069-012-0294-2

Kappes MS, Papathoma-Köhle M, Keiler M (2012b). Assessing physical vulnerability for multi-hazards using an indicator-based methodology. Applied Geography 32: 577-590. http://dx.doi.org/10.1016/j.apgeog.2011.07.002

Kharin VV, Zwiers FW, Zhang X, Wehner M (2013) Changes in temperature and precipitation extremes in the CMIP5 ensemble. Climatic Change 119(2):345-357

Komendantova N, Mrzyglocki R, Mignan A, Khazai B, Wenzel F, Patt A, Fleming K (2014). Multi-hazard and multi-risk decision support tools as a part of participatory risk governance: Feedback from civil protection stakeholders – In: International Journal of Disaster Risk Reduction (in press). http://dx.doi.org/10.1016/j.ijdrr.2013.12.006i

Knutti R and Sedláček J, 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3, 369–373 doi:10.1038/nclimate1716

Lionello P, Cogo S, Galati MB, Sanna A (2008). The Mediterranean surface wave climate inferred from future scenario simulations. Global and Planetary Change 63: pp 152–162

Mahendra RS, Prakash CM, Srinivasa Kumar T, Shenoi SSC, Shailesh RN (2010). Coastal Multi-Hazard Vulnerability Mapping: A Case Study Along The Coast of Nellore District, East Coast of India. Rivista Italiana di Telerilevamento - Italian Journal of Remote Sensing 42 (3): 67-76

Maraun D, Wetterhall F, Ireson AM, Chandler RE, Kendon EJ, Widmann M, Brienen S, Rust HW, Sauter T, Theme M, Venema VKC, Chun KP, Goodess CM, Jones RG, Onof C, Vrac M, Thiele-Eich I (2010). Precipitation downscaling under climate change. Recent developments to bridge the gap between dynamical models and the end user. Reviews of Geophysics 1-38. DOI: 10.1029/2009RG000314

Marzocchi W, Garcia-Aristizabal A, Gasparini P, Mastellone ML, Di Ruocco A (2012). Basic principles of multi-risk assessment: a case study in Italy. Nat Hazards 62: 551–573 DOI 10.1007/s11069-012-0092-x

Mojtahed V, Gain AK, Giupponi C, Biscaro C, Balbi S (2013). Part B: Socio-Economic Regional Risk Assessment (SERRA). In: Gallina V, Torresan S, Critto A, Zabeo A, Semenzin E, Marcomini A (2012). Deliverable 1.7 Development of a risk assessment methodology to estimate risk levels. FP7-ENV-2010 Project (Contract n 265280)

Morton TA, Rabinovich A, Marshall D, Bretschneider P (2011). The future that may (or may not) come: How framing changes responses to uncertainty in climate change communications. Global Environmental Change 21(1) 103–109. http://dx.doi.org/10.1016/j.gloenvcha.2010.09.013

Nicholls RJ, Cazenave A (2010). Sea-Level Rise and Its Impact on Coastal Zones. Science 328: 1517. DOI 10.1126/science.1185782

Olfert A, Greiving S, Batista MJ (2006). Regional multi-risk review, hazard weighting and spatial planning response to risk-Results from European case studies. Natural and technological hazards and risks affecting the spatial development of European regions. Geological Survey of Finland, Special Paper 42: 125–151

Papathoma-Köhle M, Kappes M, Keiler M, Glade T (2011). Physical vulnerability assessment for alpine hazards: state of the art and future needs. Nat Hazards 58: 645–680. DOI 10.1007/s11069-010-9632-4

Pasini S, Torresan S, Rizzi J, Zabeo A, Critto A, Marcomini A (2012). Climate change impact assessment in Veneto and Friuli Plain groundwater. Part II: A spatially resolved regional risk assessment. Science of The Total Environment 440: 219–235. http://dx.doi.org/10.1016/j.scitotenv.2012.06.096

Pirazzoli P A (2005). A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. Quaternary Science Reviews 24 (2005) 1989–2001

Pugh D-T and Vassie J M (1979). Extreme sea-levels from tide and surge probability, Proc. 16th Coastal Engineering Conference, 1978, Hamburg. American Society of Civil Engineers, New York ,1: p. 911-930

Ramieri E, Hartley A, Barbanti A, Duarte Santos F, Gomes A, Hilden M, Laihonen P, Marinova N, Santini M (2011). Methods for assessing coastal vulnerability to climate change, European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC CCA) Technical Paper, Bologna (IT) 93, October 2011

Reese S, King A, Bell R, Schmidt J (2007). Regional RiskScape: a multi-hazard loss modelling tool. In: Oxley L, Kulasiri D (eds) MODSIM 2007 International Congress on Modelling and Simulation, 1681–1687

Rizzi J (2014). GIS-based Regional Risk Assessment and its implementation in a Decision Support System for studying coastal climate change impacts. PhD Thesis, University Ca' Foscari Venice, Italy

Ronco P, Gallina V, Torresan S, Zabeo A, Semenzin E, Critto A, Marcomini A (2014). The KULTURisk Regional Risk Assessment methodology for water-related natural hazards – Part 2: Application to the Zurich case study. Hydrol. Earth Syst. Sci. Discuss., 11, 7875-7933, 2014

Santini M, Caccamo G, Laurenti A, Noce S, Valentini R (2010). A multi-component GIS framework for desertification risk assessment.- Applied Geography 30(3): 394-415

Santini M, Valentini R (2011). Predicting hot-spots of land use changes in Italy by ensemble forecasting. Reg Environ Change 11: 483–502. DOI 10.1007/s10113-010-0157-x

Schmidt J, Matcham I, Reese S, King A, Bell R, Smart G, Cousins J, Smith W, Heron D (2011). Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. Natural Hazards 58 (3): 1169-1192. Doi:10.1007/s11069-011-9721-z

Schmidt-Thomé P (eds) (2006). Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions. Geological Survey of Finland Espoo 2006. ESPON project 1.3.1

Tebaldi C, Strauss B H, Zervas C E (2012). Modelling sea level rise impacts on storm surges along US coasts. Environ. Res. Lett. 7 (2012) 014032 (11pp) doi:10.1088/1748-9326/7/1/014032

Thywissen K (2006). Components of Risk. A Comparative Glossary. SOURCE No. 2. UNU-EHS. Bonn. http://www.ehs.unu.edu/publication/view/35

Tomasin, A and Pirazzoli P A (2008). Extreme sea levels on the Adriatic coasts: a comparison of estimation methods, Atti dell'Istituto Veneto di Scienze, Lettere ed Arti Tomo CLXVII (2008–2009), 53–82

Torresan S (2012). Development of a Regional Risk Assessment methodology for climate change impact assessment and management in coastal zones. PhD Thesis, University Ca' Foscari Venice, Italy

Torresan S, Critto A, Rizzi J, Marcomini A (2012). Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. Nat. Hazards Earth Syst. Sci. 12: 2347–2368. DOI 10.5194/nhess-12-2347-2012

Torresan S, Critto A, Rizzi J, Marcomini A (2012). Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. Nat. Hazards Earth Syst. Sci., 12, 2347–2368, 2012

Torresan S, Gallina V, Gualdi S, Bellafiore D, Umgiesser G, Carniel S, Sclavo M, Benetazzo A, Giubilato E, Critto A, (2014). Assessment of climate change impacts in the North Adriatic coastal area. Part I: A multi-model chain for the definition of climate change hazard scenarios. Submitted to Climate Research

Torresan S, Rizzi J, Zabeo A, Critto A, Gallina V, Furlan E, Marcomini A (2013). Assessing environmental impacts of climate change at the regional scale to provide adaptation services: the DEcision support SYstem for COastal climate change impact assessment (DESYCO), in “Proceedings of the first annual conference SISC on climate change and its implications on ecosystem and society”, Lecce, Italy, pp. 468-476, ISBN 978 – 88 – 97666 – 08 – 0

Torresan S, Rizzi J, Zabeo A, Pasini S, Gallina V, Critto A, Marcomini A (2011). Climate change impacts on coastal areas: results from the SALT, TRUST, CANTICO and PEGASO projects. Proceedings of the Tenth International Conference on the Mediterranean Coastal Environment, 25-29 October 2011, Rohdes, Greece, MEDCOAST

UKCIP (2003). Climate adaptation: risk, uncertainty and decision-making. In: Willows R, Connell R (eds) pp166

Umgiesser G, Anderson J B, Artale V, Breil M, Gualdi S, Lionello P, Marinova N, Orlić M, Pirazzoli P, Rahmstorf S, Raicich F, Rohling E, Tomasin A, Tsimplis M, Vellinga P (2011). From Global to Regional: Local Sea Level Rise Scenarios Focus on the Mediterranean Sea and the Adriatic Sea. UNESCO Venice, Italy

Umgiesser G, Melaku Canu D, Cucco A, Solidoro C (2004) A finite element model for the Venice Lagoon. Development, set up, calibration and validation. Journal of Marine Systems 51 (2004) 123– 145

UN (2002). Johannesburg plan of implementation of the world summit on sustainable development. Tech. rep., United Nations

UNEP (1992). Agenda 21. Tech. rep., United Nations Environment Programme

UNEP-MAP-RAC/SPA (2010). Impact of climate change on marine and coastal biodiversity in the Mediterranean Sea: Current state of knowledge. By S. Ben Haj and A. Limam, RAC/SPA Edit., Tunis : 1-28.)

UNISDR (United Nations International Strategy for Disaster Reduction) (2009). Terminology: Basic terms of disaster risk reduction. http://www.unisdr.org/we/inform/terminology, access 19 March 2014

UNIVE Team (2013). North Adriatic CASE -Final Report-. PEGASO project, No. 244170

van Westen C, Montoya A, Boerboom L, Badilla Coto E (2002). Multi-hazard risk assessment using GIS in urban areas: a case study for the city of Turrialba, Costa Rica. In: Proceedings of the regional workshop on best practices in disaster mitigation: lessons learned from the Asian urban disaster mitigation program and other initiatives, Bali, Indonesia, 120–136

VE Region (2005), Map of national and regional established natural reserves, Environmental planning and parks Unit. Available at: http://idt.regione.veneto.it/app/metacatalog/ (In Italian)

VE Region (2006), Map of national and regional established parks, Environmental planning and parks Unit. Available at: http://idt.regione.veneto.it/app/metacatalog/ (In Italian)

VE Region (2007), Digital Elevation Model (DEM) for the Veneto Region, Geographic Information System and Cartography Unit. Available at: http://idt.regione.veneto.it/app/metacatalog/ (In Italian)

VE Region (2008), Natura 2000 network -Site of Community Importance and Special Area of Conservation-, Ecological networks and Biodiversity Unit. Available at: http://idt.regione.veneto.it/app/metacatalog/ (In Italian)

VE Region (2009a), Regional Land cover Map based on Corine Land Cover legend, Geographic Information System and Cartography Unit. Available at: http://idt.regione.veneto.it/app/metacatalog/ (In Italian)

VE Region (2009b), Regional map of soil permeability based on surface lithologies, Geology Unit. Available at: http://idt.regione.veneto.it/app/metacatalog/ (In Italian)

Veneto Region, 2012. Gestione Integrata della Zona Costiera. Progetto per lo studio ed il monitoraggio della linea di costa per la definizione degli interventi di difesa dei litorali dall’erosione nella regione Veneto. D.Lgs. 112/1998 e D.Lgs. 85/2010

Visintini Romanin M, Rismondo A, Scarton F, Leita L (2000) Interventi per il recupero morfologico della laguna di Venezia. La barena Fossei Est in laguna Sud, in «Quaderni Trimestrali» 3/4, 3-35

Wipulanusat W, Nakrod S, Prabnarong P (2009). Multi-hazard Risk Assessment Using GIS and RS Applications: A Case Study of Pak Phanang Basin. Walailak J Sci & Tech 6(1): 109-125

Woodroffe C D and Murray-Wallace C V (2012). Sea-level rise and coastal change: the past as a guide to the future. Quaternary Science Reviews 54 (2012) 4e11

World Bank (2010). Natural Hazards, UnNatural Disasters The Economics of Effective Prevention. ISBN: 978-0-8213-8050-5. eISBN: 978-0-8213-8141-0. DOI: 10.1596/978-0-8213-8050-5

Zentel K-O, Glade T (2013). International Strategies for Disaster Reduction (IDNDR and ISDR). In: Bobrowsky PT (ed) Encyclopedia of Natural Hazards: 552-563

ANNEX I

Single hazard equations and maps

Sea-level rise hazard

The objective of the hazard function for the sea-level rise inundation impact ($h_{slr,s}$) is to determine and rank potential areas inundated by sea-level rise based on the quantity of water staying at the top of each cell according to the following equation (Torresan 2012):

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

Where:

$h_{slr,s}$= single hazard score related to sea-level rise inundation impact in scenario s;

$hm_{slr,s}$= hazard metric related to the projection of sea-level rise water level according to scenario s (cm);

pf_1= pathway factor related to the elevation of the cell (cm);

s_1= threshold given by the decision maker. It represents the amount of water above a cell which generates the maximum exposure (i.e. 60 cm).

The sea-level rise hazard map used in this application (Paragraph 5.1) is related to the high scenario s (i.e. 42 cm, Paragraph 4.2) and it is represented in Figure I.1.

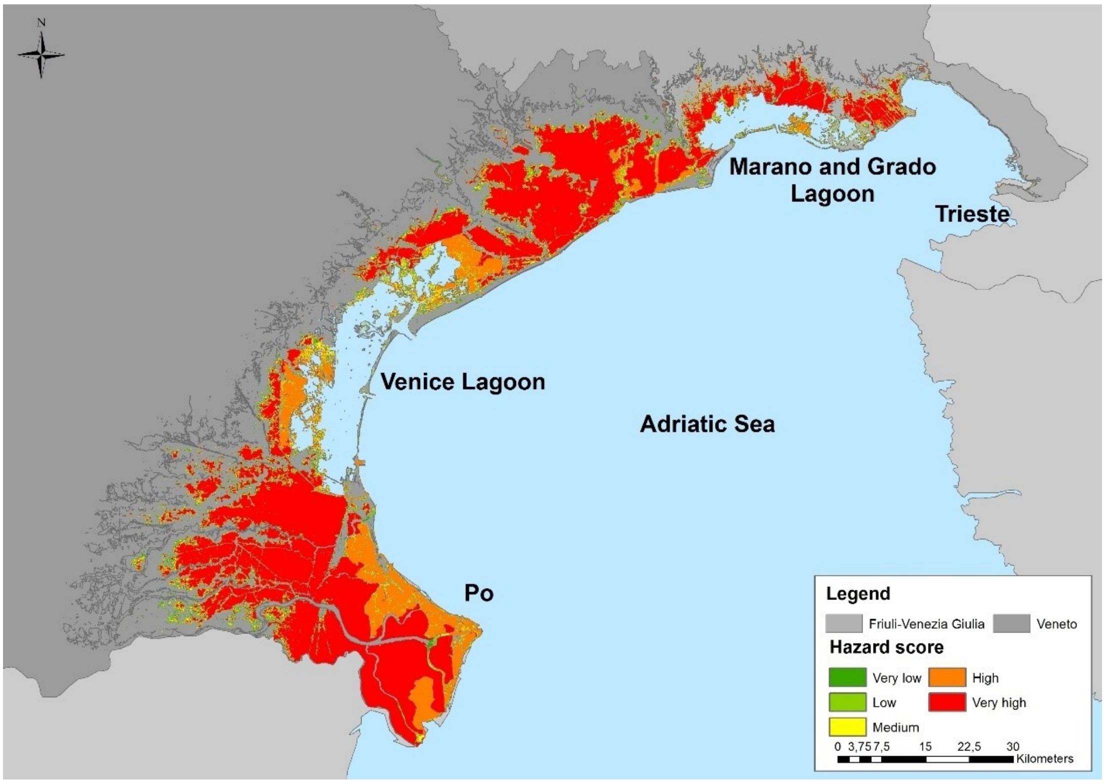


Figure I.1. Single hazard map for the sea-level rise inundation impact with a projected water level of 42 cm for the North Adriatic coast (Torresan 2012).

Storm surge hazard

Equation I.2 is aimed to represent the extent of coastal flooding for the year 2100 combining the potential sea-level rise with mean sea-level, astronomical and meteorological tides considering different return periods (i.e. 20, 50, 100, 200, 500) and the distance from the coastline (Rizzi 2014).

$$H_{ssf,s} = \begin{cases} 0 & if\ pf_1 \geq b \\ min\left[max\left(\frac{\left(\left(h_{ssf,s}\left(1-Af_1\right)\right)-pf_2\right)d_1}{s_1}, 0\right), 1\right] & otherwise \end{cases} \qquad \text{Equation I.2}$$

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= attenuation factor resulting from artificial protections;

pf_2 = elevation of the cell according to the Digital Elevation Model (DEM);

d_1 = distance factor related to distance of water penetration;

s_1 = amount of water above a cell which generates the maximum impact (i.e. 60 cm);

pf_3 = distance of the centre of the cell from the sea (always ≥ 1)

The storm surge hazard map used in this application (Paragraph 5.1) is related to the high sea-level rise scenario (i.e. 42 cm) and the higher return period (i.e. 500 years) as presented in Paragraph 4.2, and it is represented in Figure I.2.

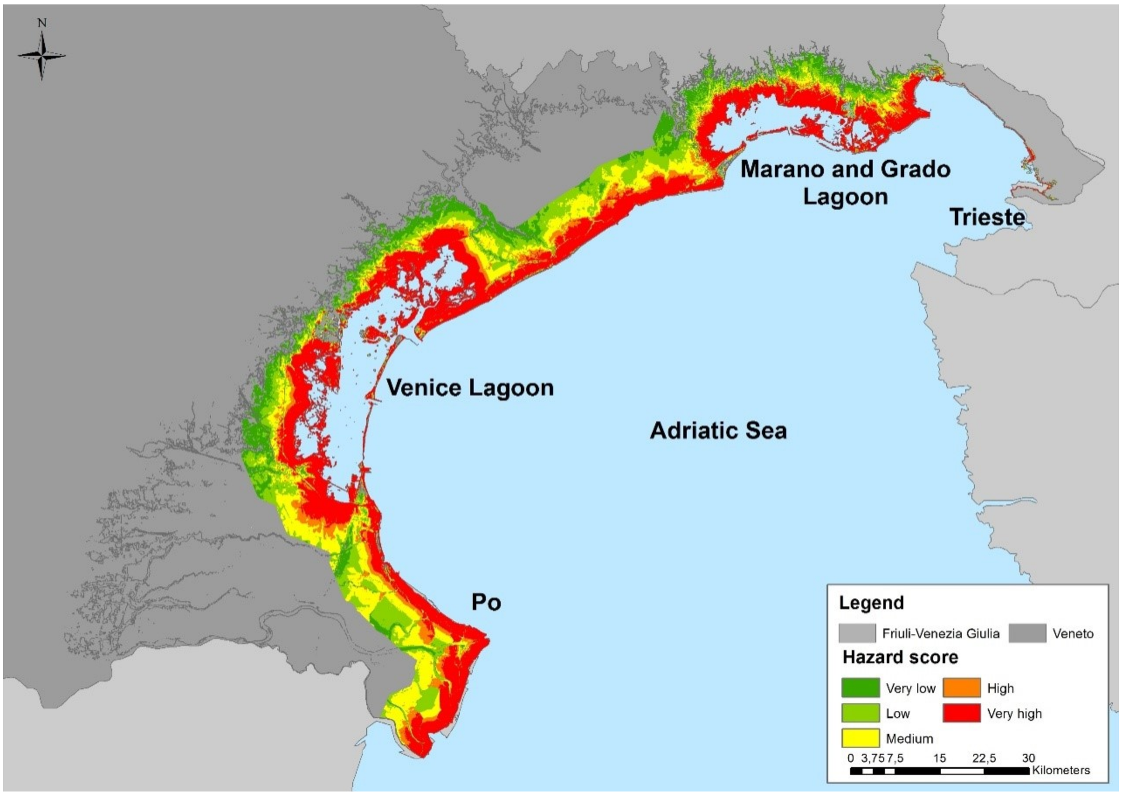


Figure I.2. Single hazard map for the storm surge inundation impact with a projected water level of 42 cm and a return period of 500 years for the North Adriatic coast (Rizzi 2012).

Coastal erosion hazard

Equation I.3 is aimed at the relative evaluation of the potential coastal erosion processes due to the evolution of two relevant hazard metrics influenced by climate change (i.e. wave height and bottom stress), the presence of artificial protections and the distance from the sea (Gallina et al. 2014).

$$h_{ce,s} = \begin{cases} 0 & if\ pf_3 \geq s_2 \\ \left(\otimes_{i=1}^{n} \left[hm'_{ce,i,s}\right]\right)(1 - At_{ce}) \cdot d_1 & otherwise \end{cases} \qquad \text{Equation I.3}$$

Where:

$h_{ce,s}$= single hazard score related to coastal erosion impact *ce* in scenario *s;*

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

s_2= threshold given by the DM (cm). It represents the distance of the center of a cell from the sea which represents the Radius of Influence of Coastal Erosion (RICE, i.e. 1 km);

$\otimes$ = "probabilistic or" function (Kalbfleisch J. G. 1985) (see Box 1);

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

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

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

Box 1. "Probabilistic or" function (Kalbfleisch J. G. 1985)**.**

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

where:

f_i= i-th generic factor f

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

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

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

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

The process can be repeated until evaluating all operands.

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

Box 2. Attenuation function for the Coastal Erosion impact.

$$At_{ce} = af_1 \qquad \text{Equation I.5}$$

where:

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

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

If the attenuation factor af_1 assumes its maximum value (i.e.1, presence of artificial protections), the attenuation function At_{ce} will be 1, and according to Equation 5, the exposure will assume the score of zero (i.e. the cell is not impacted by the coastal erosion as the attenuation is maximum). Otherwise, if the attenuation factor af_1 is minimum (i.e. 0, absence of artificial protections), the attenuation function At_{ce} will be 0 and the hazard function will assume its maximum score according to Equation I.3.

Box 3. Distance function.

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

$$\boldsymbol{d(g,k,b)\,\frac{1}{\max\left(1,\frac{g}{\left(\frac{b}{k}\right)}\right)}=\frac{1}{\max\left(1,\frac{g\,k}{b}\right)}=\min\left(1,\frac{b}{g\,k}\right)} \qquad \text{Equation I.6}$$

where:

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

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

b= *s*t*, where:

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

The coastal erosion map considered in this application (Paragraph 5.1) is the winter season, according to the available data presented in Paragraph 4.2, and it is represented if Figure I.3.

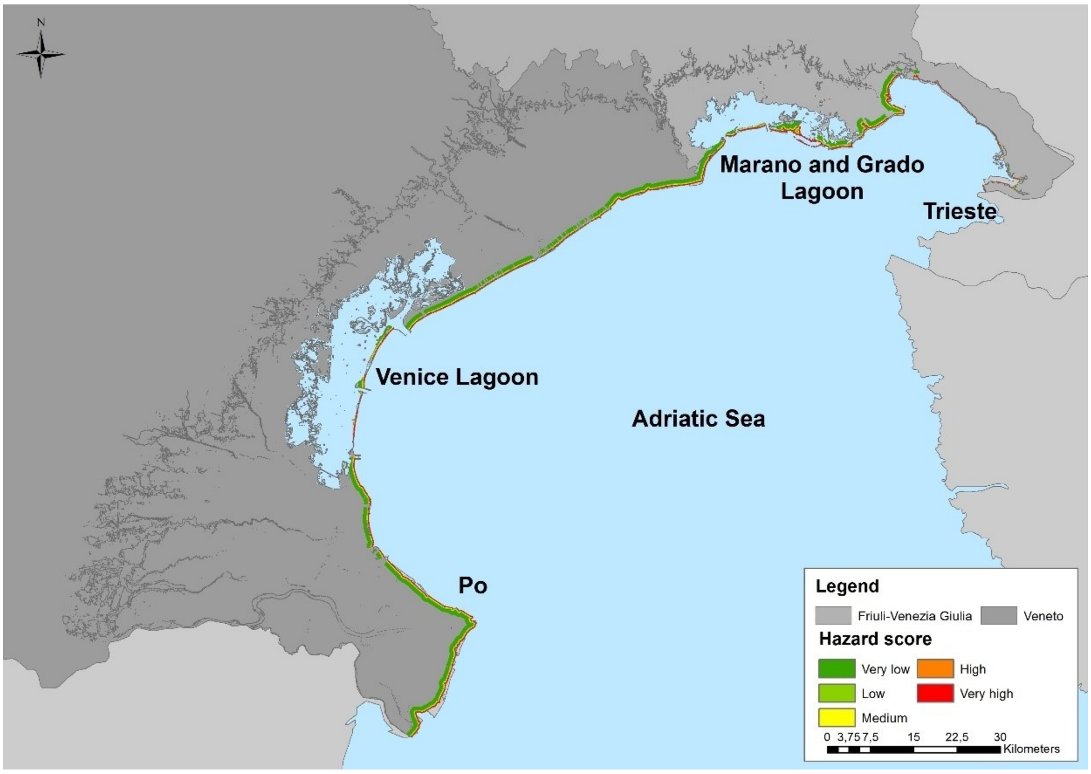


Figure I.2. Single hazard map for the coastal erosion impact in the winter season for the North Adriatic coast (Gallina et al. 2014).