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Review

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

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ABSTRACT

This paper presents a review of existing multi-risk assessment concepts and tools applied by organisations and projects providing the basis for the development of a multi-risk methodology in a climate change perspective.

Relevant initiatives were developed for the assessment of multiple natural hazards (e.g. floods, storm surges, droughts) affecting the same area in a defined timeframe (e.g. year, season, decade). Major research efforts were focused on the identification and aggregation of multiple hazard types (e.g. independent, correlated, cascading hazards) by means of quantitative and semi-quantitative approaches. Moreover, several methodologies aim to assess the vulnerability of multiple targets to specific natural hazards by means of vulnerability functions and indicators at the regional and local scale.

The overall results of the review show that multi-risk approaches do not consider the effects of climate change and mostly rely on the analysis of static vulnerability (i.e. no time-dependent vulnerabilities, no changes among exposed elements). A relevant challenge is therefore to develop comprehensive formal approaches for the assessment of different climate-induced hazards and risks, including dynamic exposure and vulnerability. This requires the selection and aggregation of suitable hazard and vulnerability metrics to make a synthesis of information about multiple climate impacts, the spatial analysis and ranking of risks, including their visualization and communication to end-users. To face these issues, climate impact assessors should develop cross-sectorial collaborations among different expertise (e.g. modellers, natural scientists, economists) integrating information on climate change scenarios with sectorial climate impact assessment, towards the development of a comprehensive multi-risk assessment process.

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1. Introduction

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. Climate change is likely to further increase the exposure to multiple-risks affecting the magnitude, frequency and spatial distribution of hazardous and disastrous events (IPCC, 2014). In this context, the relevance for adopting a multi-risk approach for the assessment of climate change impacts 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 provide more effective adaptation and reduction measures, in the present and in particular in the future.

At the global and European level, the interest about the multi-risk assessment increased in the last decades, especially when related to 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., 2012; Hinkel et al., 2011). Specifically, single-risk analysis allows to determine 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 for that particular coast (IPCC, 2012; Rosendahl, 2014).

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). Future changes in exposure and vulnerability should be considered as key determinants of losses and should be analysed together with natural climate variability and anthropogenic climate change for the assessment of disaster risks and impacts (IPCC, 2012). The aim of this paper is 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 model (Gallina et al., submitted) addressing cumulative climate change impacts on different natural and human systems and activities. 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 are not considered in this phase of analysis.

Following the review of the relevant key definitions used in literature (Section 2), Section 3 and 4 provide a critical analysis and discussion about organisations, tools, projects and methodologies applied at the international level and specifically in Europe for the assessment of different natural risks. Finally, Section 5 aims to discuss the main consequences for the development of a multi-risk assessment approach related to climate change hazards, exploring the challenges posed by the integration of climate change projections in the multi-risk analysis.

2. 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 also 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 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.

As defined by UNISDR (2009) and IPCC (2012), 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

Table 1
Concepts and definitions of the multi-risk approaches.

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
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
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
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
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 refer 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

systems (UNISDR, 2009; IPCC, 2012). While exposure represents the presence of the elements at risk (e.g. buildings, infrastructures, environments) that could be adversely affected, vulnerability characterized the different elements at risk towards a given hazard intensity. In a broad sense, vulnerability should include economic, social, geographic, demographic, cultural, institutional, governance, and environmental factors (IPCC, 2012). However, several authors strictly refer to the physical and environmental vulnerability (e.g., Glade, 2003; Papathoma-Kö;hle 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 Chapter 4 where no considerations are provided for the socio-economic 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 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 society over some specified future time periods.

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, 2011; EC, 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;
5. 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 paper will present multi-hazard, multi-hazard risk and multi-risk methodologies. The approaches interested in 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 (3 and 4) specifically for the natural hazards, while climate change consequences will be investigated in Chapter 5.

3. 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 S1).

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 to estimate 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 does neither allow 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 centre (www.amracenter.com) (AMRA, 2012) 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 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 (Table 2S) for the analysis of multi-risk and for the development of a generalised methodology for its assessment. 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 analysed 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-Thomé, 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.

4. 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. Moreover, the methodologies were resumed and analysed 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. 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). Moreover, a comparative table summarizing key features of the reviewed methodologies is provided for further details in the Supplementary Material (Table S3).

4.1. 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 application 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 Tables 1S and 2S (e.g. Bell and Glade 2004a,b; 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.

4.2. 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). 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).

4.3. 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, socio-economic and cultural assets, infrastructures 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 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).

4.4. Multi-hazard risk and multi-risk outputs

Multi-hazard risk and multi-risk methodologies require the aggregation of hazard, exposure and vulnerability 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 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, highlight 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 by 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.

5. Climate change impacts multi-risk assessment: consequences and challenges

As discussed in Section 3 and 4, most decisions on future environmental management (e.g. flood reduction measures, territorial development plans, energy infrastructures and agricultural choices), even those based on a multi-hazard or multi-risk approaches, still rely on information derived from observations and are designed to perform optimally under present climate/weather

Table 2
Climate change related issues and challenges for the multi-risk assessment.

	Climate change related issues and challenges for the 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; - Identify appropriate climate variables; - 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, infrastructures, 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 in–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.

conditions. However, since climate change is likely to alter the magnitude, frequency, return period and spatial distribution of different climate and natural variables (IPCC, 2014) there is the need to consider climate variability in future decisions, maximizing their environmental, social and financial performance. To our knowledge, very few methodologies at the present state of the knowledge have included climate change scenarios addressing future environmental risks and natural hazards. A multi-risk perspective to climate change impact assessment, instead, could reduce the likelihood that risk reduction efforts targeting one type of specific hazard will lead to maladaptation (i.e. increase vulnerability or exposure toward other kind of hazards).

Despite the relevance of the argument, the integration of climate change scenarios in the multi-risk assessment procedure necessarily leads to a variety of issues (Table 2) that should be taken into account (e.g. scale of analysis, uncertainty in the input data, variable aggregation), and makes the analysis extremely challenging for scientists, in particular in the context of multi-hazard, multi-hazard risk and multi-risk assessments. In the next paragraphs the main consequences and challenges dealing with the multi-risk assessment of climate change impacts summarized in Table 2 are critically discussed, highlighting major needs for future research.

5.1. Application context

The first step towards the development of a multi-risk methodology for climate change impacts assessment is the identification of the application context, including the definition of the aims of the assessment and of the spatial-temporal scale of analysis.

Coarser spatial scales (i.e. from national to regional/sub-national) are more suitable for screening assessments, identifying risk hotspots and supporting a first ranking of adaptation strategies and policies; more data-intensive and local assessments are needed for emergency and civil protection purposes, requiring more detailed geographical information for the definition of risk management plans. Appropriate spatial scale should be identified based on the magnitude and spatial distribution of the phenomena to tackle in order to include all the possible relations between different events: if the objective is to analyse the effect of heatwaves and droughts on wildfires, the local scale will be sufficient given the localized effects; if the aim is to consider sea-level rise effects on storm surges, a larger scale is the most appropriated considering the greater magnitude of this kind of risks (Gill and Malamud, 2014). The choice of spatial and temporal scale should be also based on the need of considering direct impacts (i.e. occurring at the same space and time of the hazard source) or indirect impacts (i.e. which can be induced far in time and space from the hazard source). To account for the direct impacts of a specific event (e.g. the damages to building and infrastructure or the losses of crops due to floods) a local analysis will be enough; however, the scale should be necessarily increased to a regional-national level if the aim is to estimate also the indirect impacts of the same events on the economic system (e.g. losses of industrial production, traffic disruption, increased prices of agricultural products/goods). In the same context, the definition of the suitable time scale requires the identification of the time lag of the cascade of events to be studied and should be consistent with the time scale of the processes selected for the analysis.

Moreover, the time scale should be long enough to consider the impacts affecting the whole life cycle of the analysed project/business. This will allow to capture all the cumulative (and differentiated) risks imposed by climate change in different stages of project development (i.e. from the early stage of design until the end of life) (Nakano, 2015). Finally, the time scale should be long enough to consider both short-term triggers (e.g. extreme events) and long-term changes (e.g. sea-level rise) (Gill and Malamud, 2014). The choice of a non-appropriate timescale (e.g. which do not consider the time lag of potential cascade events) can lead to underestimate the likelihood of occurrence of certain events. A wrong spatial scale, instead, will potentially miss to capture important relations between cascading and interconnected hazards, providing an underestimation estimation of events magnitude.

The choice of time and spatial scale, which at a first attempt could seem an easy task, is instead quite challenging when climate change scenarios come to place. In fact, if spatial distribution, magnitude and frequency of historical events are well known and estimated from historical data, the influence of climate change on such variables is characterized by high uncertainty. Therefore, a careful (and conservative) projection of multi-risks in the future, should consider that spatial and temporal distribution of events could diverge substantially from the historical records and should be based on state-of-art climate change scenarios.

5.2. Multi-hazard

The first challenge to face when assessing multi-hazard in a climate change perspective is the identification of the most appropriate climate variables to be considered as input of the analysis. Climate variables can be derived from the statistical analysis of observations (i.e. past measurements) or from the projections provided by global and regional climate models and downscaling techniques (i.e. future scenarios). Available variables include primary variables (i.e. temperature, precipitations, wind speed), compound variables (e.g. evaporation or humidity) and also proxy variables (i.e. soil moisture, river discharge or flow velocity) (UKCIP, 2003). The selected variables must be representative of the phenomenon of concern (e.g. increase in heavy precipitation, droughts, temperature extremes) and especially be able to capture the influence of climate change in determining the impacts of a particular event (e.g. anomalies between baseline and future scenarios). In addition to the choice of climate variables the selection of statistical characteristics are of particular importance. Frequently, the mean or median values are used to describe the trend of specific variables over large spatial and temporal scales, especially when the purpose is to assess the impact of slow onset phenomena (e.g. sea-level rise, global temperature increase) characterized by large magnitudes. In specific cases, instead, the use of cumulative values (i.e. total seasonal precipitation, consecutive dry days, total heating and cooling degree days) are required to estimate the negative effects on specific sectors (e.g. energy demand, agricultural yield) and to capture the inter-seasonal variability of climate change variables (UKCIP, 2003). Finally, the assessment of climate extremes (e.g. heavy rains, drought, heatwaves) should focus the analysis on absolute maximum or minimum values (e.g. daily maximum or minimum temperature) or percentile distributions (e.g. events above the 90th or 95th percentile) as well as the probability of exceeding a particular threshold (e.g. number of days of heavy precipitations, number of hot days) (UKCIP, 2003).

The second and more complex challenge that poses the multi-hazard assessment of climate change impacts is the quantification of hazard relations and the computation of a final multi-hazard value. Several types of probabilistic methodologies (e.g. Bayesian networks, event trees analysis, Monte Carlo simulations) which are commonly used for the assessment of natural hazards could be applied. Within the MATRIX project (Farrokh and Zhongqiang, 2013) especially the first two methodologies were applied in order to identify possible scenarios following an initial event providing also a quantification of their conditional probabilities.

The Bayesian networks could be useful to cope with uncertainties forced by climate change scenarios: a large number of parameters and their inter-relationships can be considered in a systematic structure and the probabilities of one parameter can be updated as long as more information are available.

However, the main gap still remain the lack of information about probabilities associated to climate change projections and related hazards. The lack of a probabilistic assessment poses some limits to the possibility of applying a quantitative (probabilistic) risk approach. In order to face this issue, the use of ensembles of global and region models represent a possible solution. Multi-model ensembles are generated collecting results from different modelling experiments (IPCC, 2014) and are characterized by a better reliability and consistency than single-model simulations, providing a higher level of confidence on climate projections for a given region (Hagedorn et al., 2005).

5.3. Exposure and vulnerability

Moving to exposure and vulnerability of given elements at risk, a multi-risk methodology requires a multidimensional and integrated approach (Table 1) in which different exposed elements (e.g. population, agriculture, infrastructures, buildings) and their vulnerability towards hazards interactions should be considered. This phase poses a further challenge as it requires, in addition to the changing hazards, the consideration of future scenarios of elements at risk. Vulnerability and exposure, in fact, are the results of different environmental, cultural and socio-economic factors which can be considered as static (e.g. slope, geomorphology) or dynamic (e.g. urbanization, population growth, environmental policy) and therefore in future scenarios they could strongly differ from the present condition. In order to capture the future changes in exposure and vulnerability the information provided by land use or land use changes models (Santini and Valentini, 2011) should be integrated in the multi-risk process. Other suitable tools that can be used to derive future scenarios of exposure and vulnerability are Integrated Assessment Models (IAMs). Coupling information provided by climate models with future socio-economic assumptions, these models allow to describe the complex relations between environmental, social and economic factors contributing to increase the vulnerability and to quantify the economic impacts of climate variables (i.e. sea-level rise, temperature) on specific targets and sectors (i.e. tourism, agriculture, health).

5.4. Multi-risk

The multi-risk approach require the coherent combination of hazards, exposure and vulnerability of different elements at risk, ensuring an objective, reproducible, justifiable and meaningful measure of the potential consequences affecting the unit of analysis (Crozier and Glade, 2005). Several multi-risk methods are currently used for the assessment of natural hazards' consequences (Section 4). However, they mostly rely on current and/or past information of hazards and vulnerabilities, neglecting considerations about future climate and socio-economic scenarios. In order to perform this difficult task different approaches (i.e. qualitative, semi-quantitative or quantitative) can be selected (or used in sequence) according to the objectives of the study, the accuracy of available data and scenarios, and the level of complexity required by the phenomenon to tackle.

Qualitative approaches are useful as first screening tools for the analysis at larger spatial scales (e.g. national or sub-national) and are often used to prioritize and rank different risks occurring in the same area of interest. Different practical tools (e.g. matrices, questionnaires) can be used to facilitate a classification of multi-risk levels in qualitative classes (i.e. high, medium, low) based on the comparison between different level of hazards and vulnerability. Powerful examples of this tools can be found in literature such as the UKCIP Adaptation Wizard (UKCIP, 2013), that is an excel-based sheet driving users through the analysis of different climate change related risks and scenarios, by means of risk matrices linking likelihoods and consequences to identify which are the main threats of concern for a certain areas or project. Another example is represented by the coastal hazard wheel methodology developed by Rosendahl (2014) which allows the multi-risk level classification of coastal areas, analysing all the possible relations between coastal hazards and the level of vulnerability associated to different typologies of coastal systems.

As far as semi-quantitative approaches are concerned, they are usually based on index-based methods in which the final multi-risk estimate is the result of a computation process between the multi-hazard and multi-vulnerability indexes (Kappes et al., 2010). Finally, more comprehensive approaches based on numerical models and simulations are needed to provide quantitative risk estimates. This level of analysis is necessary if the aim is to evaluate the effect of climate change on the dynamics of different sectors and targets (i.e. the impacts of drought on hydrology, vegetation and crops; the change of climate and land-use on ecosystem services). Moreover, in a multi-risk perspective, quantitative approaches require the evaluation of conjoint and cascading hazard relations (e.g. heavy rains triggering landslides) considering temporal and spatial trends in future climate scenarios and possibly an estimate of the related uncertainty.

Given the high complexity of the process, this kind of assessment can be performed using complex chains of climate and physical impact models (e.g. downscaled climate information on heavy precipitations forcing hydro-geological models for the assessment of floods and landslides) or Integrated Assessment Models (IAMs) allowing to estimate both direct and indirect impacts of climate change scenarios on different sectors (e.g. agriculture, tourism, industry, infrastructure, health) and relevant socio-economic metrics (e.g. GDP losses). Despite the use of climate impact modelling within single sectors is a consolidated practice, often accompanied by inter-model validation and assessment (Warszawski, 2013); the use and validation of cross-sectoral impact models in future climate scenarios represents a key challenge for future research. This requires an initial effort for harmonizing the impact assessment simulations across sectors (e.g. defining a standardized assessment protocol, comparable climatic and socio-economic scenarios and input data) (Huber, 2014).

Moreover, further significant efforts should be devoted at integrating sectorial modelling tools allowing the direct exchange of data across sectors (i.e. model output in one sector used as input for another sector) in order to systematically estimate the chain from greenhouse gases emissions, climate change scenarios and cascading impacts affecting simultaneously multiple natural systems and socio-economic sectors.

5.5. 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 and to drive decision making in a wide range of situations (i.e. environmental, financial, policy). 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). All these information characterized by different unit 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 no-scientific community in order to avoid any decision based on misjudged information.

In order to facilitate the communication between science and user interface an easy visualisation of the synthetic index of multi-risk is needed. The resulting 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).

6. Conclusions

This work presents a selection of important initiatives published in the international literature dealing with multi-hazard, multi-hazard risk and multi-risk assessment with the aim to develop a strong scientific background for the development of a multi-risk model for the assessment of multiple climate change impacts that was then empirically applied to the North Adriatic coastal zone (Italy) by Gallina et al. (submitted). The lack of a precise terminology was discussed and as solution, common definitions in the multi-risk context were provided as starting basis for this analysis. Moreover, three main approaches were identified in 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 identifying 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 provide an overview of challenges and consequences of the multi-risk assessment in a climate change perspective. A first attempt to face these challenges, providing an operational procedure to assess multiple impacts induced by climate change, is represented by the empirical model proposed and applied by Gallina et al. (submitted) to the coastal area of the North Adriatic sea (Italy) for the joined evaluation of sea-level rise, coastal erosion and storm surges risks. The approach integrates qualitative (i.e. expert interviews, stakeholder questionnaires and participatory enquiries) and quantitative methods (i.e. climate models, statistics, Geographical Information Systems) in order to develop a synthetic multi-risk index and multi-risk maps easily usable by local stakeholders and decision makers to start the definition of multi-hazard adaptation strategies.

A challenging perspective for impact assessors is still a consistent estimate of uncertainties, taking into account expected socio-economic developments and the anthropogenic influence as well as dynamic interactions and feedbacks among affected sectors (e.g. agriculture, economy, land use, infrastructures, ecosystems).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.11.011.

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