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Review of multi-hazards research and risk assessments

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Foreword

The work described in this report is a "Review of environmental multi-hazards research and risk assessment approaches" for the Natural Environment Research Council (NERC) through a UKRI contract for services (CR18075) and was compiled and led by a BGS consortium, supported by Natural Hazard Partnership (NHP) partners (HSE, CEH, and Met Office). Multi-hazard research is in its infancy, despite the growing attention it has received in the last years. Climate change, natural and anthropogenic hazards result in multi-hazard environments characterized by complex, interacting processes that generate impacts on the built environment and people, which are different to those incurred from the individual hazards happening in isolation. The recently developed methodologies for multi-hazard risk assessment processes represent an advancement in our understanding of these complexities, but they also pose specific challenges to policy makers and practitioners due to the cross-disciplinary nature required to undertake these assessments. This review strives to present an impartial and well-evidenced report of current developments in research, policy and industry with respect to multi-hazard processes and risk assessments. The need for such studies is now more apparent than ever, given the expected effects of climate change on the frequency and magnitude of weather-related hazards.

Acknowledgements

It is important to acknowledge that this report is a collaborative achievement. We express here our appreciation of all those who have contributed to its compilation. In particular, this report was only possible because of the hard work and dedication of our NHP partners: HSE, CEH and the Met Office.

In addition to the project partners, key staff have helped to review draft chapters of this report. Of the many individuals who have contributed to the project, we would particularly like to thank Vanessa Banks (BGS) and Ruth Hughes (NERC) for the support offered throughout all stages of this study. In addition, Flavia Villarroel (BGS) has also contributed to the production of this report. Their assistance is much appreciated.

A large number of individuals from academia, NGO, policy and industry representatives have contributed to the outcome of this project. In addition to offering their time to directly contribute to the stakeholder survey, many have freely given their advice, and provided specific knowledge and information so important for achieving the project objectives.

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List of acronyms

UNISDR – United Nations International Strategy for Disaster Reduction
ALARP – "as low as reasonably possible" (see the ALARP principle)
HSE – Health and Safety Executive
CEH – Centre for Ecology & Hydrology
PHE – Public Health England
UKRI – UK Research and Innovation
NHP – Natural Hazards Partnership

Executive Summary

This report is a scoping review of the existing environmental multi-hazard approaches, projects and associated literature that has been undertaken across academia and industry (policy and practice) mainly within the UK, but also highlighting where appropriate international practice. This report is aimed to identify what existing or new knowledge is required to advance our understanding of multi-hazard events, their impact, as well as the methods and approaches available to assess multi-hazard risks in policy/practice. The report was compiled and led by a British Geological Survey (BGS) consortium, supported by Natural Hazard Partnership (NHP) partners (HSE, CEH and Met Office) and was undertaken for the Natural Environment Research Council (NERC) through a UKRI contract for services (CR18075).

Definition of multi-hazards

A plethora of different definitions of multi-hazard events exist, however throughout this report, the definition of multi-hazard is assumed as meaning (1) the selection of multiple major hazards that a country faces, and (2) the specific context where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects (UNISDR, 2017). There are different types of 'interrelated effects' described by UNISDR (2017). For this report, these are summarized as: triggering relationships, amplification relationships and compound hazards. Multi-hazard assessment approaches are often more qualitative than quantitative and do not incorporate temporal changes in the vulnerability of assets over time, such as during successive hazards.

Multi-hazard approaches in academia and practice

From the academic review that was undertaken there were a limited number of papers identified that described approaches that fully understood multi-hazard interactions. The best examples were highlighted from the civil and structural engineering communities, and were applied to bridges and other critical infrastructure for the assessment of earthquake, wind and erosion hazards. Many of these examples were applied to simulated environments, rather than to actual geographical extents; potentially due to access challenges around the data needed for these multi-hazard assessments. There are a limited number of examples found in the review, which used real multi-hazard situations, which often involve multiple natural hazard types, anthropogenic processes, and a range of interaction types.

From the practice review there was again a very limited amount of literature with cases studies from industry and policy. The national and international policy literature strongly emphasize the need for development of multi-hazard approaches and risk assessment tools. Quantitative methods applied in industry were as complex and diverse as those described in the academic literature. The energy sector (e.g. nuclear, electricity, gas), in particular, demonstrated good examples of developing and applying a wide range of qualitative, semi-quantitative and quantitative multi-hazard characterisation and risk assessment approaches. There were well-established practices identified that could be adopted in other business sectors. From the review it was highlighted that the UK government is making efforts to move from recognising to assessing interdependencies and interactions between hazards, which fits well with their holistic UK perspective on assessing hazards.

What is needed to improve multi-hazard risk assessment in practice?

As part of the review of practice, data-rich interviews were carried out on a number of key stakeholders (33 stakeholders, representing 25 stakeholder organisations). From these interviews it was concluded that stakeholders perceived the science of multi-hazard assessment as immature and poorly understood. They acknowledged that process understanding was the primary knowledge gap in implementing multi-hazards risk assessments in practice. Private-public partnerships were suggested as a good ground for transferring knowledge on multi-hazard models

and methods used across sectors. Stakeholders highlighted a reasonably good understanding of the range of scenarios that may be possible in their own sector, but the application of multi-hazard methodologies in real case study examples was limited. The stakeholders identified largely triggering multi-hazard relationships (47%), followed by amplification effects (36%) and compound types (17%) as the types of interrelated effects of multi-hazards. The weight of interest across sectors lies with four multi-hazard scenarios: storm surges and flooding (identified by 21.2% of respondents), extreme rainfall triggering landslides (15.2%), river and coastal flooding (15.2%), and strong winds, snow, ice and extreme cold (12.1%). Stakeholders representing the transport, energy and geotechnical engineering services find most relevant combinations of geological (e.g., landslides, sinkholes, rockfalls), atmospheric (e.g., storms, rainfall) or/and hydrological hazards (e.g., river and groundwater flooding), while the policy sector is focused on a wider range of possible multi-hazards, both natural and anthropogenic. The existing knowledge about methodologies and approaches used to quantify economic costs of multi-hazards was highlighted as being very scarce. Systematic data collection about exposure, vulnerability, impact and dynamic modelling was highlighted by a number of stakeholders as a key barrier for advancing the state-of-the-art of multi-hazard approaches in both applied research and practice within industry. A lack of practical guidance on how/when to use existing methods for those without a technical background was indicated by stakeholders as a major knowledge gap.

Evidence for socio-economic impacts of multi-hazards

From the analysis of societal and economic consequences case studies, there was a lack of impacts identified, which enabled a fully considered and assessed cost model. Under-estimation of total economic costs was seen in all the case studies analysed due to a lack of data, an accumulation of damage in the case studies and single-hazard analysis methods used for multi-hazard events.

Gaps & opportunities

From the review of the existing environmental multi-hazard approaches, projects and associated literature, taken from across academia and practice (policy and industry), a number of potential gaps and opportunities have been concluded:

• **Gap:** Understanding of multi-hazard processes.
Opportunity: Research to understand physical processes behind multi-hazards.
• **Gap:** Testing of multi-hazard assessment methodologies**.**
Opportunity: Trial existing assessment methodologies to more complicated or alternative multi-hazard scenarios.
• Gap: Understanding of multi-hazard concepts.
Opportunity: Sharing of best practice for joined-up approaches.
• **Gap:** Limited understanding of UK multi-hazards**.**
Opportunity: Development and dissemination of guidance on UK multi-hazards.
• **Gap:** Accounting for differences between single and multi-hazards.
• **Gap:** Assessing creeping changes in vulnerability associated with multi-hazards.
• **Gap:** Lack of data for understanding costs.
• **Gap:** Lack of in-depth case studies.
Opportunity: Develop more case studies accounting for interdependencies.
• **Gap:** Assessment of cost differences.
Opportunity: Simulations should be used to prove a way to look at multi-hazards as if they occurred independently of one another and compare the impacts and the associated full economic costs with a multi-hazards scenario.
• **Gap:** Better links between science and industry/policy.
Opportunity: Facilitate further collaboration between academia and industry/policy.
• **Gap:** Baseline knowledge of multi-hazards.
• **Gap:** Knowledge transfer and communication.
• **Gap:** Lack of regulatory or legislative framework.

1. Introduction

Multi-hazard approaches to assessing hazard potential and risk are increasingly advocated as part of disaster risk reduction policies and practice (e.g. Government Office for Science, 2012; UNISDR, 2015) but have only recently been defined within the disaster risk community (UNISDR, 2016). The UNISDR definition of multi-hazard, which we adopt in this report, says:

"Multi-hazard means (1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects." (UNISDR, 2017)

We discuss the definition of 'multi-hazards' in the published literature in Appendix 2, highlighting possible alternatives and the common characteristics within these definitions. We explicitly reject definitions of multi-hazard that treat hazards as being discrete or independent and do not consider or incorporate the potential impact of hazard relationships. In Appendix 2 we also summarise the different types of 'interrelated effects' described by UNISDR (2017). We summarise these below, and provide examples of these relationships.

i. *Triggering Relationships.* One hazard triggering other hazards, or a series of triggering relationships forming a cascade or domino event. For example, a storm triggering landslides and floods.

ii. *Amplification Relationships.* One hazard changing the landscape and thereby increasing the probability of other hazards occurring. For example, sustained heavy rain increasing the likelihood of flooding (by saturating the ground).

iii. *Compound Hazards.* Hazards may coincide in space and/or time with impacts greater than the sum of the two. This could be due to a primary hazard triggering multiple secondary hazards within a given timeframe, or the coincidence of two independent hazards. For example, extreme temperatures and drought may both occur and result in greater strain on water resources. The latter includes situations where hazards occur consecutively, with one hazard changing the vulnerability so as to make exposed assets more susceptible to the impacts of a following hazard. For example, strong wind loading may weaken pylons and thereby increase the risk of subsequent hazards having a negative effect on exposed assets.

National commitments to the UNISDR Sendai Framework for Disaster Risk Reduction (SFDRR - UNISDR, 2015), which advocates multi-hazard approaches, will likely result in a demand for new assessment frameworks and methodologies building on those developed by the academic community (e.g. Gill and Malamud (2014, 2016 and 2017); Liu et al., 2015; Liu et al., 2017; Pescaroli and Alexander, 2018). Often these assessments are more qualitative than quantitative and do not incorporate changes in the vulnerability of assets over time, such as during successive hazards. For example, an initial hazard (storm) may weaken an infrastructure, and make it more vulnerable to a subsequent storm or erosion. There are large knowledge gaps, including understanding the natural physical processes and their interaction with infrastructure, and little good practice documented in the UK and internationally. Research is generally fragmented, but there are some examples of good practice in industry within the UK (e.g. HSE ALARP, nuclear, electric and gas energy).

Significant social and economic impacts following events like the 2007, 2013 – 2014 flood and storm events in the UK highlight the importance of a holistic approach on building resilience to disasters through integrated risk assessments. To this end, infrastructure experts from the NERC Environmental Risk to Infrastructure Programme (ERIIP) stakeholder panel have highlighted the need for an up-to-date mapping of current knowledge, capabilities and tools existing and available for use in practice for multi-hazard impact and risk assessment. The work described in this report is a “Review of environmental multi-hazards research and risk assessment approaches” for the Natural Environment Research Council (NERC) through a UKRI contract for services (CR18075) and was compiled and led by a BGS consortium, supported by Natural Hazard Partnership (NHP) partners (HSE, CEH, PHE and Met Office).

The scope of this work is to conduct a review of existing environmental multi-hazard literature, approaches and projects across academia and industry in the UK and internationally. In addition to these sectors, key risk assessment policy-makers in the UK are taken into account. The focus of the study is on combinations of natural hazards (e.g. floods, strong winds, extreme temperatures); however the concerns of the industry and policy-makers with respect to combination of natural with-/ or anthropogenic hazards are also partially considered.

1.1 AIMS, OBJECTIVES AND METHODOLOGICAL APPROACH

The study aimed to exploit the existing knowledge of a range of stakeholders in academia and practice (industry and policy) with respect to multi-hazard impacts and risk assessment in areas such as, but not exclusive to: scientific research results and literature; operational processes and methods; and policy guidelines and procedures. The objectives of the study are to:

- Map the research activity and capability in the academic community (mainly focused on the UK, but using international examples where relevant) and practice (industry and policy) to understand the processes underlying multi-hazard events, their social-economic impacts and associated risks;
- Understand how industry and policy-makers currently consider and approach multi-hazard risk assessment;
- Gather evidence and examples, from existing publications, of the key societal/economic consequences of multi-hazard events;
- Identify what existing or new knowledge is required to advance our understanding of multi-hazard events, their impact, as well as the methods and approaches available to assess multi-hazard risks in policy/practice;
- Consider the barriers and possible solutions to progress multi-hazard research in the UK and its use in risk assessments.

To ensure efficient and complete delivery of these objectives, the project was managed through four related work packages (onwards called WP). Figure 1.1 illustrates the methodological workflow, work packages and the associated deliverable outputs undertaken as part of this project.

1.2 WORK PACKAGE MANAGEMENT AND OUTPUTS

A Technical Steering Panel acted as the internal technical project advisor, contributing to, and reviewing all output project materials, in order to ensure that a complete and effective evidence review and short analysis of the multi-hazard research, policy and practice was undertaken. This approach has enabled a multi-disciplinary project team and a flexible group of technical experts in the Steering Panel who have provided additional specialist support (Figure 1.2).

The Project Manager successfully kept the project on program, coordinated the Technical Steering Panel, mapped and liaised with stakeholders, as well as maintained and communicated with the UKRI/NERC Innovation Manager (Ruth Hughes). A description of the research undertaken in the following sections of this study is given below and the associated WP outputs are listed in Appendix 1.

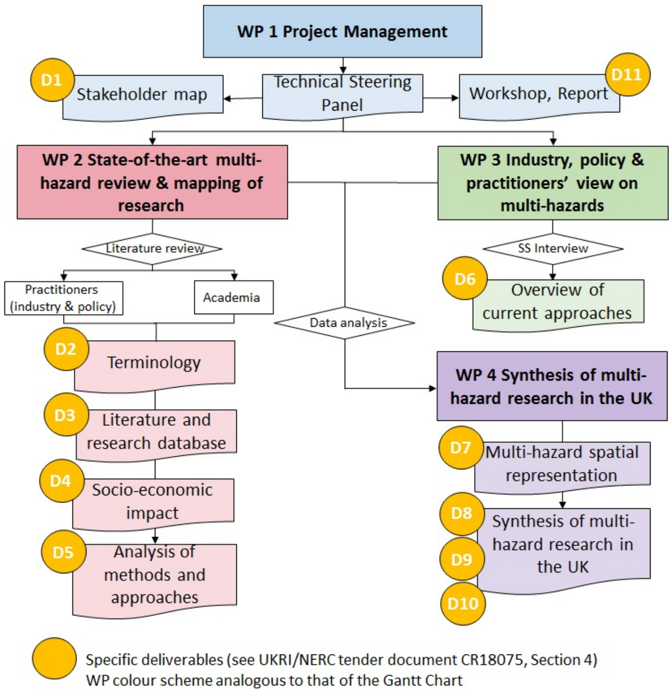


Figure 1-1 Project methodological workflow

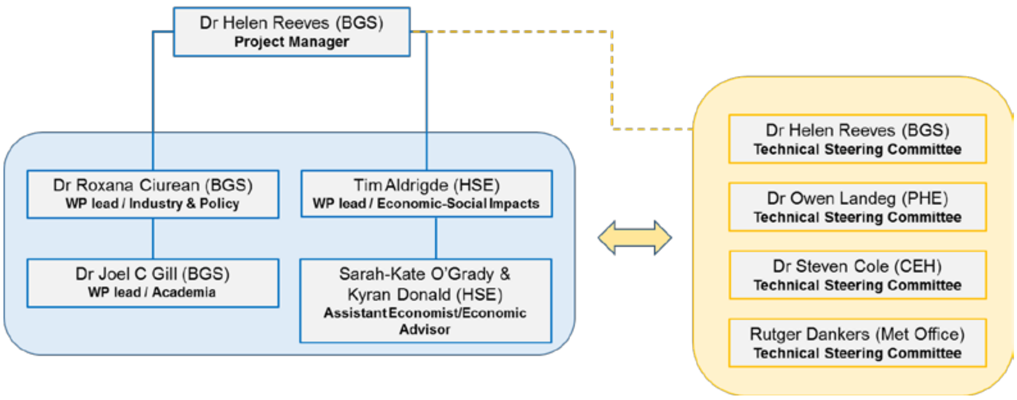


Figure 1-2 Project Organigram (Technical Working Team, in blue. Technical Steering Committee, in yellow)

Following the Introduction, **Section 2**, associated with WP2, reviews and maps past/current/planned research in the academia and practice (industry and policy). The lack of a clear definition of 'multi-hazards', until recently, means that this term has been used in different ways in the published literature. Not everything that is labelled 'multi-hazard' fell within the scope of this review, and not everything within the scope of this review was labelled 'multi-hazard'. Considering the complexity of the term multi-hazard and its several interpretations, we have reviewed and defined the common characteristics of the phenomena, using NERC's definition as the starting point. The review of the terminology has ensured that the boundaries of the project are comprehensive, consistent, feasible and repeatable. This review has helped to define the appropriate keywords to be used in the preceding literature reviews.

In the context of this review and WP2 (see Figure 1.1), and considering the experience and knowledge that the team and the Technical Steering Panel has from previous work/projects, we have examined literature that:

1. Synthesises interaction and case study-specific publications. In recent work developed by Dr Gill , 200+ references were reviewed, to develop a comprehensive, systematic and

evidenced matrix of possible interactions between 21 diverse natural hazards [Gill and Malamud, 2014].

2. Synthesises existing research approaches to identify and characterise relevant multi-hazard interactions, or present new approaches.

3. Synthesises existing approaches used for operationalising multi-hazard research and incorporating it into a risk assessments, or presents a new approach.

Where appropriate, we complemented peer-review literature with other forms of evidence, to enrich our understanding of current applications of multi-hazard approaches. The team, with multiple networks through the NHP, engaged with partners from industry, policy makers and professional organisations/NGOs. A summary of how the activities in WP2 (Section 2) have been carried out is presented below.

For Academia, we have used knowledge, experience and literature reviews from the project team, in particular Dr Gill, to deliver a methodology that identifies, reviews, maps and summarises past & current academic research and innovation projects in multi-hazard processes, impacts and the assessment of risk. We have adapted and built on a review methodology used to characterise the potential interactions of natural hazards (Gill and Malamud, 2014), using a set of review criteria (Boaz et al., 2002) to assess the types of literature in a systematic manner for the project. The literature that has been reviewed includes peer-review journal articles and edited volumes, technical reports, workshop reports and Masters and PhD theses (i.e., both peer review and grey literature). Where appropriate we have also referred to textbooks, technical reports, databases, and NGO disaster situation reports. This approach to this review has enabled us to build on the work and literature that Dr Gill has collected in previous studies, such as Gill (2016, 2017), Gill and Malamud (2014, 2016 and 2017). This has ensured an effective use of time and resources. It has also ensured a thorough review has been undertaken using similar criteria so the work is comparable.

For Practice (Industry & Policy), we have built on the stakeholder landscape mapping undertaken in WP1. We used the knowledge/experience and networks of the project team and Technical Steering Panel to conduct literature reviews and undertake discussions with key practicing stakeholders in industry (particularly in infrastructure, construction, agriculture, environmental management, and H&S). Policy strategists (particularly in central and devolved government in the UK) have also been contacted to help collate the information and knowledge that identifies, reviews, and maps past & current practices of research and innovation projects in multi-hazard process, impact and the risk assessment.

To complement the information collected from the literature reviews, 3 case studies have been identified. The case studies have provided information detailing the societal and economic impacts of multi-hazard events, using existing evidence from the literature. The research has drawn on the knowledge and experience of economists at HSE's Economic and Social Analysis Team, to identify, review and apply economic models for impact assessment. The outcomes of WP2 are listed in Appendix 1.

Section 3, associated with WP 3, investigates the industry and policy practitioner's view on multi-hazards. This research builts on the stakeholder landscape mapping undertaken in WP1. The project team selected participants based on their experience and relevance to our questions (purposeful sampling), which has ensured data-rich interviews (MacDougall and Fudge, 2001; Longhurst, 2003; Suri, 2011; Palinkas et al., 2015). The questions were structured and formulated in consultation with the Technical Steering Panel and the NERC Project Manager, around the core areas of:

- Knowledge of multi-hazard processes and risk assessment methodologies used in research and practice (both in industry and policy);

- The advantages and pitfalls of current methodologies and approaches used in practice to undertake multi-hazard risk assessments, including multi-hazard spatial representation;
- Their concerns and experience in undertaking multi-hazard risk assessment;
- The current gaps in knowledge/skills for undertaking multi-hazard risk assessments.

Due to the time constrains of this this research, a standardized questionnaire (Appendix 8) and/or a ~ 40-45 minute open-ended telephone interview were carried out. This methodology enabled us to cover the factual episodes, using the elements of a semi-structure interview for all the interviewees. The open-ended questions ensured that greater knowledge of the interviewees understanding of multi-hazard processes and risk assessment methodologies is obtained. All interviewees were given an explanation of the project, and their consent obtained to use information from these interviews. Participants have been able to choose how they are identified: by name and organisation, by organisation only, or by a code that cannot be traced to an individual or organisation. An Ethics Policy has been developed for the project (Appendix 7). The interviews provided a means to ground-truth the uptake of current research on multi-hazards and evaluate the feasibility of methodologies and approaches in practice. The outcomes of WP3 are listed in Appendix 1.

Section 4, associated with WP4, synthesized and analysed the knowledge gained in Section 2 (WP2) and Section 3 (WP3) to identify gaps (in knowledge and skills) and potential future opportunities to progress multi-hazard events and risk assessment research. To help structure the synthesis, we have used the stakeholder mapping outputs to identify areas of common challenges that are shared by academia, industry and policy. In Appendix 9, we propose a number of disciplines that could inform multi-hazard research and risk assessment and in Appendix 10, relevant initiatives, forums and conferences. This work has drawn from the findings of a workshop undertaken in 2018 internally at BGS (Gill, 2018) as part of an assessment on “Multi-Hazard Interactions: Research & Innovation Opportunities”. The outcomes of WP4 are listed in Appendix 1.

As part of this review there are some limitations that have arisen due to the short timeframe of the study. This has caused some challenges around the consultation and capture of all the potential industry and policy representatives that work and practice within the environmental multi-hazard risk assessment area. For example, in the stakeholder survey, there are no representatives from the local government emergency resilience communities, emergency response, insurance and financial sectors. To minimize the impact of this limitation, the literature reviews have identified studies that use and/or discuss data/methods/tools from the insurance industry and from different levels of the UK government (national – regional – local). The results of this review are only designed as a quick overview of the historical and current multi-hazard research landscape in how policy-makers and industry consider and approach multi-hazard assessments; the scale of the problem caused by multi-hazard events and the barriers, research gaps and potential opportunities in multi-hazard research and practice. This study should therefore, be used only as a high-level overview document and not as a complete and comprehensive study of all known activity that has taken place in environmental multi-hazard risk assessment research.

2. State-of-the-art multi-hazard review and mapping of the past/current/planned research (Academia, Industry & Policy)

2.1 SUMMARY OF PAST AND CURRENT PROJECTS, RESEARCH AND APPROACHES IN MULTI-HAZARD PROCESSES, IMPACT AND RISK ASSESSMENT

Almost 50 years ago, Hewitt and Burton (1971) noted that most research on natural hazards takes a single hazard approach, but that a greater emphasis on systematic cross-hazard approaches is required. Single hazard approaches treat natural hazards as independent phenomena, not recognising a range of potential relationships between hazards (Kappes et al., 2012). This approach can lead to a distortion of management priorities, an increased vulnerability to other spatially relevant hazards, or an underestimation of risk (Tobin and Montz, 1997; ARMONIA, 2007; Kappes et al., 2010; Gill and Malamud, 2014; Duncan et al., 2016).

While some progress towards systematic cross (or multi-) hazard approaches has been made, there is a continued focus by the natural hazard and disaster risk communities on single hazard approaches to assess hazard potential. Nevertheless, academic and practitioners (industry and policy) have developed some approaches to consider multi-hazard scenarios. The outcome of a short review on academic and practitioner methods are outlined below.

2.1.1 Academia

Here we focus on general multi-hazard tools and techniques described in the academic literature that are applicable to multiple hazards and interaction types. As outlined in Appendix 2, the term ‘multi-hazard’ is widely used, but rarely defined. This means that not all of the academic literature labelled as ‘multi-hazard’ is relevant to the scope of this review, and some review boundaries are needed, as set out in later sections.

2.1.1.1 Methodology for Identifying Academic Literature on Multi-Hazard Approaches

Search Procedure

Our review process was based on Collins et al. (2015), and used to determine current academic approaches to understanding multi-hazards, as presented in both peer-review and grey published literature. We selected Google Scholar as our primary database, ensuring both relevant peer-review and grey literature (e.g. masters and PhD theses) was returned. In order to complete a Boolean search using this database, we first selected keyword phrases relating to multi-hazard. These included both multi-hazard (Anglicised spelling) and multihazard (Americanised spelling), and multi-risk. We paired each of these terms with a set of descriptors that would likely identify approaches used to characterise multi-hazards. These keywords were methodology, approach, tool, method, review, assess, assessment, analysis, modelling, modeling, and model.

We searched for these keyword pairs in article titles to ensure that the most relevant results, likely to support the review, were returned. Results were then input into an excel spreadsheet, and the abstracts reviewed to ensure only relevant and complete results (i.e., not conference abstracts) were included in the analysis. Where we could determine relevance solely on the abstract, we subsequently reviewed the full paper.

In addition to the results of this search procedure, we also incorporate perspectives from some other general multi-hazard review papers that integrate many references and characterise multiple approaches. As the focus of these papers was not describing a single tool or methodology, these were not likely to be returned in the search procedure.

Search Results and Processing

Table 2.1 characterises nine searches completed on 14 August 2018, and the number of returned results for each search. The searches returned a total of 476 results. After the removal of duplicate results, incomplete results and irrelevant results, 84 unique articles were available for further analysis. Incomplete results included conference abstracts where a full paper was not available, and inaccessible results (e.g. due to language, paywall, or embargo restrictions). Irrelevant (and therefore excluded) results could generally be grouped into four categories:

i. *Limited in Scope*. Focusing on tools that are specific to one hazard pairing, rather than looking at the range of relevant hazards and their interactions.

ii. *Multi-Layer Single Hazard*. Completed an independent assessment of multiple single hazards, without considering the impact of hazards occurring simultaneously or successively on assets.

iii. *Other Domains*. Explored multi-hazards, but not in the context of natural hazards (e.g. finance).

iv. *Case Study Descriptions*. Described a specific multi-hazard event, without presenting an approach or method to understand or manage multi-hazards.

The database of results used in the analysis, with web links and abstracts, is given in Appendix 3.

Table 2-1 Search terms used to identify academic literature that presents methods relating to multi-hazards. Search excludes patents and citations, with results in English only.

Search Term	Returned Results	Search Engine/ Database	Search Date
allintitle: methodology (multi-hazard OR multihazard OR multi-risk)	13	Google Scholar	14 August 2018
allintitle: approach (multi-hazard OR multihazard OR multi-risk)	52	Google Scholar	14 August 2018
allintitle: tool (multi-hazard OR multihazard OR multi-risk)	17	Google Scholar	14 August 2018
allintitle: method (multi-hazard OR multihazard OR multi-risk)	10	Google Scholar	14 August 2018
allintitle: review (multi-hazard OR multihazard OR multi-risk)	9	Google Scholar	14 August 2018
allintitle: assess (multi-hazard OR multihazard OR multi-risk)	4	Google Scholar	14 August 2018
allintitle: assessment (multi-hazard OR multihazard OR multi-risk)	203	Google Scholar	14 August 2018
allintitle: analysis (multi-hazard OR multihazard OR multi-risk)	94	Google Scholar	14 August 2018
allintitle: (modelling OR modeling OR model) (multi-hazard OR multihazard OR multi-risk)	74	Google Scholar	14 August 2018
Total Results	476		
Total Unique Results	380		
Total Unique Results *After Removal of Conference Abstracts and Irrelevant Results*	84		

2.1.1.2 Conclusions from the Classification and Characterisations of Academic Approaches on Multi-Hazard Approaches

The academic literature on multi-hazards presents a range of approaches to either understand a hazard landscape (i.e., assessing hazard or components of hazard) or potential damage to assets (i.e., assessing risk). Both sets of literature include qualitative and quantitative approaches. Some approaches may focus on a particular factor that is required to support a full multi-hazard approach, while others collate multiple tools to present a more complete multi-hazard approach. In this section, we summarise the main techniques profiled in the academic literature, with relevant examples from the review results. Methodology types range from those that are fully qualitative to those that are fully quantitative, shaped by a range of factors (e.g. purpose of the study, intended audience, data availability).

(a) *Narrative Descriptions (Qualitative)*

Individual case studies (i.e., an event report) characterise actual or potential multi-hazards in a given region. For example, Collins and Jibson (2015) is an event report of the 2015 Nepal earthquake, characterising the earthquake, landslides, and associated flooding. These examples are prominent in the literature, and provide a valuable source of evidence regarding what has previously occurred, informing scenario planning. Some narrative descriptions extend towards this forward-looking approach, with qualitative discussion of what could occur given a particular natural hazard occurrence. For example, Han et al. (2007) discussed examples of hazard chains in China, and used this to develop a taxonomy of potential types of hazard chain.

(b) *Hazard Wheels (Qualitative)*

Particularly used in the context of coastal hazard management, coastal hazard wheels are used to characterise coastlines, their hazard profile, and possible management options (Appelquist and Halsnæs, 2015). Coastal hazard wheels include a classification system that incorporates the primary static and dynamic parameters that determine the characteristics of a coastal environment. This include hazards such as ecosystem disruption, gradual inundation, salt-water intrusion, erosion and flooding. The coastal hazard wheel is designed to facilitate decision making at diverse scales (local, regional and national) in areas with limited access to geological data. For example, the tool can be used to facilitate hazard screening or the identification of hazard hotspots. This approach allows the identification of appropriate management options, and visualises whether these mitigate one or more hazard types that may occur simultaneously or successively.

Such approaches are well suited to hazard management in the Global South if there are restrictions on data availability and institutional capacity. The methodology is flexible, with additional steps improving accuracy if systematic and detailed field assessments are possible. The approach has been developed for coastal management, and therefore could be used to assess hazard potential at existing and potential future sites for coastal infrastructure.

(c) *Hazard Matrices (Qualitative/Semi-Quantitative)*

Hazard matrices are a qualitative or semi-quantitative way to examine relationships between hazards. Spatially relevant hazards are first identified, before determining how each hazard relates to other hazards (Gill and Malamud, 2014). These have been produced for both natural hazards and triggering natural hazards (Gill and Malamud, 2014) and anthropogenic processes (e.g., groundwater abstraction) triggering natural hazards (Gill and Malamud, 2017). Matrices can use binary symbols (Tarvainen et al., 2006; Kappes et al., 2010) or descriptions (De Pippo et al., 2008; Kappes et al., 2010) to outline the influence of one hazard on another. Gill (2016) used this approach to characterise potential hazard relationships at national and sub-national scales in Guatemala and Barrantes (2018) used a matrix to characterise potential hazard relationships at a sub-national scale in Costa Rica.

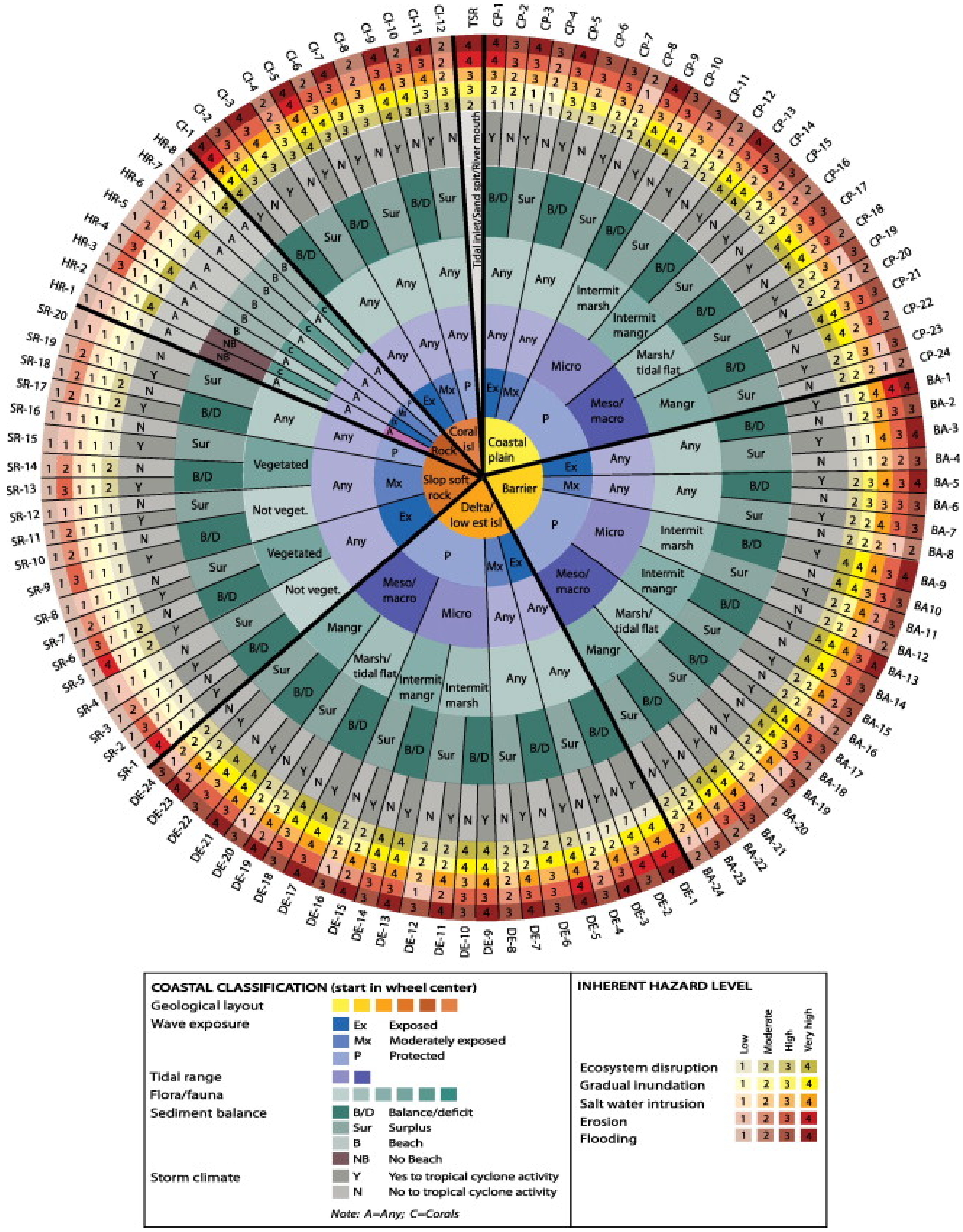
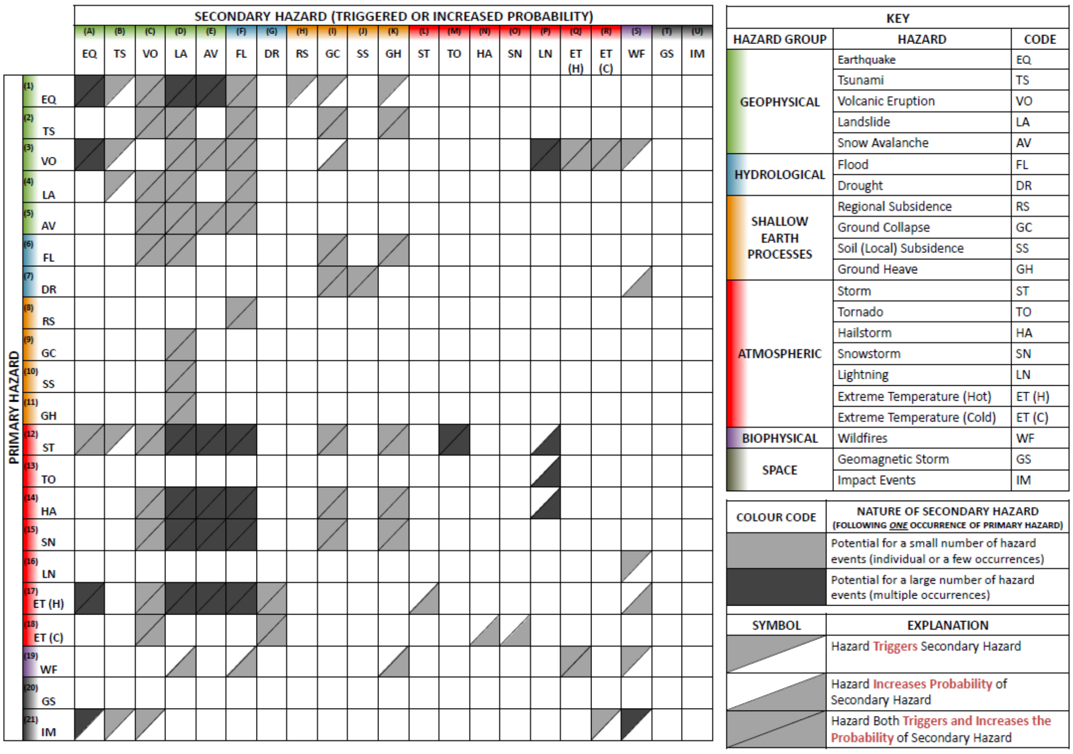


Figure 2-1 Coastal Hazard Wheel (from Appelquist and Balstrøm, 2014). **The Coastal Hazard Wheel consisting of six geo-biophysical classification circles, five hazard circles and the coastal classification codes (CP stands for coastal plain, BA for barrier, DE for delta, SR for sloping soft rock, HR for sloping hard rock, CI for coral island and TSR for tidal inlet/sand spit/river mouth).**

Hazard matrices may form one component of a more comprehensive approach. For example, Gallina (2015) uses an influence matrix to inform her multi-risk methodology applied in Italy. This semi-quantitative approach characterises the extent to which hazards influence each other, with weightings derived from expert consultation. The quality of hazard matrices differs considerably, with varying evidence to support the inclusion/exclusion of particular hazards and hazard relationships (Gill, 2016). Hazard matrices are scalable, can be used with diverse amounts of information depending on the specific context, and can represent large amounts of multidisciplinary information extracted from multiple evidence sources. For this reason, they can be an effective tool for rapid identification of secondary hazards and a popular tool in many multi-hazard approaches.



Footnotes

[1A,D,E; 3A,P; 12D-F,M,P; 13P; 14D-F,P; 15D-F; 17A,D-F; 21A] The secondary hazards in these cases are all accepted to most likely occur as large numbers of events, and are thus analysed in this way.

[1C] There is disagreement in the literature about the nature of this relationship .

[2,6,12,14,15C] Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption.

[3I] Volcanism increases the acidity of rain, promoting dissolution of carbonate material.

[12A] Low pressure systems have been shown to trigger or increase the probability of slow earthquakes on faults that are already close to failure (Liu *et al.,* 2009).

[17A,C-F] Secondary hazards triggered or have an increased probability over a range of time-scales, through snow and glacial melting.

[18C] Long term reductions in temperature can increase glaciation and thus decrease sea-levels. This reduction in sea-levels can reduce confining pressures, promoting volcanic eruptions.

Figure 2-2 Global Hazard Interaction Framework (from Gill and Malamud, 2014). **A 21 × 21 matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis.**

(d) *Network Diagrams (Qualitative/Semi-Quantitative)*

Another tool used to inform multi-hazard assessments are qualitative network diagrams, with nodes (e.g. hazards/processes) and connectors (e.g. triggering or catalysing relationships types) to generate a diagram of possible multi-hazard relationships.

Van Westen et al. (2014) used this approach to visualise the hazards and hazard relationships in an alpine mountainous environment. Such approaches are visually appealing, and can help to document the potential relationships between hazards and therefore identify possible scenarios. This approach is also scalable, with potential to be used in local, regional or national scales. While generally qualitative, additional information could be added to characterise quantitatively each hazard, or the interaction between two hazards (see (i) probabilistic and statistical assessments, below).

(e) *Hazard Maps (Qualitative/Semi-Quantitative)*

Cartographic approaches are widely used to represent the spatial overlap of multiple hazard or risk maps (e.g. Bell and Glade, 2012; Eshrati et al., 2015; Johnson et al., 2016). Such approaches can be used to assess spatial regions susceptible to multiple independent or dependent hazards. If exposure and/or vulnerability maps are also included, the overlay of hazard maps can be used to inform management strategies. For example, Johnson et al. (2016) mapped multiple hazards in Hong Kong, and used this approach with vulnerability maps to visualise concentrations of risk. They note the potential of this approach to guide prioritisation of risk management and adaptation actions for regions exposed to multiple hazards. This can ensure that actions are taken that do not increase vulnerability to other spatially relevant hazards. A key challenge with prioritisation decisions when overlaying hazard maps is ensuring comparability of hazards (Kappes et al., 2012). Potential losses may be greater in a region susceptible to one high impact or high frequency hazard, than a region with multiple low impact or low frequency hazards. One possible solution is to apply some form of weighting relating to the impact of different hazards (Mukhopadhyay et al., 2016).

(f) *Development of Hazard/Risk Indices (Semi-Quantitative)*

The calculation of hazard and risk indices can be used to characterise multi-hazard environments and inform decision-making. The simple aggregation of multiple single hazard indices, however, may not be sufficient to determine a multi-hazard index (Marzocchi et al., 2012). Araya-Muñoz et al. (2017) developed a semi-quantitative approach, based on fuzzy logic modelling, to identify hazard combinations that have the greatest influence on hazard impacts. Indicators relating to multiple weather-related hazards (coastal flooding, fluvial flooding, water scarcity, heat stress, and wildfire) were determined, standardised and aggregated into a multi-hazard impact index, with the ability to explore how interactions between indicators influences this index.

(g) *Systems Based or Physical Modelling (Quantitative)*

There is a growing ability to develop sophisticated process-based models that can be used to explore multiple hazards and relationships between these. For example, Chen et al. (2016) present a physically based model to look at interactions between rainfall, slope failures and debris flows, in a seismically active region. Machine learning, or artificial neural networks, are another modelling approach, used to understand complex connections between a range of meteorological factors (wind, pressure, storm surge, and precipitation resulting in inland flooding) generating damage during a tropical cyclone (Pilkington and Mahmoud, 2017a). These can help to predict the impacts of such multi-hazard events, where impacts vary significantly depending on landfall location, wind speed, storm surge, and inland flooding from precipitation (Pilkington and Mahmoud, 2017b). Developing new, location specific, multi-hazard models that incorporate the environmental heterogeneity of that location would require significant investment and research. There may be scope to combine existing models relating to single hazards to develop something that provides useful information that is more than the sum of its parts.

(h) *Probabilistic and Statistical Approaches (Quantitative)*

Another quantitative approach used to characterise multi-hazards is through probabilistic and statistical assessments. For example, Mignan et al., (2014) present a probabilistic framework using a Monte Carlo Method, a variant of a Markov chain, and time-variant vulnerability and exposure to generate multiple time-series of risk scenarios. Analysis of these time series helps to develop a probabilistic assessment of potential losses and identifies which risk paths (i.e., scenarios) are more likely to occur. This approach can be used with differing levels of information regarding interactions, as it becomes available. Probabilistic and statistical approaches include a range of possible techniques (e.g. fragility functions, scenario trees, expert elicitation, fault tree analysis, life cycle cost assessments, Bayesian networks, copula for joint probabilities) to better understand the likelihood of a particular hazard sequence.

One method is to harmonise losses from different hazard types to understand the impact of different multi-hazard scenarios on infrastructure. For example, recognising that bridges are made of different components that respond in different ways to diverse hazard types, Gehl et al. (2016) derived hazard-specific component fragility curves (i.e., showing the probability of exceeding a stated level of damage or performance, as a function of an engineering demand) to quantify the occurrence of multiple failure modes for combinations of hazard and component. They proceeded to estimate functionality losses for each component failure mode as a metric to characterise the performance of infrastructure systems. Finally, system failure modes can be considered by combining component damage states, with the calculation of system fragility functions to characterise different multi-hazard configurations. This approach can be used on different types of infrastructure, including bridges and road networks (Gehl and D'Ayala, 2015; Gehl et al., 2016; Gehl and D'Ayala, 2016, Gehl, 2017).

Probability or scenario trees set out a range of potential scenarios, and associate numerical information (e.g. probability, frequencies, impacts) with each step of these scenarios. For example, Neri et al. (2013) used an interaction scenario tree for the Kanlaon volcano (Philippines), showing the types of hazardous events in this location and estimates of their frequencies. Neri et al. (2008) compiled a probability tree for possible future scenarios at the volcano Vesuvius. This probability tree included possible eruption styles and the secondary hazards associated with them. The authors used both quantitative processes and expert elicitation (a structured approach to gain scientific consensus) to calculate a range of conditional probabilities (the probability of an event, given that another event has already occurred). Marzocchi et al. (2009) also describe the identification of different scenarios and the quantification of these scenarios using probability trees, but did this for a simulated environment rather than a real case study.

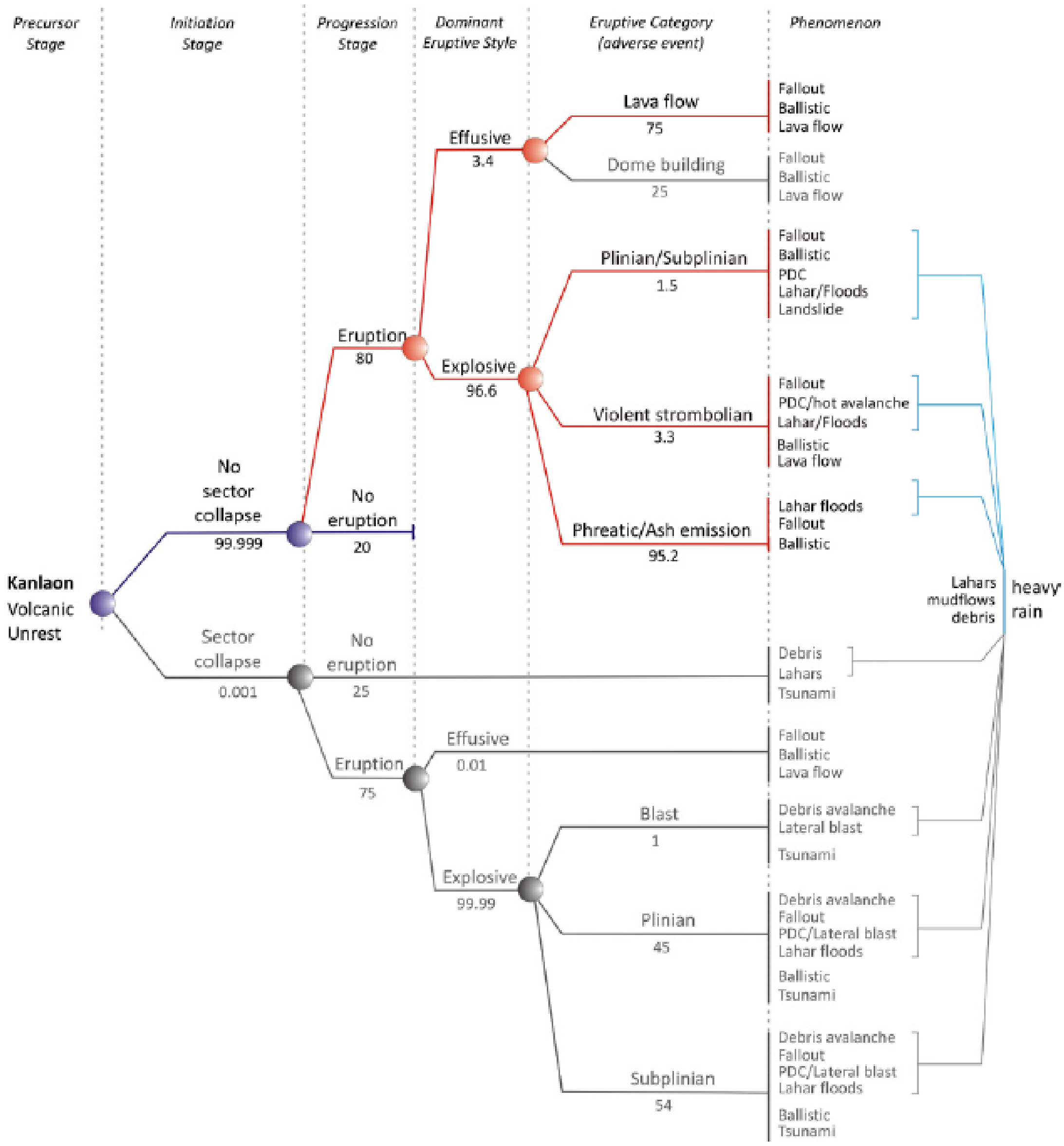


Figure 2-3 Type of hazardous events and their possible frequencies at Kanlaon volcano. (from Neri *et al*, 2013). In grey are rare events at Kanlaon, where reliable statistical calculations are not permitted.

A related approach is the use of fault tree analysis, aimed at analysing the effects of faults or weaknesses on a complex system. These approaches are a component of multi-hazard assessment done in the context of infrastructure engineering. For example, Unobe and Sorenson (2015) used a fault tree analysis to estimate numerically the possible effect of a seismic load (earthquake) on a wind turbine foundation that has undergone fatigue over time from constant exposure to wind forces. Another example is given in Gehl and D'Ayala (2015) in the context of analysing the multiple hazards that affect bridges. The use of a fault tree analysis is sometimes complemented with the use of a Bayesian network approach to represent causation or conditional relationships (e.g. Gehl and D'Ayala, 2015).

Some studies integrate probabilistic assessments of multiple hazards affecting infrastructure either simultaneously or successively to calculate a Life Cycle Cost assessment, a method for evaluating all relevant costs over the lifespan of the infrastructure (e.g. bridge). For example, Fereshtehnejad and Shafieezadeh (2017) examine the likelihood of infrastructure being impacted by a hazard before it has recovered from another hazard. This is then used within a life cycle cost assessment framework to determine the potential cost of hazard induced consequences compared to retrofit options.

2.1.1.3 Summary observations from review

From the results of Section 2.1.1.2, we make a number of observations.

- *Limited papers*. The literature describing approaches to understand multi-hazard interactions is limited, with clear scope for further research and innovation. We acknowledge that further papers may exist that were not returned in our search, but anticipate these including additional examples of the approaches described in Section 2.1.1.2.

- *Infrastructure (e.g. bridges).* Some of the most developed methods can be found within the civil and structural engineering communities, applied to bridges and other critical infrastructure. These methods currently focus on earthquake, wind and erosion hazards. Greater dialogue between natural hazard scientists and civil/structural engineers could enable the translation of methods for point source infrastructure (e.g. bridges) to other assets of interest, as well as the inclusion of other hazards of interest.

- *Simulations vs. actual events*. Many of the methods described are applied to simulated environments, rather than to actual geographical extents. This could be due to a lack of access to the data needed to test methods in a real world context. It is feasible that unpublished data, held by the private sector, exists that could help academia to develop more real-world (vs. simulated) applications of methods.

- *Multi-Method*. A comprehensive understanding of multi-hazard risk involves many stages, and therefore is a multidisciplinary and multi-method activity. Many of the studies characterised in this review integrated multiple methods to build understanding of multi-hazard relationships (e.g. Thierry et al., 2008; Lari, 2009; Nadim et al., 2014; Ming et al., 2015; Chen et al., 2016). The approaches outlined in Section 2.1.1.2 can be used in combination or succession to understand multi-hazard risk.

- *Desired application guiding appropriate methods*. Liu et al. (2015) present a three level framework to understand multi-hazards, noting that the most appropriate level of information to generate will depend both on data availability and the end purpose. While a quantitative assessment of risk may be preferable in some contexts, other groups will prefer the development of maps or scenarios. Organisational discussion around these can help to guide institutional understanding of multi-hazard relationships, and build capacity to respond appropriately.

- *Two hazards vs many hazards.* Many of the quantitative methods articulated in Section 2.1.1.2 are developed and applied to a specific combination of two natural hazards. Real multi-hazard situations often involve multiple natural hazard types, anthropogenic processes, and a range of interaction types. More work is needed to test these methods with more complex multi-hazard scenarios. Selva (2013) noted that extending methods to more than two hazards could lead to much more complicated analyses and many scenarios in long-term risk assessments. While these are valid comments, the development of multi-hazard approaches that can explore more than two hazards is clearly important in many contexts.

2.1.2 Practice (Industry & Policy)

The review of academic literature outlined in Section 2.1.1 identifies a range of current projects, methods and approaches for multi-hazard processes, impact and risk assessment potentially applicable into practice. Building on this review and additional grey literature, the current section focuses on the tools and techniques for multi-hazard risk assessment adapted or developed by the industry and policy sectors. The key questions that this section addresses are:

- What frameworks/approaches are being used in industry & policy to understand multi-hazards events, their impacts and risk assessment methodologies?
- What similarities and differences exist between the methods and approaches available in academia and those used or recommended by the industry and policy?

2.1.2.1 Methodology for identifying industry and policy literature on multi-hazard approaches

This review is based on the identification of relevant industry sectors and policy levels (Figure 2.4) and the selection of primary and secondary search databases. Google Scholar and Web of Science were used as primary search databases. A separate search was performed on individual web-sites of relevant industry and policy stakeholders (e.g. Cabinet Office, https://www.gov.uk/).

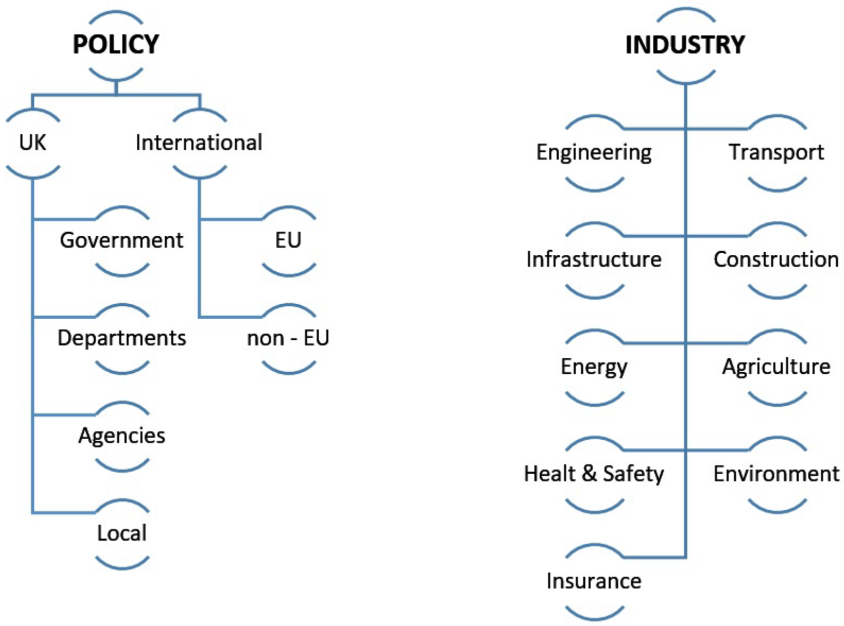


Figure 2-4 Identified policy levels and industry sectors

In addition to the results of this procedure, other documents indicated by the project stakeholders were incorporated into the analysis. The keywords or phrases used to search were a combination of two or three terms denoting the term multi-hazard (e.g. “multihazard”, “multi-risk”, “multi-hazard”), the industry/policy sector (“infrastructure”, “railways”) and/or a specific stakeholder (e.g. “Network Rail”, “Transport Scotland”). The literature search returned predominantly grey literature (reports, guidance notes, project deliverables, working papers, etc.), the majority of which were filtered in a subsequent phase of processing in accordance with their relevance. It should be noted that the selection is based on a non-exhaustive review limited by time and direct access to relevant documentation.

2.1.2.2 SEARCH RESULTS AND ANALYSIS OF FINDINGS

Twenty-one documents were identified from UK and international policy and industry sources as being potentially relevant for the review analysis. These were assessed in terms of differences or similarities with the academic approaches classified in section 2.1.1.2 and are summarized in Table 2.2. A detailed description of findings is provided in Appendix 3.

Table 2-2 Summary of findings from the industry & policy literature

Sector (no. of documents)	Source	Multi-hazard frameworks/approaches
Policy UK (10)	DfID, Cabinet Office, Committee on Climate Change, Environment Agency, HSE (2018)	Narrative descriptions (a), scenario analysis (h), physical modelling (g)
Industry UK (3)	Office for Nuclear Regulation (ONR), Espinoza et al. (2016), ETI (2018)	Fragility curves (h), tabulates (a) showing potential secondary/associated hazards with primary hazard; hazard curves (h); empirically-based, Markov chains, multi-variate Bayesian, joint tail models, kernel density, copulas (h)
Policy International (1)	European Commission (EC)	No methods are actually presented (it rather suggest the need for multi-hazard approaches)
Industry International (7)	Swedish Nuclear Inspectorate (SKI), Derek et al. (2016), Cazzoli et al. (2016)	Hazard matrices (c), probabilistic methods (c), event trees (h), expert judgement (h)

Characterisation of multi-hazards frameworks and approaches in policy

As demonstrated in a recent analysis (Chutmina et al., 2016), the UK policy framework focuses on a multiple hazard perspective, taking into account both natural as well as man-made threats (see The National Risk Assessment). National policies serve as a background and guidance for implementation at local level, while recognising the interdependencies between services/systems that may be disrupted on one hand and multiple, interacting threats on the other hand. It is apparent that government departments such as the Department for International Development (DfiD) and the Cabinet Office use both qualitative and quantitative methods. The Department for International Development (DfID, 2016) focused on narrative descriptions (type (a) in section 2.1.1.2) that bring together diverse sources of qualitative information to inform decision making in financing. The same department endorses the development of a risk matrix (similar to hazard matrix, type (c) in section 2.1.1.2) to compare different hazards in the Multi-Hazard Disaster Risk Assessment v2 Guidance Note (DfID, 2012). No explicit methodology is presented or requested as a minimum standard before embedding disaster resilience in DfID country offices (DfID, 2013).

Following the UK 2007 flooding events, the Cabinet Office produced a report on the lessons learned and future recommendations (Cabinet Office, 2008). Both physical modelling (type (g) in section 2.1.1.2) and scenario analysis (type (h) in section 2.1.1.2) are suggested in order to ensure that the possibility of multiple floods events occurring both simultaneously and within different overlapping time periods are taken into account. Nevertheless, no description of specific methodologies or tools are provided.

Consideration of multi-hazards is a key component of HSE's approach to land use planning and risk assessment for sites with hazardous substance consent (HSE, 2018). Sites are considered individually, with the risk assessment incorporating a wide range of factors including (but not exclusively): substance type, storage methods, quantities, and storage locations on site (see Box 1, page 42). Multiple hazards are identified based on these factors and then the hazards, or risk presented by those hazards, are summed to provide the overall individual risk (i.e. the risk of harm to an individual person at different locations around the site). The results are translated into zones used for land use planning purposes. HSE's approach also considers consequential hazards (for example where a fire may lead to an explosion), and the domino effects of sites in close proximity (scenario analysis, type (h) in section 2.1.1.2).

The NHP have developed a Hazard Impacts Framework (HIF; Gunawan et. al., 2017) that outlines concepts for hazard impact modelling, including consideration of multi-hazard assessment. They put an emphasis on using standards to ease the compatibility of modelling approaches (multi-hazard or otherwise) including common inputs and outputs, shared terminology and standardised impact categories.

At European level, the paper on Risk Assessment and Mapping Guidelines for Disaster Management (European Commission, 2010) does not present a standard way of developing multi-hazard risk assessments, it rather advises that both multi-hazard and multi-vulnerability perspectives are needed.

Characterisation of multi-hazards frameworks and approaches in industry

The international literature on multi-hazard risk assessment approaches that are used in industry is represented by a limited number of sectors. Among them, nuclear safety is one of the most advanced. For example, Knochenhauer & Louko (2003) present a method for identifying combined hazards using matrices (type (c) in section 2.1.1.2), network diagrams (type (d) in section 2.1.1.2) and engineering judgment (or expert elicitation, type (h) in section 2.1.1.2). Cazzolli et al. (2016) discuss the development and quantification of events trees (type (h) in section 2.1.1.2) in addition to fragility analyses (type (h) in section 2.1.1.2) to describe the interaction between internal and external events leading to failure in a nuclear plant. As part of the same international effort (Advanced Safety Methodologies: Extended PSA, FP7 Project), Decker & Brinkman (2016) present a 101 x 101 natural and external man-made hazard matrix (type (c) in section 2.1.1.2), with expert opinion identifying 579 event combinations and correlations. Correlations discriminate between: (1) causally connected hazards (cause-effect relation) where one hazard may cause another hazard, or where one hazard is a prerequisite for a correlated hazard, and (2) associated hazards which are probable to occur at the same time due to a common root cause.

Several international guidance documents point towards the importance of combined hazard analysis but do not provide any explicit guidance on how it should be performed. The Electric Power Research Institute (EPRI, 2015) focuses on hazard matrices (type (c) in section 2.1.1.2), and the use of engineering judgement (type (h) in section 2.1.1.2), together with an overview of some probabilistic and statistical approaches to assess correlated, consequential, and coincidental hazards. The document makes reference to EDF's methodology, which determines the frequency of combined hazards (either dependent or independent), based on their seasonality.

The UK Office for Nuclear Regulation (ONR) produces similar guidelines (ONR, 2018). When considering external hazards, ONR focuses mainly on methods that evaluate single hazards. Nevertheless, to analyse the relationship between primary and potential secondary or associated hazards, narrative descriptions (type (a) in section 2.1.1.2) are used. Also, the ONR Annual Report illustrate the use of hazard curves for storms.

The UK Energy Technologies Institute (ETI) recently finalized the Natural Hazards Project delivered by EDF Energy, Met Office and Mott Macdonald[1]. The aim of the project was to develop a consistent methodology for the characterisation of natural hazards, and to produce a high-quality peer-reviewed set of documents suitable for use across the energy industry to better understand the impacts of natural hazards on new and existing infrastructure (ETI, 2018). Technical Report Volume 12 (ETI, 2018) illustrates the use of copulas for calculating joint probabilities (type (h) in

[1] http://www.imeche.org/policy-and-press/energy-theme/enabling-resilient-uk-energy-infrastructure

section 2.1.1.2) of meteorological hazards, in addition to other quantitative methods listed from the literature (empirical, Markov chains, multivariate Bayesian, joint tail models and kernel density, type (h) in section 2.1.1.2).

2.1.2.3 Summary of observations from review:

The literature describing practical approaches to understanding multi-hazard interactions and associated risks in industry and policy is very limited. We acknowledge the existence of further relevant documents that were not returned by the search, but assume the overall result is still valid.

From the results of Section 2.1.2.2, we make a number of observations.

- *Limited literature*. Both national and international policy literature strongly emphasize the need for multi-hazard approaches and risk assessment tools. However, the number of cases where these are not only recommended but also developed and implemented in practice is limited.

- The range of qualitative and semi-quantitative methods identified in the academic literature is greater than those identified in the industry literature. The energy sector favours the application of narrative descriptions, hazard matrices and network diagrams and does not consider hazard wheels, hazard maps and hazards/risk indices. This may be due to the scale of analysis, in that there is a need to identify and characterise all actual or potential multi-hazards linked with a given point-receptor (e.g. nuclear plant). Visualisation tools, such as network diagrams, are used to better understand linkages and relationships between hazards rather than their spatial overlap over extended regions. Nuclear plants may be connected with other receptors within a spatially distributed electrical grid network (e.g. nuclear power reaches the distribution networks through AC/DC overhead lines and underground AC/DC cables and transformers). Thus, there is an opportunity to explore the application of cartographic approaches (hazards maps), when the risk to multi-hazards is assessed spatially for the entire electrical system structure. Likewise, the infrastructure sector could benefit from the transfer of both spatially and non-spatially explicit approaches for transport infrastructure networks.

- Quantitative methods applied in industry are as complex and diverse as those described in academia. In the energy sector, probabilistic and statistical approaches (e.g., scenario analysis, fault trees, expert judgement, copulas, Markov chains, multi-variate Bayesian, kernel density, joint-tail models, etc.) have the widest use, while systems based or physical modelling approaches are not as common. Well-established practices in the energy sector can be adopted as new instruments for other business sectors, such as the utilities, telecommunications and agriculture, while the application of process-based models developed by the academia to case studies in the energy or infrastructure sectors could be explored in order to test their applicability.

- *Multiple-hazard vs multi-hazard policy focus*. Whilst the UK government's perspective on hazards is holistic, when scrutinised, in practice, it currently focuses on the assessment of multiple single hazards. However, efforts are being undertaken to move from recognising to assessing interdependencies and interactions between hazards. In this sense, the development of hazards and risk indicators can be used as a first step to characterise multi-hazard environments and inform decision-making. In addition, hazard matrices and maps can aid the identification of hazard relationships and guide prioritisation of risk management and adaptation strategies.

Energy sector. The energy sector represents a good example of an industry developing and applying a wide range of qualitative, semi-quantitative and quantitative multi-hazard characterisation and risk assessment approaches. Existing guidance documents could potentially be used to support the transfer of methods from one industry to another.

2.2 SUMMARY OF CASE STUDY EVIDENCE OF THE SOCIETAL AND ECONOMIC CONSEQUENCES OF MULTI-HAZARD EVENTS

To identify relevant case studies, this analysis uses the two literature searches (academic and practice/grey literatures – section 2.1) undertaken as part of this report as they covered much of the multi-hazard literature and have also captured studies of the economic costs of these events.

2.2.1 Methodology for identifying case studies which present the socio-economic impacts from multi-hazard events

The abstracts from the academic literature search (several hundred papers and reports) were searched for relevant terms e.g. 'economic', 'impact', 'loss', 'cost', '£', '€', 'million', 'billion' and so on. The practice literature searches predominantly brought up grey literature, articles or unpublished papers without abstracts. Therefore, each paper was searched for the same relevant terms.

Eight papers were identified from the academic search and ten from the grey search as being potentially relevant and were assessed for inclusion in this report against the following criteria:

- *Fitness*: how well did the multi-hazard assessment methods in the paper fit the specification for the case studies from the NERC call?
- *Robustness*: how robust were the methods and the data used?
- *Completeness*: how many of the expected full range of costs did the paper attempt to estimate?
- *Clarity*: how clear was the paper in its description of methods, data and results?

Each paper was scored against each criterion as either 3 (very good fit/ no significant gaps); 2 (partial fit/ some gaps); 1 (poor fit/ significant gaps); or 0 (no fit/ missing content).

Overall, there was not a large number of relevant papers in the literature and none that fit all of the criteria perfectly – as such, this analysis has had to make practical compromises. Selection of the papers for inclusion in this study was agreed among the project's Technical Steering Panel and decided additionally on the criterion of 'variety', to give a range of multi-hazard types, method of estimation and cost components estimated. These are:

- Forzieri et al. (2018) Escalating impacts of climate extremes on critical infrastructures in Europe
- Environment Agency (2018) Estimating the economic costs of the 2015-16 winter floods
- Pielke et al. (2008) Normalized hurricane damage in United States: 1900-2005

Each case study has limitations in terms of the economic costs and no study estimates the 'full economic cost' of a multi-hazard event. Therefore, we will first present the framework and elements of the 'full cost' we would attempt to use when estimating economic costs and critique each paper against this framework. This will be explained further in section 2.2.2 below. The three case studies selected are individually presented and discussed in detail in section 2.2.3.

2.2.2 Economic costs framework used for case studies which present the socio-economic impacts from multi-hazard events

When a multi-hazard event happens there can be a large number of different impacts to society. This would be true of any major incident, whether natural or man-made, but multi-hazard events have the added complication that there is more than one hazard occurring and their impacts can interact in different ways. However, we can attempt to group impacts in to four broad sections as shown in Table 2.3 (more detail on the economic framework categories can be found in Appendix 4).

Table 2-3 Economic cost framework

Population and work	**Fatalities & Casualties**	**Lost Working Hours**	**Social**
Assets	**Infrastructure**	**Buildings**	**Other losses**
Economic Activity	**Business Disruption (local)**	**Business Disruption (national/international)**	**Lost Tourism**
Enviro and Other	**Environmental Damage**	**Environmental Decontamination**	**Emergency Response & Evacuation**

Most of the impact categories will contain some components of financial cost as measured by prices or insurance valuations; and of intangible welfare costs, some of which can be monetised to some extent. The financial and the welfare costs together comprise the ‘full economic cost’.

To value intangible welfare costs there are two broad methods used by the UK Government: stated-preference methods and revealed-preference methods (see Fujiwara & Campbell, 2011 for a detailed discussion of valuation techniques). In summary, stated preference methods ask people to directly report their willingness-to-pay (WTP) or willingness-to-accept (WTA) to obtain/ give up a specified object or outcome. The main disadvantages of stated-preference methods are that they are based on hypothetical situations and their application can be complex and studies can be resource intensive.

Revealed preference methods seek to determine preferences for the goods/service listed above, from actual, observed market-based information such as travel costs and market prices in other markets. People’s preferences for goods can be ‘revealed’ indirectly by their behaviour. However, their applicability is limited to a small number of goods and services and rely on perfectly functioning markets.

Summing the ‘financial’ costs with the ‘intangible welfare’ costs will provide the ‘economic cost’ to society. However, this assumes that the financial costs comprise both the price paid in markets and the social welfare provided by these financial goods (known as consumer and producer surplus). This is the value over and above the market price that an individual is willing to pay for a good or service. For example, when a railway is damaged in a storm, the rail company may not just refund passengers tickets but pay them compensation over and above this cost for the distress it causes to their life. For non-market goods and services, we assume that this consumer/ producer surplus is implicit in their WTP or WTA.

Economic costs should estimate costs at a national level vs an individual household, business or local area, they should also have been adjusted when using financial data so that they take into account: transfer costs (e.g. between government and employers), displacement of economic activity from one part of country (e.g. tourism moving to other cities) and betterment (where something damaged will be replaced with an improved, more up-to-date version). As some impacts may cut across some of the categories above there is a risk of double-counting some costs. For example, the costs to infrastructure may be counted under both 'Business Disruption' and 'Lost Working Hours' and so these must be carefully estimated.

In all cases, monetisation of cost components may not be possible. Cost-benefit analysis should seek to qualitatively describe all impacts; then to quantify those that can be quantified; and finally, to monetise those that can be monetised. It is vital for the presentation and interpretation of such analysis that one understands that just because an impact cannot be monetised does not mean it is not just as important as those that can be monetised. Each component in Table 2.3 is explained in detail in Appendix 4.

Below each of the methods used in the three chosen papers to monetise economic impacts and the impacts they include are briefly described in Table 2.4. A more in depth analysis of each of the case studies is presented in Appendix 5. However, a common theme that occurred in the academic papers is that they did not present a detailed description of how the economic costs were estimated, which makes it more difficult to analyse and compare methods. This could be for several reasons:

- Papers on multi-hazard events are generally not found in economic journals and therefore the economic analysis is not a focus of the paper
- There is limited space in published academic papers which means the method can only be summarised
- The costs tended to be focused around asset costs and so there was little economic valuation of non-market impacts

Table 2-4 Summary of cost estimates from the three selected case studies

Author and title of paper	Context	Economic cost
Forzieri et al. (2018) Escalating impacts of climate extremes on critical infrastructures in Europe	Estimated the cost of climate hazards over the next 80 years across Europe	Annual cost of climate change across the EU Baseline - $3.4 billion 2020'S – $9.3 billion 2050's - $19.6 billion 2080's - $37.0 billion
Environment Agency (EA) (2018) Estimating the economic costs of the 2015-16 winter floods	Estimated the cost of the winter floods in the UK in 2015/16. The EA have also estimated the cost of flooding in 2007 and 2013/14 (also provided)	2007 – £3.9 billion 2013/14 – £1.3 billion 2015/16 – £1.6 billion
Pielke et al. (2008) Normalized hurricane damage in United States: 1900-2005	Estimated the cost of 50 hurricanes in the U.S. over the last 100 years. We have provided the cost for the 3 most damaging hurricanes	Great Miami Hurricane (1926) – $157.0 billion Katrina (2005) - $81.0 billion Galveston (1) (1900) - $78.0 billion

The figures from the 3 studies analysed are highlighted above. All papers refer to very different contexts. Pielke (2008) and EA (2018) are costing events at a single point in time whereas Forzieri (2018) is costing multiple events over a long time period. They also differ in terms of the location (country) and impacts included in the analysis and methods for estimation. Therefore, they cannot be directly compared.

Examples of less rigorous cost estimations for multi-hazards events are reported in the media. In 2018, Storm Emma and "the beast from the East" probably caused the construction industry a loss up to £2bn over the three worst days[2], while the total cost of severe winter weather in 2015 was estimated at £13bn[3]. Similarly, in 2010, heavy snow and sub-zero temperatures costed the aviation and retail industries many millions of pounds, with a total for the economy of approximately £13bn[4]. Lastly, the damage caused by Storm Desmond in 2015 was estimated at £400m - £500m, with the insurance industry paying out between £250m and £325m[5].

2.2.3 Summary observations from review

The review of the papers in this chapter reveals a number of themes which refer to some of the issues outlined in Section 1 of this report.

One issue relates to compound hazards (defined in Section 1), including two or more independent hazards coinciding in space and/or time with impacts greater than the sum of the two. We would expect to see this, however none of the case studies prove that this is true because they are generally estimating total costs or cannot distinguish which impact caused the damage. This may be due to a lack of methods which model how different impacts interact but also a lack of data to estimate costs for different impacts. Simulations may prove a way to look at multi-hazards as if they occurred independently of one another and compare the impacts with a scenario where they occurred together, but case studies do not provide an opportunity to do this.

Another issue is "one hazard changing vulnerability and thereby increasing the risk of subsequent hazards having a negative effect one exposed assets". This may be a reason why the case studies in this chapter are unable to prove that the total impacts are greater than the sum of its parts. The case studies demonstrate that the accumulation of damage over time can push systems or infrastructures beyond operability thresholds. Often the effects of one hazard can hamper the mitigation of the effects of another hazard. Therefore, the costs from one event may be an accumulation of costs from smaller preceding events which have increased the vulnerability of infrastructures and negative effects from future events. In the selected case studies, costs are often estimated using repair costs and insurance costs which often reflect impacts from several years e.g. EA 2018. Therefore, it is difficult to elicit the actual impacts from an event or distinguish between hazard impacts in an event, as the methods to estimate costs do not reflect this.

Another issue is "one hazard triggering other hazards, or a series of triggering relationships forming a cascade or domino event" which we would expect to result in a wide variety of impacts to society. Standard cost-benefit analysis techniques can be applied to multi-hazard events, even if the events are part of cascade or domino events – the domino effect presents more of a challenge to the risk assessment and modelling stages of the work than the economic assessment, which is based more on summing the instances of damage multiplied by a unit cost. The cases in this analysis demonstrate that – they do not use different costing techniques than could be used for single-hazard events. However, as discussed above, the use of repair costs once a piece of infrastructure has been damaged beyond a certain threshold masks the previous incremental damage and can apportion the accumulated damage of several sequential events to just one event in that chain. Adjusting for this could necessitate techniques of estimating not-yet-revealed damage prior to repair; or of revising previous cost estimates of damaging events to apportion some amount of subsequent repair costs once they are revealed.

One common factor across all the case studies is that they are based in developed data-rich countries and a constraint from multi-hazard cost estimation in other less developed countries could be the high levels of informality in recording data on things such as housing, infrastructure and livelihoods. To correct for this could require significant on-the-ground evidence-gathering.

[2] https://www.theguardian.com/uk-news/2018/mar/03/freezing-weather-storm-emma-cost-uk-economy-1-billion-pounds-a-day
[3] https://www.independent.co.uk/news/uk/home-news/economy-feels-chill-as-uk-grinds-to-a-halt-2164827.html
[4] https://www.independent.co.uk/news/uk/home-news/economy-feels-chill-as-uk-grinds-to-a-halt-2164827.html
[5] https://pwc.blogs.com/press_room/2015/12/updated-estimates-on-cost-of-storm-desmond-pwc.html

A significant gap in both Forzieri et al. (2018) and Pielke et al. (2008) is the lack of impacts which are analysed relative to our full ideal cost model. This is consistent with the remaining literature which was reviewed in our search, but not selected for analysis in this chapter. Pielke et al. (2008) uses insured losses which do not account for many of the impacts in our ideal costing framework and Forzieri uses historical loss data focused on impacts to infrastructure. The reason why EA 2018 does include the majority of impacts could be due to the EA being a government agency that uses evidence to inform policy-making at a societal level. Other analyses tend to focus on particular losses, often financial costs or financial losses adjusted to become economic costs. This could be because the larger part of the analysis is the modelling of the multi-hazard and its impacts and the costing of numerous impacts including non-marketed outcomes like pain, grief and suffering can add significant complexity.

A key factor in the under-estimation of total economic costs is the assumption that financial costs comprise both the price paid in markets and the social welfare provided by these financial goods. Forzieri et al. (2018) base the value of social infrastructure on the amount of public expenditure which would almost certainly lead to under-estimates, as we expect these infrastructures to have social and economic benefits well beyond the cost of supply. EA 2018 also misses some social welfare costs even though they adjust financial costs into economic costs, however they highlight that their assumptions are also likely to lead to under-estimating the true economic cost. Pielke et al. (2008) method (the insured losses x2 approach) is not discussed in any detail and so is unclear whether this seeks to represent just uninsured losses or attempts some valuation of social welfare. Accounting for the social welfare costs should be present in any future economic analysis of a multi-hazard event.

3. Industry & Policy Practitioner's Views on Multi-hazards

3.1 STAKEHOLDER IDENTIFICATION & MAPPING

In the framework of this review, stakeholders are defined as individuals, groups or institutions involved in and/or affected by multi-hazard events and their associated risks, who can influence or be influenced by the outcome of this project. To address the objectives of this study, a stakeholder mapping exercise was undertaken to identify representatives from the academia, industry and policy areas involved in and/or affected by multi-hazard events. Each stakeholder has a different social and cultural background, interests and motivations and resources. Although we are aware that the list of relevant stakeholders is longer than the one used in this work, we have aimed to identify academic, industry and policy representatives, whether they represent the interests of multiple organisations or of a single individual. Due to time limitations, we were not able to include representatives from the insurance sector, emergency managers and Local Resilience Forums (LRF) while other interested actors were deliberately excluded from the analysis, as their participation would not serve the scope of the project (e.g. media, population, etc.).

3.1.1 Objectives and methodology

The aim of this analysis was to derive insights from qualitative and quantitative data (stakeholder's role, specialization, sector, willingness to engage, etc.) and elicit stakeholder requirements and knowledge in line with a project's aim. In this study, the stakeholder analysis objectives are to:

- Understand the general landscape of stakeholders that are involved in managing multi-hazard risks;
- Identify the relevant sectors and actors affected by or which can influence the development, testing and implementation of multi-hazard research and risk assessments in policy and industry.

An initial list of stakeholders was provided by NERC based on their experience of involvement on similar initiatives, such as the 2017 ERIIP Workshop on "Multi-hazards for Infrastructure" (ERIIP, 2017). In addition, a number of contacts from universities, not-for-profit organisations, construction, energy, transport industries, utility companies, public bodies, engineering consultancies and government departments were added using the project partners' networks. The compiled stakeholder list was distributed among consortium partners for consultation and to the Technical Steering Committee for validation. Finally, the list was submitted to NERC for final approval.

The selection of participants in any stakeholder analysis is essential (Bryson, 2004). Due to the project's lifetime, we had to limit the number of participants and period in which their feedback could be used as input in this analysis. Nevertheless, we attempted to balance different schedules and trade-offs between early and late participation based on one or more of the following: representation, accountability, legitimacy and the ability to provide a significant input to the study. As a result, we accommodated a few later additions but had to decline others who were unable to contribute in time. Throughout the stakeholder identification and selection process, we were guided by impartiality and transparency. Table 3.1 illustrates the main stakeholder categories and their specialism (a complete list is provided in Appendix 6).

Table 3-1 Type and specialism of stakeholders per sector

Organisation type	Specialization	Examples
	Research	
University, private company, research centre, not-for-profit, research institution	Geoscience research and innovation, marine science, climate change research, space technology and applications	King's College London, UKRI/BGS, University of Portsmouth, National Oceanography Centre, Satellite Space Catapult, Practical Action, CIRIA, NCAS/DEFRA
	Industry/Practitioners	
(Non-departmental) public body (weather, transport, environment, health & safety), private companies, independent consultants	Railway infrastructure and asset management, highways authority, electricity and gas utilities, energy, safety regulation for civil nuclear industry, engineering consulting and management, DRR, resilience, environmental protection, public water and sewerage services, hydro-meteorological services	Environment Agency, Met Office, National Grid, Transport Scotland, Network Rail, HSE, Office for Nuclear Regulation, Scottish Water, Anglian, Water, Jacobs Eng. Group, Mott MacDonalds, ARUP, SSE, Highways England, Temple Group, Atkins, Flood Forecasting Centre, HR Wallingford, NHBC, HS2, WSP, Yorkshire Water, London Underground
	Policy	
Public body (climate, environment, food, rural affairs, health), government department, not-for-profit organisation, government	Management of natural resources, government agency, telecommunications, railway safety and standards, governmental advisor on climate change adaptation, transport network, supporting agency for resilience to emergencies, government advisory for science policy	Cabinet Office, Scottish Government (Resilience Division), SEPA, Department for Communications, Media and Sport (DCMS), Natural Resources Wales, UKWIR, Historic Environment Scotland

The Stakeholder Mapping Tool

The first part of the analysis was to identify the stakeholders focusing not only on the organisational group or the position title, but also on the individual's expertise and their role in the organisation. This was because individuals will have different levels of influence and status within an organisation and will likely also have different levels of expertise. In some instances, more than one person was contacted within an organisation to ensure fair representation.

Subsequently, we have used a number of criteria to prioritize stakeholders in terms of how critical they could be in contributing to the outcomes of the next steps of this project. The criteria were related to either the "power" to make the changes to incorporate multi-hazard approaches and risk assessments in practice or the "expertise" to develop, guide or advise the process. Each criterion was scored and used to calculate a total and an overall relevance score for each stakeholder organisation. The latter two scores (total and overall relevance) were used for an initial discrimination between stakeholders, whereas the former two (power and expertise) served for a more detailed comparison using a matrix. **The total score** was calculated by summing up all criteria scores registered for a particular stakeholder, while the **overall relevance** score represented the ratio between the total score and the maximum score possible (see Table 3.2 and Appendix 6). The following list of criteria was used to assess the stakeholders:

a. Contribution to the study: what is the relevance and/or amount of relevant information provided by the stakeholder. It is measured on a scale from 1 to 4, where 1 is no contribution, 2 – limited contribution, 3 – moderately relevant contribution, 4 – relevant contribution with additional inputs (e.g. reports, papers, contact names, etc.).

b. Legitimacy on the subject: based on the stakeholders current portfolio or current business strategy; or, if they are recognized as a "legitimate voice" by peers. It is measured on a scale from 1 to 3, where 1 is no portfolio or business strategy on single or multi-hazard investigation and risk assessment, 2 – current portfolio or business strategy on advanced single hazard investigation and risk assessment, 3 – current portfolio or business strategy on multi-hazard investigation and risk assessment.

c. Willingness to engage: defined by the level of stakeholder's level of involvement with the current study. It is measured on a scale from 1 to 3, where 1 is no feedback, 2 – positive feedback, 3 – positive feedback with openness to follow-up contact.

d. Influence: the capacity of the stakeholder to determine actors within their or other sectors that could adapt multi-hazard approaches and risk assessment or consider it as part of their agenda. It is measured on a scale from 1 to 3, where 1 is low (stakeholder that "plays by the industry standards" or has an agenda that does not attend the immediate needs of the industry), 2 – medium (stakeholder with attributed reputation by peers; their input is valued and respected by end-users, for example advisory public bodies, independent consultants with a "high voice", established private companies, etc.), 3 – high (actors that would demand a change in the industry or establish a new set of standards; for example, private or public corporations with autonomy to set their own agenda and direct funding).

e. Necessity of involvement: based on the general aim of the project, which is to consider and define future research and innovation funding (p.8, Tender Document). It is measured on a scale from 1 to 3, where 1 is low (stakeholders that might adopt the outcomes, if required, such as those in the industry sector), 2 – medium (actors that would adopt tools or processes or that would develop, validate or test tools (e.g. non-for-profit organisations, universities, private organisations, etc.), 3 – high (actors that would facilitate the incorporation of multi-hazard research, risk assessment approaches and tools within legislative frameworks, strategies and public guiding policies (e.g. government agencies, regulators, public bodies, etc.).

The stakeholder matrix tool (Figure 3.3) was adapted from Kennon et al. (2010) and directed at improving project planning and implementation. The tool features a 16 square matrix with

$$\textbf{Power} = (\textbf{d} + \textbf{e})/(\text{ d maximum score} + \textbf{e} \text{ maximum score}) \qquad \text{(Eq. 1)}$$

On the x-axis, where **d** is the influence and **e** is necessity of involvement and

$$\textbf{Expertise} = (\textbf{a} + \textbf{b})/(\textbf{a} \text{ maximum score} + \textbf{b} \text{ maximum score}) \qquad \text{(Eq.2)}$$

On the y-axis, where **a** is contribution to the study and **b** is legitimacy.

A score varying between 1 and 4 was attributed to each criteria for each stakeholder, as a result of the feedback (positive or negative) after receiving a formal request of participation to the semi-structured interview. In case of no response from any individual within an organisation, the stakeholder organisation was then ranked by its public profile and scores where attributed according to the expert knowledge within the project technical team. Listed stakeholders with more than one point of contact were verified and in case of two or more positive feedbacks, the results of the individual with the highest total or overall score was plotted in the matrix.

3.1.2 Results and discussion

The stakeholder list contains 91 contacts from 61 institutions. All listed contacts were requested to participate in a survey focused on identifying what approaches are being used in industry and by policy-makers to understand and assess the risk from multi-hazards. The methodology and obtained results are presented in detail in section 3.2.

Overall, one third of the 91 contacts (33 representing 25 stakeholder organisations) responded positively to the semi-structured interview, which is commendable given the limited time to feedback, and the need for some to coordinate responses at an organisational level. Figure 3.1 shows their distribution per sector category. The addition of representatives from the research sector was intended to ensure a benchmark for future analysis of the survey results; for this reason they comprised the smallest percentage from the total 33 (21%). The industry sector contacts represented 52% of the total, while the policy stakeholders 27%. The response rate indicates the high relevance and interest of the practitioners, especially for the policy sector, in multi-hazard research and risk assessment approaches.

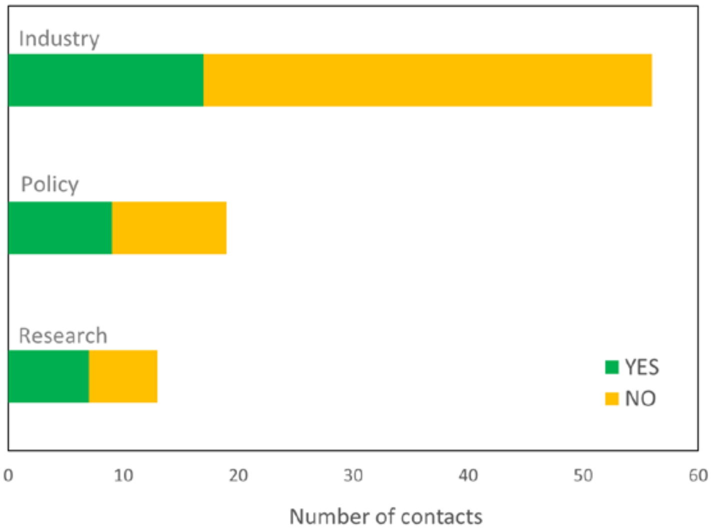


Figure 3-1 Stakeholder contacts participation response rate

The results of the criteria scoring for each stakeholder are summarized in Appendix 6 and illustrated in Figure 3.2. For example, Stakeholder 1 has a high power with respect to the adoption and implementation of multi-hazard approaches and risk assessments in the industry. Stakeholder 2 has a higher degree of expertise than Stakeholder 1, but less power. With an equal overall relevance score, both would be equally important for this study, providing different perspectives according to their specialism. However, this indicator does not give enough insight with respect to their different attitudes and influencing power. To obtain such information, the power and expertise scores were calculated and plotted as indicated in Table 3.2.

Table 3-2 Example of scoring and comparison between stakeholders using the power/expertise scores

Name of organisation	Contribution	Legitimacy	Willingness to engage	Influence	Necessity of Involvement	Total Score	Overall Relevance (For this study)	Power Score	Expertise Score
Max Score	3	3	4	3	3	16			
Stakeholder 1 - Policy / Public body	2	2	3	3	3	13	0.81	1.00	0.67
Stakeholder 2 - Research/Academia	3	3	4	1	2	13	0.81	0.50	1.00
Stakeholder 3 - Practitioner / Eng Consulting	1	2	2	1	1	7	0.44	0.33	0.50

In Figure 3.2, the yellow dots represent contacts who did not reply to the survey participation request. Conversely, the green dots represent contacts from the 25 organisations whose positive feedback is analysed in WP3. The size of the dot indicates the number of contacts represented by the symbol.

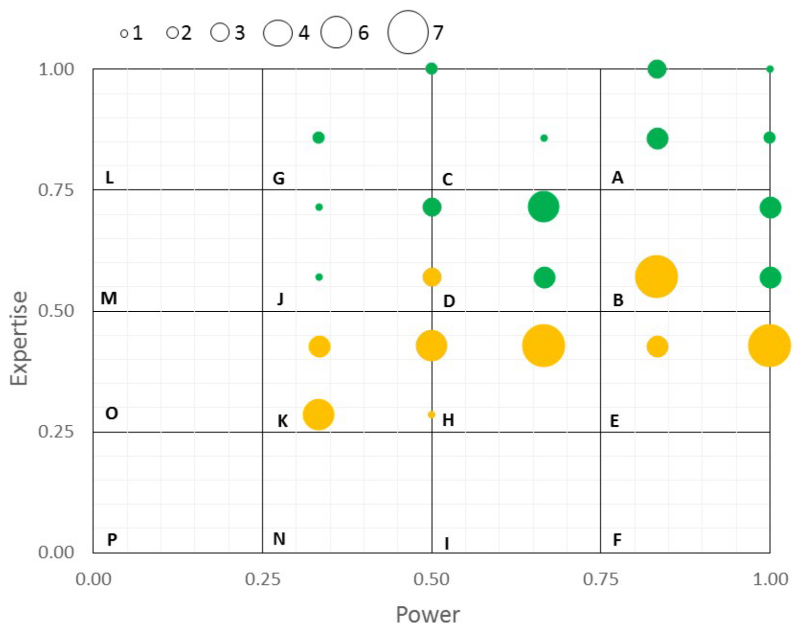


Figure 3-2 Power - Expertise Matrix (61 stakeholders, 91 contacts). Dot size indicates the number of contacts represented by the symbol

On a scale of relative importance from A to P, with A being the highest and P the lowest, one can rank the stakeholders in terms of their overall relevance, power (i.e., influence and necessity of involvement) and expertise (i.e., contribution to the study and legitimacy) in relation to multi-hazard approaches and risk assessments. The results (Table 3.2) indicate that a limited number of stakeholders, mostly publicly funded organisations, possess both the highest power and expertise to influence and shape future research and its adoption into practice (zone A). The stakeholders that score highest in overall relevance in zone A (0.94) are the Cabinet Office, HSE and Office for Nuclear Regulation (ONR). Second to this category is a group of stakeholders that have either higher power (zone B) or expertise (zone C) in multi-hazard research and risk assessment approaches. These stakeholders complement each other and could support the early integration between various disciplines and approaches into practice. The stakeholders that score highest in relevance in zone B and C (0.81) are Environment Agency, Flood Forecasting Centre, Network Rail, King's College London and National Oceanography Centre.

Table 3-3 Ranking of stakeholders in terms of power and expertise in zones A to D

Matrix zone*	Stakeholder
A	Cabinet Office, Environment Agency, Met Office, UKRI/BGS, SEPA, HSE, ONR, Energy company**
B	Network Rail, Scottish Government, FFC, CCC, PHE, CEH
C	KCL, University of Portsmouth, National Oceanography Centre
D	Practical Action, NCAS, CIRIA, Loughborough University, Leeds University, HR Wallingford, National Grid, Transport Scotland, NRW, Government department for transport**, DCMS

*Stakeholders in zones E to K are listed in the Stakeholder Database (Appendix 6). **Anonymous and non-identifiable stakeholder

Zone D is represented by all sectors (research, industry, policy) and the highest number of stakeholders. Overall, they have higher expertise (0.57 - 0.71) than power (0.50 – 0.67) scores, which means they could be early adopters or developers of knowledge with the capacity to generate large public support or impact. The stakeholders that score highest in relevance in zone D (0.75) are the National Grid, Transport Scotland and Department for Transport.

3.1.3 Summary observations from analysis

The main scope of the current stakeholder mapping exercise was to contextualize and set the boundaries for the review performed in this study, particularly with respect to the industry and policy practitioner's view on multi-hazards (section 3.2). From the results of section 3.1.2, we made a number of observations:

- *Multi-hazards are of concern.* There is a significant interest in multi-hazard research and risk assessment approaches amongst the selected practitioners in industry and policy, across management and organisational levels. One third (33 out of 91 contacts) of all stakeholders contributed directly to the results of this review, with more input if additional time and resources were available. In order to ensure data-rich interviews, the selection of participants was based on their experience and relevance to the research objectives (i.e. purposeful sampling, Palinkas et al. 2015) rather than a random approach.

- The stakeholders with the highest overall relevance, ranked using the methodology above, pertain to different stakeholder communities: the Cabinet Office, Office for Nuclear Regulation and HSE. They are complementary in terms of power and expertise (e.g. government department, non-departmental public body specialized in health & safety and public body specialized in regulation of the civil nuclear industry).

- *Roles and responsibilities match across stakeholders*. Although, a full stakeholder analysis for strategic planning (e.g. accounting for stakeholders roles, potential risks, network relationships, etc.) was outside the scope of this project, the matrix indicates a positive outcome with respect to the contributing stakeholders: overall, decision-makers and senior management have slightly lower level of expertise than technical staff and experts.

- A further detailed review and mapping of the multi-hazards expertise amongst practitioners is needed. The distribution of stakeholders into zones of relative importance indicates a high number of actors whose expertise score is lower than 0.6. This is mainly due to the contribution criterion, which reflects their lack of participation in the survey, but can also be linked to their legitimacy on the topic (as defined above). Further investigations could define more clearly their level of knowledge of multi-hazard research and risk assessments and interest in moving from an "outer-layer organisation" to a "contributing organisation" (Bryson, 2004).

3.2 STAKEHOLDER SURVEY

Stakeholder engagement in multi-hazard research has received increasing attention in recent years. From stakeholders involved in governance to those providing specialized knowledge and advice in support of operational capabilities, the solicitation of their knowledge, priorities and needs early on in the decision-making processes can contribute to learning, innovation and promote a greater acceptance of decisions.

This section presents the results of a stakeholder survey predominantly designed to analyse the industry and policy practitioner's view on multi-hazard research and risk assessment in practice. This method was selected due to its (i) efficiency in capturing critical information from numerous and geographically dispersed stakeholders, (ii) external validity in terms of producing findings, which can to some extent be generalized to a wider population and (iii) capacity to access directly the participant's understanding, judgement and experience on a given problem. Undoubtedly, there are also limitations in using stakeholder surveys. Depending on the chosen method (e.g. interview, questionnaire, focus group, etc.), these include: the potential for interviewer's subconscious bias; time-consuming data collection and analysis and incorporation of potential inconsistencies. Finally, the survey results are significantly dependent on the chosen sampling technique and the success of the techniques used to acquire the information required.

3.2.1 Objectives and methodology

The specific objectives of the stakeholder survey were to:

- Analyse the industry and policy practitioner's level of knowledge about multi-hazard processes and risk assessment methodologies used in research and practice;
- Evaluate the interest in and use of current multi-hazard risk assessment methodologies and approaches in different industry and policy sectors;
- Identify common barriers/enablers and current gaps in knowledge and skills for understanding multi-hazard events and their impact in a given sector;
- Inform the needs and future requirements for adopting methodologies and approaches for multi-hazards identification, characterisation and risk assessment in practice.

Data collection

Two methods of collecting survey data were used, namely telephone interviews and questionnaires. Telephone interviews and questionnaires are an effective and economical way of collecting data and particularly useful if the respondents are widely geographically distributed or busy professionals. Questionnaires are also a useful option to consider when respondents need to consult with peers or want to spend more time on investigating the researched problem. For this review both methods were simultaneously used to ensure a higher response rate as limited time was available for gathering evidence.

The survey was aimed at two stakeholder groups, namely UK industry and policy practitioners. Academia participants were included in order to allow a direct comparison of the three groups participating in this research. Identification and selection of survey participants is described in section 3.1. We used a non-random sampling technique (purposeful sampling) with a sample size depending on an assumed response rate of <50%. The total number of participants was 91 (representing 61 stakeholder institutions).

Questionnaire and telephone interview design

Initially, a draft questionnaire was devised taking into account the objectives of the study and the stakeholders' profile. The questionnaire was distributed amongst consortium partners for consultation and the Technical Steering Committee for review and evaluation. The open-ended questionnaire contained an explanatory note and 11 questions classified in four categories: self-assessment, state-of-the art, multi-hazard risk assessment and gaps in knowledge (see Appendix 8). Topics covered included:

- Plausible multi-hazard scenarios for a given sector
- Level of knowledge about multi-hazard processes, impacts and risk assessment methodologies in research and practice
- Use of multi-hazard methodologies and approaches in own organisation
- State-of-the art in current methodologies to undertake multi-hazard research
- Enablers and barriers for developing multi-hazards risk assessment in own sector
- Gaps in knowledge and skills to better understanding and assess risk to multi-hazards in own sector

The questionnaire was emailed together with a covering letter and an Ethical Policy document (Appendix 7) to all participants identified through the stakeholder mapping (section 3.3.1). The latter contained an information sheet and a consent form explaining the research problem, the aim of the study and use of the information that was provided. Participants were asked to choose their preferred survey method, how they would like to be identified and if they agree with the phone interview being audio recorded. To ensure a reasonable response rate, reminder emails were sent to recipients who had not completed the survey within the initial deadline.

The semi-structured telephone interview was based on the open-ended questionnaire and aimed at exploring more systematically and comprehensively the respondent's knowledge. Technically, the interview was a 45 minutes structured conversation around the 11 core questions with associated, pivotal questions and/or necessary clarifications. The audio recordings and hand note contents were used to generate clean transcripts of the interviews (Appendix 11).

Limitations of the analysis

- *External validity*. The results of this analysis represent the views and experiences of a limited number of stakeholders from a limited number of industry and policy sectors. Although the total (36%) and sectorial response rate (54% - research, 47% - policy, 30% - industry) ensured an adequate sample for statistical analysis, the generalization of findings per sector should be made with caution

- *One questionnaire for all*. A single questionnaire was designed for all participants irrespective of provenience sector. This might have reduced the potential to capture the diversity of perspectives, experience and perceptions amongst stakeholder groups

- *Inconsistencies in collected data*. The questionnaire was used both in a self-administered form as well as being instrumented by two interviewers in the telephone interviews. This might have resulted in inconsistencies due to (no) access to explanatory questions, possibility to add clarifying points and exposure to different interviewing techniques

- *Inconsistencies in communication/no real feedback/short response time*. Great care was taken to ensure a coherent and clear communication between stakeholders and the survey team. Yet, instances of miscommunications occurred. It is therefore likely that some of the stakeholders were not fully satisfied with the survey experience. Due to the lack of time, a feedback inquiry was not performed and the engagement request was noted as being expeditious.

3.2.2 Results and discussion of findings

One third of the 91 contacts (33 representing 25 stakeholder organisations) responded positively to the semi-structured interview (see Figure 3.1). Figure 3.3 illustrated the stakeholder map per field of activity and sector.

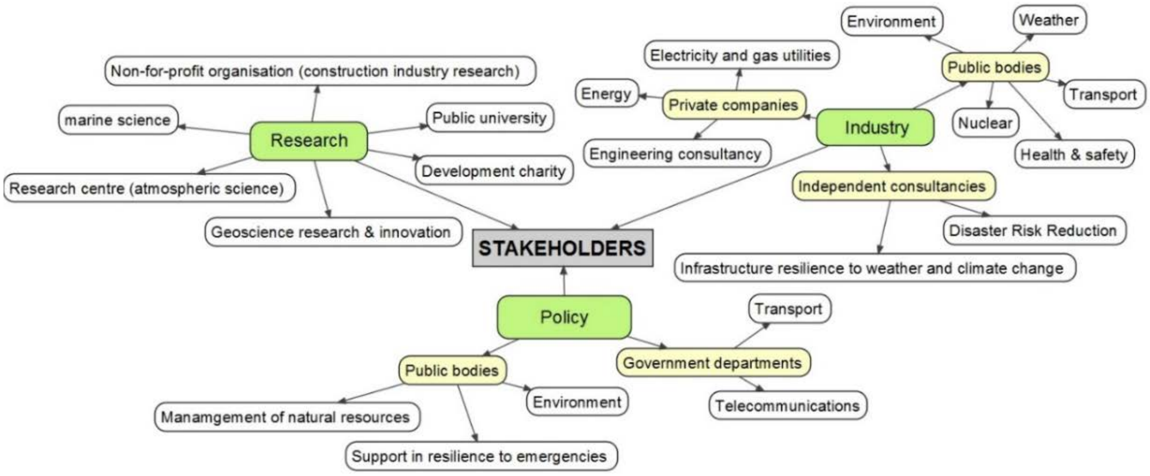


Figure 3-3 Stakeholder map per sector of activity

The response rate to each question in the survey varies both by sector and question type/category. Overall, the response rate is between 82% - 100%, with maximum values for Q1 (related with multi-hazard scenarios relevant for own sector) and Q8 (related with barriers and enablers for undertaking robust multi-hazard risk assessment). The lowest overall response rates are associated with questions regarding advantages and pitfalls of current methodologies (Q5) and the accessibility, applicability and usefulness of current multi-hazard methods (Q6). Survey results for each question category (A to D, see Appendix 8) follow.

A. *Self-assessment*

Self-assessment questions focused on:

- multi-hazard scenarios relevant for each sector (Q1);
- the respondents' knowledge with regards to multi-hazard processes and risk assessment methodologies in research and practice (Q2);
- methods and approaches used in own organisation/sector to understand the processes underlying multi-hazard events, their impacts and risk (Q3);
- Impacts and economic costs of multi-hazards, including the awareness of evidence or best-practice guidance to support such analysis (Q4).

(Q1) Overall, participants identified 36 multi-hazard scenarios, pertaining to all hazard relationship types. The respondents focused on multi-hazard scenarios most relevant for their sector (see Table 3.4), which could overlap, to some extent, with those of their greatest concern. It should be noted, however, that this is an assumption and the identified scenarios represent only a temporary snapshot, as interest and priorities are expected to change.

Participants identified largely triggering multi-hazard relationships (47%), followed by amplification effect (36%) and compound type (17%). The weight of interest across sectors lies with four multi-hazard scenarios: storm surges and flooding (identified by 21.2% of respondents), extreme rainfall triggering landslides (15.2%), river and coastal flooding (15.2%), and strong winds, snow, ice and extreme cold (12.1%). Stakeholders representing the transport, energy and geotechnical engineering services find most relevant combinations of geological (e.g., landslides, sinkholes, rockfalls), atmospheric (e.g., storms, rainfall) or/and hydrological hazards (e.g., river and groundwater flooding), while the policy sector is focused on a wider range of possible multi-hazards, both natural and anthropogenic.

Table 3-4 Relevant multi-hazard scenarios identified by stakeholders (ordered by frequency of selection)

Stakeholder(s)	Relationship type	Multi-hazard Scenario	% of respondents
Government department for transport, EA, National Grid, ONR, Cabinet Office, Dept. for Communication, Media and Sport (DCMS)	Compound	Storm surges and flooding	21.2
BGS, National Grid, Network Rail, geotechnics company	Triggering	Extreme rainfall triggers landslides	15.2
Energy company, EA, SEPA	Compound	River and coastal flooding	15.2
Met Office, National Grid, Network Rail, geotechnics company	Compound	Strong winds, snow, ice and extreme cold	12.1
Network Rail, geotechnics company, SEPA	Triggering	Extreme rainfall trigger river/surface flooding	9.1
BGS, Met Office, geotechnics company	Triggering	Landslide blockage triggers flooding	9.1
Historic Environment Scotland, Met Office, Natural Resources Wales	Compound	Fluvial, pluvial and groundwater flooding	9.1
Historic Environment Scotland, Met Office, ONR	Compound	Rainfall and windstorm	9.1
Network Rail, ONR, geotechnics company	Amplification	Storms and (coastal) erosion	9.1
Met Office, NCAS	Amplification	Heatwave, poor air quality, high pollen count	6.1
National Grid, Cabinet Office	Compound	Cyber-attacks and terrorist attacks	6.1
Network Rail, DCMS	Amplification	Extreme high temperatures and wildfires	6.1
UKWIR, geotechnics company	Amplification	Drought and shrink-swell	6.1
Geotechnics company, DCMS	Amplification	Wildfires and landslides	6.1
UKWIR, SEPA	Triggering	Flooding and environmental hazards	6.1
BGS	Triggering	Extreme rainfall triggers groundwater flooding	3.0
CIRIA	Triggering	Flooding triggers landslide	3.0
BGS	Triggering	Geomagnetically induced currents triggered by magnetic (solar) storms	3.0
NOC	Triggering	Submarine landslides trigger tsunami	3.0
ONR	Triggering	Earthquake triggers tsunami	3.0
SEPA	Triggering	Landslide triggers reservoir overtopping	3.0
NOC	Triggering	Tropical cyclones trigger turbidity currents	3.0
NOC	Triggering	Earthquakes trigger landslides	3.0
NOC	Triggering	River flooding leads to increased sediment transport offshore and high turbidity currents activity	3.0

Geotechnics company	Amplification	Warm winds trigger snowmelt, which leads to landsliding	3.0
Geotechnics company	Triggering	Strong wind leading to root jacking and subsequent rockfall	3.0
SEPA	Amplification	Snowmelt and flooding	3.0
Historic Environment Scotland	Triggering	Coastal flooding and landslides	3.0
Met Office	Amplification	Space weather and extreme cold	3.0
Met Office	Amplification	Volcanic ash and poor air quality	3.0
National Grid	Amplification	Extreme temperatures, drought, wildfires	3.0
Natural Resources Wales	Triggering	Reservoir failure and landslide	3.0
NCAS	Amplification	Drought and wildfire	3.0
NCAS	Amplification	Air quality and cold weather	3.0
NCAS	Amplification	Air quality and volcanic eruptions	3.0
Geotechnics company	Triggering	Sinkholes and extreme rainfall	3.0

(Q2) With respect to stakeholders' knowledge of multi-hazard methodologies used in research and practice, Figure 3.4 illustrate the perceived levels of knowledge across sectors. Overall, 33.3% of all participants evaluated their knowledge of multi-hazard methodologies used in research as fair, whereas only 27.3% have the same level of knowledge for methodologies used in practice.

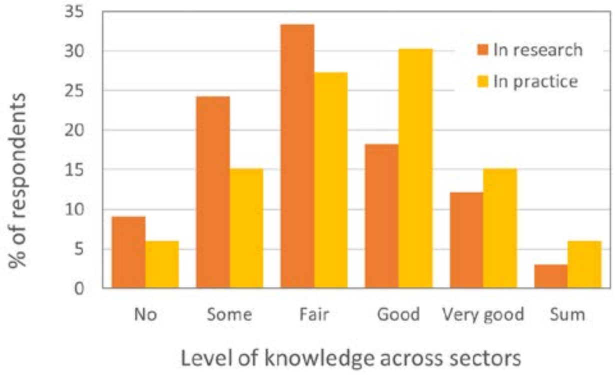


Figure 3-4 Stakeholders' level of knowledge about multi-hazard methodologies used in research and practice (NA – respondents did not answer)

The proportion is inversed when looking at respondents with a good and very good knowledge of multi-hazard approaches. Participants have a better knowledge of approaches and methods used in practice than in research (30.3% vs. 18.2%, for good knowledge; 15.2% vs. 12.1%, respectively for very good knowledge). This is apparent also when results are analysed per sector category. Figure 3.5 (A and B) indicates that 33.3% of policy stakeholders have a fair knowledge of methods used in research and practice. However, none indicated a good/very good knowledge of methods available in research, as opposed to 22.2% and 11.1%, respectively, that are aware of methods used in practice.

Over on third (35.3%) of the industry representatives have a fair knowledge of methods available in research, while 23.5% and 11.8% recognize a good and very good level, respectively. It is worth noting that, 18.8% of industry participants indicated no or limited knowledge about methodologies or approaches used in practice. This indicates the need for a better transfer of existent multi-hazard approaches and methods in practice between industry stakeholders.

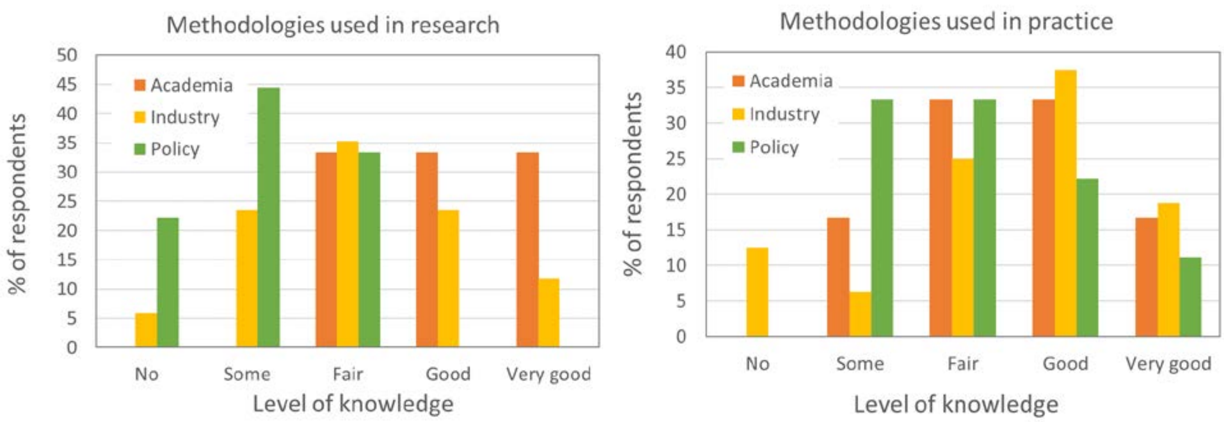


Figure 3-5 Stakeholders' level of knowledge about multi-hazard methodologies used in research (A) and practice (B)

(Q3) Survey participants were asked to state if they use multi-hazard approaches and procedures in their own organisation. From the total number, 42% answered positively, 46% negatively and 12% did not answer the question directly (Figure 3.6). The range of multi-hazard methodologies used by policy, industry and academia representatives are classified according to the typology proposed in section 2.1.1.2.

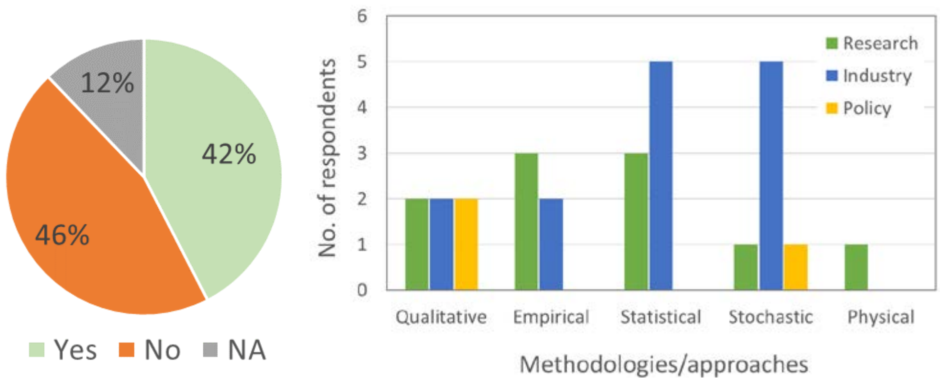


Figure 3-6 Use of multi-hazard methodologies/approaches (left) and their typology per sector of activity (right)

Figure 3.6 also shows that the number of research, industry and policy stakeholders employing qualitative methods is equal. This might suggest that qualitative methods are fairly accessible and readily usable in all sectors. This is not the case for statistical and stochastic methods, which are most used in industry or physical models, employed solely by one research representative. One common finding between the research and industry sectors, noted also in the review of academic literature (section 2.1.1.3), is that both sectors integrate multiple methods to develop an understanding of multi-hazard processes and their associated risks. For instance, UKRI/BGS employs both empirical observations (both in natural and experimental regimes) and probabilistic methods to develop hazard risk scenarios. Similarly, the National Oceanography Centre uses primarily observational (empirical) methods through direct monitoring and repeat sensing backed up by statistical and hindcast analysis. In studies of air pollution performed by NCAS, the atmospheric modelling accounts for meteorological processes in order to understand the representativity of air pollution measurements and to interpret the variations observed. For this purpose, both modelling and measurement data are used. Finally, energy companies use statistical techniques to estimate joint probability of multi-hazards (specifically copulas and multivariate extreme value statistical distributions) together with numerical models (e.g. hydrodynamic models such as TELEMAC and TOMOWAC) that can simulate, for example, coastal flooding processes such as waves, storm surges, tides, wind, etc.

(Q4) When asked to identify impacts multi-hazards can have on their sector, respondents' answers were specific according to their main activity. A list of most important impacts is provided in Figure 3.7.

Nuclear industry	• Direct damage to infrastructure • Safety of operatives working on site
Environment	• Danger to life • Direct economic costs
Health & Safety	• Danger to life
Offshore industry	• Damage to infrastructure
Transport industry	• Increased maintenance and repair costs • Increased delays and compensation costs • Decreased reputation • Increased safety risks • Direct damage to infrastructure • Loss of revenue and public confidence
NGOs	• Increased need of resources for response
Government	• Direct and indirect impact on the tourism industry • Stretch of capabilities for local and national emergency response
Telecommunications	• Loss of revenue and business continuity

Figure 3-7 Examples of multi-hazard impact identified by stakeholders per sector of activity

Generally, there is a lack of awareness about specific studies that have attempted to quantify the costs of multi-hazard in comparison to single hazards events (not aware – 5, aware – 1, no answer – 27 respondents). Few stakeholders identified studies as evidence of best-practice or guidance for multi-hazard consequences assessment (8 respondents). However, some of these studies are not relevant to the remit of this work, examining either cascading consequences (e.g., chain failures and associated costs of the Buncefield fire) or do not focus on economic costs assessment. For instance, the ENA's Engineering Technical Report (ETR 132) provides guidance on improving electric network performance under abnormal weather conditions by enhancing the resilience of the network.

Respondents commonly agree that:

(1) The understanding of multi-hazard events lags behind the understanding of single hazard ones;
(2) There is an increasing interest in the impact of multi-hazards across sectors as demonstrated by recent events (e.g. the 2011 Fukushima disaster), but
(3) There are significant challenges with quantifying associated impacts and economic costs.

Lastly, respondents recognise that no universally accepted methodology for the quantification of costs or impacts exists and there is considerable research required to develop good-practice and standardised methodologies.

B. State-of-the-art

Questions in this category focus on the:

- Advantages and pitfalls of current methodologies and approaches used to undertake multi-hazard risk assessments (Q5);
- Accessibility, applicability and usefulness of current methodologies and approaches (Q6).

Table 3.4 summarizes the advantages and pitfalls of current methodologies and approaches used to undertake multi-hazard risk assessments as indicated by the respondents. When asked to assess these methods (Q6), 45.5% of respondents did not answer the question directly. Of those that did (54.5%), 21.2% found that current methodologies are accessible, while 15.2% found them to be useful. A lower percentage found them applicable (6.1%), while the same percentage characterised them as not applicable/not accessible (6%) or to a very low and low degree of accessibility and applicability (6%). If accessible (mostly those stemming from academic research), current methodologies are difficult or impossible to apply in practice at large, especially when using complex models and simulations. Other methodologies, such as gathering case studies, are very accessible but difficult to apply due to human power and lack of data.
Regarding specific methodological approaches, deterministic methods are now superseded by probabilistic models that are better equipped to assess the uncertainties associated with data and modelling results. The quality/quantity of these outputs, however, is challenged by data availability and computational power. One other noted limitation of both qualitative and quantitative approaches is that they fail to take into account the low probability high magnitude events (e.g., large earthquakes in Kenya).

Finally, participants recognized there is a lack of practical guidance on how/when to use existing methodologies and approaches for those without a technical background (e.g. NGOs, government, etc.). Moreover, methodologies and approaches that are accessible and useful might not always be applicable to different regions or case studies, therefore they need to be tested on a case-by-case basis to know if they can result in a better outcome or decision-making.

C. Multi-hazard risk assessment

Questions in this category investigate:

- If and how existing risk assessment methodologies in own organisation take into account multi-hazards (Q7);
- Barriers (Q8) and enablers (Q9) for undertaking or developing robust multi-hazard risk assessment in own organisation/sector.

Table 3-5 Summary of advantages (left) and pitfalls (right) of current methodologies and approaches used to undertake multi-hazard risk assessments

+	−
- Inform improved decision-making	- Computational capacity
- Defensible response plans	- Limited foresight due to reliance on past events
-Estimate of the joint probability of multiple hazards occuring	- The existance of different approaches which provide different answers and are case study specific
- Becoming more widely used and the literature is becoming more organised and mature for some specific hazard relationships	- Many of the current approaches are bivariate only and fail to take into account every-day natural hazards (e.g. heat increase)
- Current methodologies are reasonably good at identifying and screening possible combinations of hazards	- Lack of understanding of spatial - temporal contexts
- Potentially better response, preparedness, mitigation	- Lack of current currency in terms of consequences and risk metrics
- Can reduce unknowns and "swiss cheese" effect of cascading disasters	- Insufficient data and knowledge to work with low probability events
- Opportunity for inter-disciplinary collaborations	- Many current approaches fail to take into account dynamic vulnerability and uncertainty
	- Distinguishing between combined hazards and combined impacts

(Q7) From the total number of respondents, 36% stated that their organisation takes into account multi-hazards (21.2% for industry, 9% for policy, 5.8% research), whereas 6% (3% policy, 3%, research, none for industry) answered negatively. Some respondents from the energy and transport sectors stated that their organisation partially takes into account multi-hazard risk assessment (6%), while for 3% of the policy representatives this is still work in progress. Finally, 58% from the total number of respondents did not answer the question directly.

The methodologies and approaches employed by stakeholders vary from qualitative (e.g. narrative descriptions) to quantitative (probabilistic, scenario based, statistical), as categorized in section 2.1.1.2. For example, stakeholders representing the energy sector use screening processes for combined (paired) hazards, whilst transport sector representatives strive to incorporate multi-hazards into asset management systems and resilience strategy plans (without developing a full risk assessment). For strategic resilience planning at national scale, government departments use a “reasonably worse-case scenario” approach to assess the cascading risks and how they might impact a whole range of sectors. The environmental sector uses for instance probabilistic risk assessment approaches (e.g. joint probability analysis for river and coastal flooding) and multi-variate analysis. The health and safety sector uses a combined approach of hazard and risk zoning and scenario analysis (see Box 1.)

Box 1 Case study: HSE's Approach on multi-hazards

The hazards (for COMAH) that HSE are interested in fall into three groups: thermal, overpressure and toxic. For modelling purposes, the first two are assessed from a hazard perspective by calculating thermal dose and pressure (bar) respectively, while toxic (describing the release of a toxic substance into the atmosphere) takes into account different release scenarios and is assessed based on risk. The levels of hazard and risk calculated are used to define geographical zones that delineate HSE's dangerous dose (http://www.hse.gov.uk/chemicals/haztox.htm). There are three zones – inner, middle, outer – which are used for land use planning purposes.

For sites that hold multiple substances, or store substances in different locations around a site, there is a need to construct combined zones on a site-by-site basis. Where the assessment is based on hazards only (e.g. multiple tanks holding the same substance, or sites with thermal and overpressure hazards), the zones are combined using a worse-case approach. This means that triggering, amplification, and compounding of hazards is not explicitly calculated. Where the assessment is based on risk (i.e. the likelihood of receiving a dangerous dose), the risk is combined by summing the likelihoods of the multiple hazards.

For sites that combine toxic (risk) and thermal/pressure (hazard), the assessment combines the zones.

Respondents were asked to identify barriers (Q8) and enablers (Q9) that hinder or support them in performing robust multi-hazard risk assessment within their organisation. These could be interpreted as possible drivers or motivators behind action/inaction (Table 3.5). They are categorised as follows:

a. *Collaboration and knowledge transfer*. Respondents recognise that hazards experts are often siloed within organisations, i.e., they are experts in just 'one' hazard, and do not think across multiple hazards. This leads to a lack of understanding of which single hazards might affect a given region and time period and how these might interact. There is a need for more dialog between those involved in the fundamental science and those concerned with assessing impacts, particularly the less measurable ones, such as loss of productivity or psychological impact. Moreover, there is a lack of initiatives across UK research councils (research, training and knowledge exchange) that address the existing knowledge and skills gaps. Accordingly, a wider institutional partnerships and effective collaboration between disciplines and experts nationally and internationally (encouraged through across UK research council funding of research, training and knowledge exchange) is needed.

b. *Evidence-based research/knowledge*. The lack of firm evidence on the need for multi-hazard research (not enough research that demonstrates the usefulness of multi-hazard approaches) makes it difficult for industry stakeholders to provide a solid "needs case" for investing in multi-hazard research and development. Respondents also acknowledge the limited number of systematic reviews of current methodologies being used to understand multi-hazards. Therefore, more systematic reviews, evidence-based research and easier access to projects that provide new methodologies and approaches that help built consensus between academia and practice are needed.

c. *Data and uncertainties*. Lack of data from reasonably well documented events (i.e. evidence that supports developments in science) and for changing vulnerability.

Uncertainties are inherently linked with the data and models used to assess and characterise vulnerability, exposure and hazard cascades.

d. *Resources*. Lack of resources (time, computing power, specialist skills, funding for/from partner agencies to support development and pull through into information services of multi-hazard impact assessments), competing priorities and access to data due to confidentiality or commercially-sensitivity projects.

e. Guidance. Participants note the lack of clarity from the regulator on which particular set of multi-hazard scenarios or which hazard combinations they should investigate. Therefore, they acknowledge the need for legislative incentives and guidance on how to apply multi-hazard risk assessments, especially in industry.

D. Gaps in knowledge and skills

The last survey questions address current gaps in knowledge and skills for better understanding multi-hazard events and their impact (Q10) on one hand, and undertaking multi-hazard risk assessments (Q11) on the other hand. Stakeholders' answers are classified and summarised below:

a. *Collaboration and knowledge transfer.* Participants recognised the limited amount of knowledge transfer between multi-hazard professionals (academics and practitioners) and the lack of cross-hazard research to understand the relationships and interactions between processes.

b. Process understanding. The primary gap in multi-hazard knowledge relates to the poor understanding of critical processes and associated uncertainties, as well as the physical, chemical and biological regimes within which they occur and potentially interact. Hazards do differ by their nature, intensity, return period and the effect they may have on exposed assets. Our knowledge about their physical manifestation is limited due to, for example, data limitations and measurement errors (epistemic uncertainty), or their natural variability (aleatory uncertainty). As a result, our understanding of process relations and interactions (i.e., understanding how one process influences the manifestation of another) is very limited.

c. Lack of interoperability of hazard models and data. One limitation of the current methods and models is posed by the need to compare hazards with different process characteristics across different spatial scales. Few approaches to overcome this problem have been proposed. For instance, the Global Earthquake Model (GEM), have sought to standardise methodologies with partner organisations that focus on non-earthquake hazards - such as the Global Volcano Model (GVM), the Global Tsunami Model (GTM) and the global flood partnership (GFP). However, these approaches are possibly restricted to other organisations due to data and model availability, training and wider capacity issues.

d. Receptor and impact information. Participants recognise there is a lack of impact and receptor data (exposure, vulnerability) collected in a consistent and systematic manner, which can then be used to analyse multi-hazard events and importantly help to understand the spatial and temporal dynamic processes associated with multi-hazard cascades.

e. *Resources and skills*. Lack of skilled multi-hazard professionals (academics and practitioners) that have experience of understanding multi-hazards relationships, applying and developing appropriate multi-hazards risk assessment methodologies based on the available data and information. Moreover, there is limited experience and understanding of how to communicate the results of multi-hazard assessments to differing stakeholder communities. Lastly, there is a need for more time and resource to review multi-hazard events after they have happened, and learn from these situations to help generate real modelled examples of multi-hazard processes.

f. *Governance*. Stakeholders identified a lack of knowledge around the interdependencies between different agencies and government departments within the assessment of multi-hazards processes. General guidance on what multi-hazard scenarios could affect the UK is also required. This could be a synthesis of the available information from academic and industrial sources dealing with the probabilities of multi-hazard events occurring. The synthesis could address all different types of impacts (e.g. human health, social, physical, etc.) and the dissemination of the information to a range of stakeholders. Finally, respondents acknowledge that the regulatory or legislative framework is currently not well adapted for the assessment of multi-hazards.

3.2.3 Summary observations and gaps analysis

The stakeholder survey provides a means to ground-truth the adoption of current research on multi-hazards and evaluate the feasibility of risk assessment methodologies and approaches in practice. A number of summary observations result from the above analysis:

- Stakeholders perceive the science of multi-hazard assessment as being immature. Although they generally have a reasonably good understanding of the range of scenarios that may be possible in their own sector, they regard the science and quantitative techniques to characterise these as poorly understood and developed. Therefore, the application of multi-hazard methodologies in real life is scarce.

- While we can say that practitioners and scientists may understand most hazards individually, there is a lack of understanding on how these processes influence, trigger and/or amplify each other. Process understanding is acknowledge as being the primary gap in implementing multi-hazards risk assessments, which affects the capacity to test existing models or develop innovative ones.

- If knowledge about the combined effect of interacting hazards is limited, the existing knowledge about methodologies and approaches used to quantify economic costs of multi-hazards is very scarce. Systematic data collection about exposure, vulnerability, impact and their dynamic modelling is key for advancing the state-of-the-art of multi-hazard approaches in research and practice. Currently, in industry, such data is often lacking, not readily available or completely inaccessible.

- Industry provides a limited number of examples where multi-hazard risk assessment approaches are taken into account. The energy sector provides a good case due to its experience in using a wide range of methods and tools (qualitative, quantitative, semi-quantitative). Multi-hazard frameworks in policy on the other hand, focus on qualitative and semi-quantitative methods, which corresponds to their end purpose in most if not all the cases.

- Current methodologies are difficult or impossible to apply in practice at large, especially when using complex models and simulations. There is a lack of practical guidance on how/when to use existing methods for those without a technical background (e.g. NGOs, government, etc.). Moreover, methodologies and approaches that are accessible and useful might not always be applicable to different regions or case studies, therefore they need to be tested on a case-by-case basis to know if they can result in a better outcome or aid decision-making.

- Private - public partnerships represent a good ground for transferring knowledge on multi-hazard models and methods used across sectors, as demonstrated by the recent ETI Natural Hazards Project (ETI, 2018). Stronger collaboration and knowledge transfers between experts, institutions and sectors is recognised as an incentive for further development.
- The barriers and enablers to effectively implement multi-hazard risk assessments are found in both the science and practice domains as well as between those sectors. The most common drivers behind action or inaction are related with the lack or state of existent collaboration and knowledge transfer; evidence-based research; uncertainties in the natural variability of processes, data and models; available resources and guidance (see Q8 and Q9 for details).
- Accordingly, the gaps in knowledge and skills for the development and application of multi-hazard risk assessments are associated with the current process understanding; data, methods and models; existent information about exposure and impact; resources and skills needed to undertake the analysis; collaboration and knowledge transfer between stakeholders and the governance framework (see Q10 and Q11 for details).

4. Outcomes from the multi-hazard review

4.1 CONCLUSIONS

From the reviews and analysis undertaken as part of this study, and presented in detail in Sections 2 and 3, there are a number of common conclusions that have been identified. These have been grouped into common themes and are outlined below:

Multi-hazard approaches and assessment methodologies

- There are many examples of single hazard risk assessment approaches in both the academic and grey literature, which treat natural hazards as independent phenomena, not recognising a range of potential relationships between hazards. Literature describing approaches to understand multi-hazard interactions is limited, with clear scope for further research and innovation, especially around understanding the physical processes which underlie the interactions between hazards and the assessment of the social economic impact of multi-hazard events.
- The most developed multi-hazard assessment methods were found within the civil/structural engineering - applied to bridges and other critical infrastructure, and energy (nuclear power generation and electricity/gas distribution) communities. These methods currently focus on earthquake, wind and erosion hazards.
- Many of the methods described are applied to simulated environments, rather than to actual geographical extents. This is due to the availability and quality of data needed to test methods in a real world context.
- Many of the quantitative methods identified in Section 2.1.1.2 are developed and applied to a specific combination of two hazards. Real multi-hazard situations often involved multiple hazard types, and a range of interaction types. This approach can lead to a distortion of management priorities, an increased vulnerability to other spatially relevant hazards, or an underestimation of risk.
- Interdependencies of receptors (e.g. people, infrastructure) are not explicitly modelled, especially in the social economic case studies, due to a lack of metrics and models that capture these relationships; rather they have been assumed that they are captured in some way in the reported damage, being based on actual prior events where interdependencies between receptors would have been observed. As such, there is a risk that the total cost of the impacts may be under-estimated.
- Current methodologies are difficult or impossible to apply in practice at large, especially when using complex models and simulations. There is a lack of practical guidance on how/when to use existing methods for those without a technical background (e.g. NGOs, government, etc.). Moreover, methodologies and approaches that are accessible and useful might not always be applicable to different regions or case studies, therefore they need to be tested on a case-by-case basis to know if they can result in a better outcome or decision-making.

Multi-hazard risk assessment

- Stakeholders have a need to better assess risk to multi-hazards by analysing the processes of cascading consequences. There needs to be better understanding and integration of hazards relationships and cascading consequences.
- A comprehensive understanding of multi-hazard risk involves many stages, and therefore is a multidisciplinary and multi-method activity. Many of the studies characterised in this review integrated multiple methods to build understanding of multi-hazard relationships.

- The most appropriate level of information to generate a multi-hazard risk assessment will depend both on data availability and the end purpose. While a quantitative assessment of risk may be preferable in some contexts, other groups will prefer the development of maps or scenarios. Organisational discussion around these can help to guide institutional understanding of multi-hazard relationships, and build capacity to respond appropriately.
- The hazard combinations of greatest interest across sectors lies with four multi-hazard scenarios: storm surges and flooding, extreme rainfall triggering landslides, river and coastal flooding, and strong winds, snow, ice and extreme cold. Stakeholders representing the transport, energy and geotechnical engineering services find most relevant combinations of geological (e.g., landslides, sinkholes, rockfalls), atmospheric (e.g., storms, rainfall) or/and hydrological hazards (e.g., river and groundwater flooding), while the policy sector is focused on a wider range of possible multi-hazards, both natural and anthropogenic.
- Industry provides a limited number of examples where multi-hazard risk assessment approaches are taken into account. The energy sector provides a good case due to its experience in using a wide range of methods and tools (qualitative, quantitative, semi-quantitative). Multi-hazard frameworks in policy on the other hand, focus on qualitative and semi-quantitative methods, which corresponds to their end purpose in most if not all the cases.
- The barriers and enablers to effectively implement multi-hazard risk assessments are found in both the science and practice domains as well as between those sectors. The most common drivers behind action or inaction are related with the lack or state of existent collaboration and knowledge transfer; evidence-based research; uncertainties in the natural variability of processes, data and models; available resources and guidance.

Economic costs of multi-hazards

- A common theme from the academic papers is that there is no detail about how the economic costs were estimated, which makes it difficult to analyse and compare methods. Economic figures given in the case studies are only indicative and are subject to numerous uncertainties such as not accounting for increases of capital over time, which would raise costs, or the uncertainty and bias associated with loss data due to the wide variety of sources from which it is collected and by the multiple methods of collection (particularly with disaggregated information from the insurance industry).
- There are practical difficulties in distinguishing between different multi-hazard processes and the associated impact. To estimate costs, we need to understand the unit cost to each impact and be able to multiply to the number of assets or people affected. Also, need to ensure that costs are being adjusted to represent full economic costs rather than solely financial costs.
- Damage to infrastructure is often sequential and gets worse over time meaning that the impacts from one or multiple hazards could have been made worse due to several preceding hazards. In many of the case studies costs are gathered from repair work and insurance costs which may reflect impacts over time. Therefore, it is difficult to elicit the actual impacts from an event or distinguish between hazard impacts in an event, as the methods to estimate costs do not reflect this. There needs to be a method to adjust costs so that they reflect the true cost of the event being analysed.

Terminology

- Some stakeholders define multi-hazards to be the cascading consequences of one or more hazards, due to their focus on the impact of events on their particular industry (e.g. power shortage as a result of a wind storm).

4.2 GAPS (KNOWLEDGE/SKILLS)

From the conclusion and observations made in this review there are a number of gaps that have been identified and are outlined briefly below. Where relevant, potential opportunities have been highlighted to address the gaps:

- **Gap 1: Understanding of multi-hazard processes.**
  The primary gaps in multi-hazard knowledge relate to our poor understanding of critical processes (and associated uncertainties), as well as the physical, chemical and biological regimes within which they occur.
  Opportunity: Research to understand physical processes behind multi-hazards.

- **Gap 2: Testing of multi-hazard assessment methodologies.** More work is needed to test all the various multi-hazard assessment methodologies, outlined in Section 2.1.1.2, with more complex multi-hazard scenarios. Extending methods to more than two hazards could lead to much more complicated analyses and many scenarios in long-term risk assessments.
  Opportunity: Trial existing assessment methodologies to more complicated or alternative multi-hazard scenarios.

- **Gap 3: Understanding of multi-hazard concepts.** Multi-hazards need to be thought of as seamless holistic processes that incorporate both natural and anthropogenic causes and are assessed through a joined up risk assessment methodology, where the hazards can initiate independently or dependently and then interact (e.g. trigger, amplify, coincide) as outline in Appendix 2.
  Opportunity: Sharing of best practice for joined-up approaches.

- **Gap 4: Limited understanding of UK multi-hazards.** Some general guidance on what multi-hazard scenarios could affect the UK. This would help to focus multi-hazard research into the most relevant areas and provide evidence for risk assessment approaches.
  Opportunity: Development and dissemination of guidance on UK multi-hazards

- **Gap 5: Accounting for differences between single and multi-hazards.** Failure to look explicitly at the interdependencies between interacting hazards; rather they look at the summing up of single hazard events, which may occur at the same time. This is a common finding among the academic and grey literature reviewed and it seems it is more to do with a lack of models which can fully capture these multi-impacts systematically and consistently.

- **Gap 6: Assessing creeping changes in vulnerability associated with multi-hazards.** Multi-hazard risk assessments are often more qualitative than quantitative and do not incorporate temporal changes in vulnerability during successive hazards, resulting in an under estimation of the potential impacts. This highlights a large knowledge gap in understanding the natural physical processes and their interaction with potential receptors (e.g. infrastructure, buildings, people). As a result there is very little good practice documented in the UK and internationally to help guide and bridge this gap.

- **Gap 7: Lack of data for understanding costs.** There is a lack of impact and receptor data collected, in a consistent and systematic manner, which can be analysed relative to the recommend full ideal cost model outlined in this report (Section 2.2.1). The impacts and the costing of numerous impacts including: non-marketed outcomes like pain, grief and suffering need to be considered, but will add significant complexity.

- **Gap 8: Lack of in-depth case studies.** Case studies based on actual prior events where interdependencies between different receptors are known would be an advantage and produce

better social economic case studies that look at the true total cost of impacts and hence not under-estimate them.
Opportunity: Develop more case studies accounting for interdependencies

- **Gap 9: Assessment of cost differences.** None of the social economic case studies, in this review (Section 2.2), could prove if the sum of the impacts and the associated full economic costs of a multi-hazard event would be greater than the sum of the individual hazards due to accumulation of damage.
  Opportunity: Simulations should be used to prove a way to look at multi-hazards as if they occurred independently of one another and compare the impacts and the associated full economic costs with a multi-hazards scenario.

- **Gap 10: Better links between science and industry/policy.** Greater dialogue between natural hazard scientists and other professionals working with risk assessment methodologies (e.g. civil/structural engineers).
  Opportunity: Facilitate further collaboration between academia and industry/policy.

- **Gap 11: Baseline knowledge of multi-hazards.** Lack of skilled multi-hazard professionals (academics and practitioners) that have experience of understanding multi-hazards relationships, applying and developing appropriate multi-hazards risk assessment methodologies based on the available data and information.

- **Gap 12: Knowledge transfer and communication.** Limited amount of knowledge transfer between multi-hazard professionals (academics and practitioners). Limited experience and understanding of how to communicate the results of multi-hazard assessments to differing stakeholder communities.

- **Gap 13: Lack of regulatory or legislative framework.** A framework would help to ensure the application and assessment of multi-hazards by Government and industry.

4.3 RECOMMENDATIONS

From this review, in light of the barriers and enablers identified in Section 3.2.2 and gaps in knowledge and skills indicated above, a number of recommendations have been identified:

- Workshop to share best practice identified in this review (including contributions from those applying best practice).
- Build a multi-hazard community that brings together academic, industry and policy representatives from the scientific, social science, engineering and other professional disciplines to address the multidisciplinary and multi-method nature of multi-hazards risk assessment methodologies. In Appendix 9, we note the range of disciplines that could be involved in multi-hazard work, and in Appendix 10, we note select forums, conferences and networks that could help to build a multi-hazard community. A multi-hazard community would aim to develop more integrated hazards and disaster research, and bridge silos within and between research, industry and policy communities. A multi-hazard community is being proposed within the European Geosciences Union, which if accepted could help to foster dialogue between hazards researchers, with a view to engaging with those outside of academia. A community of practice, coordinated by a professional body (e.g., *Institute of Civil Engineers*) could also help to bring together stakeholders from diverse sectors, but would have to ensure diverse disciplines were also represented. If effective, a multi-hazard community could lead to agreement of common/accepted/standard terminology across disciplines and industries and knowledge exchange of the methods used to assess point source receptors (e.g. bridges) or spatially extensive receptors (spatial considerations). There could also be knowledge exchange

on how to deal with the difference between the fast and slow on-set of multi-hazards events (temporal considerations).

- Some general guidance on what multi-hazard scenarios could affect the UK.
- Guidance on multi-hazard methodologies and approaches used to assess them. This could be a synthesis of the available information from academic and industrial sources and provide a common framework for aiding multi-hazard assessment methodologies into practice.
- Case studies based on actual prior events where interdependencies between different receptors would be an advantage and produce better social economic case studies that look at the true total cost of impacts and hence not under-estimate them.
- Funding call (and /or special issue peer-review publications) to encourage publishing and capture of multi-hazard approaches/applications.

Appendix 1 Project outcomes

For this study, we used a research data management informed by an objective and comprehensive assessment of the evidence base, together with the need to make the most of existing knowledge. The approach that was followed used the principles outlined by Collins et al. (2015) in "The Production of Quick Scoping Reviews and Rapid Evidence Assessments". The outcomes of the project and their associated WP are listed below.

Table A1. Project deliverables associated with the methodology illustrated in Fig 1.1.

WP	Deliverables	Section/Appendix
1	Successful delivery of this project (D11 in Fig. 1.1)	Project report, workshop
1	A database of stakeholders involved with multi-hazard assessments in academia and practice (industry and policy) and their landscape mapping (D1 in Fig. 1.1)	Appendix 6, Section 3.1
2	A review of terminology and definitions around multi-hazard events and risk assessments (D2 in Fig .1.1)	Appendix 2
2	A database of existing literature – including past/current projects – and past/current evidence from practice (industry/policy) on multi-hazards research & innovation (D3 in Fig. 1.1)	Appendix 3
2	A list of disciplines which could inform multi-hazard research and risk assessment	Appendix 9
2	A list of relevant initiatives, forums and conferences	Appendix 10
2	Identification of case studies for the analysis of socio-economic impacts from multi-hazard events (D4 in Fig. 1.1)	Section 2.2, Appendix 4
2	Summary observations from the analysis of past and current academic and practice (industry and policy) based projects, research and approaches in multi-hazard processes, impact and risk assessment (D5 in Fig. 1.1)	Section 2.1.1.3, 2.1.2.3, 2.2.4
3	An overview of the current industry and policy awareness of and approaches used to assess multi-hazard risks (D6 in Fig. 1.1)	Section 3
3	Transcripts of interviews and questionnaires	Appendix 11
4	A review and summary of gaps, barriers and potential future enablers to progress multi-hazard research in the UK (D8 to D10 in Fig. 1.1)	Section 3 and Section 4

Appendix 2 Definition of multi-hazard & associated terminology

A1. Overview

In this Appendix, we first evaluate 'multi-hazard' definitions in the peer-review and grey literature, and the extent to which others then refer to these definitions (**Section A2**). We examine consistencies/differences with the working definition proposed in the UKRI 'invitation to quote' document (UKRI, 2018):

"'Multi-hazard' is the succession of the same hazard, or combinations of different hazards that occur within a time and/or space window that generate an impact that is different to that of the individual hazards in isolation, through one or more of the following mechanisms:

(1) Interact with each other to change the impact
(2) Change the background conditions thus changing the likelihood or severity of subsequent hazards
(3) Interact with the infrastructure network at different points or times, which may change the resilience/flexibility of the network.

Importantly, the outcome of the impact will be different to a scenario where the hazards occurred in isolation. This may be an amplified, modified or even reduced impact to that expected by a single hazard."

We also discuss variation in terminology associated with hazard relationships (**Section A3**).

A2. Definitions of Multi-Hazard

a. Review Context

'Multi-hazard' approaches have long been advocated for (e.g. Hewitt and Burton, 1971), and are now widely encouraged by major frameworks to facilitate disaster risk reduction (DRR). For example, both the UN Hyogo Framework (2005–2015) and Sendai Framework for Disaster Risk Reduction (2015–2030) advocate for DRR to be 'multi-hazard' (UNISDR, 2015). Despite this encouragement of multi-hazard approaches, the term is rarely explicitly defined. This has resulted in some academics (e.g. Kappes *et al.*, 2012; Garcia-Aristizabal *et al.*, 2013; Duncan, 2014; Gill and Malamud, 2014; Liu *et al.*, 2015) commentating that 'multi-hazard' (or 'multihazard') is frequently being used to mean different things by different authors.

In 2017, the UNISDR therefore added 'multi-hazard' to their list of defined terminology, ensuring those implementing and monitoring progress against the Sendai Framework for Disaster Risk Reduction (SFDRR) have clarity regarding what is necessary to fulfil its aim and guiding principles. Their definition is:

"Multi-hazard means (1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects." (UNISDR, 2017)

In this context, multi-hazard approaches are considered to include but extend beyond the collation (or overlay) of distinct information for multiple single natural hazards (or 'multi-layer single hazard' approaches), to also characterise different relationships (see **Section A3**) between natural hazards. This definition aligns with the UKRI (2018) definition, and some (but not all) uses of the term 'multi-hazard' in the literature. It is currently unclear if an agreed UNISDR definition of multi-hazard will help to improve consistency in the use of this term within the broader natural hazards and DRR communities.

b. Review Methodology and Characterisation of Results

In this section, we describe and present the results of a short review to determine how 'multi-hazard' is defined in academic (peer-review and grey) published literature, and the extent to which these definitions are consistent with other proposed definitions (e.g. UNISDR, 2017; UKRI, 2018). We completed a search for short phrases that are logically followed or preceded by a definition of 'multi-hazard/s' or 'multihazard/s', in order to ensure explicit attempts to define these terms were included. We note nine search terms in **Table A1**, together with the number of returned results.

Table A1. Nine search terms used to understand the definition of multi-hazard in peer-review and grey literature. All searches were done with Google Scholar, and a search date of 9 August 2018.

Search Term	Returned results where 'x' = …			
	multi-hazard	**multi-hazards**	**multihazard**	**multihazards**
"define x"	5	1	0	0
"definition of x"	13	0	3	0
"defined x"	6	0	0	0
"x can be defined"	0	0	0	0
"x definition"	0	1	1	0
"x means"	2	0	0	0
"x is"	50	37	7	7
"z suggests"	0	0	0	0
"the term x"	21	7	10	1

These searches returned 172 results, of which 144 were unique papers and reports. Of the 144 unique results, these included 54 journal articles, 28 Masters and PhD theses, 24 conference papers, 15 books/book chapters, 15 technical reports, and 8 miscellaneous items of literature (workshop reports, presentations, patent applications, legal documents). The 144 unique results were largely published after 2010, as illustrated in **Figure A1**. We outline our analysis of the context of the 144 unique search results in the next section.

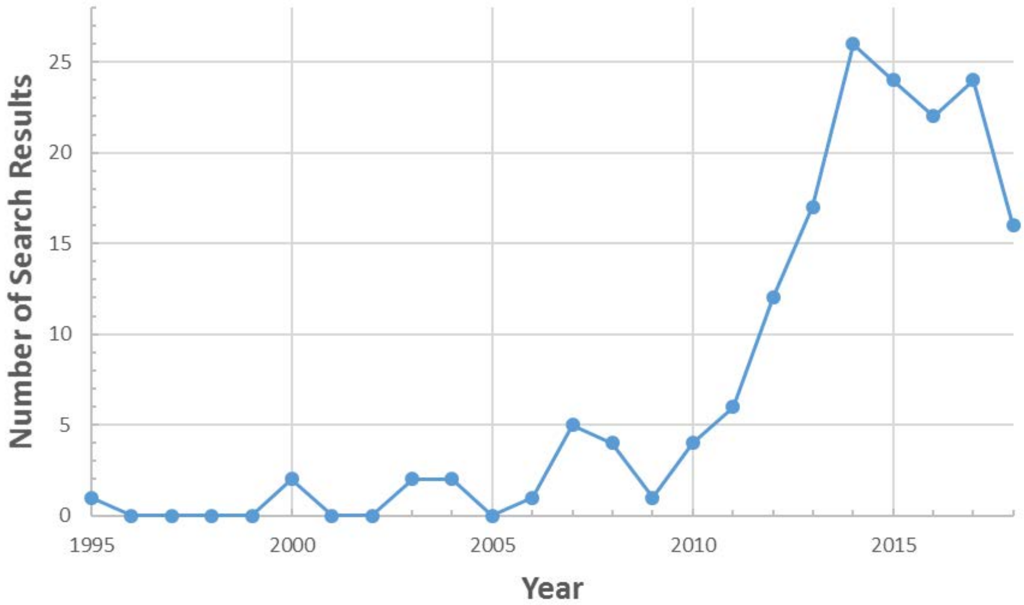


***Figure A1**. Number of unique search results (using the terms in Table A1) by year.*

While a context analysis of any paper referring to multi-hazard/multihazard (16,500 returns on Google Scholar, 15 August 2018) could allow us to determine the implicit way in which many more authors' use this term, and thus highlight other definitions of the term multi-hazard, this is beyond the scope of our review. We believe our search approach, focusing on more explicit definitions, captures a range of ways in which the term is used. While it is possible that additional search terms could identify further definitions of 'multi-hazard', it is more likely that they would generate additional examples of definitions already included within our search results. The significant number of returns not explicitly defining the term multi-hazard highlights the challenge of this being a term that is frequently used, but rarely defined (Kappes *et al.*, 2012; Garcia-Aristizabal *et al.*, 2013; Duncan, 2014; Gill and Malamud, 2014). Approximately 172 (or just over 1%) of the 16,500 returns for multi-hazard/multihazard include a definition (either original or referenced) of what they mean by the term.

c. Review Analysis

Of the 144 unique results, access was available to 126 (88%) of these articles with others restricted by language, embargoes, or paywall barriers. Using the 126 available results, we first assessed these for relevance to the specific question '*how is multi-hazard defined in the context of natural hazards and/or risk?*' and then captured the proposed definition and if and how this relates to other definitions in the literature. We found that 30 (24%) of the 126 results clearly define multi-hazard, either in their own words (19 of the results) or by referencing an existing definition (11 of the results). The remaining results are either not relevant to the question, use the term multi-hazard but not in a context where it is defined within the paper, or refer to a piece of software (Hazus-MH, or Hazus MultiHazard) produced by the US Federal Emergency Management Agency (FEMA).

The 30 results defining multi-hazard are presented in **Table A2**, placed into two groups according to how they define multi-hazard. The first group includes nine definitions that focus on multiple hazard types that could spatially overlap, but that are generally treated as being independent. The second group includes 21 definitions that focus on multiple hazard types that could spatially overlap, with relationships between these hazards (i.e., non-independence).

***Table A2**. Definitions of the term multi-hazard used in the academic (peer-review and grey) literature, including referenced work if the definition is extracted from elsewhere.*

a. More than one hazard type, independent occurrence of hazards, or overlap of single hazards.

Source	Definition Used	Referenced Work
USA Public Law 106-390 (2000)	'Multihazard advisory map' means a map on which hazard data concerning each type of natural disaster is identified simultaneously for the purpose of showing areas of hazard overlap.	N/A
Lee *et al.* (2003)	The newly defined "multi-hazard engineering" is meant to emphasize an integrated and cost-effective disaster operation against all types of serious hazards.	N/A
Franklin County (2011)	"Multi-Hazard" was used where the initiative would apply to more than one hazard type.	N/A
Ballarin-Denti and Oliveri (2011)	We can define multi-hazard assessment as the evaluation of the occurrence probability of dangerous events arising from a variety of sources/processes in the same site.	N/A
van Westen (2012).	[Multi-hazard] is often used to indicate all relevant hazards that are present in a specific area, while in the scientific context it frequently refers to "more than one hazard".	N/A
Corominas *et al.* (2014)	Multi-hazard assessment should, sensu stricto, refer to the joint probability of independent events occurring in the same area in a given time span.	N/A
Eshrati *et al.* (2015)	Multi-hazards risk can be interpreted as the consideration of multiple (if possible all relevant) hazards posing risk to a certain area under observation.	N/A
Klibi *et al.* (2018)	'Multi-hazard' is used to refer to area exposed to several natural disasters of different types during the planning horizon	N/A
Clark-Ginsberg *et al.* (2018)	We understand multi-hazard risk assessments as the process of identifying, categorizing by a normalized probability and impact, and comparing risks found within the same context or circumstance.	N/A

b. Multiple hazards and relationships between these hazards.

Source	Definition Used	Referenced Work
King (1995)	Multi-hazard refers to the consideration of ground shaking and the secondary site effects of soil amplification, liquefaction, landslide, and surface fault rupture.	N/A
May (2007)	This new concept [multihazard] related multiple hazards to each other through causation sequences.	N/A
Wylie (2008)	The concept of the multi-hazard is presented, as hazards seldom occur in isolation, one often induces another.	N/A

Source	Definition Used	Referenced Work
Kappes *et al.* (2012)	Delmonaco *et al.* (2006b, p. 15) define multi-hazard analyses as the "[i]mplementation of methodologies and approaches aimed at assessing and mapping the potential occurrence of different types of natural hazards in a given area." The employed methods "have to take into account the characteristics of the single hazardous events […] as well as their mutual interactions and interrelations (e.g. landslide induced earthquake, floods and landslides triggered by extreme rainfall, natural disasters as secondary effect from main disaster types)" (Delmonaco *et al.*, 2006b, p. 15).	Delmonaco *et al.* (2006)
Garcia-Aristizabal and Di Ruocco (2013)	Multi-hazard… can be defined as "the process to determine the probability of occurrence of different hazards, either occurring at the same time or shortly following each other, because they are dependent upon one another or because they are caused by the same triggering event or hazard, or merely threaten the same elements at risk without chronological coincidence" (European Commission, 2010; Garcia-Aristizabal *et al.*, 2012).	European Commission (2010); Garcia-Aristizabal *et al.* (2012)
Garcia-Aristizabal *et al.* (2013)	Multi-hazard is a wide concept that, in general terms, can be split into two possible lines of applications: (1) multi-hazard assessment may be seen as the process of assessing different (independent) hazards threatening a given (common) area, and (2) it represents the process of assessing possible interactions and/or cascade effects among the different hazardous events.	N/A
Xu *et al.* (2014)	Multi-hazards are multiple hazards that occur in a certain region during a particular period of time, whether the hazards are related in consequence or not.	Hewitt and Burton (1971); Kappes (2011)
Duncan (2014)	Multi-hazard is defined as comprising two key components, which require determination through an analysis of varying temporal and spatial scales: (1) more than one hazard, (2) interrelations between hazards.	N/A
Echevarria (2014)	It could be argued that multihazard implies multiple hazards acting simultaneously or sequentially, but it could also be argued that multihazard implies that a structural component has the inherent ability to resist multiple hazards without specific hardening for each separate hazard.	N/A
Gill and Malamud (2014)	We also use the term [multihazards] to refer to all possible and relevant hazards, and their interactions, in a given spatial region and/or temporal period.	N/A
Chen *et al.* (2015)	[Multi-hazard] is regarded as all hazard scenarios that possibly occur in bridge life-cycle, including hazard scenarios of a single hazard and hazard scenarios of hazard combination.	N/A
Liu (2015)	It [multi-hazard] takes into account the characteristics of each hazardous event (e.g. probability, frequency, magnitude), and their mutual interactions and interrelations (e.g. one hazard may occur repeatedly in time; different hazards may independently occur in the same place; different hazards may occur dependently in the same place) (Kappes *et al.*, 2012; Marzocchi *et al.*, 2012).	Kappes *et al.* (2012); Marzocchi *et al.* (2012)
PHAROS (2015)	[We] consider the term multi-hazard to be a holistic one, stressing the necessity for a broader approach (spatially, scientifically, technically), taking into account effects and relationships beyond the pure (limited) scope of a single hazard.	Gill and Malamud (2014)

Source	Definition Used	Referenced Work
Bibi and Rahman (2015)	The term “multi-hazards” refers to all expected and related hazards, and their interactions, in a given spatial region over a temporal period (Gill and Malamud, 2014). It is used in most cases closely related to the objective of risk reduction (Kappes *et al.* 2012).	Gill and Malamud, (2014); Kappes *et al.* (2012)
Liu *et al*. (2015)	‘Multi-hazard assessment’ may be understood as the process: "to determine the probability of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk without chronological coincidence. (European Commission 2010)".	European Commission (2010)
Harbitz *et al.* (2016)	Multi-hazard… can be defined as “the process to determine the probability of occurrence of different hazards, either occurring at the same time or shortly following each other, because they are dependent upon one another or because they are caused by the same triggering event or hazard, or merely threaten the same elements at risk without chronological coincidence” (European Commission, 2010). Following this definition, multi-hazard analysis comprises both the process of analysing different (independent) hazards threatening a given (common) area, and the process of analysing possible interactions and/or cascade effects among the different types of hazardous events.	European Commission (2010)
Hart and Dawke (2016)	A useful example framework for what constitutes a multi-hazard approach has been described by Gill and Malamud (2014), as illustrated in Figure 3. This approach involves four key steps that form a critical pathway for moving from a multi-layer ‘single hazard’ approach to a ‘multi-hazard’ approach.	Gill and Malamud (2014)
Gill and Malamud (2017)	The term multi-hazard was defined as meaning “all possible and relevant hazards and their interactions, in a given spatial region and/or temporal period”	Gill and Malamud (2014)
Marasco *et al.* (2017)	The concept of multihazard is defined as the “implementation of methodologies and approaches aimed at assessing and mapping the potential occurrence of different types of natural hazards in a given area. The employed methods have to take into account the characteristics of the single hazardous events as well as their mutual interactions and interrelations” (Delmonaco *et al.* 2007).	Delmonaco *et al.* (2007)
Christou *et al.* (2017)	“Multihazard” refers to hazards that can be either correlated or uncorrelated, and either sequential or nonsequential.	N/A
Espinosa-Vega *et al.* (2017)	Multi-hazard describes the presence of more than one relevant hazard in the geosystem with different levels of interaction.	N/A

Eleven results in **Table A2** refer to definitions of multi-hazard expressed by others, drawing on 7 publications (5 of which are in addition to those listed above, and 2 of which are included above): Hewitt and Burton (1971); Delmonaco *et al.* (2007); European Commission (2010); Kappes (2011); Marzocchi *et al.* (2012); Garcia-Aristizabal *et al.* (2012); and Gill and Malamud (2014). While Kappes *et al.* (2012) is also referenced, this itself refers back to Delmonaco *et al.* (2007). We outline these definitions in **Table A3**.

Table A3. Cited definitions of multi-hazard in the search results outlined in Table A2.

Source	Definition Used
Hewitt and Burton (1971)	*[N.B. Uses the term 'cross-hazard' rather than 'multi-hazard']* A review of the literature quickly reveals that most work has been on single hazards, whereas the expanded concern demands a more systematic cross-hazard approach. It was with this in mind that the "all-hazards-at-a-place" research design was formulated…. Hazards may be "simple", "compound", or "multiple".
Delmonaco *et al.* (2007)	Implementation of methodologies and approaches aimed at assessing and mapping the potential occurrence of different types of natural hazards in a given area. Analytical methods and mapping have to take into account the characteristics of the single hazardous events (e.g. affected area, intensity/magnitude, frequency of occurrence) as well as their mutual interactions and interrelations (e.g. landslide-induced earthquake, floods and landslides triggered by extreme rainfall, natural disasters as secondary effect from main disaster types).
European Commission (2010)	Multi-hazard assessments determine the likelihood of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk (vulnerable/ exposed elements) without chronological coincidence.
Kappes (2011)	The totality of relevant hazards in a defined area, whereby relevant has to be clearly defined according to the specific situation and setting.
Marzocchi *et al.* (2012)	Multi-risk assessment… requires the use of the same space-time window, the same metric for losses evaluation, and to account for the possible interactions among the risks, both in terms of probabilistic hazard and vulnerability.
Garcia-Aristizabal *et al.* (2013)	Multi-hazard is a wide concept that, in general terms, can be split into two possible lines of applications: (1) multi-hazard assessment may be seen as the process of assessing different (independent) hazards threatening a given (common) area, and (2) it represents the process of assessing possible interactions and/or cascade effects among the different hazardous events.
Gill and Malamud (2014)	We also use the term [multihazards] to refer to all possible and relevant hazards, and their interactions, in a given spatial region and/or temporal period. A multihazard risk assessment should identify all possible and relevant hazards and the valid comparison of their contributions to hazard potential, including the contribution to hazard potential from hazard interactions and spatial/temporal coincidence of hazards, while also taking into account the dynamic nature of vulnerability to multiple stresses.

From **Tables A2** and **A3** we note that definitions proposed generally fall into one of two groups (multiple independent hazards, multiple hazards and their interactions), with only little variation in the detail included within the definition. The majority of the definitions in **Tables A2** and **A3** fall into the latter category, *including relationships between natural hazards*. This aligns with the UNISDR (2017) and UKRI (2018) definitions.

Spatial considerations (hazards affecting the same site) are more frequently highlighted than temporal considerations (hazards occurring one after another, whether due to causation effects or not). Most of the definitions recognise that multiple hazards (whether related or not) can occur in a specific region (e.g. van Westen, 2012; Xu *et al.*, 2014; Gill and Malamud, 2014; Eshrati *et al.*, 2015; Klibi *et al.*, 2018) and this results in calls to assess areas of hazard overlap (e.g. USA Public Law 106-390, 2000). Fewer definitions characterise the temporal implications of a multi-hazard scenario, although this factor is more prevalent in the definitions where relationships between hazards are included (e.g. Garcia-Aristizabal and Di Ruocco, 2013; Xu *et al.*, 2014; Duncan, 2014; Gill and Malamud, 2014; Chen *et al.*, 2015; Christou et al. (2017).

Both the UNISDR (2017) and UKRI (2018) definitions incorporate spatial and temporal considerations, linking to the occurrence of natural hazards in a defined time and/or space window. UNISDR (2017) focuses on national spatial scales, and UKRI (2018) focuses on 'infrastructure networks' which can range from local, regional, national or multi-national scales. Both note relationships occurring over time, but neither places limitations on the temporal scale that relationships can occur. It is important that any definition is not too restrictive, as relevant multi-hazard relationships could have an impact days, weeks, months or years after the occurrence of a primary hazards. For example, an earthquake may change slope conditions so as to immediately trigger landslides (minutes to hours afterwards) or to increase the likelihood of landslides during a following monsoon (weeks to months afterwards).

Although some of the definitions relate their definition to 'impact' or 'elements at risk' (e.g. Garcia-Aristizabal *et al.*, 2013; Liu *et al.*, 2015), most of the definitions are limited to characterising hazard processes (e.g. Wylie, 2008; Duncan, 2014; Gill and Malamud, 2014; Xu *et al.*, 2014; Christou *et al.*, 2017; Espinosa-Vega *et al.*, 2017). This contrasts with the UKRI (2018) definition, which specifically relates multi-hazard events to an impact that is different to that of individual hazards occurring in isolation. Impacts can vary, and could include damage to infrastructure, loss of lives, injuries, loss of livelihoods, economic losses, or changes to institutional responses. We suggest that any general definition of multi-hazard, recognises this range of potential impacts, and is not too restrictive on what the cumulative impacts of multiple hazards must be for a situation to be regarded as multi-hazard.

A3. Hazard Interaction Types and Terminology

In addition to returning definitions of 'multi-hazard', the search outlined in **Section A2** concurred with Kappes *et al.* (2012) and van Westen *et al.* (2014) that there is wide variation in the terminology used to describe relationships between natural hazards (e.g. interactions, interrelationships) and specific types of relationship (e.g. triggering, cascading, coincident). Kappes *et al.* (2012) note that these different terms are also rarely defined. Some authors have characterised these relationships and developed taxonomies to describe different ways by which one hazard may relate to another hazard, as outlined in **Table A4**.

Table A4*. *Four taxonomies of hazard relationships presented in the academic literature.

Paper	Taxonomy of Hazard Relationships
Kappes *et al.* (2010)	i. One process **triggers** the next (cascades, domino effects). ii. **Changes to the disposition** (e.g. frequency, magnitude alterations) of one hazard is altered by another.
Duncan (2014)	i. **Causation** (hazards generate secondary events, which may occur immediately or shortly after the primary hazard, including cascading hazards). ii. **Association** (hazards increase the probability of secondary events, but it is difficult to quantify this link and therefore confirm causation). iii. **Amplification** or alleviation (hazards exacerbate or reduce future hazards). iv. **Coincidence** (hazards occur in the same place simultaneously, or closely timed, resulting in compounded effects or secondary hazards).
Gill and Malamud (2014); Gill and Malamud (2016)	i. **Triggering** relationships (extending beyond hazard pairs to result in linear or non-linear networks of hazard interactions). ii. Changes in the background conditions to **change the likelihood** (increase or decrease) of a further hazard. iii. Spatial and/or temporal **coincidence** of two hazards.
van Westen *et al.* (2014)	i. **Coupled hazards (**different hazard types triggered by the same event). ii. **Changes to the disposition** of one hazard by the actions of another hazard.

	iii. **Chains,** with one hazard causing the next and resulting in cascades or concatenated hazards.

While each author presents a slightly different taxonomy, there are strong commonalities between them with three emerging types of hazard relationship. They all describe *triggering* as one hazard relationship where one hazard causes another hazard to occur. This can result in chains, networks of cascades of hazards. They also all note an *amplification effect*, whereby the occurrence of one hazard can change the likelihood and/or magnitude of additional hazards in the future. While this could be a reduction in likelihood/magnitude, of more pertinence to disaster risk reduction are situations where one hazard results in an increase in the likelihood and magnitude of another hazard. The third type of hazard relationship is *compound hazards*, described in terms of hazards coinciding in space and/or time with impacts greater than the sum of the two. This could be due to a primary hazard triggering multiple secondary hazards within a given timeframe, or the coincidence of two independent hazards. The latter includes situations where hazards occur consecutively, with one hazard changing the vulnerability so as to make exposed assets more susceptible to the impacts of a following hazard.

A4. Conclusions

While a range of definitions of multi-hazard exist, many of these share two critical factors in common: (a) recognition that a region may be susceptible to multiple hazards, (b) recognition these multiple hazards may relate to one another through different relationship types (i.e., triggering, amplification, compound hazards). The UNISDR (2017) definition of multi-hazard captures these two critical components.

> *"Multi-hazard means (1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects." (UNISDR, 2017)*

While some definitions articulate the importance of assessing multi-hazard relationships (e.g. we do this because the impacts may be greater than the sum of their parts), this is more generally included in the narrative around the definition rather than as a substantial part of the definition.

Appendix 3 Database of existing academic literature and past/current evidence from practice (Industry & Policy)

[See separate file A3_NERC_Multi-Hazard_Literature Compilation_Academia and A3_NERC_Multi-Hazard_Literature Compilation_Practice.xls)

AUTHORS	TITLE	PUBLICATION	VOL.	NO.	PAGES	YEAR	PUBLISHER	HYPERLINK	ABSTRACT
Bhartia, Binod Kumar; Vanmarcke, Erik H;	Multi-hazard risk analysis: case of a simple offshore structure	NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH, Technical Report NCEER-88-0023				1988	National Center for Earthquake Engineering Research	https://nehrpsearch.nist.gov/static/files/NSF/PB89145213.pdf	This report develops and illustrates methodology for multi-mode, multi-hazard risk assessment. The case study involves an offshore structure subjected to earthquake shaking and storm-generated wind, wave, and current loads. Two classes of risks are calculated: (1) conditional failure probabilities under short-term loads; and (2) long-term or overall risks, which depend on occurrence patterns of loads of different intensities. This report shows that the relative importance of different loads depends on the limit states and on the load and structural characteristics. For a flexible offshore structure, the storm loads dominates in the case of a displacement limit state, but is unimportant compared to the earthquake load in relation to an acceleration limit state. Parameter uncertainty is shown to always increase the long-term risk; in the case study, the increase is more pronounced for the displacement limit state than for the acceleration limit state. Also, it is shown that the ambient load increases the risk due to earthquake loads alone, especially at the lower resistance levels.
Bhartia, BK; Vanmarcke, EH;	Multi-hazard risk assessment of an offshore structure	Structural Safety and Reliability			447-454	1989	ASCE	http://cedb.asce.org/CEDBsearch/record.jsp?dockey=0064335	This paper develops and illustrates a methodology for multi-hazard modal risk assessment. The case study involves assessing risk to an offshore structure in a load environment consisting of earthquakes and seastorms. The risks, both short-term and long-term, are assessed in function of two limit states defined respectively in terms of the allowable displacement and acceleration at the deck of the structure. A clear distinction is made between the physical and parameter uncertainty present in the system, and the effect of the latter explicitly quantified on the response statistics as well as on risks. The paper also determines the influence of ambient load on the earthquake safety and performs sensitivity analyses.
Van Westen, Cees J; Montoya, Lorena; Boerboom, Luc; Badilla Coto, Elena;	Multi-hazard risk assessment using GIS in urban areas: a case study for the city of Turrialba, Costa Rica	Proc. Regional workshop on Best Practise in Disaster Mitigation, Bali			120-136	2002		https://www.researchgate.net/profile/CJ_Westen/publication/228809150_Multi-Hazard_Risk_Assessment_using_GIS_in_urban_areas_A_case_study_for_the_city_of_Turrialba_Costa-Rica/links/0c9605238d87160e23000000.pdf	In the framework of the UNESCO sponsored project on "Capacity Building for Natural Disaster Reduction" a case study was carried out on multi-hazard risk assessment of the city of Turrialba, located in the central part of Costa Rica. The city with a population of 33,000 people is located in an area, which is regularly affected by flooding, landslides and earthquakes. In order to assist the local emergency commission and the municipality, a pilot study was carried out in the development of a GIS –based system for risk assessment and management. The work was made using an orthophoto as basis, on which all buildings, land parcels and roads, withinthe city and its direct surroundings were digitized, resulting in a digital parcel map, for which a number of hazard and vulnerability attributes were collected in the field. Based on historical information a GIS database was generated, which was used to generate flood depth maps for different return periods. For determining the seismic hazard a modified version of the Radius approach was used and the landslide hazard was determined based on the historical landslide inventory and a number of factor maps, using a statistical approach. The cadastral database of the city was used, in combination with the various hazard maps for different return periods to generate vulnerability maps for the city. In order to determine cost of the elements at risk, differentiation was made between the costs of the constructions and the costs of the contents of the buildings. The cost maps were combined with the vulnerability maps and the hazard maps per hazard type for the different return periods, in order to obtain graphs of probability versus potential damage. The resulting database can be a tool for local authorities to determine the effect of certain mitigation measures, for which a cost-benefit analysis can be carried out. The database also serves as an important tool in the disaster preparedness phase of disaster management at the municipal level.
Khatsu, Petevilie; Van Westen, CJ;	Urban multi-hazard risk analysis using GIS and remote sensing: a case study from Kohima town, Nagaland India	ACRS 2005: proceedings of the 26th Asian conference on remote sensing, ACRS 2005, 7-11 November 2005, Hanoi, Vietnam. Hanoi: 26th Asian Conference on Remote Sensing and 2nd Asian Space Conference, volume 1. ISBN: 978-1-60423-751-1. pp. 603-611				2005	ACRS	https://webapps.itc.utwente.nl/librarywww/papers_2005/msc/ereg/khatsu.pdf	Not Available
Fleischhauer, Mark; Greiving, Stefan; Schlusemann, Benedikt; Schmidt-Thomé, Philipp; Kallio, Hilkka; Tarvainen, Timo; Jarva, Jaana;	Multi-risk assessment of spatially relevant hazards in Europe	ESPON, ESMG symposium, Nürnberg	14			2005		https://www.researchgate.net/profile/Philipp_Schmidt-Thome/publication/255667455_Multi-risk_assessment_of_spatially_relevant_hazards_in_Europe/links/58b6c7a2a6fdcc2d14d6c5e6/Multi-risk-assessment-of-spatially-relevant-hazards-in-Europe.pdf	Disasters like earthquakes, coastal and river floods or nuclear power plant accidents show that physical structures and regional development more generally may be severely threatened by natural and technological hazards. The impacts of such hazardous events are often exacerbated by interactions with other hazards or by taking place in areas with a high economic and/or social vulnerability. All these conditions converge in particular places thus highlighting the need for a spatially oriented risk assessment. The task of such a risk assessment is not only to find out where risk related problems are located, but also to quantitatively or qualitatively determine the significance of risks (Smith, 2001). Thus, a spatially oriented risk assessment has to take into account all risks that are related to a specific area. This paper describes the Integrated Risk Assessment of Multi-Hazards approach and presents selected results of the European Spatial Planning Observation Network (ESPON) project 1.3.1 "The spatial effects and management of natural and technological hazards in general and in relation to climate change" which are based on this methodology.
Greiving, Stefan;	Multi-risk assessment of Europe's regions	Measuring vulnerability to natural hazards: Towards disaster resilient societies			210-26	2006	United Nations University Press Tokyo, New York	https://books.google.co.uk/books?hl=en&lr=&id=ICzUxp-BiSEC&oi=fnd&pg=PA210&dq=info:3HKwf7Mh0lwJ:scholar.google.com&ots=bn4tpZ3-RK&sig=DmcjzoNyRgFrUtmoNyFzrGI1jIw&redir_esc=y#v=onepage&q&f=false	This chapter presents a methodology for assessing the risk potential of a certain area by means of aggregating all spatially relevant risks that are caused by natural and technological hazards. The approach was elaborated and applied Europe-wide in the context of the project" Spatial effects of natural and technological hazard in general and in relation to climate change", which is part of the European Spatial Planning Observation Network (ESPON, see www. espon. lu). An aggregated hazard map, an integrated vulnerability map and an aggregated risk map are the key results of this research project. Vulnerability is recognised as the key component of risk and consists of two elements: degree of exposure to hazard, one the one hand, and coping capacity on the other.
Asprone, D; Jalayer, F; Prota, A; Manfredi, G;	Multi-Hazard Risk Assessment of Structures Subjected to Seismic Excitation and Blast for the Limit State of Collapse	AIP Conference Proceedings	1020	1	1677-1684	2008	AIP	https://s3.amazonaws.com/academia.edu.documents/43280162/MultiHazard_Risk_Assessment_of_Structure20160302-8715-3p4c29.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1534262702&Signature=ddbZUWTwUExpom1WY3vD8voPB2I%3D&response-content-disposition=inline%3B%20filename%3DMulti-hazard_risk_assessment_of_structur.pdf	Multi-hazard approach represents a convenient way to address structural reliability of a critical infrastructure. Objective of the present paper is to present a multi-hazard methodology for evaluation of the risk associated with the limit state of collapse for a reinforced concrete (RC) structure subject to both seismic and blast threats. Blast fragility can be defined as the probability of collapse given a blast event has taken place and its evaluation is here suggested via a Monte Carlo procedure, generating different possible blast configurations. For each blast scenario, the consequent damages occurring to the investigated structure are identified and an updating of the structure is then performed. The structural stability under gravity loading is then verified by employing a kinematic plastic limit analysis. The conditional probability of collapse or the blast fragility is then calculated as the mean value of the collapse indicator variable over the number of cases generated by the simulation procedure. Therefore, the seismic fragility is also determined via classical methods described elsewhere and the total risk of collapse is evaluated as the sum of blast and seismic contributions.
Thierry, Pierre; Stieltjes, Laurent; Kouokam, Emmanuel; Nguéya, Pierre; Salley, Paul M;	Multi-hazard risk mapping and assessment on an active volcano: the GRINP project at Mount Cameroon	Natural Hazards	45	3	429-456	2008	Springer	https://link.springer.com/article/10.1007/s11069-007-9177-3	To help improve the safety of its population faced with natural disasters, the Cameroon Government, with the support of the French Government, initiated a programme of geological risk analysis and mapping on Mount Cameroon. This active volcano is subject to a variety of hazards: volcanic eruptions, slope instability and earthquakes. Approximately 450,000 people live or work around this volcano, in an area which includes one of Cameroon's main economic resources. An original methodology was used for obtaining the information to reply to questions raised by the authorities. It involves several stages: identifying the different geological hazard components, defining each phenomenon's threat matrix by crossing intensity and frequency indices, mapping the hazards, listing and mapping the exposed elements, analysing their respective values in economic, functional and strategic terms, establishing typologies for the different element-at-risk groups and assessing their vulnerability to the various physical pressures produced by the hazard phenomena, and establishing risk maps for each of the major element-at-risk groups (population, infrastructures, vegetation, atmosphere). At the end of the study we were able (a) to identify the main critical points within the area, and (b) provide quantified orders of magnitude concerning the dimensions of the risk by producing a plausible eruption scenario. The results allowed us to put forward a number of recommendations to the Cameroon Government concerning risk prevention and management. The adopted approach corresponds to a first level of response to the authorities. Later developments should make it possible to refine the quality of the methodology.
Bovolo, C Isabella; Abele, Simon J; Bathurst, James C; Caballero, David; Ciglan, Marek; Eftichidis, George; Simo, Branislav;	A distributed framework for multi-risk assessment of natural hazards used to model the effects of forest fire on hydrology and sediment yield	Computers & Geosciences	35	5	924-945	2009	Elsevier	https://www.staff.ncl.ac.uk/isabella.bovolo/Bovolo-et-al-MEDIGRID.pdf	Within the European Commission-funded MEDIGRID project, Grid computing technology is used to integrate various natural hazard models and data sets, maintained independently at different centres in Europe, into a single system, accessible to users over the internet. Each centre forms a process (application) or data storage node and has been fitted with the Globus toolkit, which provides the distributed computing environment functionality that is required for the system set up. In addition, several Grid data management components were developed to allow the system to operate on different computing platforms. Access to the data and application management services is enabled through a Grid Portal. A series of portlets enable users to access the system, providing a personalised interface to the Grid. Integration of the individual models required them to be modified as web services, so as to be run remotely over the internet. As the models have different data characteristics, a common data format was adopted for creating harmonised data sets and allowing the exchange of data between the models. As an example, the Fire Spread Engine model is used to derive a map of areas that have been burnt by fire. This forms an input to the SHETRAN hydrology, soil erosion and landslide model, which in turn could provide data for other models such as vegetation regeneration. The use of the system is demonstrated for a site in south-west Spain where a large forest fire occurred on 2 August 2003. The MEDIGRID system marks an advance in the integration of independently constructed models to provide improved hazard assessment technology.

Marzocchi, W; Mastellone, Maria Laura; Novelli, P; Romeo, E; Gasparini, P;	Principles of multi risk assessment	EU Report				2009	EUROPEAN COMMISSION-DIRECTORATE GENERAL FOR RESEARCH & INNOVATION	https://cordis.europa.eu/docs/publications/1060/106097581-6_en.pdf	In this document, we propose a new quantitative procedure for multi-risk assessment that makes easier the comparison among different threats and accounts for possible triggering effects. We consider only the major threats typical for Southern Europe, which were the objectives of the EC FP6 NaRaS (Natural Risk Assessment) Project. Forest fires, snow avalanches, wind storms, heat waves are not specifically considered, although the general methodology we propone can be applied to evaluate risk related to these adverse events. In this part of the document, a clarification of the used terminology and a homogenization of the concepts used by the scientists and practitioners in the different risks areas are proposed. This effort does not aim at providing 'the solution' of the lack of homogeneity in terminology, but just at being a useful reference to clarify the meaning of the terms used here. At the end of part 1, we report the principles and rationales that stand behind our procedure for multi-risk assessment. In part 2, a short description of the most advanced procedures generally adopted to estimate individually natural and anthropogenic risks representing major threats for Southern Europe is provided. In part 3, we tackle directly the problem of multi-risk assessment applying innovative procedures and protocols to the case study of a town close to Naples (Casalnuovo). The multi-risk problem is split in two distinct phases: in a first phase, the whole set of risks is homogenized to facilitate their comparison ranking; in the second phase, we explore in detail possible "triggering" effects, showing how they can increase significantly the risk in a specific site. We want to underline that the logical sequence of the multi-risk procedure is contained in Parts 1 and 3, which are self-consistent. Part 2 contains several details on the actual way to compute different parameters. Anyway it can be omitted by readers who are interested only in the logical process we have followed.
Lari, Serena;	Multi scale heuristic and quantitative multi-risk assessment in the Lombardy region, with uncertainty propagation					2009	Thesis (PhD), Universita degli Studi di Milano Bicocca	https://scholar.google.co.uk/scholar?hl=en&as_sdt=1%2C5&q=Multi+scale+heuristic+and+quantitative+multi-risk+assessment+in+the+Lombardy+region%2C+with+uncertainty+propagation&btnG=	In this thesis, some methodologies for multi-risk assessment are presented, that can be applied to regional or local scale. At the local scale, the problem of uncertainty propagation in risk assessment is treated, testing different methodology for calculation. The work is organised in four parts: 1. Multi risk analysis at the regional scale in Lombardy (PRIM project, 2007). The methodology integrates information with different degree of accuracy into an indicator based approach, in order to develop a regional scale multirisk assessment and to identify "hot spot" risk areas for more detailed analysis. Eventually, the sensitivity of weights is investigated, and the effect on risk assessment of different individual attitudes and perception (i.e., expert, social, political, risk aversion). 2. Quantitative multi risk assessment (QRA) at the local scale on the hot spots, for lower Valtellina and the area of Brescia and lower Val Trompia, Val Sabbia, and Valcamonica. The methodology is based on the use of historical data and modelling to assess for each threat the expected number of casualties and the expected economic damage. 3. Quantitative risk assessment (QRA) for floods, earthquakes and industrial accidents in the area of Brescia (420 km2), with uncertainty propagation analysis. Frequency-damage curves were calculated. Three methods were used and compared to calculate the uncertainty of the expected economic losses: Monte Carlo Simulation, First Order Second Moment approach, and Point Estimate. 4. Realization of a tool based on a system of indicators aimed at assigning a priority for the realization of new mitigation works, at the evaluation of efficacy of existent works, and at the comparison of different alternatives for the same risk scenario. Indicators are referred to the risk scenario, to the most recent and most significant event occurred in the analysed area, to the planning stage of the work, and to the technical characteristics of realization and maintenance of the work itself.
Van Westen, CJ; Quan Luna, B; Vargas Franco, R; Malet, JP; Jaboyedoff, M; Horton, P; Kappes, M;	Development of training materials on the use of geo-information for multi-hazard risk assessment in a mountainous environment	Proceedings of the Mountain Risks International Conference, Firenze, Italy			24-26	2010		https://www.researchgate.net/profile/CJ_Westen/publication/234139496_Development_of_training_materials_on_the_use_of_geo_-_information_for_multi_-_hazard_risk_assessment_in_a_mountainous_environment/links/0912f50f86e5713aeb000000.pdf	The analysis of multi-hazard risk requires the use of models that are very data demanding. Data is needed of the areas that might be affected and the characteristics of the hazard, but also of the elements at risk that might be impacted, and their vulnerability. In the framework of two European projects (FP6-PEOPLE-2006-ITN Marie curie Mountain risks and FP7 SafeLand) a training package has been developed on the use of spatial information for the assessment and management of mountain risks. This training package explains the procedures to collect, analyze and evaluate spatial information for risk assessment from natural hazards in a mountainous environment. It aims at researchers and practitioners that have to carry out risk assessments at a medium scale, and use the risk information in disaster risk reduction planning. The training package guides the participants through the entire process of risk assessment, on the basis of a case study of an area exposed to multiple hazards in Barcelonnette, France. In order to achieve maximum applicability the training package is made for use with Open Source software. Three-dimensional stereoscopic image interpretation using images downloaded from Google Earth is used to familiarize the participants with the hazard phenomena. These are then used in either a statistical or heuristic approach for modelling the initiation areas for landslides, debris flows, snow avalanches and rockfalls. The source areas are used for run-out modelling on a medium scale using a routing-spreading model and the results are converted into impact maps. Flood hazard assessment is done using a 1D-2D flood propagation model and flood impulse is calculated for different return periods. The source maps and run-out maps for mass movements and the flood maps are then used in a quantitative multi-hazard risk assessment, by calculating the exposed elements at risk, the temporal and spatial probability and the vulnerability of the elements at risk. Also emphasis is given to the evaluation of uncertainty in the risk assessment process. A qualitative method for multi-hazard risk assessment is also included, using Spatial Multi-Criteria Evaluation, in which a hazard index and a vulnerability index are generated. The final part of the training package deals with the use of risk information for disaster risk management, e.g. by incorporating the risk information in preparedness planning, cost-benefit analysis for the planning of remedial measures, and land use zoning.
Asprone, D; Jalayer, F; Prota, A; Manfredi, G;	Proposal of a probabilistic model for multi-hazard risk assessment of structures in seismic zones subjected to blast for the limit state of collapse	Structural Safety	32	1	25-34	2010	Elsevier	https://www.sciencedirect.com/science/article/pii/S016747300900037X	It is desirable to verify the structural performance based on a multi-hazard approach, taking into account the critical actions the structure in question could be subjected to during its lifetime. This study presents a proposal for a probabilistic model for multi-hazard risk associated with the limit state of collapse for a reinforced concrete (RC) structure subjected to blast threats in the presence of seismic risk. The annual risk of structural collapse is calculated taking into account both the collapse caused by an earthquake event and the blast-induced progressive collapse. The blast fragility is calculated using a simulation procedure for generating possible blast configurations, and verifying the structural stability under gravity loading of the damaged structure, using a kinematic plastic limit analysis. As a case study, the blast and seismic fragilities of a generic four-storey RC building located in seismic zone are calculated and implemented in the framework of a multi-hazard procedure, leading to the evaluation of the annual risk of collapse.
Lozoya, Juan Pablo; Sarda, Rafael; Jiménez, José A;	A methodological framework for multi-hazard risk assessment in beaches	Environmental science & policy	14	6	685-696	2011	Elsevier	https://www.sciencedirect.com/science/article/pii/S1462901111000682	Beach management has traditionally concentrated on recreational uses and geomorphologic processes, overlooking environmental values. Traditional risk analysis also overlooks environmental services focusing on socio-economic damages and only accounting for a part of the total risk. To overcome this situation, a systemic approach dealing with ecological and social dimensions is required. This paper proposes a risk analysis framework in which coastal hazards and beach ecosystem services are jointly considered. The first phase consists of the definition of the risk profile. This is done by building the beach Pathway of Effect, where links between coastal hazards and ecosystem services are identified following the DPSIR approach. The second phase, risk assessment, includes risk valuation and hazard prioritization, which will help managers to decide where to allocate resources to cope with hazards affecting beach functionality. The methodology was validated at S'Abanell beach (Spanish Mediterranean coast), which provides several ecosystem services and is subjected to a variety of hazards.
Schmidt, Jochen; Matcham, Iain; Reese, Stefan; King, Andrew; Bell, Rob; Henderson, Roddy; Smart, Graeme; Cousins, Jim; Smith, Warwick; Heron, Dave;	Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling	Natural Hazards	58	3	1169-1192	2011	Springer	https://link.springer.com/article/10.1007/s11069-011-9721-z	This paper introduces a generic framework for multi-risk modelling developed in the project 'Regional RiskScape' by the Research Organizations GNS Science and the National Institute of Water and Atmospheric Research Ltd. (NIWA) in New Zealand. Our goal was to develop a generic technology for modelling risks from different natural hazards and for various elements at risk. The technical framework is not dependent on the specific nature of the individual hazard nor the vulnerability and the type of the individual assets. Based on this generic framework, a software prototype has been developed, which is capable of 'plugging in' various natural hazards and assets without reconfiguring or adapting the generic software framework. To achieve that, we developed a set of standards for treating the fundamental components of a risk model: hazards, assets (elements at risk) and vulnerability models (or fragility functions). Thus, the developed prototype system is able to accommodate any hazard, asset or fragility model, which is provided to the system according to that standard. The software prototype was tested by modelling earthquake, volcanic ashfall, flood, wind, and tsunami risks for several urban centres and small communities in New Zealand.
Bell, R; Glade, T;	Multi-hazard analysis in natural risk assessments	Landslides. Safety & security engineering series			01-Oct	2012		https://www.witpress.com/Secure/elibrary/papers/RISK04/RISK04018FU.pdf	Analysis of natural risks in mountainous regions includes several typical natural processes such as snow avalanches, floods, earthquakes, and different types of landslides. Separate investigations of single processes only might lead to a misjudgement of the general natural risks for these areas. To avoid this trap, natural risk assessments should not focus on a singular process but on multiple processes. Within this study a general methodology is developed to analyse natural risk for multiple processes. The method is applied in Bildudalur, NWIceland. In particular snow avalanches, rock falls and debris flows pose a hazard to the village of 300 inhabitants. The natural risk calculation is a function based on the input parameters hazard, vulnerability, probability of the spatial impact, probability of the temporal impact, probability of the seasonal occurrence and damage potential. First, the risk posed by each process is calculated. Results are presented as individual risk and object risk to life, and as economic risk for each process. Finally, single process risk maps are combined into multi-hazard risk maps. In the study area the highest risks throughout all of the analyses (individual risk to life, object risk to life and economic risk) are caused by debris flows, followed by snow avalanches and rock falls. It is demonstrated that risk varies heavily depending on the process considered. The total risk to life caused by snow avalanches, debris flows, rock falls and multi-hazards is 0.19, 0.63, 0.009 and 0.83 deaths per year, respectively. Multi-hazard approaches are not only valuable to get an overview on the overall risk but have also a high significance for planning effective countermeasures. It can be concluded that the newly developed method is applicable to other natural processes as well as to further catchments in Iceland as well as in other countries with different environmental settings.

Marzocchi, Warner; Garcia-Aristizabal, Alexander; Gasparini, Paolo; Mastellone, Maria Laura; Di Ruocco, Angela;	Basic principles of multi-risk assessment: a case study in Italy	Natural hazards	62	2	551-573	2012	Springer	https://link.springer.com/article/10.1007/s11069-012-0092-x	The assessment of the impact of different catastrophic events in a given area requires innovative approaches that allow risks comparison and that account for all the possible risk interactions. In the common practice, the risk evaluation related to different sources is generally done through independent analyses, adopting disparate procedures and time--space resolutions. Such a strategy of risks evaluation has some evident major drawbacks as, for example, it is difficult (if not impossible) to compare the risk of different origins, and the implicit assumption of independence of the risk sources leads to neglect possible interactions among threats and/or cascade effects. The latter may amplify the overall risk, and potentially the multi-risk index could be higher than the simple aggregation of single-risk indexes calculated considering each source as independent from the others. In this paper, we put forward some basic principles for multi-risk assessment, and we consider a real application to Casalnuovo municipality (Southern Italy), in which we face the problem to make different hazards comparable, and we highlight when and how possible interactions among different threats may become important.
Kappes, Melanie S; Keiler, Margreth; von Elverfeldt, Kirsten; Glade, Thomas;	Challenges of analyzing multi-hazard risk: a review	Natural hazards	64	2	1925-1958	2012	Springer	https://link.springer.com/article/10.1007/s11069-012-0294-2	Many areas of the world are prone to several natural hazards, and effective risk reduction is only possible if all relevant threats are considered and analyzed. However, in contrast to single-hazard analyses, the examination of multiple hazards poses a range of additional challenges due to the differing characteristics of processes. This refers to the assessment of the hazard level, as well as to the vulnerability toward distinct processes, and to the arising risk level. As comparability of the single-hazard results is strongly needed, an equivalent approach has to be chosen that allows to estimate the overall hazard and consequent risk level as well as to rank threats. In addition, the visualization of a range of natural hazards or risks is a challenging task since the high quantity of information has to be depicted in a way that allows for easy and clear interpretation. The aim of this contribution is to give an outline of the challenges each step of a multi-hazard (risk) analysis poses and to present current studies and approaches that face these difficulties.
Komendantova, N; Scolobig, A; Vinchon, C; Bengoubou-Valerius, M; Patt, A;	Institutional challenges for multi risk management: Comparative analysis of Naples, Italy, and Guadeloupe, France, case studies	EU Report (Matrix Project)				2012		http://pure.iiasa.ac.at/id/eprint/10167/1/XO-12-008.pdf	A variety of natural extreme events, including earthquakes, landslides, volcano eruptions, tsunamis, river floods, winter storms, wildfire, and coastal phenomena, threaten different regions in the world. European planners and policymakers, as well as scientists who inform their judgment, usually treat the hazards and risks related to such events separately from each other, without consideration of interdependencies between the different types of phenomena, as well as the importance of risk comparability. In this paper we focus on the institutional aspects of the management of multiple hazards. The benefits anticipated by the adoption of this approach are numerous, such as: 1. Multi-hazard risk assessment may have relevant policy implications and could emphasize, for example that efficient mitigation actions do not necessary need to be focused on reduction of the highest risk but on the risks that could be mostly reduced; 2. Addressing multiple hazards may lead to significant costs reductions and improvement in the efficiency of risk mitigation and management measures, comparatively to cases when hazards are treated separately from each other; 3. This approach may help to develop a better coordination and interfacing between different specialized authorities and agencies which each deal with specific hazards or risks without developing an overview of the knock-on, domino and cascading effects (EN 2009:28).
Serlet, Alyssa;	A critical analysis and proposal of a conceptual multi-hazard framework for natural hazard mitigation and adaptation in the EU policy framework					2012		https://sapientia.ualg.pt/bitstream/10400.1/2744/1/Thesis_Alyssa%20Serlet_Erasmus%20Mundus%20Master%20of%20Science%20in%20Ecohydrology.pdf	The assessment and management of natural hazards has received a greater attention in the European Union during the last years. This can be explained by an increase in disastrous events in the EU due to natural hazards which resulted in tremendous economic losses and loss of human lives. The key to decrease impacts is to address the vulnerability of our communities by using mitigation and adaptation measures. These hazard management strategies aim to build on resilience and sustainability. For not ignoring certain risks a multi-hazard approach is necessary. Policies and guidelines concerning the natural hazard assessment and management are set up on different scale levels. This research work provides a critical review on the current EU policy framework. The analysis addresses the weaknesses and challenges and leads to a proposal of a conceptual multi-hazard framework for natural hazard mitigation and adaptation in the EU policy framework. It is proposed to set up basic standards in a new directive and combine those with official EU guidelines to assist the Member States in achieving those standards.
Selva, Jacopo;	Long-term multi-risk assessment: statistical treatment of interaction among risks	Natural hazards	67	2	701-722	2013	Springer	https://link.springer.com/article/10.1007/s11069-013-0599-9	Multi-risk approaches have been recently proposed to assess and compare different risks in the same target area. The key points of multi-risk assessment are the development of homogeneous risk definitions and the treatment of risk interaction. The lack of treatment of interaction may lead to significant biases and thus to erroneous risk hierarchization, which is one of primary output of risk assessments for decision makers. In this paper, a formal statistical model is developed to treat interaction between two different hazardous phenomena in long-term multi-risk assessments, accounting for possible effects of interaction at hazard, vulnerability and exposure levels. The applicability of the methodology is demonstrated through two illustrative examples, dealing with the influence of (1) volcanic ash in seismic risk and (2) local earthquakes in tsunami risk. In these applications, the bias in single-risk estimation induced by the assumption of independence among risks is explicitly assessed. An extensive application of this methodology at regional and sub-regional scale would allow to identify when and where a given interaction has significant effects in long-term risk assessments, and thus, it should be considered in multi-risk analyses and risks hierarchization.
Neri, Marco; Le Cozannet, Gonéri; Thierry, Pierre; Bignami, Christian; Ruch, Joel;	A method for multi-hazard mapping in poorly known volcanic areas: an example from Kanlaon (Philippines)	Natural Hazards and Earth System Sciences				2013		http://www.vliz.be/en/imis?refid=229449	Hazard mapping in poorly known volcanic areas is complex since much evidence of volcanic and non-volcanic hazards is often hidden by vegetation and alteration. In this paper, we propose a semi-quantitative method based on hazard event tree and multi hazard map constructions developed in the frame of the FP7 MIAVITA project. We applied this method to the Kanlaon volcano (Philippines), which is characterized by poor geologic and historical records. We combine updated geological (long-term) and historical (short-term) data, building an event tree for the main types of hazardous events at Kanlaon and their potential frequencies. We then propose an updated multi-hazard map for Kanlaon, which may serve as a working base map in the case of future unrest. The obtained results extend the information already contained in previous volcanic hazard maps of Kanlaon, highlighting (i) an extensive, potentially active ~5 km long summit area striking north–south, (ii) new morphological features on the eastern flank of the volcano, prone to receiving volcanic products expanding from the summit, and (iii) important riverbeds that may potentially accumulate devastating mudflows. This preliminary study constitutes a basis that may help local civil defence authorities in making more informed land use planning decisions and in anticipating future risk/hazards at Kanlaon. This multi-hazard mapping method may also be applied to other poorly known active volcanoes.
Gruber, FE; Mergili, M;	Regional-scale analysis of high-mountain multi-hazard and risk in the Pamir (Tajikistan) with GRASS GIS	Natural Hazards and Earth System Sciences Discussions	1		1689-1747	2013	Citeseer	https://www.nat-hazards-earth-syst-sci.net/13/2779/2013/nhess-13-2779-2013.html	We present a model framework for the regional-scale analysis of high-mountain multi-hazard and -risk indicators, implemented with the open-source software package GRASS GIS. This framework is applied to a 98 300 km2 study area centred in the Pamir (Tajikistan). It includes (i) rock slides, (ii) ice avalanches, (iii) periglacial debris flows and (iv) lake outburst floods. First, a hazard indicator is assigned to each relevant object (steep rock face, glacier or periglacial slope, lake). This indicator depends on the susceptibility and on the possible event magnitude. Second, the possible travel distances, impact areas and, consequently, impact hazard indicators for all types of processes are computed using empirical relationships. The impact hazard indicators are finally superimposed with an exposure indicator derived from the type of land use, resulting in a raster map of risk indicators finally discretized at the community level. The analysis results are presented and discussed at different spatial scales. The major outcome of the study, a set of comprehensive regional-scale hazard and risk indication maps, shall represent an objective basis for the prioritization of target communities for further research and risk mitigation measures.
Komendantova, Nadejda; Mrzyglocki, Roger; Mignan, Arnaud; Khazai, Bijan; Wenzel, Friedemann; Patt, Anthony; Fleming, Kevin;	New Multi-Hazard and Multi-Risk Assessment Methods for Europe	EU Report (Matrix Project)				2013		http://matrix.gpi.kit.edu/downloads/MATRIX-D8.5.pdf	As populations increase, especially in urban areas, the number of people affected by natural hazards is growing, as many regions of the world subject to multiple hazards. Although the volume of geophysical, sociological and economic knowledge is expanding, so are the losses from natural catastrophes. The slow transfer of appropriate knowledge from theory to practice may be due to the difficulties inherent in the communication process from science to policy-making, including perceptions by stakeholders from disaster mitigation practice regarding the usability of any developed tools. As scientific evidence shows, decision-makers are faced with the challenge of not only mitigating against single hazards and risks, but also multiple risks, which must include the consideration of their interrelations. As the multi-hazard and risk concept is a relatively young area of natural risk governance, there are only a few multi-risk models and the experience of practitioners as to how to use these models is limited. To our knowledge, scientific literature on stakeholders' perceptions of multi-risk models is lacking. In this document, we identify the perceptions of two decision-making tools, which involve multi-hazard and multi-risk. The first one is a generic, multi-risk framework based on the sequential Monte Carlo method to allow for a straightforward and flexible implementation of hazard interactions which may occur in a complex system. The second is a decision-making tool that integrates directly input from stakeholders by attributing weights to different components and constructing risk ratings. Based on the feedback from stakeholders, we found that interest in multi-risk assessment is high, but that its application remains hampered by the complexity of the processes involved.
Sandri, Laura; Thouret, Jean-Claude; Constantinescu, Robert; Biass, Sébastien; Tonini, Roberto;	Long-term multi-hazard assessment for El Misti volcano (Peru)	Bulletin of volcanology	76	2	771	2014	Springer	https://link.springer.com/article/10.1007/s00445-013-0771-9	We propose a long-term probabilistic multi-hazard assessment for El Misti Volcano, a composite cone located <20 km from Arequipa. The second largest Peruvian city is a rapidly expanding economic centre and is classified by UNESCO as World Heritage. We apply the Bayesian Event Tree code for Volcanic Hazard (BET_VH) to produce probabilistic hazard maps for the predominant volcanic phenomena that may affect c.900,000 people living around the volcano. The methodology accounts for the natural variability displayed by volcanoes in their eruptive behaviour, such as different types/sizes of eruptions and possible vent locations. For this purpose, we treat probabilistically several model runs for some of the main hazardous phenomena (lahars, pyroclastic density currents (PDCs), tephra fall and ballistic ejecta) and data from past eruptions at El Misti (tephra fall, PDCs and lahars) and at other volcanoes (PDCs). The hazard maps, although neglecting possible interactions among phenomena or cascade effects, have been produced with a homogeneous method and refer to a common time window of 1 year. The probability maps reveal that only the north and east suburbs of Arequipa are exposed to all volcanic threats except for ballistic ejecta, which are limited to the uninhabited but touristic summit cone. The probability for pyroclastic density currents reaching recently expanding urban areas and the city along ravines is around 0.05 %/year, similar to the probability obtained for roof-critical tephra loading during the rainy season. Lahars represent by far the most probable threat (around 10 %/year) because at least four radial drainage channels can convey them approximately 20 km away from the volcano across the entire city area in heavy rain episodes, even without eruption. The Rio Chili Valley represents the major concern to city safety owing to the probable cascading effect of combined threats: PDCs and rockslides, dammed lake break-outs and subsequent lahars or floods. Although this study does not intend to replace the current El Misti hazard map, the quantitative results of this probabilistic multi-hazard assessment can be incorporated into a multi-risk analysis, to support decision makers in any future improvement of the current hazard evaluation, such as further land-use planning and possible emergency management.

Nadim, Farrokh; Liu, Zhongqiang; Vangelsten, Bjørn Vidar; Garcia, Alexander;	MATRIX Framework for multi-risk assessment	EU Report				2014		https://www.researchgate.net/profile/Phajm_Gelder/publication/323416567_MATRIX_Framework_for_multi-risk_assessment/links/5a9953d045851535bce1eb51/MATRIX-Framework-for-multi-risk-assessment.pdf	Many regions of the world are exposed to and affected by several types of natural hazard. The assessment and mitigation of the risk posed by multiple natural and man-made threats at a given location requires a multi-risk analysis approach that is able to account for the possible interactions among the threats, including possible cascade events. Performing quantitative multi-risk analysis using the methodologies available today presents many challenges (e.g., Kappes et al., 2012, Marzocchi et al., 2012). The risks associated with different types of natural hazards, such as volcanic eruptions, landslides, floods, and earthquakes, are often estimated using different procedures and the produced results are not comparable. Furthermore, the events themselves could be highly correlated (e.g., floods and debris flows could be triggered by an extreme storm event), or one type of threat could be the result of another (e.g., a massive landslide that is triggered by an earthquake, an example of a cascade effect). It is obvious that a mathematically rigorous approach to multi-risk assessment that addresses all the challenges named above, as well as the uncertainties in all steps of the analysis, will be complicated and require resources and expertise. On the other hand, in many situations, the decision-maker in charge of risk management can identify the optimum alternative among the possible options without undertaking a detailed, rigorous multi-risk analysis. Therefore, the framework recommended herein is based on a multi-level approach where the decision-maker and/or the risk analyst will not need to use a more sophisticated model than what is required for the problem at hand, or what would be reasonable to use given the available information.
van Westen, Cees; Kappes, Melanie S; Luna, Byron Quan; Frigerio, Simone; Glade, Thomas; Malet, Jean-Philippe;	Medium-scale multi-hazard risk assessment of gravitational processes	Mountain risks: From prediction to management and governance			201-231	2014	Springer	https://www.researchgate.net/profile/Thomas_Glade/publication/289887587_Medium-Scale_Multi-hazard_Risk_Assessment_of_Gravitational_Processes/links/56d8a6d308aee1aa5f802c5c/Medium-Scale-Multi-hazard-Risk-Assessment-of-Gravitational-Processes.pdf	This section discusses the analysis of multi-hazards in a mountainous environment at a medium scale (1:25,000) using Geographic Information Systems. Although the term 'multi-hazards' has been used extensively in literature there are still very limited approaches to analyze the effects of more than one hazard in the same area, especially related to their interaction. The section starts with an overview of the problem of multi-hazard risk assessment, and indicates the various types of multi-hazard interactions, such as coupled events, concatenated events, and events changing the predisposing factors for other ones. An illustration is given of multi-hazards in a mountainous environment, and their interrelationships, showing triggering factors (earthquakes, meteorological extremes), contributing factors, and various multi-hazard relationships. The second part of the section gives an example of a medium scale multi-hazard risk assessment for the Barcelonnette Basin (French Alps), taking into account the hazards for landslides, debris flows, rockfalls, snow avalanches and floods. Input data requirements are discussed, as well as the limitations in relation to the use of this data for initiation modeling at a catchment scale. Simple run-out modeling is used based on the energy-line approach. Problems related to the estimation of temporal and spatial probability are presented and discussed, and methods are shown for estimating the exposure, vulnerability and risk, using risk curves that expressed the range of expected losses for different return periods. The last part presents a software tool (Multi-Risk) developed for the analysis of multi-hazard risk at a medium scale.
Mignan, Arnaud; Wiemer, Stefan; Giardini, Domenico;	The quantification of low-probability–high-consequences events: part I. A generic multi-risk approach	Natural Hazards	73	3	1999-2022	2014	Springer	https://link.springer.com/article/10.1007/s11069-014-1178-4	Dynamic risk processes, which involve interactions at the hazard and risk levels, have yet to be clearly understood and properly integrated into probabilistic risk assessment. While much attention has been given to this aspect lately, most studies remain limited to a small number of site-specific multi-risk scenarios. We present a generic probabilistic framework based on the sequential Monte Carlo Method to implement coinciding events and triggered chains of events (using a variant of a Markov chain), as well as time-variant vulnerability and exposure. We consider generic perils based on analogies with real ones, natural and man-made. Each simulated time series corresponds to one risk scenario, and the analysis of multiple time series allows for the probabilistic assessment of losses and for the recognition of more or less probable risk paths, including extremes or low-probability–high-consequences chains of events. We find that extreme events can be captured by adding more knowledge on potential interaction processes using in a brick-by-brick approach. We introduce the concept of risk migration matrix to evaluate how multi-risk participates to the emergence of extremes, and we show that risk migration (i.e., clustering of losses) and risk amplification (i.e., loss amplification at higher losses) are the two main causes for their occurrence.
Desramaut, Nicolas; Réveillère, Arnaud; Wang, Justin; Gehl, Pierre; Marti, José;	The temporal dimension in multi-risk assessment: Effects of antecedent conditions and simultaneous events on the functional vulnerability of critical infrastructures.	New Multi-Hazard and Multi-Risk Assessment Methods for Europe				2014	GFZ Potsdam	http://pure.iiasa.ac.at/id/eprint/11194/1/XO-14-026.pdf#page=29	The MATRIX project aimed to develop methodologies to assess and compare some of the different natural risks that society has to face. Hence, in order to address multi-risks, one has to take into account the different interactions that might exist between the risks. These interactions, at the hazard and the vulnerability levels, might happen with different delays. It is, therefore, necessary to consider the temporal aspect of such interactions to properly assess multi-risk. The time dependencies might involve the following: • The repetition of events over time. • The concomitance of simultaneous-yet-independent events. • The succession of dependent phenomena (cascading events). The study of the time-dependency of vulnerability was the objective of work package 4 of the MATRIX project.
Scolobig, Anna; Komendantova, Nadejda; Patt, Anthony; Gasparini, Paolo; Di Ruocco, Angela; Garcia-Aristizabal, Alexander; Vinchon, Charlotte; Bengoubou-Valerius, Mendy; Monfort-Climent, Daniel; Wenzel, Friedmann;	Multi-risk assessment and governance: research into practice	New Multi-Hazard and Multi-Risk Assessment Methods for Europe				2014	GFZ Potsdam	https://core.ac.uk/download/pdf/52953013.pdf#page=59	In risk assessment research and policy, there is currently much debate on multi-type hazard and risk assessment and the definition and use of realistic scenarios. This debate has been evoked, not least, by several specific disasters in recent years that have resulted in extremely high numbers of fatalities and massive damage to properties and infrastructure. Recent examples are the Super Typhoon Haiyan, which hit the Philippines in November 2013, causing floods and landslides, and the Tohoku earthquake that struck Japan in March 2011, with the resulting devastating tsunami and nuclear accident. The research undertaken in MATRIX Work package 6 "Decision support for mitigation and adaptation in a multi-hazard environment" aimed at providing guidance on how to maximize the benefits arising from, and overcome the barriers to, the implementation of a multi-hazard and risk assessment approach within current risk management regimes. This reference report focuses on the synthesising the identified benefits and barriers to multihazard mitigation and adaption9. It is addressed to practitioners within the public/private sector working in communities exposed to multiple risks as well as to those active at the science-policy interface, thus including researchers, policy and decision makers in risk and emergency management.
Frigerio, SIMONE; Kappes, MELANIE S; Glade, THOMAS; Malet, JEAN-PHILIPPE;	MultiRISK: a platform for Multi-Hazard Risk Modelling and Visualisation					2014		http://www.mae-srl.it/allegati/3_22_692.pdf#page=34	interference and overlap of natural events both as triggering factors for both the domino effect. The classic methodological analysis methodologies for single process types are increasingly integrated frequently in Multi-Hazard systems, where the phenomena do not they are simply superimposed but are considered for several potential new interactions. The validation system it results to the realization of a MultiRISK platform prototype, based on a modeling module, of integrated modeling, and a Visualization module, for a concrete analysis by experts of the proposed results, through simple web services. The operational steps therefore have as their objective to offer a complete modeling system but at the same time one clear strategy for understanding and using the product data.
Gehl, Pierre; D'Ayala, Dina;	Integrated multi-hazard framework for the fragility analysis of roadway bridges	12th international conference on applications of statistics and probability in civil engineering (ICASP12), Vancouver, BC, Canada			Dec-15	2015		https://www.researchgate.net/profile/Pierre_Gehl/publication/280151254_Integrated_Multi-Hazard_Framework_for_the_Fragility_Analysis_of_Roadway_Bridges/links/55acc6a708ae481aa7ff71a5/Integrated-Multi-Hazard-Framework-for-the-Fragility-Analysis-of-Roadway-Bridges.pdf	This paper presents a method for the development of bridge fragility functions that are able to account for the cumulated impact of different hazard types, namely earthquakes, ground failures and fluvial floods. After identifying which loading mechanisms are affecting which bridge components, specific damage-dependent component fragility curves are derived. The definition of the global damage states at system level through a fault-tree analysis is coupled with a Bayesian Network formulation in order to account for the correlation structure between failure events. Fragility functions for four system damage states are finally derived as a function of flow discharge Q (for floods) and peak ground acceleration PGA (for earthquakes and ground failures): the results are able to represent specific failure configurations that can be linked to functionality levels or repair durations.
Jonckheere, Maxine; De Maeyer, Philippe; Deruyter, Greta;	A GIS-BASED FLOOD RISK TOOL FOR JAMAICA: THE FIRST STEP TOWARDS A MULTI-HAZARD RISK ASSESSMENT IN THE CARIBBEAN	Cartography and GIS				2015		https://www.researchgate.net/profile/Hanne_Glas/publication/285429188_A_GIS-based_flood_risk_tool_for_Jamaica_The_first_step_towards_a_multi-hazard_risk_assessment_in_the_Caribbean/links/5745772e08ae298602f76b8d/A-GIS-based-flood-risk-tool-for-Jamaica-The-first-step-towards-a-multi-hazard-risk-assessment-in-the-Caribbean.pdf	The Caribbean is known to be one of the most hazard-prone regions in the world. Hurricanes, flooding, storm surges, earthquakes and landslides lead to extensive material, human and economic losses in the region. The growing intensity of these hazards, combined with the consequences of climate change, rapidly increases the concern among decision makers. Although many researchers have succeeded in developing a single-hazard risk assessment that accurately estimates the risk of one type of hazard, the complexity of the relation between the different types of hazards is causing difficulties in the development of a multi-hazard risk analysis. This research aims to develop such a model. In a first step, the consequences of each type of hazard will be assessed individually, starting with riverine flooding. In the next step, the methodology used in this tool will be assessed and modified to fit other types of hazards. Finally, all single-hazard tools will be combined into a generic multi-hazard risk assessment tool for the region. In Jamaica, local governments use a flood risk methodology that is based on building water defence structures to evacuate the water as quickly as possible. This methodology, however, causes bigger damages downstream. Another method, based on minimizing the consequences of the overall flood, is already in use in many countries. In the Flemish region of Belgium, it is implemented in a tool called LATIS and has already proven to decrease losses after a flood event. Therefore, this risk-based methodology is used as the base for developing the Jamaican flood risk tool. The biggest concern during this research is the lack of data in the region. The methodology used, is based on the Flemish flood risk tool and the acquired data is thus very elaborate. During the implementation of the methods for the Caribbean, especially the lack of sufficient rainfall data and adequate damage functions has proven to result in less accurate damage and vulnerability maps.

Van Verseveld, HCW; Van Dongeren, AR; Plant, Nathaniel G; Jäger, WS; den Heijer, C;	Modelling multi-hazard hurricane damages on an urbanized coast with a Bayesian Network approach	Coastal Engineering	103		Jan-14	2015	Elsevier	https://ac.els-cdn.com/S0378383915000927/1-s2.0-S0378383915000927-main.pdf?_tid=49a3cdd9-d90c-4147-8474-702f5f5480e7&acdnat=1534261289_61249c3d46fc946c4bb007bc868dd2d2	Hurricane flood impacts to residential buildings in coastal zones are caused by a number of hazards, such as inundation, overflow currents, erosion, and wave attack. However, traditional hurricane damage models typically make use of stage-damage functions, where the stage is related to flooding depth only. Moreover, these models are deterministic and do not consider the large amount of uncertainty associated with both the processes themselves and with the predictions. This uncertainty becomes increasingly important when multiple hazards (flooding, wave attack, erosion, etc.) are considered simultaneously. This paper focusses on establishing relationships between observed damage and multiple hazard indicators in order to make better probabilistic predictions. The concept consists of (1) determining Local Hazard Indicators (LHIs) from a hindcasted storm with use of a nearshore morphodynamic model, XBeach, and (2) coupling these LHIs and building characteristics to the observed damages. We chose a Bayesian Network approach in order to make this coupling and used the LHIs 'Inundation depth', 'Flow velocity', 'Wave attack', and 'Scour depth' to represent flooding, current, wave impacts, and erosion related hazards.The coupled hazard model was tested against four thousand damage observations from a case site at the Rockaway Peninsula, NY, that was impacted by Hurricane Sandy in late October, 2012. The model was able to accurately distinguish 'Minor damage' from all other outcomes 95% of the time and could distinguish areas that were affected by the storm, but not severely damaged, 68% of the time. For the most heavily damaged buildings ('Major Damage' and 'Destroyed'), projections of the expected damage underestimated the observed damage. The model demonstrated that including multiple hazards doubled the prediction skill, with Log-Likelihood Ratio test (a measure of improved accuracy and reduction in uncertainty) scores between 0.02 and 0.17 when only one hazard is considered and a score of 0.37 when multiple hazards are considered simultaneously. The LHIs with the most predictive skill were 'Inundation depth' and 'Wave attack'. The Bayesian Network approach has several advantages over the market-standard stage-damage functions: the predictive capacity of multiple indicators can be combined; probabilistic predictions can be obtained, which include uncertainty; and quantitative as well as descriptive information can be used simultaneously.
Davide, Murgese; Giorgio, Giraudo; Daniela, Testa; Giulia, Airoldi; Roberto, Cagna; Mauro, Bugnano; Sara, Castagna;	Multi-risk Assessment of Cuneo Province Road Network	Engineering Geology for Society and Territory-Volume 6			657-661	2015	Springer	https://link.springer.com/chapter/10.1007/978-3-319-09060-3_117	Natural risk assessment for urban areas and infrastructures is important for the definition of management and prevention plans against consequences of natural events. In this paper we present the results of a multi-risk assessment for the Cuneo Province road network. The study defined specific risk levels with regard to landslides, floods, torrential floods, debris-flows, snow-avalanches, earthquakes and forest fires. Consequences for infrastructures were assessed by quantifying exposed elements value and vulnerability. All acquired data are then combined in order to produce specific hazard and risk maps. Specific risk levels were then processed to produce a multi-risk map for the Cuneo province road network. Landslide runout was numerically simulated in a GIS environment, for a comparison with hazard assessment results obtained following the methodology here proposed. Multi-risk assessment represents a valuable tool for enhancing scheduling activities related to the implementation of mitigation structure/measures and for supporting the coordination of risk management procedures at a cross border level.
Liu, Zhongqiang; Nadim, Farrokh; Garcia-Aristizabal, Alexander; Mignan, Arnaud; Fleming, Kevin; Luna, Byron Quan;	A three-level framework for multi-risk assessment	Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards	9	2	59-74	2015	Taylor & Francis	https://www.tandfonline.com/doi/abs/10.1080/17499518.2015.1041989	The effective management of the risks posed by natural and man-made hazards requires all relevant threats and their interactions to be considered. This paper proposes a three-level framework for multi-risk assessment that accounts for possible hazard and risk interactions. The first level is a flow chart that guides the user in deciding whether a multi-hazard and risk approach is required. The second level is a semi-quantitative approach to explore if a more detailed, quantitative assessment is needed. The third level is a detailed quantitative multi-risk analysis based on Bayesian networks. Examples that demonstrate the application of the method are presented.
Eshrati, Leila; Mahmoudzadeh, Amir; Taghvaei, Masoud;	Multi hazards risk assessment, a new methodology	International Journal of Health System and Disaster Management	3	2	79	2015	Medknow Publications	http://www.ijhsdm.org/article.asp?issn=2347-9019;year=2015;volume=3;issue=2;spage=79;epage=88;aulast=Eshrati	Multi-hazards pose a serious threat to human life. It can cause considerable damages. The evaluation of the expected losses due to multi-hazards requires a risk assessment. Multi-hazards risk assessment allow the identification of the most endangered areas and suggest where further detailed studies have to be carried out. Aim: This study aims to give a new methodology for Multi-hazard risk assessment that makes easier the comparability analysis of vulnerability for different hazards and accounts for possible triggering (domino) effects. Materials and Methods: Methods used in this paper are based on theoretical approach and documentation. Two types of hazards will be assessed, namely earthquake and fire following earthquake. Statistical Analysis: Semi-quantitative and quantitative approach would assess risk rates at both regional and local levels. Result: In this study, representation of a new methodology for multi-hazards risk assessment includes determination of a model with parameters, consideration of the indicator-based pattern of vulnerability assessment that selected of all the relevant indicators and presented new classification of indicators based on comparison to different hazards and possible triggering (domino) effects. This means a potential multi-hazard indicator could be higher than the simple aggregation of single risk indicators calculation. Conclusion: The focus is on establishing a general overview of the emerging issues, and indicating how hazard relations can be considered in multi-hazard studies. The hazard relation is identified and studied by means of a new method and the overlay of hazard areas to determine overlaps in final multi-hazards map.
Appelquist, Lars Rosendahl; Halsnæs, Kirsten;	The Coastal Hazard Wheel system for coastal multi-hazard assessment & management in a changing climate	Journal of coastal conservation	19	2	157-179	2015	Springer	https://link.springer.com/article/%2010.1007%2Fs11852-015-0379-7	This paper presents the complete Coastal Hazard Wheel (CHW) system, developed for multi-hazard-assessment and multi-hazard-management of coastal areas worldwide under a changing climate. The system is designed as a low-tech tool that can be used in areas with limited data availability and institutional capacity and is therefore especially suited for applications in developing countries. The CHW constitutes a key for determining the characteristics of a particular coastline, its hazard profile and possible management options, and the system can be used for local, regional and national hazard screening and management. The system is developed to assess the main coastal hazards in a single process and covers the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. The system was initially presented in 2012 and based on a range of test-applications and feedback from coastal experts, the system has been further refined and developed into a complete hazard management tool. This paper therefore covers the coastal classification system used by the CHW, a standardized assessment procedure for implementation of multi-hazard-assessments, technical guidance on hazard management options and project cost examples. The paper thereby aims at providing an introduction to the use of the CHW system for assessing and managing coastal hazards.
Jaimes, Miguel A; Reinoso, Eduardo; Esteva, Luis;	Risk analysis for structures exposed to several multi-hazard sources	Journal of Earthquake Engineering	19	2	297-312	2015	Taylor & Francis	https://www.researchgate.net/profile/Luis_Esteva/publication/258728017_Seismic_Vulnerability_of_Building_Contents_for_a_Given_Occupancy_Due_to_Multiple_Failure_Modes/links/54b7b7670cf2e68eb28042bd/Seismic-Vulnerability-of-Building-Contents-for-a-Given-Occupancy-Due-to-Multiple-Failure-Modes.pdf	A criterion for the estimation of losses of a structure exposed to several hazards is presented. It includes an expression to obtain the probability density function of the total damage that may be generated by the superposition of the effects of several simultaneous hazardous events that can be associated with a main primary event. It considers the probabilistic correlation of damage or failure of a structure due to the combined action of those simultaneous associated hazards. Finally, the intensities and times of occurrence of all relevant events of different natural origin that may significantly contribute to the risk for the structure of interest are taken into account, considering them as independent, with a negligible probability of producing simultaneous groups of significant associated hazardous events.
Gabriela, Guimarães Nobre;	MULTI-HAZARD FLOOD ASSESSMENT	MSc Thesis				2015	Kiel University	https://www.researchgate.net/profile/Gabriela_Guimaraes_Nobre/publication/311276821_Multi-Hazard_Flood_Assessment/links/58407e6e08ae8e63e61f82b6.pdf	Therefore, the aim of this master project study is to apply a range of statistical methodology for analysis of simultaneously occurring extreme hazards for coastal and urban flooding. The study area where this methodology was applied is the Elwood Catchment, which is a highly urbanised catchment located in the city of Port Phillip, Melbourne, Australia. Previous mapping has detected that the areas circumjacent the Elwood Canal are especially vulnerable to storm surge and sea level rise. The first part of the investigation deals with the marginal extreme distributions. Two approaches to extract extreme value series were applied and different probability distribution functions performed to fit the observed sample. Results obtained by the Generalised Pareto distribution demonstrate the ability of the Pareto family to model the return period of the extreme events. Advancing into multivariate extreme analysis, the prior aim consisted of an investigation regarding the asymptotic properties of an extremal dependence. As a weak positive asymptotic dependence between the bivariate extreme pairs was found, the Conditional method proposed by Heffernan and Tawn (2004) was adopted for the investigation. This approach is suitable to bivariate extreme values which are relatively unlikely to occur together. The results show that the probability of an extreme storm surge occurring during a one-hour intensity extreme precipitation event (or vice versa) can be twice as great as what would occur when assuming that the events are independent. Therefore, presuming independence between these two variables would result in future undervaluation of flooding risk at the study area.
Ming, Xiaodong; Xu, Wei; Li, Ying; Du, Juan; Liu, Baoyin; Shi, Peijun;	Quantitative multi-hazard risk assessment with vulnerability surface and hazard joint return period	Stochastic environmental research and risk assessment	29	1	35-44	2015	Springer	https://link.springer.com/article/10.1007/s00477-014-0935-y	Risk assessment plays an important role in disaster risk management. Existing multi-hazard risk assessment models are often qualitative or semi-quantitative in nature and used for comparative study of regional risk levels. They cannot estimate directly probability of disaster losses from the joint impact of several hazards. In this paper, a quantitative approach of multi-hazard risk assessment based on vulnerability surface and joint return period of hazards is put forward to assess the risk of crop losses in the Yangtze River Delta region of China. The impact of strong wind and flood, the two most prominent agricultural hazards in the area, is analyzed. The multi-hazard risk assessment process consists of three steps. First, a vulnerability surface, which denotes the functional relationship between the intensity of the hazards and disaster losses, was built using the crop losses data for losses caused by strong wind and flood in the recent 30 years. Second, the joint probability distribution of strong wind and flood was established using the copula functions. Finally, risk curves that show the probability of crop losses in this multi-hazard context at four case study sites were calculated according to the joint return period of hazards and the vulnerability surface. The risk assessment result of crop losses provides a useful reference for governments and insurance companies to formulate agricultural development plans and analyze the market of agricultural insurance. The multi-hazard risk assessment method developed in this paper can also be used to quantitatively assess multi-hazard risk in other regions.

Unobe, Ikwulono D; Sorensen, Andrew D;	Multi-hazard analysis of a wind turbine concrete foundation under wind fatigue and seismic loadings	Structural Safety	57		26-34	2015	Elsevier	https://www.sciencedirect.com/science/article/pii/S0167473015000570	In order to assess the vulnerability of structural systems to multiple hazards occurring simultaneously, it is necessary to carry out a multi-hazard analysis of the system. Over time, and under continuous, albeit varying cyclic loading from wind forces, there may be a reduction in the structural integrity of structural systems due to fatigue that increases their vulnerability to additional non-typical loads such as seismic and impact. This results in multi-hazard loading scenario not typically considered in current design. This paper aims to present research directed towards numerically estimating the possible effect of a seismic load (earthquake) on a wind turbine foundation that has undergone fatigue over time from constant exposure to wind forces. Although the practical effect of wind induced fatigue on foundations may be relatively small, its cumulative behavior over time reduces the foundation's capacity making it more susceptible to high impact loads such as seismic events. The analysis is done by considering the two loading events in a fault tree analytical procedure with each event taken as independent and combined together in series. Reliability analysis utilizing the computational tools MATLAB and finite element analysis (using ANSYS) is carried out to understand the behavior of the structure under each specific and combined load effects. The resulting analyses carried out using reliability analysis methods such as first order second moment reliability method and Monte Carlo simulations show a definite decrease in the foundation's performance and a concurrent increase in its probability of failure within the structure's design life. The results of this study will help understand the behavior of a simplified structure under the combined effect of these load types thus leading to a more accurate depiction of the actual behavior of structures.
Chen, ZhiQiang; Guo, Xuan;	Multi-Hazard Life-Cycle Analysis of Flood-Scour Effects on Seismic Bridge Performance	Structures Congress 2015			1370-1379	2015		https://ascelibrary.org/doi/abs/10.1061/9780784479117.117	A multi-hazard life-cycle methodology is used to assess the effects of flood-induced scour on the seismic system failure performance of bridge systems. Based on a case-study for a simple bridge system supported by shallow foundation systems, our results show that scour effects are time-varying: during the first 45 years, scour has insignificant effect on modifying the seismic vulnerability of the bridge in terms of two levels of system failures (i.e. extensive system damage or system collapse); after 65 years, scour dominates the cause to system failure; and while between 45 to 65 years, bridge scour and earthquakes jointly contribute to system failure. This result implies that caution is necessary for managing aging bridges serving in both seismicity and flooding active regions.
Bibi, T; Rahman, A Abdul;	A Review of Multi-Hazard Risk Assessment (mhra) Using 4d Dynamic Models	The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences	40		79	2015	Copernicus GmbH	https://s3.amazonaws.com/academia.edu.documents/40664261/A_REVIEW_OF_MULTI-HAZARD_RISK_ASSESSMENT_MHRA_USING_4D_DYNAMIC_MODELS.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1534930516&Signature=vnbHhZQ6bq1WJfD%2FNPZFeoZY7TY%3D&response-content-disposition=inline%3B%20filename%3DA_REVIEW_OF_MULTI-HAZARD_RISK_ASSESSMENT.pdf	This paper reviews the 4D dynamic models for multi natural hazard risk assessment. It is important to review the characteristic of the different dynamic models and to choose the most suitable model for certain application. The characteristic of the different 4D dynamic models are based on several main aspects (e.g. space, time, event or phenomenon etc.). The most suitable 4D dynamic model depends on the type of application it is used for. There is no single 4D Dynamic model suitable for all types of application. Therefore, it is very important to define the requirements of the 4D Dynamic model. The main context of this paper is spatio temporal modelling for multi hazards.
Kloos, Julia; Asare-Kyei, Daniel; Pardoe, Joanna; Renaud, Fabrice G;	Towards the development of an adapted multi-hazard risk assessment framework for the West Sudanian Savanna zone	UN University Working Paper 19				2015	UNU-EHS	http://collections.unu.edu/view/UNU:3137	West Africa is a region considered highly vulnerable to climate change and associated with natural hazards due to interactions of climate change and non-climatic stressors exacerbating the vulnerability of the region, particularly its agricultural system (IPCC, 2014b). Taking the Western Sudanian Savanna as our geographic target area, this paper seeks to develop an integrated risk assessment framework that incorporates resilience as well as multiple hazards concepts, and is applicable to the specific conditions of the target area. To provide the scientific basis for the framework, the paper will first define the following key terms of risk assessments in a climate change adaptation context: risk, hazard, exposure, vulnerability, resilience, coping and adaptation. Next, it will discuss the ways in which they are conceptualized and employed in risk, resilience and vulnerability frameworks. When reviewing the literature on existing indicator-based risk assessment for West African Sudanian Savanna zones, it becomes apparent that there is a lack of a systematic and comprehensive risk assessment capturing multiple natural hazards. The paper suggests an approach for linking resilience and vulnerability in a common framework for risk assessment. It accounts for societal response mechanism through coping, adaptation, disaster risk management and development activities which may foster transformation or persistence of the social ecological systems. Building on the progress made in multi-hazard assessments, the framework is suitable for analyzing multiple-hazard risks and existing interactions at hazard and vulnerability levels. While the framework is well grounded in theories and existing literature, and advances the knowledge by including and linking additional elements, it still remains to be tested empirically.
Gallina, Valentina;	An advanced methodology for the multi-risk assessment: an application for climate change impacts in the North Adriatic case study (Italy)	Doctoral Thesis				2015	Università Ca'Foscari Venezia	http://dspace.unive.it/handle/10579/5613	from long-term climate trends and disasters triggered by weather extremes. Till 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 trough 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 sensible 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
Liu, Baoyin;	Modelling multi-hazard risk assessment: a case study in the Yangtze River Delta, China	Doctoral Thesis				2015	University of Leeds	http://etheses.whiterose.ac.uk/11544/	Multi-hazard risk assessment (MHRA) has become a major concern in the risk study area, but existing approaches do not adequately meet the needs of risk mitigation planning. The main research gap in the existing approaches was identified that they cannot consider all hazard interactions when calculating possible losses. Hence, an improved MHRA model, MmhRisk-HI (Model for multi-hazard Risk assessment with a consideration of Hazard Interaction), was developed. This model calculates the possible loss caused by multiple hazards, with an explicit consideration of interaction between different hazards. A more complete perspective, the regional disaster system perspective, was selected as the basic theory, and two categories of multi-hazard risk expressions were combined in the model construction. Hazard identification, hazard analysis, hazard interaction analysis, exposure analysis and vulnerability analysis are the five basic modules of the developed model. The concept of hazard-forming environment was introduced into the MHRA research as the basis for hazard identification, hazard analysis, and hazard interaction analysis. The methods used for exposure analysis depend on the scale of the region to be addressed and the assessment units. A Bayesian Network was adopted to calculate the loss ratio in the vulnerability analysis. This developed model was applied into the Yangtze River Delta (YRD) and validated by comparison with an observed multi-hazard sequence. The validation results (simulation results are consistent with observed results in 76.36% of the counties, and the deviation of an estimated aggregate loss value from its actual value is less than 2.79%) show that this model can more effectively represent the real world, and that the outputs, possible loss caused by multiple hazards, obtained with the model are reliable. The outputs can additionally help to identify which area is at greatest risk (of loss), and allow a determination of the reasons that contribute to the greatest losses. Hence, it is a useful tool which can provide further information for planners and decision-makers concerned with risk mitigation.
Komendantova, Nadejda; Leroy, Cyril; Battaglini, Antonella;	Protection of Electricity Transmission Infrastructure from Natural Hazards: from Multi-Risk Assessment to Multi-Risk Governance.					2015		https://books.google.co.uk/books?hl=en&lr=lang_en&id=0KLRCgAAQBAJ&oi=fnd&pg=PA57&dq=Protection+of+Electricity+Transmission+Infrastructure+from+Natural+Hazards:+from+Multi-Risk+Assessment+to+Multi-Risk+Governance.&ots=9epZNOYmpM&sig=2kfyk6Rz3wQPLCAcNH4rr3cjQqw#v=onepage&q=Protection%20of%20Electricity%20Transmission%20Infrastructure%20from%20Natural%20Hazards%3A%20from%20Multi-Risk%20Assessment%20to%20Multi-Risk%20Governance.&f=false	The complexity of the task of protecting the electricity transmission system is increasing, taking into account multiple trans-boundary risks, factors influencing its vulnerability, grids' changing architecture and patterns of public opposition or support for upgrading existing lines or construction of new ones. Several best practices have been developed based on different research projects supported by the European Commission, addressing each phase of risk reduction for critical infrastructure, such as risk assessment, mitigation and ...
Burns, Patrick O;	Multi-hazard damage and loss assessment of bridge networks					2015		https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/mw22v7999	The overarching objective of this study is to examine and compare the vulnerabilities of bridges combining effects of earthquake-induced ground shaking, ground failure (e.g., landslides and lateral spreading), and tsunami inundation. A parametric study is performed to understand the sensitivity of economic loss and traffic capacity with respect to the demand, resistance, and dispersion of the fragility functions of bridges for the combined hazards. The predicted damage varies substantially based on the selected fragility functions for the bridge structure. Additionally, when ground failure models are considered, there is an overwhelming increase in bridge damage and economic loss estimates, reinforcing the need for more refined ground failure analyses to reduce epistemic uncertainty. The loss estimates are significantly sensitive to fragility parameters, particularly the resistance models, emphasizing the need to develop more specific and systematic fragility functions suitable for an entire bridge inventory. Economic loss estimates based on these cascading hazards are ultimately provided with the M9.0 Cascadia Subduction Earthquake Zone scenario.

Gehl, Pierre; Wanga, M; Taalaba, K; D'Ayalaa, D; Meddaa, F; Chenga, T;	Use of multi-hazard fragility functions for the multi-risk assessment of road networks	1st International Conference on Natural Hazards & Infrastructure: INCONHIC 2016				2016		https://www.researchgate.net/profile/Pierre_Gehl/publication/304789745_Use_of_multi-hazard_fragility_functions_for_the_multi-risk_assessment_of_road_networks/links/577b725d08aec3b74336221b/Use-of-multi-hazard-fragility-functions-for-the-multi-risk-assessment-of-road-networks.pdf	This paper presents a method for the multi-risk assessment of infrastructure systems, which concentrates on the harmonization of losses from different hazard types. Within a bridge, each type of structural component has a different exposure and susceptibility to different hazard types, such as earthquakes, ground failures and floods. Therefore hazard-specific component fragility curves are derived in order to quantify the occurrence of these failure modes for each combination of hazard and component. In parallel, functionality losses, which are crucial metrics for the performance assessment of infrastructure systems, are estimated for each component failure mode through an expert-based survey. System failure modes can then be defined from combinations of component damage states to lead to consistent levels functionality losses. The derived system fragility functions have then the potential to treat various multi-hazard configurations, such as independent or cascading events, while being directly associated to functionality losses. This approach is tested on a virtual yet realistic road network, where the effects of multi-risk interactions are quantified. The synergistic effect of joint hazard events is especially observed for extreme events. Network analysis tools and restoration models are finally applied in order to estimate the resilience of the infrastructure system.
Chen, HX; Zhang, Shuai; Peng, Ming; Zhang, Li Min;	A physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows	Engineering Geology	203		15-29	2016	Elsevier	https://www.sciencedirect.com/science/article/pii/S0013795215301058	Rainfall-induced slope failures and debris flows are two major hazards in mountainous areas. A physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows has been developed in this study. The platform enables prompt assessment of risks posed by regional rainfall-induced slope failures and debris flows across multiple catchments, which is required in landslide risk management in a large area. It considers the contribution of slope failures to debris flows and the scenario of a location impacted by multiple slope failures or debris flows or both. The contribution of slope failures to debris flows is considered by adding the increased amount of channel deposit from slope failures to the source material of debris flows. The platform is applied to a highway near the epicentre of the 2008 Wenchuan earthquake. The platform predicts the impact areas and runout distances of regional debris flows reasonably well. The risk assessment results indicate that both slope failures and debris flows pose a great danger to travellers along the road shortly after the earthquake due to the presence of a large amount of loose landslide deposits on steep terrains. The materials from the slope failures triggered during a storm substantially increase the channel deposit volume, leading to significantly increased debris flow volume and risk. A multi-hazard risk assessment approach is necessary to consider the scenario of a location impacted by multiple slope failures or debris flows or both, since assessing risks of slope failures and debris flows separately may underestimate the risk.
Chen, Lixia; van Westen, Cees J; Hussin, Haydar; Ciurean, Roxana L; Turkington, Thea; Chavarro-Rincon, Diana; Shrestha, Dhruba P;	Integrating expert opinion with modelling for quantitative multi-hazard risk assessment in the Eastern Italian Alps	Geomorphology	273		150-167	2016	Elsevier	https://www.sciencedirect.com/science/article/pii/S0169555X16306699	Extreme rainfall events are the main triggering causes for hydro-meteorological hazards in mountainous areas, where development is often constrained by the limited space suitable for construction. In these areas, hazard and risk assessments are fundamental for risk mitigation, especially for preventive planning, risk communication and emergency preparedness. Multi-hazard risk assessment in mountainous areas at local and regional scales remain a major challenge because of lack of data related to past events and causal factors, and the interactions between different types of hazards. The lack of data leads to a high level of uncertainty in the application of quantitative methods for hazard and risk assessment. Therefore, a systematic approach is required to combine these quantitative methods with expert-based assumptions and decisions. In this study, a quantitative multi-hazard risk assessment was carried out in the Fella River valley, prone to debris flows and flood in the north-eastern Italian Alps. The main steps include data collection and development of inventory maps, definition of hazard scenarios, hazard assessment in terms of temporal and spatial probability calculation and intensity modelling, elements-at-risk mapping, estimation of asset values and the number of people, physical vulnerability assessment, the generation of risk curves and annual risk calculation. To compare the risk for each type of hazard, risk curves were generated for debris flows, river floods and flash floods. Uncertainties were expressed as minimum, average and maximum values of temporal and spatial probability, replacement costs of assets, population numbers, and physical vulnerability. These result in minimum, average and maximum risk curves. To validate this approach, a back analysis was conducted using the extreme hydro-meteorological event that occurred in August 2003 in the Fella River valley. The results show a good performance when compared to the historical damage reports.
Johnson, Katie; Depietri, Yaella; Breil, Margaretha;	Multi-hazard risk assessment of two Hong Kong districts	International journal of disaster risk reduction	19		311-323	2016	Elsevier	https://www.sciencedirect.com/science/article/pii/S2212420916301935	The assessment of multi-hazard risks in urban areas poses particular difficulties due to the different temporal and spatial scales of hazardous events, and the potential interactions between hazards and socio-economic fragilities. Yet this exercise is important, as identifying the spatial distribution and concentration of risks in urban areas helps determine where and how preventive and corrective actions can reduce levels of vulnerability and exposure of urban populations. This article presents the results of a GIS-based assessment of present day risk to socio-natural hazards in two socio-economically distinct districts of Hong Kong (PRC) by utilizing indicators to describe the hazards and vulnerabilities. Hong Kong is a densely populated coastal metropolis exposed to multiple intense and potentially overlapping hydro-meteorological hazards, including heat waves, typhoons, and landslides. Mapping hazards and vulnerabilities in this urban area helps to visualize the spatial distribution and concentrations of risk located throughout the city, and thereby facilitate the tailoring of measures that can reduce risk at the very local scale. This approach has the potential of providing city planners and policy makers with visual guidance in prioritizing risk management and adaptation actions with respect to current and future risks existing in specific parts of the city, taking into account more than one hazard at the time. We found that the two districts considered have comparable and distributed levels of risk being both exposed to multiple hazards and notwithstanding the socio-economic groups. However, elements of criticality are potentially more widespread in the less wealthy parts of the city.
Harbitz, Carl B; Kaiser, Gunilla; Glimsdal, Sylfest; Jaedicke, Christian; Vafeidis, Athanasios T; Göthlich, Stephan E; Høydal, Øyvind Armand; Løvholt, Finn; Nadim, Farrokh;	Coastal inundation multi-hazard analysis for a construction site in Malaysia	International Journal of Risk Assessment and Management	19	01-Feb	142-164	2016	Inderscience Publishers (IEL)	https://www.inderscienceonline.com/doi/pdf/10.1504/IJRAM.2016.074444	Coastal inundation due to multiple hazards was analysed for a potential manufacturing plant at the Batu Kawan Industrial Park in Penang state, Malaysia. The analysis accounted for river floods, rainfall and flash floods, cyclones, tides, storm surges, sea-level rise, and tsunamis. Earthquakes, volcanoes, and the effects of climate changes were also briefly evaluated. The proposed site elevation of 2.60 m LSD (land survey data level; 30 cm above mean sea level) will probably be reached by both the 100-year flood and the 100-year combined tide and storm surge. The flooding risk is low, but coincidence with storm surge or high tide will aggravate the situation. Sea level rise over the next 100 years is assumed less than 0.55 m. The relative level for the other hazards was found to be lower. A further comparison of the various hazard levels is not meaningful without considering also the consequences (i.e., the risk).
Salman, Abdullahi M; Li, Yue;	Multihazard risk assessment of electric power systems	Journal of Structural Engineering	143	3	4E+06	2016	American Society of Civil Engineers	https://www.researchgate.net/profile/Abdullahi_Salman/publication/309343545_Multihazard_Risk_Assessment_of_Electric_Power_Systems/links/59b2b73caca2728472d50d3f/Multihazard-Risk-Assessment-of-Electric-Power-Systems.pdf	Electric power systems are susceptible to damage due to natural hazards such as hurricanes and earthquakes. Considerable effort has been made to develop methodologies for assessing the reliability of electric power systems under a single hazard such as hurricanes or earthquakes. However, there are parts of the world, such as the coastal areas of South Carolina, which are affected by both hazards. In such regions, more comprehensive risk assessment can be achieved when the focus is shifted from single-hazard to multihazard analysis. There is, therefore, a need to develop methods for quantifying the risk posed by the combined effect of multiple hazards on structures and infrastructure systems in these regions. This paper presents a framework for multihazard risk assessment of electric power systems subjected to seismic and hurricane wind hazards. The framework includes hazard and structural component vulnerability models, system reliability analysis, and multihazard risk assessment. A notional electric power network assumed to be located in Charleston, New York, and Seattle is used to demonstrate the proposed framework. The framework can be used for predisaster preparation, mitigation, and postdisaster response planning.
Padgett, Jamie E; Kameshwar, Sabarethinam;	Supporting life cycle management of bridges through multi-hazard reliability and risk assessment	Multi-hazard approaches to civil infrastructure engineering			41-58	2016	Springer	https://link.springer.com/chapter/10.1007/978-3-319-29713-2_3	Bridge infrastructure is susceptible to damage from a large host of threats including natural hazards, aging and deterioration, and demands that increase with population growth and urbanization. Life cycle management of bridge infrastructure requires an understanding of the relative contribution of these threats to the risk of damage or impending consequences, such as life cycle costs. Traditionally, limited attention has been given to understanding the hazard risk profile to bridge infrastructure, defined as the relative risks posed by multiple hazards and the synergies or trade-offs in protecting for different hazards. Furthermore, effective strategies are needed to jointly consider cumulative damage (e.g., from aging) and punctuated damage (e.g., from natural hazards) when assessing the influence of design or upgrade decisions that may mitigate risks from multiple potentially competing hazards. This chapter utilizes metamodels as an efficient strategy for developing parameterized time-dependent bridge fragilities for multiple hazards, thereby facilitating multi-hazard risk assessment and life cycle management. Threats considered in the case studies include earthquakes, hurricanes, aging and deterioration, and live loads. The applications illustrate the relative contribution of earthquake and hurricane hazards to the risk of losses given variation in bridge parameters, the influence of considering aging when assessing the hazard risk profile, and the impact of concurrent threats (e.g., truck and earthquake) on the life cycle risk.
Unnikrishnan, Vipin U; Barbato, Michele;	Performance-based hurricane engineering: A multi-hazard approach	Multi-hazard approaches to civil infrastructure engineering			337-356	2016	Springer	https://www.researchgate.net/profile/Michele_Barbato/publication/304371790_Performance-Based_Hurricane_Engineering_A_Multi-Hazard_Approach/links/5b5e3128458515c4b252219c/Performance-Based-Hurricane-Engineering-A-Multi-Hazard-Approach.pdf	Hurricanes are among the most costly natural hazards affecting communities worldwide. The landfall of a hurricane involves different hazard sources (i.e., wind, wind-borne debris, flood, and rain) that interact to generate the hazard scenario for a given structure. Thus, hurricanes can be viewed and must be analyzed as multi-hazard scenarios. In this chapter, a probabilistic Performance-Based Hurricane Engineering (PBHE) framework is used for the risk assessment of a residential structure subjected to hurricane hazard. The general multilayer Monte Carlo simulation (MCS) approach is specialized for the risk assessment of preengineered or non-engineered buildings. A case study of a hypothetical residential house subjected to the combined hazards of wind, wind-borne debris, flood, and rainfall is considered to illustrate the sequential procedure for the probabilistic risk assessment. The results obtained from the application example include the annual probability of exceedance of repair cost for the target residential building due to each hazard and their combined effects. These results highlight the importance of considering the interaction between different hazard sources.

Mukhopadhyay, Anirban; Hazra, Sugata; Mitra, Debasish; Hutton, C; Chanda, Abhra; Mukherjee, Sandip;	Characterizing the multi-risk with respect to plausible natural hazards in the Balasore coast, Odisha, India: a multi-criteria analysis (MCA) appraisal	Natural Hazards	80	3	1495-1513	2016	Springer	https://link.springer.com/article/10.1007/s11069-015-2035-9	Coastal zones are often prone to several natural hazards, and where the coastal zone has high population density and infrastructural assets, these hazards can render severe loss to both life and properties. The present paper reports a comprehensive assessment of the multi-hazard and multi-risk (keeping in view the population and assets exposed to multi-hazards) in the Balasore coast, situated in the state of Odisha, India, facing the Bay of Bengal immediately to its east. In most of the multi-hazard and multi-risk assessments, the importance of any one hazard in relation to others is often determined arbitrarily. To overcome this limitation, this work presents a multi-criteria analysis implemented on six hazards, namely coastal erosion, storm surge, sea level rise, coastal flooding, tsunami, and earthquake. The respective hazards were ranked according to their relative weight computed by pair-wise comparison, and the overall multi-hazard map of the coast was prepared using weighted overlay technique in GIS environment. In order to assess the exposure, population density and urban assets of the study area were also mapped. Finally, the population and urban density data were overlain on the multi-hazard map in order to derive the final map portraying the multi-risk of the Balasore coast. Coastal erosion and storm surge inundation are the two most substantial natural hazards that regularly affect this coast. It is also observed that hazard from the perspective of coastal erosion is spatially concentrated along the central part of the coast, while in the southern part, the effect of storm surge is higher. The area in and around Chandipur, which is situated in the central portion of the Balasore coast, has been found to have the highest multi-risk, which also happens to be a popular tourist destination.
Omidvar, Babak; Kivi, Hamid Karimi;	Multi-hazard failure probability analysis of gas pipelines for earthquake shaking, ground failure and fire following earthquake	Natural hazards	82	1	703-720	2016	Springer	https://link.springer.com/article/10.1007/s11069-016-2214-3	This paper was aimed to provide a quantitative failure probability analysis for multiple hazards. To achieve this, the 1724-kPa (250 Psi) gas pipelines of one of the district neighborhoods of Tehran metropolitan are analyzed to establish the probability of damage against earthquake, fire and liquefaction as a multi-hazard case study. The pipeline is approximately 4 km long and is divided into 14 segments, each of which has 300 m length. We used probabilistic analysis to identify the sources of earthquakes in the area. We calculated the probability that an earthquake with a given maximum magnitude will occur, the probability of liquefaction, that of post-earthquake fires, and the probability of pipeline failure for each segment. In order to take into account uncertainty in the location of epicenters, different points on the North Ray fault were randomly selected as epicenters, and the analysis was carried out for each point. Finally, based on the proposed method, the upper bound of failure probability of the main pipeline resulting from multiple hazards was estimated to be 65.7 %. If ductile pipelines were installed, this amount could be reduced to 32.7 % which shows a reduction of 51.79 % of the upper bound of failure probability.
Liu, Baoyin; Siu, Yim Ling; Mitchell, Gordon;	Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment	Natural Hazards and Earth System Sciences	16	2	629-642	2016	European Geosciences Union	https://www.nat-hazards-earth-syst-sci.net/16/629/2016/	This paper develops a systematic hazard interaction classification based on the geophysical environment that natural hazards arise from – the hazard-forming environment. According to their contribution to natural hazards, geophysical environmental factors in the hazard-forming environment were categorized into two types. The first are relatively stable factors which construct the precondition for the occurrence of natural hazards, whilst the second are trigger factors, which determine the frequency and magnitude of hazards. Different combinations of geophysical environmental factors induce different hazards. Based on these geophysical environmental factors for some major hazards, the stable factors are used to identify which kinds of natural hazards influence a given area, and trigger factors are used to classify the relationships between these hazards into four types: independent, mutex, parallel and series relationships. This classification helps to ensure all possible hazard interactions among different hazards are considered in multi-hazard risk assessment. This can effectively fill the gap in current multi-hazard risk assessment methods which to date only consider domino effects. In addition, based on this classification, the probability and magnitude of multiple interacting natural hazards occurring together can be calculated. Hence, the developed hazard interaction classification provides a useful tool to facilitate improved multi-hazard risk assessment.
Gehl, P; D'Ayala, D;	Development of Bayesian Networks for the multi-hazard fragility assessment of bridge systems	Structural Safety	60		37-46	2016	Elsevier	https://www.sciencedirect.com/science/article/pii/S0167473016000229	This article proposes an approach for the derivation of multi-hazard fragility functions, through the use of system reliability methods and Bayesian Networks. A bridge system is broken down into its constitutive components to isolate specific failure mechanisms and damage states at the component level. At the system level, the probability of occurrence of failure modes (i.e. various configurations of component damage states) is estimated thanks to a Bayesian analysis. These system fragility functions can then be directly related to harmonized functionality levels in order to get accurate predictions of downtime or traffic reduction. The applicability of the Bayesian Network formulation is compared to the matrix-based system reliability method, in terms of accuracy and computation time, while modeling strategies are proposed in the case of large systems with complex failure modes or multi-state components. Finally, the proposed approach is applied to a bridge system that is exposed to multiple hazard events (earthquakes, ground failures and floods): using the Bayesian framework, four functionality loss levels can be predicted with fragility surfaces that are expressed as a function of peak ground acceleration and flow discharge, taking into account multi-hazard interactions at the vulnerability level (i.e. cumulated damage events).
Clarke, Julie; O'Brien, Eugene J;	A multi-hazard risk assessment methodology, stress test framework and decision support tool for transport infrastructure networks	The 6th European Transport Research Conference: Moving Forward: Innovative Solutions for Tomorrow's Mobility, Warsaw, Poland, 18-21 April 2016				2016	Elsevier	https://researchrepository.ucd.ie/handle/10197/9128	Natural hazards can cause serious disruption to societies and their transport infrastructure networks. The impact of extreme hazard events is largely dependent on the resilience of societies and their networks. The INFRARISK project is developing a reliable stress test framework for critical European transport infrastructure to analyse the response of networks to extreme hazard events. The project considers the spatio-temporal processes associated with multi-hazard and cascading extreme events (e.g. earthquakes, floods, landslides) and their impacts on road and rail transport infrastructure networks. As part of the project, an operational framework is being developed using an online INFRARISK Decision Support Tool (IDST) to advance decision making approaches, leading to better protection of existing transport infrastructure. The framework will enable the next generation of European infrastructure managers to analyse the risk to critical road and rail infrastructure networks due to extreme natural hazard events. To demonstrate the overarching risk assessment methodology developed in the project, the methodology is demonstrated for two case studies, which comprise portions of the European TEN-T network; a road network in the region of Bologna, Italy and a rail network extending from Rijeka to Zagreb in Croatia. This paper provides an overview of the INFRARISK multi-hazard risk assessment methodology and a brief introduction to the case studies, as the project is currently ongoing.
Kwag, Shinyoung;	Probabilistic Approaches for Multi-Hazard Risk Assessment of Structures and Systems.					2016		https://repository.lib.ncsu.edu/bitstream/handle/1840.16/11436/etd.pdf?sequence=2	Performance assessment of structures, systems, and components for multi-hazard scenarios has received significant attention in recent years. However, the concept of multi-hazard analysis is quite broad in nature and the focus of existing literature varies across a wide range of problems. In some cases, such studies focus on hazards that either occur simultaneously or are closely correlated with each other. For example, seismically induced flooding or seismically induced fires. In other cases, multi-hazard studies relate to hazards that are not dependent or correlated but have strong likelihood of occurrence at different times during the lifetime of a structure. The current approaches for risk assessment need enhancement to account for multi-hazard risks. It must be able to account for uncertainty propagation in a systems-level analysis, consider correlation among events or failure modes, and allow integration of newly available information from continually evolving simulation models, experimental observations, and field measurements. This dissertation presents a detailed study that proposes enhancements by incorporating Bayesian networks and Bayesian updating within a performance-based probabilistic framework. The performance-based framework allows propagation of risk as well as uncertainties in the risk estimates within a systems analysis. Unlike conventional risk assessment techniques such as a fault-tree analysis, a Bayesian network can account for statistical dependencies and correlations among events/hazards. The proposed approach is extended to develop a risk-informed framework for quantitative validation and verification of high fidelity system-level simulation tools. Validation of such simulations can be quite formidable within the context of a multi-hazard risk assessment in nuclear power plants. The efficiency of this approach lies in identification of critical events, components, and systems that contribute to the overall risk. Validation of any event or component on the critical path is relatively more important in a risk-informed environment. Significance of multi-hazard risk is also illustrated for uncorrelated hazards of earthquakes and high winds which may result in competing design objectives. It is also illustrated that the number of computationally intensive nonlinear simulations needed in performance-based risk assessment for external hazards can be significantly reduced by using the power of Bayesian updating in conjunction with the concept of equivalent limit-state.
Fereshtehnejad, Ehsan; Shafieezadeh, Abdollah;	OPTIMAL RETROFIT DECISION-MAKING FOR BRIDGE SYSTEMS BASED ON MULTI-HAZARD LIFECYCLE COST ANALYSIS	Eleventh International Bridge and Structures Management Conference			160	2017		http://onlinepubs.trb.org/onlinepubs/circulars/ec224.pdf#page=166	Various types of hazards each with the potential to occur multiple times during the long service life of bridges may threaten the functionality of transportation systems and significantly impact the society. In hazard-prone areas, as the recovery time becomes longer, the likelihood of other hazard events occurring before the system is recovered increases. This can result in the accumulation of damage and higher vulnerability of the infrastructure. This study presents a multihazard life-cycle cost assessment framework to find optimal solutions for retrofit strategies. The possibility of multiple occurrences of multiple types of hazard incidents is probabilistically incorporated in the framework. This methodology accurately determines the expected life-cycle cost of hazard-induced consequences by comprehensively including direct and indirect incurred costs. The presented framework is applied to a realistic multispan reinforced concrete bridge in California that is exposed to flood and earthquake hazards. The total life-cycle cost of several practical retrofit strategies are evaluated and compared for a wide range of bridge service lives. A sensitivity analysis is also performed to characterize the impacts of several key variables on the expected life-cycle cost of the bridge and the optimal retrofit plans.
Garcia-Aristizabal, Alexander; Capuano, Paolo; Russo, Raffaella; Gasparini, Paolo;	Multi-hazard risk pathway scenarios associated with unconventional gas development: Identification and challenges for their assessment	Energy Procedia	125		116-125	2017	Elsevier	https://www.sciencedirect.com/science/article/pii/S1876610217335695	In this paper we summarize a number of risk pathway scenarios that are often claimed in literature as of priority for risk analyses in unconventional gas development. The resulting scenarios are structured in diagrams representing causal relationships between events. We argue that science is called to fill gaps regarding the main processes characterizing the involved events and defining the conditions under which their occurrence may be enhanced or inhibited. In this way, these scenarios can be more objectively parameterized, making their quantitative assessment a more feasible task and opening the way for the formulation of appropriate risk mitigation strategies.

Chulahwat, Akshat; Mahmoud, Hussam;	A combinatorial optimization approach for multi-hazard design of building systems with suspended floor slabs under wind and seismic hazards	Engineering Structures	137		268-284	2017	Elsevier	https://www.sciencedirect.com/science/article/pii/S0141029617303334	**The possibility of structures experiencing multiple hazards of different types during their service life has always been present. However, design of structures has primarily been geared towards addressing the most dominant hazard at the location of interest. In recent years, the design philosophy of structures has shifted towards a more holistic approach of addressing multiple hazards to ensure adequate performance under different loading scenarios.** This requires the utilization of new structural systems and the development of effective optimization methods that can address multiple hazards. In this study, a suspended floor slab-isolated structure is utilized as an optimization test system subjected to wind and seismic demands. To perform the optimization a new combinatorial optimization approach is proposed, which is a combination of two methods – Nelder-Mead and Coevolutionary Matrix Adaptation Evolution Strategy (CMA-ES). The two algorithms are integrated simultaneously to optimize three key design variables of the suspended slab system and to obtain a family of optimal solutions that can accommodate varying level of participation of each hazard. In doing so, a set of alternatives is provided to the designer to accommodate wide variations and combinations in hazards intensities. The results of the study highlight the effectiveness of tuning the suspended slab system to meet the wind and seismic performance objectives. The system is seen to be more effective in case of taller structures than shorter structures. For taller structures, the system can be optimized to improve performance under both wind and seismic hazards without significant trade-off on individual hazard performance. Furthermore, the system is seen to be more sensitive to wind loading than earthquake loading.
van Westen, Cees J; Greiving, Stefan;	Multi-hazard risk assessment and decision making	Environmental Hazards Methodologies for Risk Assessment and Management			31	2017	IWA Publishing	https://www.researchgate.net/profile/CJ_Westen/publication/317044185_Environmental_Hazards_Methodologies_for_Risk_Assessment_and_Management/links/5922d1400f7e9b9979459d03/Environmental-Hazards-Methodologies-for-Risk-Assessment-and-Management.pdf	Not Available (Book)
Pilkington, Stephanie F; Mahmoud, Hussam N;	Real-time Application of the Multihazard Hurricane Impact Level Model for the Atlantic Basin	Frontiers in Built Environment	3		67	2017	Frontiers	https://www.frontiersin.org/articles/10.3389/fbuil.2017.00067/full	Tropical cyclones are an example of a multihazard event with impacts that can highly vary depending on landfall location, wind speed, storm surge, and inland flooding from precipitation. These storms are typically categorized by their wind speed and pressure, while evacuation orders are typically given based on storm surge. The general public relies on these single hazard assessment parameters when attempting to understand the risk of an oncoming event. However, after the fact, these events are ranked by economic damage and death toll. Therefore, it is imperative that when these events are communicated to the public, during the forecast period, the multiple hazards are incorporated in terms the public can easily associate with, such as economic damage. This article provides an evaluation of the potential for real-time use of artificial neural networks, through the utilization of an already developed Hurricane Impact Level (HIL) Model, to forecast a range of economic damage from tropical cyclone events, during the 2015 and 2016 United States hurricane season. The HIL Model is built prior to the start of each season and simulated every 3 h, in conjunction with National Hurricane Center (NHC) issued advisories, for oncoming tropical cyclones forecasted to make landfall. Weaker and more common tropical cyclones have a less varied forecast and produce more accurate impact level (IL) predictions. More complicated and uncertain events, such as 2016 Hurricane Matthew, require the user's discretion in communicating varying landfall locations for a complex track forecast to the model. As NHC forecasts change with respect to both track and meteorological hazards affecting land, the estimated IL and the HIL model confidence will also change. In other words, if a track shifts to a more vulnerable location, or to more locations, or the meteorological hazards increase, the IL will subsequently increase. All tropical cyclones from the 2015 and 2016 seasons demonstrate the validity of the HIL Model with a forecast confidence of at least 60% for up to 30 h out from an impending landfall.
Mignan, Arnaud; Komendantova, Nadejda; Scolobig, Anna; Fleming, Kevin;	Multi-risk assessment and governance	Handbook of Disaster Risk Reduction and Management; Madu, CN, Kuei, CH, Eds			357-381	2017	World Scientific	https://www.worldscientific.com/doi/abs/10.1142/9789813207950_0014	Multi-risk assessment involves the inclusion of hazard and risk interactions within the modeling of the disaster risk chain. These interactions include more than one disastrous event at the same time, cascading events, and how changes in exposure and vulnerability arise over time, including as a result of previous events. At a first glance, multi-risk assessment appears to be a better means of approaching disaster risk reduction actions. However, it is hindered by a lack of knowledge about the fundamental physical processes involved, difficulties in comparing hazards and risks of different types and, especially, the topic of this chapter, barriers within risk governance for the successful implementation of necessary risk mitigation actions. Such barriers include a lack of standardization in terminology, a deficiency in expertise in the range of disciplines that are relevant to multi-risk reduction planning, inadequate resources, and biases and barriers in communication between the relevant public and private actors, as well as between researchers and policy-makers. This chapter details some of the social, institutional and scientific barriers that are associated with the full consideration of multi-risk governance, and provides some suggestions as to how these may be overcome.
Bernal, Gabriel A; Salgado-Gálvez, Mario A; Zuloaga, Daniela; Tristancho, Julián; González, Diana; Cardona, Omar-Darío;	Integration of probabilistic and multi-hazard risk assessment within urban development planning and emergency preparedness and response: Application to Manizales, Colombia	International Journal of Disaster Risk Science	8	3	270-283	2017	Springer	https://link.springer.com/article/10.1007/s13753-017-0135-8	The details of a multi-hazard and probabilistic risk assessment, developed for urban planning and emergency response activities in Manizales, Colombia, are presented in this article. This risk assessment effort was developed under the framework of an integral disaster risk management project whose goal was to connect risk reduction activities by using open access and state-of-the-art risk models. A probabilistic approach was used for the analysis of seismic, landslide, and volcanic hazards to obtain stochastic event sets suitable for probabilistic loss estimation and to generate risk results in different metrics after aggregating in a rigorous way the losses associated to the different hazards. Detailed and high resolution exposure databases were used for the building stock and infrastructure of the city together with a set of vulnerability functions for each of the perils considered. The urban and territorial ordering plan of the city was updated for socioeconomic development and land use using the hazard and risk inputs and determinants, which cover not only the current urban area but also those adjacent areas where the expansion of Manizales is expected to occur. The emergency response capabilities of the city were improved by taking into account risk scenarios and after updating an automatic and real-time post-earthquake damage assessment.
Sperotto, Anna; Molina, José-Luis; Torresan, Silvia; Critto, Andrea; Marcomini, Antonio;	Reviewing bayesian networks potentials for climate change impacts assessment and management: A multi-risk perspective	Journal of environmental management	202		320-331	2017	Elsevier	https://www.sciencedirect.com/science/article/pii/S0301479717307211	The evaluation and management of climate change impacts on natural and human systems required the adoption of a multi-risk perspective in which the effect of multiple stressors, processes and interconnections are simultaneously modelled. Despite Bayesian Networks (BNs) are popular integrated modelling tools to deal with uncertain and complex domains, their application in the context of climate change still represent a limited explored field. The paper, drawing on the review of existing applications in the field of environmental management, discusses the potential and limitation of applying BNs to improve current climate change risk assessment procedures. Main potentials include the advantage to consider multiple stressors and endpoints in the same framework, their flexibility in dealing and communicate with the uncertainty of climate projections and the opportunity to perform scenario analysis. Some limitations (i.e. representation of temporal and spatial dynamics, quantitative validation), however, should be overcome to boost BNs use in climate change impacts assessment and management.
Tyagunov, Sergey; Vorogushyn, Sergiy; Jimenez, Cristina Muñoz; Parolai, Stefano; Fleming, Kevin;	Multi-hazard fragility analysis for fluvial earthen dikes in earthquake and flood prone areas	Natural Hazards and Earth System Sciences				2017	Copernicus	https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-287/nhess-2017-287.pdf	The paper presents a methodological framework for multi-hazard fragility analyses for fluvial earthen dikes in earthquake and flood prone areas. The methodology and results are an integral part of the multi-hazard (earthquake-flood) 10 risk study implemented within the framework of the EU FP7 project MATRIX (New Multi-Hazard and Multi-Risk Assessment Methods for Europe) for the area around Cologne, Germany. The study area covers the Rhine River reach and adjacent floodplains between the gauges Andernach and Düsseldorf. Along this domain, the inhabited areas are partly protected by earthen embankments (dikes or levees), which may be prone to failure in case of exceptional floods and/or earthquakes. The main focus of the study is to consider the damage potential of the dikes within the context of the possible interaction between the two hazards. The fragility of the earthen dikes is analyzed in terms of liquefaction potential characterized by the factor of safety. Uncertainties in the geometrical and geotechnical dike parameters are considered by using a Monte Carlo approach. The damage potential of the earthen structures is presented in the form of a fragility surface showing the damage probability as a function of both seismic ground shaking and flood water level. The obtained results can be used for multi-hazard risk assessment in earthquake and flood prone areas and, in particular, are intended for comprehensive risk assessment in the area around the city of Cologne.
Pilkington, Stephanie; Mahmoud, Hussam;	Spatial and temporal variations in resilience to tropical cyclones along the United States coastline as determined by the multi-hazard hurricane impact level model	Palgrave Communications	3	1	14	2017	Nature Publishing Group	https://www.nature.com/articles/s41599-017-0016-1	The United States coastline, where over 50% the population lives, is vulnerable to hurricanes along the East and Gulf coasts. However, the question remains as to whether these two areas are equally resilient to a landfalling hurricane. In addition, while it is assumed that improvements in building codes, infrastructure protections, and changing policy over the past century have been effective in reducing the impacts to a community from historically extreme hurricane events, such an assumption is still to be validated. Here, a multi-hazard artificial neural network model is used to address these questions. The Hurricane Impact Level Model is the first prediction model to utilize machine-learning techniques (artificial neural networks) to established complex connections between all meteorological factors (wind, pressure, storm surge, and precipitation resulting in inland flooding) of a tropical cyclone and how those interact with the location of landfall to produce a certain level of economic damage. This model allows for a more all-encompassing assessment of how the impacts of tropical cyclones vary along the coastline. The Hurricane Impact Level Model was trained with historical tropical cyclone events from 1998 to present day, resulting in established locational associations to modern relevant building codes and mitigation practices. Simulating the meteorological factors from historical events allows for a new assessment of economic impact changes due to infrastructure improvements and policy adaptations over time. In essence, if Hurricane Sandy hit Florida instead of New York, it would have a lower economic impact due to lower population density and more stringent building codes, which the artificial neural network has associated with the latitudes and longitudes within the state of Florida. If the Galveston hurricane were to hit today, the seawall would not succeed in lowering the economic impact to the Texas coastline. Over the years, significant effort has been put in to improving the resiliency of the United States coastline, mainly in the southern states, but it has not been enough to counteract the effects of population growth within coastal counties.

Araya-Muñoz, Dahyann; Metzger, Marc J; Stuart, Neil; Wilson, A Meriwether W; Carvajal, Danilo;	A spatial fuzzy logic approach to urban multi-hazard impact assessment in Concepción, Chile	Science of the Total Environment	576		508-519	2017	Elsevier	https://www.sciencedirect.com/science/article/pii/S0048969716322434	Even though most cities are exposed to more than one hazard, local planners and decision-makers still have a limited understanding of the exposure and sensitivity to and the spatial distribution of hazards. We examine the impact of multiple hazards in the Concepción Metropolitan Area (CMA), Chile. A flexible methodology based on spatial fuzzy logic modelling was developed to explore the impact of weather-related hazards, including coastal flooding, fluvial flooding, water scarcity, heat stress, and wildfire. 32 indicators were standardised and then aggregated through a stepwise approach into a multi-hazard impact index. We find that all the municipalities in the CMA increased their level of impact between 1992 and 2002, due to a larger increase in the exposure rather than the modest decrease in sensitivity. Municipal sensitivity was driven mostly by changes in the population's age structure. Wildfires and water scarcity appeared to have the largest impact on all municipalities. Fuzzy modelling offered high flexibility in the standardisation and aggregation of indicators with diverse characteristics, while also providing a means to explore how the interaction of numerous indicators influenced the index. The resulting maps can help identify indicators, components, and hazards or combinations of hazards that most influence the impact on municipalities. The results can be used to improve and promote dialogue among policy-makers and stakeholders regarding prioritisation of resources for urban development in ways that can also reduce exposure and sensitivity and lower vulnerability to climate change. The methods presented can be adapted to other cities.
Gehl, Pierre;	Bayesian networks for the multi-risk assessment of road infrastructure	Doctotal Thesis				2017	UCL (University College London)	http://discovery.ucl.ac.uk/1546080/	The purpose of this study is to develop a methodological framework for the multi-risk assessment of road infrastructure systems. Since the network performance is directly linked to the functional states of its physical elements, most efforts are devoted to the derivation of fragility functions for bridges exposed to potential earthquake, flood and ground failure events. Thus, a harmonization effort is required in order to reconcile fragility models and damage scales from different hazard types. The proposed framework starts with the inventory of the various hazard-specific damaging mechanisms or failure modes that may affect each bridge component (e.g. piers, deck, bearings). Component fragility curves are then derived for each of these component failure modes, while corresponding functional consequences are proposed in a component-level damage-functionality matrix, thanks to an expert-based survey. Functionality-consistent failure modes at the bridge level are then assembled for specific configurations of component damage states. Finally, the development of a Bayesian Network approach enables the robust and efficient derivation of system fragility functions that (i) directly provide probabilities of reaching functionality losses and (ii) account for multiple types of hazard loadings and multi-risk interactions. At the network scale, a fully probabilistic approach is adopted in order to integrate multi-risk interactions at both hazard and fragility levels. A temporal dimension is integrated to account for joint independent hazard events, while the hazard-harmonized fragility models are able to capture cascading failures. The quantification of extreme events cannot be achieved by conventional sampling methods, and therefore the inference ability of Bayesian Networks is investigated as an alternative. Elaborate Bayesian Network formulations based on the identification of link sets are benchmarked, thus demonstrating the current computational difficulties to treat large and complex systems.
El Khoury Antoun, Jad;	Multi-Hazard Performance Assessment of High-Rise Buildings					2017		https://digitalcommons.lsu.edu/gradschool_theses/4368/	In the last few decades, there has been an important increase in building high-rise constructions in many cities around the world. Since they offer several benefits in populous areas in terms of space efficiency, economy and sustainability, tower buildings attracted practitioners and researchers to understand better their exclusive behavior and response to natural hazards (e.g., hurricanes, earthquakes). Because of their flexibility and their commonly limited damping, skyscrapers are more susceptible to wind and earthquake actions than low- and mid-rise buildings. Moreover, many locations are prone to multiple hazards; hence, it is important to understand thoroughly the structural behavior of structures undergoing the effect of each hazard separately in order to obtain better designs. In this study, the general methodology of performance-based loss assessment is applied to a hypothetical 74-story office building located in Miami, FL, and New Madrid, MO. Seismic hazard, wind hazard, and hurricane hazard are considered. The expected losses related to the seismic hazard are evaluated following the Performance-Based Earthquake Engineering (PBEE) framework proposed by the Pacific Earthquake Engineering Research (PEER) center; whereas the Performance-Based Wind Engineering (PBWE) and the Performance-Based Hurricane Engineering (PBHE) frameworks are used to calculate the losses corresponding to wind- and hurricane-induced actions on the same building. The monetary losses considered include those due to damage to structural and non-structural components, as well as those due to occupants' discomfort. The results from the two analyses are compared to each other to form a consistent foundation for future investigations of the appropriate mitigation techniques (e.g., using dampers) to minimize the total expected losses for the considered building when taking into account both hazards. This research is a first step toward a general approach to multi-hazard performance-based engineering and uniform risk design for multiple hazards.
Todd, D; Moody, L; Cobby, D; Hart, DE; Hawke, K; Purton, K; Murphy, A;	Multi-Hazard Analysis: Gap Analysis Report					2017	Jacobs	https://ir.canterbury.ac.nz/handle/10092/15312	assess the effects of the earthquakes on flood risk to Christchurch. In the course of these investigations it has become better understood that floodplain management should be considered in a multi natural hazards context. Council have therefore engaged the Jacobs, Beca, University of Canterbury, and HR Wallingford project team to investigate the multihazards in eastern areas of Christchurch and develop flood management options which also consider other natural hazards in that context (i.e. how other hazards contribute to flooding both through temporal and spatial coincidence). The study has three stages: ☐ Stage 1 Gap Analysis –assessment of information known, identification of gaps and studies required to fill the gaps. ☐ Stage 2 Hazard Studies –a gap filling stage with the studies identified in Stage 1. ☐ Stage 3 Collating, Optioneering and Reporting –development of options to manage flood risk. This present report is to document findings of Stage 1 and recommends the studies that should be completed for Stage 2. It has also been important to consider how Stage 3 would be delivered and the gaps are prioritised to provide for this. The level of information available and hazards to consider is extensive; requiring this report to be made up of five parts each identifying individual gaps. A process of identifying information for individual hazards in Christchurch has been undertaken and documented (Part 1) followed by assessing the spatial co-location (Part 2) and probabilistic presence of multi hazards using available information. Part 3 considers multi hazard presence both as a temporal coincidence (e.g. an earthquake and flood occurring at one time) and as a cascade sequence (e.g. earthquake followed by a flood at some point in the future). Council have already undertaken a number of options studies for managing flood risk and these are documented in Part 4. Finally Part 5 provides the Gap Analysis Summary and Recommendations to Council. The key findings of Stage 1 gap analysis are: - The spatial analysis showed eastern Christchurch has a large number of hazards present with only 20% of the study area not being affected by any of the hazards mapped. Over 20% of the study area is exposed to four or more hazards at the frequencies and data available. - The majority of the Residential Red Zone is strongly exposed to multiple hazards, with 86% of the area being exposed to 4 or more hazards, and 24% being exposed to 6 or more hazards. - A wide number of gaps are present; however, prioritisation needs to consider the level of benefit and risks associated with not undertaking the studies. In light of this 10 studies ranging in scale are recommended to be done for the project team to complete the present scope of Stage 3. - Stage 3 will need to consider a number of engineering options to address hazards and
Kameshwar, Sabarethinam;	Multi-hazard Fragility, Risk, and Resilience Assessment of Select Coastal Infrastructure					2017	Rice University	https://scholarship.rice.edu/handle/1911/96101	The performance of coastal infrastructure is threatened by natural hazards such as hurricanes and floods. The intensity and frequency of many of these climate related hazards are expected to be influenced by climate change, which will add uncertainty to the performance of coastal infrastructure. Furthermore, coastal regions are experiencing rapid population growth, which is expected to continue in the future as well. Therefore, in view of multiple hazards, uncertainty due to climate change, and increasing coastal population, comprehensive performance assessment of regional portfolio of coastal infrastructure is essential for managing the existing infrastructure and ensuring adequate performance after extreme events such as hurricanes and earthquakes. Therefore, this study focuses on the development of a methodology and supporting tools that can be used to facilitate comprehensive multi-hazard performance assessment of regional portfolios of costal infrastructure.
YORDANOVA, Radina P; Corinne, CURT;	Towards a systematic qualitative methodology for multi-hazards risk representation and preliminary assessment	10th Meeting on Reliability of Materials and Structures - Bordeaux, 27-28 Mars 2018				2018		https://www.researchgate.net/profile/Corinne_Curt/publication/326416896_Towards_a_systematic_qualitative_methodology_for_multi-hazards_risk_representation_and_preliminary_assessment/links/5b4c89c80f7e9b4637de38bd/Towards-a-systematic-qualitative-methodology-for-multi-hazards-risk-representation-and-preliminary-assessment.pdf	This work aims at qualitatively assessing risks resulting from various direct or indirect chains of natural and technological hazards for a defined geographical/administrative area - the community of Ciotat. A systematic qualitative methodology is proposed based on a cause-effect interaction structure that assigns conditions to causes, impacts to effects, protection barriers and types of interactions to a given flux between one cause and one effect. Five classes of interactions are used: direct triggers, indirect triggers, increases in frequency/probability of occurrence, in intensity and in the vulnerability of the exposed elements-at-risk. Various hazards links are conceptualized and represented via a two-dimensional matrix abbreviated as matrix-of-interactions. It contains every possible interaction, therefore chains of multi-hazards are produced that approximate different worst-case scenarios given a set of initial causative conditions. A scenario of wildfire and its hazard chain is demonstrated in detail. In its qualitative form, this supporting methodology proves useful tool for the decision-making processes of multi-hazards risk assessment and management.
Fereshtehnejad, Ehsan; Shafieezadeh, Abdollah;	A multi-type multi-occurrence hazard lifecycle cost analysis framework for infrastructure management decision making	Engineering Structures	167		504-517	2018	Elsevier	https://www.sciencedirect.com/science/article/pii/S0141029617317868	**Infrastructure systems, especially in hazard-prone regions, may face multiple occurrences of multiple types of hazards during their lifetime. The type and intensity of the hazards and impacts on systems can vary from one event to another. An important factor that has yet to be properly addressed in natural hazard loss estimation models is the impact of damage induced by various types of prior events on the increased vulnerability of systems against various types of potential future hazards**. This paper presents a new hazard lifecycle cost analysis framework that addresses this gap and accounts for effects of incomplete repairs of damage conditions induced by prior natural hazards on the future hazard performance of systems. Considering that the space of scenarios for multi-hazard occurrences and the impacts over the lifetime of infrastructure systems is significantly large, a recursive algorithm is proposed to efficiently determine the lifecycle cost of the system. This framework is applied to a realistic bridge exposed to flood and earthquake hazards to determine the optimal retrofit plan that reduces the overall lifecycle cost of the bridge. Results show the significance of considering different damage types induced by multiple types of hazards and repair time variations for lifecycle cost analysis of infrastructure systems.
Sadegh, Mojtaba; Moftakhari, Hamed; Gupta, Hoshin V; Ragno, Elisa; Mazdiyasni, Omid; Sanders, Brett; Matthew, Richard; AghaKouchak, Amir;	Multi-hazard scenarios for analysis of compound extreme events	Geophysical Research Letters				2018	Wiley Online Library	https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018GL077317	Compound extremes correspond to events with multiple concurrent or consecutive drivers (e.g., ocean and fluvial flooding, drought, and heat waves) leading to substantial impacts such as infrastructure failure. In many risk assessment and design applications, however, multihazard scenarios of extremes and compound events are ignored. In this paper, we review the existing multivariate design and hazard scenario concepts and introduce a novel copula-based weighted average threshold scenario for an expected event with multiple drivers. The model can be used for obtaining multihazard design and risk assessment scenarios and their corresponding likelihoods. The proposed model offers uncertainty ranges of most likely compound hazards using Bayesian inference. We show that the uncertainty ranges of design quantiles might be large and may differ significantly from one copula model to the other. We also demonstrate that the choice of marginal and copula functions may profoundly impact the multihazard design values. A robust analysis should account for these uncertainties within and between multivariate models that translate into multihazard design quantiles.

Bonacho, João; Oliveira, Carlos Sousa;	MULTI-HAZARD ANALYSIS OF EARTHQUAKE SHAKING AND TSUNAMI IMPACT	International Journal of Disaster Risk Reduction				2018	Elsevier	https://www.sciencedirect.com/science/article/pii/S2212420918306678	Tsunami damage on buildings in regions subjected to shaking is commonly modeled disregarding the occurrence of a previous earthquake and damages that have already occurred at those buildings. In Portugal, there are studies for the regions of Lisboa, Setúbal and Algarve that access damages or vulnerability of buildings due to the action of tsunami waves. Even so, they never took into account that, if near to the epicenter, usually prior to the tsunami, there was an earthquake shaking capable of provoking some level of damages to the building stock in the affected area. In this paper, we propose a way of combining earthquake shaking damages with tsunami damages – the aggregated damage. This is defined as an additive function. The aggregated damage of a building is the sum of damages caused by the earthquake plus those caused by the tsunami. As for earthquake shaking damage assessment, we use a home-developed software model based on standard vulnerability indexes conveying fragility curves for 5 different damage states (DSi), for reinforced concrete and other building typologies (only masonry is considered in the present case). The tsunami fragility curves corresponding to similar DSi, were obtained from recent published literature where the main variable was the water maximum height reaching each building which was estimated using a Geographic Information System (GIS) approach.
Barrantes, Gustavo;	Multi-hazard model for developing countries	Natural Hazards	92	2	1081-1095	2018	Springer	https://link.springer.com/article/10.1007/s11069-018-3239-6	Disaster risk assessment related to natural events has generally been carried out separately by specialists in each area of earth sciences, which has two negative consequences: Firstly, results of investigations are presented in different formats, mainly maps, which differ significantly from each other in aspects such as scale, symbols and units; secondly, it is common for an area or territory to contain several hazards that can potentially interact with each other, generating cascade effects or synergies. While some authors have proposed a multi-hazard analysis framework based on the use of probabilities, the quality and quantity of data required for this approach are rarely available in developing countries. Qualitative methods, on the other hand, have traditionally been limited to overlapping maps, without considering possible spatial interactions. Given the importance of integrated assessment of natural hazards for land use planning and risk management, this article proposes a heuristic multi-hazard model appropriate for developing countries, based on a standardization of classifications and a spatial interaction matrix between hazards. The model can be adjusted to be applied at different scales and in different territories; to demonstrate its versatility, it is applied to the municipality of Poás, Costa Rica, a territory with multiple natural hazards.
Gehl, Pierre; D'Ayala, Dina;	System loss assessment of bridge networks accounting for multi-hazard interactions	Structure and Infrastructure Engineering			Jan-17	2018	Taylor & Francis	https://www.tandfonline.com/doi/abs/10.1080/15732479.2018.1434671	This paper details an integrated method for the multi-hazard risk assessment of road infrastructure systems exposed to potential earthquake and flood events. A harmonisation effort is required to reconcile bridge fragility models and damage scales from different hazard types: this is achieved by the derivation of probabilistic functionality curves, which express the probability of reaching or exceeding a loss level given the seismic intensity measure. Such probabilistic tools are essential for the loss assessment of infrastructure systems, since they directly provide the functionality losses instead of the physical damage states. Multi-hazard interactions at the vulnerability level are ensured by the functionality loss curves, which result from the assembly of hazard-specific fragility curves for local damage mechanisms. At the hazard level, the potential overlap between earthquake and flood events is represented by a time window during which the effects of one hazard type on the infrastructure may still be present: the value of this temporal parameter is based on the repair duration estimates provided by the functionality loss curves. The proposed framework is implemented through Bayesian Networks, thus enabling the propagation of uncertainties and the computation of joint probabilities. The procedure is demonstrated on a bridge example and a hypothetical road network.

Type	Author	Title	Publication	Volume	Number	Pages	Year	Publisher	Online Sourc	Access date	Notes	Comparison with Academic Approaches (a) to (h)
Book chapter	Chutmina K. & Bosher L.S.	Managing disaster risk and resilience in the UK	Response vs. Prevention in policy and practice. IN: Chandler, D. and Coaffee, J. (eds.)			267 - 279	2016	Taylor & Francis (Routledge	https://dspac	10-Sep		
Report	DfID	Risk Management and Financing. Evidence on Demand, UK	DfID			73	2016	Department for Internation	https://assets	10-Sep		Focuses on **narrative descriptions** (a) that bring together diverse sources of qualitative information to inform decision making. Recognises complexity and interactions between hazards, but does not describe methods to identify what interactions are relevant.
Guidance note	DfID	Minimum Standards for Embedding Disaster Resilience in DFID Country Offices	DfID			4	2013	Department for Internation	https://www.	10-Sep		Requests multi-hazard risk assessments, but no methods presented (likely focus on assessment of multiple single hazards).
Guidance Note	DfID	Multi-Hazard Disaster Risk Assessment (v2)	DfID			6	2012	Department for Internation	https://assets	10-Sep		Endorses development of a **risk matrix** to compare different hazards. Paper focuses on understanding multiple single hazards.
Report	Gunawan et al.	Natural Hazards Partnership. Hazard Impact Framework: First Edition	NHP			109	2017	NHP	http://www.n	10-Sep		
Report	Cabinet Office	Keeping the Country Running: Natural Hazards and Infrastructure	Cabinet Office			98	2011	Civil Contingencies Secretar	https://assets	15-Sep		
Report	Cabinet Office	The Pitt Review - Learning lessons from the 2007 floods - Executive Summary	Cabinet Office			43	2008	Cabinet Office	http://webarc	15-Sep		Impact report and Future Recommendations following UK flooding in 2007. Minimal overlap with focus on approaches to assessing multiple hazards in academic review. Calls on The Environment Agency to develop its tools and techniques for predicting and modelling river flooding, taking account of extreme and multiple events (including coincidental events) and depths and velocity of water. Suggests running different extreme **scenarios** through the systems, and making sure that the possibility of multiple flood events occurring both simultaneously and within different overlapping time periods is taken into account. **(g and h)**
Report	Cabinet Office	National Risk Register of Civil Emergencies	Cabinet Office			71	2017	Cabinet Office	https://www.	15-Sep		Generally focuses on multiple single hazards, using a **matrix** to compare the impact/likelihood of these.
Report	Committee on Climate Change. Synthesis report: priorities for the next five years	UK Climate Change Risk Assessment	Committee on Climate Change			86	2017	Committee on Climate Char	https://www.	15-Sep		Notes that risks arise from risks arise from the exposure of interdependent infrastructure networks to multiple, correlated hazards (e.g. flooding and high winds). Focus on impacts to infrastructure, with call for additional action to understand cascading failures. Not sure this report sets out methods for understanding multi-hazard and multi-hazard risk.
Report	HSE	Land use plannign methodology	Health and Safety Executive			35	2018	HSE	http://www.h	22-Nov		Scenario analysis **(h)**; HSE's method also takes into account domino effects and consequential hazards (e.g., where a fire may lead to an explosion)
Report	Environment Agency	Estimating the economic costs of the 2015 to 2016 winter floods	Environment Agency			50	2018	Environment Agency	https://assets	25-Oct	Groundwater and river floods impacts are aggregated	Report is focused on impact (economic) of multiple storms and therefore does not overlap with the academic review which examined approaches to understand multi-hazards.
Working Paper	European Commission	Risk Assessment and Mapping Guidelines for Disaster Mana	EC			43	2010	EC		24-Sep		Although this paper talks about risk assessment and mapping guidelines, it does not present a standard way of developing multi-hazard risk assessments, rather it suggests that both multi-hazard and multi-vulnerability perspectives are needed. Some narrative is included about what these should entail, but no method presented.
Article	Espinoza et al.	Multi-phase assessment and adaptation of power systems resilience to natural hazards	Electric Power Systems Research	136		352 - 361	2016	Elsevier	https://www.	15-Sep	research applied in not by industry	**Fragility curves are used (h)**, which provide the failure probabilities of the power system's components as a function of a weather parameter (e.g. wind speed) at any given time.
Report	ONR	External Hazards	ONR Guide			84	2018	Office for Nuclear Regulatio	www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-013.pdf	19-Oct	Nuclear Safety Technical Assessment Guide	**Tabulates (a)** potential secondary/asscoiated hazards with primary hazards. Focus is on methods for evaluating single hazards. ONR Annual Report slides show **hazard curve (h)** for storms.
Report	ETI	Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies, Volume 12 — Hazard Combinations. IMechE, IChemE	Energy Technologies Institut	12		49	2018	ETI	http://www.ir	19-Nov	Technical Report prepared for ETI by EDF Energy R&D UK Centre Limited, the Met Office and Mott MacDonald Limited	The report draws from the literature a number of methods (e.g. **empirically-based, Markov chains, statistical** (multivariate Bayesian, joint tail models, kernel density) and illustrates the use of **copulas (h)** to assess join probabilties of combined hazards.
Article	Bruneau et al.	State of the art of multihazard design	American Society of Civil En	143	10	Jan-25	2017	ASCE	https://ascelil	24-Sep	US focused; research applied in not by industry	Review paper and therefore touches on a number of methods and relevant approaches. Focus is on resilience of engineered structures (e.g., bridges) and design to accommodate threats from multiple hazards.
Report	EPRI	Identification of External Hazards for Analysis in Probabilistic Risk Assessment: Update of Report 1022997	Electric Power Research Institute (EPRI)			142	2015	EPRI	https://www.	19-Oct	US based corporation	This paper points to several guidance documents that note the importance of combined hazard analysis but do not give guidance on how to do this. It refers to one paper (SKI 02:27, see below) that does include a methodology for identifying and screening combined events, albeit with limitations. The chapter focuses on **hazard matrices (c)**, and the use of **engineering judgement (h)**, together with an overview of some **probabilistic and statistical approaches (i)** to assessing correlated, consequential, and coincidental hazards. The document makes reference to EDF's methodology, which determines the frequency of combined hazards (either dependent or independent), based on their seasonality.
Report	Knochenhauer M & Louko P	Guidance for External Events Analysis	Swedish Nuclear Inspectorate (SKI)		SKI Repor	82	2003	SKI	https://www.	19-Oct		Presents a method for identifying combined events, using **matrices (c) and engineering judgement (h)**.
Report	Western European Nuclear Reg	Guidance Document Issue T: Natural Hazards	WENRA			26	2015	WENRA		19-Oct	Guidance for the WENRA Safety Reference Levels for Natural Hazards introduced as lesson learned from TEPCO Fukushima Dai-Ichi accident.	Use of **matrix (c)** to assess hazard interactions. Closely reflects comments in ASAMPSA reports. Suggests **probabilistic methods can be used (h)** if data is available. Guidance notes rather than detailed applications or worked examples.
Report	Decker K & Brinkman H	List of external hazards to be considered in ASAMPSA_E	Project Report			51	2016	ASAMPSA_E	http://asamps	19-Oct	project deliverable	Presents a 101 x101 **hazard matrix (c)**, with expert opinion identifying 577 relationships. Considers causally connected hazards, and correlated hazards (where hazards are likely to occur at the same time due to a shared root cause).
Report	Cazzoli et al.	Implementing external Events modelling in Level 2 PSA	Project Report	2		54	2016	Rapport IRSN-PSN-RES/ SAG	http://asamps	19-Oct	project deliverable	Discusses development and quantification of **event trees (h)** although it is not clear if these were actually developed.

Appendix 4 Detailed description of the economic costs framework used for case studies

Each component in Table 2.2 is explained as follows:

- ***Fatalities & Casualties*** – These will contain both financial costs (e.g. lost productivity, healthcare costs etc.) and welfare costs (e.g. pain, grief and suffering). Financial costs can be modelled using available data on average per-head costs and wage data. Welfare costs can be monetised using a variety of methods as described in HMT Green Book , although such estimates can be expensive and difficult to create and are often best used from the existing literature.
- ***Lost Working Hours*** – This cost often appears as a productivity cost component of Fatalities & Casualties for those killed or injured, but working hours can be lost, too, by healthy people whose working life is disrupted by the incident. This is typically estimated using averages wages and 'on-wage' costs, such as pension and National Insurance contributions, as an estimate of the full economic value of people's work; and multiplied by the total of hours lost. Care should be taken not to double-count with costs estimated under Infrastructure or Business Disruption – in incidents that are likely to feature all three cost types, it is suggested to try to capture all such impacts within one estimate rather than estimating separate and possibly overlapping costs.
- ***Social*** – This can refer to losses of 'social infrastructure', such as certain government, charity or other services; social impacts, such as a breakdown of law and order; or Social infrastructure such as schools and hospitals are affected by hazard events e.g. closure of schools.
- ***Infrastructure*** – This includes roads, railways, ports, airports, electricity, utilities, communications etc. We can estimate the physical damage placed on infrastructure using the cost of additional time to repair/replace it; and the lost value of the infrastructure being unusable by measuring and valuing its lost 'throughput' at market prices. However, this does not take into account welfare damages or other financial costs as infrastructure often has large positive externalities that may not be captured in these prices.
- ***Buildings*** – Damage and destruction costs can be estimated using insurance costs, estimated repair costs or house prices. Care should be taken adjusting insurance costs for underinsurance and factors such as tax. We must also consider that house prices will include a valuation of the land the building sits upon, which will likely still be present.
- ***Other losses*** – This could include cars, building contents and so on. These may be estimated though insurance costs, or they could be estimated using, for example, the observed number of destroyed cars and the average prices of a car on the road.
- ***Business Disruption (local and regional/national)*** – This is the effects of businesses being closed due to damage or inaccessibility (local); or throughout the rest of the economy if local businesses formed part of supply chains. Care should be taken with double-counting with infrastructure costs. Business disruption might be included within insurance costs, or it can be estimated using gross value added estimates and details of the locations of businesses damaged in the area. Bear in mind that lost business activity can be displaced to elsewhere in the economy.
- ***Lost Tourism*** – This could be thought of as within the compass of local business disruption, but is much more easily displaced elsewhere as tourists deciding whether or not to visit a, say, flood-hit area can very easily just decide to visit somewhere else.
- ***Environmental Damage and Decontamination*** – Multi-hazard events can damage environmental resources and amenities; and lead to costs for repair or decontamination.
- ***Emergency Response & Evacuation*** – This is the additional cost incurred to emergency services such as the police, fire and rescue and ambulance services; and costs to house people for the long- or short-term.

Appendix 5 Three social-economic case studies

5.1 THREE CASE STUDIES WHICH PRESENT THE SOCIO-ECONOMIC IMPACTS FROM MULTI-HAZARD EVENTS

5.1.1 Forzieri et al. (2018) Escalating impacts of climate extremes on critical infrastructures in Europe

Forzieri et al. (2018) focuses on the impacts of severe weather arising from climate change across Europe to the year 2100. These severe events are 'multi-hazard' as they refer to seven climate hazards: heat, cold, river and coastal floods, droughts, wildfires, and windstorms, which may occur in parallel. They focus on the impact these events have on multiple critical infrastructure that they define as "an array of physical assets, functions, and systems that are vital to ensuring the European Union's health, wealth, and security ([including] transport systems, renewable and non-renewable energy generation plants, industry, water supply networks, and education and health infrastructures)."

The quantification of impacts derives from a model for multi-hazard risk assessment. Forzier et al. (2018) developed an approach employed in Forzieri et al. (2017) to estimate the susceptibility to climate hazards of critical infrastructures and monetise the consequent impacts, referred to as 'damage estimates'. These are undiscounted over time and expressed in 2010 euros. They should be interpreted as structural damage to assets and losses due to production interruption.

In order to assign economic values to each of the assets and to allow comparability between them, Forzieri et al. (2018) allocate a value to each sector (industry, transport, social, energy) that expresses the level of vulnerability (very high, high, moderate, low, very low, none) to climate hazards based on a survey of experts. Industry and infrastructure are then distributed in space in the model and it estimates the intensity of economic value ('intensity values') in terms of kilo-tonnes of oil equivalent (electricity produced), kilo-tonnes of freight transported (good transport), annual turnover (industry) and public expenditure (social, e.g. health and education). Only assets that had high or very high levels of risk were assumed to contribute to the estimated impacts.

In order to determine the baseline (that is the cost of environmental damage to Europe if climate change were not to intensify in the future), more than 1,100 disaster loss records for climate-related hazards that occurred between 1981-2010 were collected from the Emergency Events Database. All the data provided was converted into 2010 euros using the Harmonised Index of Consumer Prices (HICP). Using this data, Forzieri et al. (2018) were able to model the relationship between assets which are exposed to risk and the damage incurred. Once this relationship can be expressed as a function, it enables them to translate the intensity value (explained above) of each infrastructure at risk, into the corresponding economic damage from the climate event's reported damage expressed in euros. The multi-hazard damage was estimated by summing up single-hazard median expected annual damage (EAD) values; in doing so an assumption is made that there is complete post-event recovery and independence of hazards (although they can occur at the same time). This may mean that the estimates are underestimated for the 'multi-hazard' context. This could be due to the first hazard causing impact and the proceeding hazards worsening the situation and hence not allowing a full recovery of assets as a result the costs are likely to increase.

The results are presented for the EU, (plus Switzerland, Norway and Iceland) and by sector. Table 2.5 presents the EAD (baseline – costs that Europe would incur anyway) in column 2, followed by the increase in costs that are only as a result of the effects of climate change in each time frame (2020s, 2050s and 2080s) up until the end of the century. The table shows all sectors see large increases from their EAD to the 2080s.

The damage can also be expressed as a proportion of gross fixed capital formation (GFGC), which is a measure of the annual investment in fixed assets. As risk rises across Europe the proportion of investment value lost to climate events will also rise from 0.12% of GFGC at present to 1.37% by the end of the century. The largest proportion being seen in southern European countries where risk is set to increase significantly (e.g. Greece – 4.32% and, Croatia – 5.21%).

Table 5-1 Estimated increase in costs due to climate change to 2080s

Location/Sector	EAD (baseline)	2020'S	2050'S	2080'S
EU+	€3.4 bn	€9.3 bn	€19.6 bn	€37.0 bn
Energy	€0.5 bn	€1.8 bn	€4.2 bn	€8.2 bn
Transport	€0.8 bn	*	*	€11.9bn
Industry	€1.5 bn	*	*	€16.2 bn +
Social	€0.6 bn	*	*	More than double

*Figures are given in text in Forzieri et al. (2018), but are incomplete for the 2020s and 2050s for some sectors. Full data for each decade is given in Figure 2 in Forzieri et al. (2018), but this is difficult to accurately interpret by eye.

For the energy sector the largest rise in damage costs is borne by energy production (as opposed to energy transmission) as a result of its sensitivity to droughts and heat waves. For the transport sector, the largest rise will be caused by heat waves (92% of total damage) mainly being driven through impacts to roads and railways. For the industry sector, the largest rise in damage will be caused by floods and windstorms driven by structural damage to infrastructures, machinery and equipment. Finally, for the social sector, damage from flooding and windstorms will rise and remain important whereas drought-induced damage may rise considerably. Forzieri et al. (2018) illustrate the distribution of hazard impacts over infrastructure types per sector (page 104 in the paper). These include: gas pipelines, electricity transport, nuclear power, airports, ports, inland waterways, rails, roads, water/waste, chemicals, minerals, health and education.

The final costs presented in this paper are those of adapting infrastructure to climate change. In order to make critical infrastructures resilient up to the end of the century, Forzieri et al. (2018) estimate that capital costs may exceed €200 billion and operating and maintenance costs of potentially €5.4 billion per year.

These numbers are only indicative and are subject to numerous uncertainties, as explained by Forzieri et al. (2018). Nonetheless, they suggests that adaption can be an effective cost-strategy as it is clear that the €200 billion adaption costs over the century would be less than the annual costs over the course of the century outlined in Table 5.1 above. Although, the distribution of this cost could vary considerably between parts of Europe where risks are highest i.e. southern Europe.

Discussion

The costs which are included in Forzieri et al. (2018) are shown in Table 5.2 in black; and those not included, in grey.

It is implicit in this method that Lost Working Hours and Business Disruption will be captured within the method used for valuing costs to infrastructure, even if these are not made explicit. It is implied also that the value of some building will be captured, where those buildings form part of the value of the infrastructure or where the costs to industry stem from loss of buildings from which to operate, but the method will have missed valuations of residential buildings.

Table 5-2 Cost framework for Forzieri et al. (2018)

Population and work	Fatalities & Casualties	**Lost Working Hours**	**Social**
Assets	**Infrastructure**	**Buildings**	Other losses
Economic Activity	**Business Disruption (local)**	**Business Disruption (national/international)**	Lost Tourism
Enviro and Other	Environmental Damage	Environmental Decontamination	Emergency Response & Evacuation

Social costs are captured within the narrow range of certain social services provided by governments, but wider social impacts of climate change are not addressed. It should be highlighted that such an omission (indeed, all omitted cost components) are not a failing of the method Forzieri et al. (2018) apply, as the paper was not aimed toward developing a fully costed model. However, the method of estimating the value of social infrastructure, which is to base it on the amount of public expenditure, would almost certainly lead to a large underestimate relative to the full economic cost. We would expect government services such as education and healthcare to have social and economic benefits that go well beyond their cost of supply and this will be missed by the Forzieri et al. (2018) method.

Impacts of extremes for infrastructure may go beyond damage to physical assets and into wider economic, social and environmental impacts. The strength of these impacts will vary based on the interdependencies of critical infrastructures in certain economies. Interdependencies of infrastructure have not been explicitly modelled in this study due to lack of metrics and models that capture these relationships; rather there is an assumption that they are captured in some way in the reported damage, being based on actual prior events where interdependencies between infrastructure would have been observed. As such, there is a risk that the total cost of climate extreme impacts in this study may be under-estimated.

Estimates are naturally subject to uncertainty due to them being based on simulation data over an extremely long time-scale. One thing that Forzieri et al. (2018) do not model is increases of capital over time, which would raise costs; and its possible redistribution or increased resilience to climate change risks, which would lower costs, over the century. Modelling of capital distribution and resilience could only be speculative, but average rates of capital accumulation should be available.

Estimates are made through modelling future scenarios based on the number of extreme events in the past and the location of exposed assets. Therefore, any deviation from the damage which has been reported previously will alter the future impacts and thus costs to an unknown degree. Forzieri et al. (2018) also highlight that their understanding of long-term climate risks is limited by the lack of detailed knowledge of climate impacts due to poor loss data collected in the past.

The loss data used from the Emergency Events Database (EMDAT) is also subject to uncertainty and bias as its content is provided from a wide variety of sources which is collected through multiple methods. The varying methods may provide data which is not comparable or robust. Forzieri is not clear on how the data is collated in EMDAT or what biases they envisage.

A final limitation to this paper is that although they look at multiple hazards and multiple types of infrastructures they fail to look explicitly at the interdependencies between both; rather they look at the summing up of single hazard events, which may occur at the same time across Europe. This is a common finding among the literature reviewed and it seems it is more to do with a lack of models which can capture these multi-impacts.

5.1.2 Environment Agency (EA) (2018) Estimating the economic costs of the 2015-16 winter floods

This report, referred to as EA 2018, looks at the economic costs of the winter floods of 2015 to 2016 which were a result of multiple storms including: Storms Desmond, Eva and Frank. The EA explains their methodology to produce high-level economic estimates of costs which build on three earlier reports they produced; EA (2010), EA (2015) and EA (2018).

EA 2018 tries to value not only the financial cost from damages but also the welfare cost associated with impacts to reflect full economic costs. It looks at past storms which are within the definition of a ’multi-hazard’ event as storms may include multiple hazards at a given time; wind, floods etc. A limitation of EA 2018 is that its primary focus is on the flood damages within these storms rather than the totality of the storm, although in EA (2015) they do distinguish between multiple types of flooding (fluvial and coastal) and the different impacts they create. In addition, all of the EAs reports do not look at one single flood, rather than multiple floods over a period of time, therefore the estimated economic costs are those of the accumulated effect. The EA 2018 report derives damage estimates from a number of impact categories which are of interest:

- Residential property damages: physical damage to residential properties and contents
- Non-residential (including business property damages): physical damage to non-residential (including business) properties and contents
- Temporary accommodation: the costs of temporary accommodation
- Vehicle damage: physical damage to vehicles
- Public health: an estimate of additional psychological distress caused to households as a result of flooding
- Emergency services: additional costs (for example, overtime) incurred by the emergency services (fire, police and ambulance services)
- Local authorities: damages to public buildings, public spaces and additional costs faced by local authorities such as recovery grants (damages to local roads are considered in the transport section)
- Education: welfare costs of education days lost
- Transport: costs of repairs and induced losses from disrupted journeys for road and rail
- Utilities: costs for repairs and induced losses caused by loss and/or interrupted utility services for water and electricity
- Flood risk management infrastructure and service: cost of repairs to flood defence assets and additional service costs including staff and contractor overtime and materials
- Agriculture: damage to agricultural land, including losses of output and additional production costs
- Other including tourism, heritage and wildlife sites: damage to physical assets and, where possible to determine, indirect impacts on the wider economy

The EA 2018 method is to estimate the economic cost of each impact category separately and add them together in a cost calculator they developed in 2012 to give total damages. They take care in their calculations to reduce the risk of double-counting impacts in different categories which may lead to incorrectly over-estimating impacts. For example, in many of the impact categories, capital costs are removed as these are thought to be covered by insurance and so included within the Association of British Insurers (ABI) business insurance claims. If they were not removed, they would be double-counted.

Estimates were calculated through a desk-based study using national level data obtained from a range of partner organisations[6]. They estimate both economic costs and financial costs.

The costs to each of the impact categories are presented in Table 5.3 alongside the economic costs from their two previous publication. We have focused our review on the impacts with the largest proportion of costs.

Table 5.3 shows that in 2015/16 the total cost of flooding within the storms that occurred was £1.6 billon, a similar cost to those seen in the 2013/14 floods. The cost calculator used in EA 2018 assumes that most impact categories are related to the number of properties damaged by flooding e.g. vehicles, public health, emergency services. This may explain the differences in cost from the 2007 floods to the 2015/16 floods. In 2007 48,000 residential properties and 7,000 business properties were affected; whereas over 2015/16 16,000 residential properties and 5,000 business properties were affected. It could also be argued that the government response to extreme weather events has improved since the 2007 floods leading to a reduction in costs as the 2007 floods led to the Pitt review in 2008, which made recommendations for improving flood management. Finally, for each EA study different types of flooding occurred, and the 2007 floods included surface water flooding.

It can be seen that businesses incurred the biggest proportion of costs with just over 30% in 2015/16, an increase from the 2007 floods where they incurred just over 20%.

EA 2018 suggests it is hard to compare rail damages between different floods and the increase in costs for the road transport is largely down to money paid by central Government to Local Authorities (LAs) for repairing physical damages to local roads. This figure was not adjusted for betterment or VAT, which would have reduced the road transport costs in the 2015/16 floods number by approximately half.

Breaking down the economic costs to the transport sector in 2015/16, £121 million was due to rail and £220 million due to roads. A limitation to the transport costs for roads is that although data reported by LAs and Department for Communities and Local Government (DCLG) provides estimates for physical damages, welfare damages are unknown, and no estimates of disrupted journeys were estimated. These 'welfare' damages if included could increase costs considerably, particularly where roads are closed for several weeks. Welfare damages were however estimated in the rail transport sector using data from Network Rail. A further limitation which may be present, as mentioned in the paper by Network Rail (2016), is that for this and other impact categories, it is not easy to discriminate between wind storm damage and flood damage. This limitation should be considered when estimating other multi-hazard event costs.

The utilities (energy and water) sector is the next category with the largest proportion of damages at around 7% of the total costs in 2015/16. The costs include: physical damages to infrastructure, additional operational costs and welfare damages to consumers suffering disruption. Although the proportion of costs increased slightly from 2013/14 to 2015/16, both are decreases from 2007 where utility costs contributed just over 10% of total costs. This decrease may be due to the flood protection investment programmes implemented by utility companies between 2010 and 2015 which were reported to cost around £800 million. Data on the effectiveness of these programmes is not included in EA 2018 and so it is unclear why costs increased from 2013/14 to 2015/16 when they were in place.

[6] Organisations include: Association of British Insurers ABI, Department for Communities and Local Government DVLG, Department for Energy and Climate Change DECC (now part of BEIS), Highways England, National Farmers Union, Network Rail, Rural Payments Agency, water companies

Table 5-3 Comparison of economic costs by flood event by impact category (2015 prices) (£million)

Impact category	2007 (summer floods)	2013 to 2014 (winter floods)	2015 to 2016 (winter floods)
Residential properties	£1,500	£320	£350
Businesses	£910	£270	£513
Temporary accommodation	£120	£50	£37
Vehicles, boats, caravans	£98	£37	£36
Local authorities (excluding roads)	£170	£57	£73
Emergency services	£5	£3	£3
Flood risk management infrastructure and service	£24	£147	£71
Utilities (energy and water)	£398	£30	£104
Transport (roads, rail, air, ports)	£310	£295	£341
Agriculture	£59	£19	£7
Health	£340	£25	£43
Education	£14	£2	£4
Other (wildlife, heritage and tourism)	–	£13	£19
Totals	**£3,900**	**£1,300**	**£1,600**

Loss of life and health-related quality of life impacts were estimated to be around £43 million from the 2015/16 floods. The prevention of fatalities and injuries is an impact considered in a variety of UK public policies and there is a common method across Government included in HM Treasury's Green Book, which recommends using a willingness to pay method from the Department for Transports (DfT) that estimates the reduction of risk of death in the context of road transport. In 2014 prices, the estimate is around £1.84 million per fatal casualty. For injuries, EA 2018 use a unit value of £72,000 per injury (DEFRA, 2012). It is not clear whether they adjust this value to account for severity of injury or illness. A limitation of using these monetary values is that they were designed for use in ex-ante policy assessment not ex-post analysis as they are based on the willingness to pay to prevent loss of life or loss of quality of life, rather than an assessment of actual after-the-fact welfare costs. However, without any better method or data they have been used as a next best alternative. EA 2018 identifies that improvements should be made through on-going research which began in 2007. All of the remaining costs are discussed in the full report.

Discussion

A strength of this this report, which we can see from Figure 5.4, is that EA 2018 estimates a large proportion of the impacts which we would expect to see from a multi-hazard event. This contrasts with many academic papers and grey literature which tend to be focused on one or two impact categories. The reason why the EA look at so many cost impacts may be because they are a government agency who use their evidence to inform policy making. In order to do this, they need to understand the total welfare loss to society and how costs are distributed across impact categories to understand where they can make the biggest impact.

Table 5-4 Cost framework for EA (2018)

Population and work	**Fatalities & Casualties**	**Lost Working Hours**	**Social**
Assets	**Infrastructure**	**Buildings**	**Other losses**
Economic Activity	**Business Disruption (local)**	**Business Disruption (national/international)**	**Lost Tourism**
Enviro and Other	**Environmental Damage**	**Environmental Decontamination**	**Emergency Response & Evacuation**

The EA may also have better access to data, although the EA 2018 highlights their key limitations to be around the availability and quality of data (particularly disaggregated information from the insurance industry); and the number and types of assets affected, which could be improved by data sharing agreements with key partners. These improvements around data would significantly improve confidence in future estimates of flood damages.

The method in EA 2018 is clear, and they highlight their assumptions and uncertainties under each impact category. They also consider the difference between financial and economic costs which can often be a weakness of other papers. However, the method used to adjust 'financial' costs into 'economic' costs are not infallible and assumptions are made e.g. assuming 50% betterment on certain assets where the replacement or repair was of equal quality to a new asset. A further assumption made is that grant money is used as a proxy for the economic costs to different stakeholders and so is unadjusted. They say that this probably under-estimates total costs as in certain cases the amount of grant funding received is capped such that private costs may not be covered.

Finally, it is hard to distinguish the costs of each single storm or flood during 2015/16 as the costs are presented over the whole period. This may be due to many factors, such as that residential and non-residential properties are unlikely to make an insurance claim after each single storm (depending obviously on the severity of that storm). Also, after a single storm, the damage to an asset will be 'carried' in that asset and will worsen each time another storm occurs. Over a period of time, like 2015/16 reported in EA 2018, the multiple storms will have created accumulated damage to assets which then require a single claim for replacement or repair in a particular year or following a particular storm, which could place the totality of the cost of several years' worth of damage in just one time period. This is also true for grant money and funds to LAs as it is unlikely that every time a storm hits the government can release funds and more likely that money is granted at the end of a period of time when an assessment is made of where funds are required and who these are given to. This is true whether the successive events are of single hazard or multi-hazard nature.

5.1.3 Pielke et al (2008) Normalized hurricane damage in United States: 1900-2005

The final paper, Pielke et al. (2008), looks at the damage incurred from hurricanes. Hurricanes fall within definition of 'multi-hazard' events as they include multiple hazards within them; high winds, heavy rain and flooding etc. Pielke et al. (2008) estimate economic damage costs incurred by numerous hurricanes in the United States between 1900-2005 and normalises them to provide an estimate of the damage that would arise if they occurred in a contemporary level of population and development, for which Pielke et al. (2008) use 2005 as a benchmark. Although this paper is not looking at multi-hazard events in the UK we can hopefully draw out some useful findings from their method and estimation of economic costs to such events.

Pielke et al. (2008) define ‘economic damages’ as the direct losses associated with a hurricane’s impact as determined in the weeks (and sometimes months) after the event. Pielke et al. (2008) are not explicit as to what ‘direct’ impact categories are included within this cost as damage costs are presented as ‘total’ economic losses from each hurricane. However, Pielke et al. (2008) state that costs are in part dependent on insured losses which we would expect to include; homes, cars, buildings, buildings contents, possibly business earnings and possibly life and health impacts (at least to some extent). Impacts which we would expect not to be included in the ‘total’ costs would be things which are not insured such as; social impacts, individuals’ lost working hours, environmental impacts, emergency response and everything owned by individuals too poor to insure their assets or who choose not to do so.

The loss data applied by Pielke et al. (2008) originates from the ‘Monthly Weather Review’ annual hurricane summaries recorded in Landsea (1991) together with loss estimations from the National Hurricane Centre (NHC). Piekle et al. (2008) highlight that although they use economic loss figures, the estimates presented are in part dependent on insurance figures since about 1987 that may have been doubled by the NHC to estimate for uninsured losses, although Pielke et al. (2008) were unable to demonstrate whether this had been done consistently. This means there may be a lack and accuracy to the results. The EA (2018) suggests a method for adjusting insurance costs so that they represent economic costs which may improve the applicability of Pielke et al. (2008) estimates, although the long time period of Pielke et al. (2008) analysis and differing legal and tax regimes could make this challenging. Pielke et al. (2008) do acknowledge that the relationship between economic and insured damages will vary substantially between events due to a number of factors such as: extent of flooding, damage to infrastructure and the number of uninsured properties but does not explain how they could adjust for these variations or the extent of the variability in the results.

Table 5.5 displays the top 10 of the top 50 hurricanes with the largest normalised economic cost having occurred in 2005. Pielke et al. (2008) refer to independent analysis, which has found that in some locations losses are in fact doubling every 10 years (ABI, 2005). This is supported by a report by Sound (2006) which suggests that this is because of increases in building values, increases in infrastructure and changes in their characteristics.

Table 5-5 Top 10 most damaging storms 2005 (US $billions)

Hurricane	Method 1 normalised cost	Method 2 normalised cost
Great Miami Hurricane (1926)	$157.0	$139.5
Katrina (2005)	$81.0	$81.0
Galveston (1) (1900)	$78.0	$71.9
Galveston (2) (1915)	$61.7	$57.1
Andrew (1992)	$57.7	$54.3
New England (4) (1938)	$39.2	$37.3
11 (1944)	$38.7	$35.6
Lake Okeechobee (4) (1928)	$33.6	$31.8
Donna (1960)	$29.6	$31.9
Camille (1969)	$21.2	$24.0

Pielke et al. (2008) find no trend of increasing normalised damage from hurricanes over the period; however, their results illustrate the rising growth in societal vulnerability in the United States to multi-hazard events such as hurricanes. This societal vulnerability is only set to increase with increasing populations, personal wealth and greater demand on infrastructures resulting in escalating damage from extreme events such as storms placing a severe burden on society.

Discussion

Table 5-6 Cost framework for Pielke et al. (2008) (inferred only)

Population and work	Fatalities & Casualties	Lost Working Hours	Social
Assets	**Infrastructure**	**Buildings**	**Other losses**
Economic Activity	**Business Disruption (local)**	**Business Disruption (national/international)**	Lost Tourism
Enviro and Other	Environmental Damage	Environmental Decontamination	Emergency Response & Evacuation

This paper demonstrates the value of using large legacy data sets to extrapolate useful information. However, due to the age of data, Pielke et al. (2008) made several assumptions where data was missing, not collected or not correct in certain years. Pielke et al. (2008) concludes that although there are likely to be large uncertainties in loss estimations for individual hurricanes, they find no evidence for systematic bias in losses through the dataset.

Pielke et al. (2008) highlight the practical difficulties in distinguishing between flood damages and non-flood damages which is a point also highlighted in the EA (2018) report. This may be a common factor when looking at impacts from multiple hazards occurring in unison. Even though we might not be able to see the costs of each hazard which affect one another, e.g. high winds and flooding, the method for estimation of these hazards as multi-hazards may not differ hugely. To estimate costs, we need to understand the unit cost to each impact and be able to multiply to the number of assets or people affected. We also need to ensure that costs are being adjusted to represent full economic costs rather than solely financial costs. Pielke et al. (2008) approach to this (the insured losses x2 method) is an important factor to understand the validity of the approach, but is not discussed by Pielke et al. (2008) in any detail. We would need to understand where this x2 factor comes from, what it attempts to add onto insured losses (is it just uninsured assets or does it include the social welfare of assets) and whether there is any evidence to support the x2 factor. Otherwise, the cost estimates presented are not robust or complete in their estimation.

The use of insured losses does also not account for all impacts that we expect from multi-hazard events such as hurricanes. You can see from Table 5.6 that the boxes of included impact are inferred only based on impacts that we would expect to be insured, but it is hard to know for sure. However, Pielke et al. (2008) have made use of the best data available on a semi-consistent basis over a century and such shortcomings are unavoidable.

The normalisation methodologies in Pielke et al. (2008) do not explicitly reflect two important factors driving losses: demand surge and loss mitigation. Adjustments for these factors were beyond the scope of their paper. Demand surge refers to the increase in costs that can occur after large events due to shortages of labour and materials required for reconstruction. Loss mitigation refers to practises which can prevent future losses. There is evidence that stronger building codes, for example, can significantly reduce losses. However, strong codes in the U.S. have only been implemented in recent years and so their effect on overall losses is unlikely to be large in this paper. In the future, significant efforts to improve building practices and encourage retrofit of existing structures could see a large impact on reducing damage and such mitigations would need to be estimated, as well as they could, if an analysis such as Pielke et al. (2008) were to be attempted looking at the next hundred years.

Appendix 6 Stakeholder Database

[See separate file A6_Stakeholder Database.xls]

Name of organisation	Name of contact	Position in organisation	Stakeholder	Type	Description	Identification	Participation	Contribution	Legitimacy	Willingness to engage	Influence	Necessity of Involvement	Total Score	Overall Relevance (for this study)	Power Score	Expertise Score	Rank (place in matrix)
Max Score								**4**	**3**	**3**	**3**	**3**	**16**				
Stakeholder 1 - Policy / Public body								**2**	**2**	**3**	**3**	**3**	**13**	**0.81**	**1.00**	**0.57**	
Stakeholder 2 - Research/Academia								**3**	**3**	**4**	**1**	**2**	**13**	**0.81**	**0.50**	**0.86**	
Stakeholder 3 - Practitioner / Eng Consulting								**1**	**2**	**2**	**1**	**1**	**7**	**0.44**	**0.33**	**0.43**	
Satellite Space Catapult	**Elena Lobo**	Senior Space Innovation Facilitator	research	private company	space technology and applications		N	1	2	1	2	2	8	0.50	0.67	0.43	H
UKRI/BGS	***Anonymous***	*Anonymous*	research	partly publicly-funded company	geoscience research and innovation	**n.a.**	**Y**	3	3	2	2	3	13	0.81	0.83	0.86	A
King's College London	**Bruce Malamud**	Professor of Natural Hazards	research	academia	public research university	name and organisation identified	**Y**	4	3	2	1	2	12	0.75	0.50	1.00	C
University of Portsmouth	***Anonymous***	*Anonymous*	research	academia	natural hazards research university	only organisation	**Y**	4	3	3	1	2	13	0.81	0.50	1.00	C
Practical Action	**Mirianna Budimir**	Senior DRR Advisor	research	charity	development programme themes on sustainable energy access,	name and organisation identified	**Y**	3	2	3	2	1	11	0.69	0.50	0.71	D
National Oceanography Centre	**Mike Clare**	Researcher	research	research institution	marine science	name and organisation identified	**Y**	4	2	3	2	2	13	0.81	0.67	0.86	C
NCAS/DEFRA	***Anonymous***	*Anonymous*	research	research centre	atmospheric science	**n.a.**	**Y**	3	2	2	2	2	11	0.69	0.67	0.71	D
UKCIP	**Roger Street**		research	research centre	climate change research		N	1	3	1	1	2	8	0.50	0.50	0.57	D
CIRIA	***Anonymous***	*Anonymous*	research	non-for-profit organisation	construction industry research	**n.a.**	**Y**	3	1	2	2	2	10	0.63	0.67	0.57	D
Loughborough University	**Dr Neil Dixon**		research	academia	public research university		N	1	3	1	1	2	8	0.50	0.50	0.57	D
Leeds University	**Dr Bill Murphy**		research	academia	public research university		N	1	3	1	1	2	8	0.50	0.50	0.57	D
LQM Ltd.	**Prof Paul Nathanial**		research	private company	environmental consultancy		N	1	1	1	1	1	5	0.31	0.33	0.29	K
Environment Agency	***Anonymous***	*Anonymous*	practitioner	public body (environment)	non-departmental public body for protection and enhancement of	**n.a.**	**Y**	2	3	2	3	3	13	0.81	1.00	0.71	B
	Andy Croxford	Deputy Director, Research	practitioner	public body (environment)	non-departmental public body for protection and enhancement of		N	1	3	1	3	3	11	0.69	1.00	0.57	B
	David Hornby (Replacing Karen Alford)	Flood Risk Mapping and Data Management Officer	practitioner	public body (environment)	non-departmental public body for protection and enhancement of	name and organisation identified	**Y**	3	3	2	3	3	14	0.88	**1.00**	**0.86**	A
	Andy Moores		practitioner	public body (environment)	non-departmental public body for protection and enhancement of		N	1	3	1	3	3	11	0.69	1.00	0.57	B
	Paul Robinson	Nuclear Waste Assessor	practitioner	public body (environment)	non-departmental public body for protection and enhancement of	name and organisation identified	**Y**	4	1	2	3	3	13	0.81	1.00	0.71	B
	Charles Pilling	Chief Hydrometeorologist	practitioner	public body (environment)	non-departmental public body for protection and enhancement of	name and organisation identified	**Y**	3	3	2	3	3	14	0.88	1.00	0.86	A
Met Office	**Ian Lisk**	Head of Environmental Hazards & Partnerships	practitioner	public body (weather)	national weather service	name and organisation identified	**Y**	3	3	2	2	3	13	0.81	**0.83**	**0.86**	A
	Anonymous	*Anonymous*	practitioner/research	public body (weather)	energy and transport - weather, seasonal and climate timescales	only organisation	**Y**	3	3	3	2	3	14	0.88	0.83	0.86	A
	Prof Brian Golding	Fellow in Weather Impacts, co-chair HIWeather	practitioner	public body (weather)	national weather service and WMO		N	1	3	1	2	3	10	0.63	0.83	0.57	B
National Trust	**Virginia Portman**	General Manager - White Cliffs & Winchelsea	practitioner	charity	conservation organisation		N	1	1	1	1	1	5	0.31	0.33	0.29	K
HS2	**Nick Sartain**	Professional Head Geotechnics	practitioner	private company	railway infrastructure development		N	1	2	1	2	3	9	0.56	**0.83**	**0.43**	E
	Sarah Trinder	Lead Geotechnical Engineer	practitioner	private company	railway infrastructure development		N	1	2	1	2	3	9	0.56	0.83	0.43	E
	Alison Walker	Climate Change Manager	practitioner	private company	railway infrastructure development		N	1	2	1	2	3	9	0.56	0.83	0.43	E
HR Wallingford	**Ben Gouldby**	Chief Technical Director (Flood Risk)	practitioner	private company	research & consultancy civil engineering, environmental hydraulics,		N	1	3	1	2	2	9	0.56	0.67	0.57	D
	Jonathan Simm	Technical Direcor, Flood Management	practitioner	private company	research & consultancy civil engineering, environmental hydraulics,		N	1	3	1	2	2	9	0.56	**0.67**	**0.57**	D
Network Rail	***Anonymous***	*Anonymous*	practitioner	public body (transport)	railway infrastructure and asset management	**n.a.**	**Y**	3	2	2	3	3	13	0.81	**1.00**	**0.71**	B
	Eifion Evans	Principal Engineer	practitioner	public body (transport)	railway infrastructure and asset management		N	1	2	1	1	3	8	0.50	0.67	0.43	H
	Anonymous	*Anonymous*	practitioner	public body (transport)	railway infrastructure and asset management	**n.a.**	**Y**	3	2	2	1	3	11	0.69	0.67	0.71	D
	Anonymous	*Anonymous*	practitioner	public body (transport)	railway infrastructure and asset management	only organisation	**Y**	3	2	2	1	3	11	0.69	0.67	0.71	D
NHBC	**John Jones**	Engineering Manager, NHBC Technical Services	practitioner	non-profit distributing company	house building regulations, insurance ans waranty		N	1	1	1	2	1	6	0.38	0.50	0.29	H
Canals & Rivers Trust	**Siobhan Bulter**		practitioner	non-governmental organisation	guardship of British Waterways canals, rivers, reservoirs and docks		N	1	2	1	1	1	6	0.38	0.33	0.43	K
Arup	**Matt Free**	Director of Geotechnics	practitioner	engineering consulting	engineering, design, planning consulting company		N	1	2	1	2	2	8	0.50	**0.67**	**0.43**	H
	Laurance Donnelly	Associate Director Geologist	practitioner	engineering consulting	engineering, design, planning consulting company		N	1	2	1	1	1	6	0.38	0.33	0.43	K
	Kate Canning	Associate & UK-MEA Research Champion	practitioner	engineering consulting	engineering, design, planning consulting company		N	1	2	1	1	1	6	0.38	0.33	0.43	K
Highways England	**David Patterson**	Principal Geotechnical Advisor	practitioner	public body (transport)	highway authority		N	1	2	1	3	3	10	0.63	**1.00**	**0.43**	E
	James Codd		practitioner	public body (transport)	highway authority		N	1	2	1	3	3	10	0.63	1.00	0.43	E
National Grid	**Doug Dodds**	Environmental Resilience Specialist - Natural Hazards	practitioner	private company	electricity and gas utility company	name and organisation identified	**Y**	3	2	3	1	3	12	0.75	**0.67**	**0.71**	D
	David McCollum	Team Leader Safety Engineering	practitioner	private company	electricity and gas utility company		N	1	2	1	1	3	8	0.50	0.67	0.43	H
Flood Forecasting Centre	**Graeme Boyce**	NHP Rep	practitioner	public body (Met Office & EA)	public partnership for 24/7 hydrometeorological service		N	1	3	1	2	3	10	0.63	**0.83**	**0.57**	B
	Rob Cowling	EA Rep in FFC	practitioner	public body (Met Office & EA)	public partnership for 24/7 hydrometeorological service		N	1	3	1	2	3	10	0.63	0.83	0.57	B
	Daniel Lamb	EA Rep in FFC	practitioner	public body (Met Office & EA)	public partnership for 24/7 hydrometeorological service		N	1	2	1	2	3	9	0.56	0.83	0.43	E
AECOM	**Patrick Cox**	Director Major Projects	practitioner	private company	engineering consulting and management company		N	1	1	1	1	1	5	0.31	0.33	0.29	K
Jacobs Eng. Group	**Tom Berry**		practitioner	private company	engineering, design, planning consulting company		N	1	1	1	1	1	5	0.31	0.33	0.29	K
Transport Scotland	**Paul Mellon & Graham Edmond**		practitioner	public body (transport)	transport agency	name and organisation identified	**Y**	3	2	3	1	3	12	0.75	0.67	0.71	D
Scottish Canals	**Rebecca Fletcher**		practitioner	public body (transport)	inland waterways management		N	1	2	1	1	2	7	0.44	0.50	0.43	H
Scottish Water	**Will Carroll**	Technical Lead (Resilience and Area Strategy)	practitioner	public body (water & sewerage)	public water and sewerage services		N	1	2	1	1	1	6	0.38	**0.33**	**0.43**	K
	Mark Williams		practitioner	public body (water & sewerage)	public water and sewerage services		N	1	2	1	1	1	6	0.38	0.33	0.43	K
	Miranda Jacques-Turner		practitioner	public body (water & sewerage)	public water and sewerage services		N	1	2	1	1	1	6	0.38	0.33	0.43	K
Transport for London	**Fiona Thomson**		practitioner	public body (transport)	transport authority		N	1	2	1	2	2	8	0.50	0.67	0.43	H
Independent Consultant	**John Dora**	Resilience Specialist in Rail Sector	practitioner	independent consultant	Resilience Specialist in Rail Sector	name and organisation identified	**Y**	3	1	2	1	1	8	0.50	0.33	0.57	J
Mott MacDonalds	**Chris Power**		practitioner	private company	engineering consultancy		N	1	2	1	2	2	8	0.50	**0.67**	**0.43**	H
	Paul Maliphant		practitioner	private company	engineering consultancy		N	1	2	1	2	1	7	0.44	0.50	0.43	H
Independent Consultant	***Anonymous***	*Anonymous*	practitioner	independent consultant	Consultant DRR specialist	**anonymous and non-identifiable**	**Y**	3	3	3	1	1	11	0.69	0.33	0.86	G
Geotechnics Company	***Anonymous***	*Anonymous*	practitioner	private company	engineering consultancy	**anonymous and non-identifiable**	**Y**	4	2	2	1	1	10	0.63	0.33	0.86	G
Energy Company	***Anonymous***	*Anonymous*	practitioner	energy	energy company	**anonymous and non-identifiable**	**Y**	3	3	3	3	2	14	0.88	0.83	0.86	A
Atkins	**Anthony Concannon**		practitioner	private company	engineering, design, planning consulting company		N	1	1	1	1	1	5	0.31	0.33	0.29	K
	Stephen Wade	Associate Director, Climate & Resilience					N	1	2	1	2	2	8	0.50	**0.67**	**0.43**	H
Temple Group	**Mark Skelton**	Executive Director	practitioner	private company	environmental consultancy		N	1	1	1	1	1	5	0.31	0.33	0.29	K
Translink	**Anthony Stove**	Engineering Manager	practitioner	public body (transport)	transport infrastructure		N	1	2	1	1	1	6	0.38	0.33	0.43	K
SSE	**George Cobb**	Low Carbon Team	practitioner	energy	energy company, Scotland		N	1	2	1	1	2	7	0.44	**0.50**	**0.43**	H
	Lucy Byrne	Partnership Funding Coordinator	practitioner	energy	energy company, Scotland		N	1	2	1	1	2	7	0.44	0.50	0.43	H
London Underground	**Melina Kakouratou**	External Risks Engineer Infrastructure Protection	practitioner	private company	public underground transport company		N	1	2	1	2	1	7	0.44	0.50	0.43	H
WSP	**Paul Munday**	Principal Consultant	practitioner	private company	engineering, design, planning consulting company		N	1	2	1	1	1	6	0.38	0.33	0.43	K
Cabinet Office	**Dr Owen Jackson**	Assistant Director - International Resilience	policy	public body	government department		N	1	3	1	3	3	11	0.69	1.00	0.57	B
	Anonymous	*Anonymous*	policy	public body	government department	**anonymous and non-identifiable; only organisatio**	**Y**	2	3	2	3	3	13	0.81	1.00	0.71	B
	Ed Foale	Assistant Director, Catastrophic Emergency Planning	policy	public body	government department	name and organisation identified	**Y**	4	3	2	3	3	15	0.94	**1.00**	**1.00**	A
Government Office for Science	**Arthi Kumar**	Resilience lead GoScience	policy	public body	government advisory for science policy		N	1	2	1	3	3	10	0.63	1.00	0.43	E
UNISDR/PHE	**Prof Virginia Murray**		policy	UN Office/public body (health)	health agency		N	1	2	1	3	3	10	0.63	1.00	0.43	E
Historic Environment Scotland	***Anonymous***	*Anonymous*	policy	public body	investigator, carer and promotor of historic environment	**n.a.**	**Y**	3	2	3	1	1	10	0.63	0.33	0.71	J
Scottish Government, Resilience Division	***Anonymous***	*Anonymous*	policy	public body	supporting agency for resilience to emergencies	only organisation	**Y**	3	1	2	3	3	12	0.75	1.00	0.57	B
SEPA	**David Faichney**	Flood Act Business Change Manager (Evidence and Flooding) - NHP	policy	public body (environment)	environmental protection and regulation	name and organisation identified	**Y**	4	3	2	3	2	14	0.88	0.83	1.00	A
DEFRA	**Stewart Larter-Whitcher**	DEFRA NHP rep	policy	public body (environment, food, rural affairs)	environmental protection, food production and standards,		N	1	2	1	3	3	10	0.63	**1.00**	**0.43**	E
	Tim Preece	DEFRA NHP rep	policy	public body (environment, food, rural affairs)	environmental protection, food production and standards,		N	1	2	1	3	3	10	0.63	1.00	0.43	E
Welsh Government	**Dr Wyn Price**	Head of Resilience at the Welsh Government	policy	government	government		N	1	2	1	3	3	10	0.63	1.00	0.43	E
Natural Resources Wales	***Anonymous***	*Anonymous*	policy	public body (environment)	management of natural resources	**n.a.**	**Y**	3	2	2	1	2	10	0.63	0.50	0.71	D
Climate Change Committee	**Kathryn Brown**	Head of Adaptation	policy	public body (climate)	governmental advisor on climate change adaptation		N	1	3	1	2	3	10	0.63	**0.83**	**0.57**	B
	Andrew Russell	CCC NHP Rep	policy	public body (climate)	governmental advisor on climate change adaptation		N	1	3	1	2	3	10	0.63	0.83	0.57	B
Government department for transport	***Anonymous***	*Anonymous*	policy	government department	transport network	**anonymous and non-identifiable**	**Y**	3	2	3	3	1	12	0.75	0.67	0.71	D
Rail Safety & Standards Board	**John Lane**		policy	non-for-profit organisation	railway safety and standards		N	1	2	1	2	1	7	0.44	0.50	0.43	H
UKWIR	***Anonymous***	*Anonymous*	policy	private company	research programme for water & sewerage companies	**n.a.**	**Y**	3	1	2	2	2	10	0.63	0.67	0.57	D
Department for Communications, Media & Sport	**Rob Willis**	Data Infrastructure Resilience	policy	government department	telecommunications	name and organisation identified	**Y**	3	2	2	2	1	10	0.63	0.50	0.71	D
HSE	***Anonymous***	*Anonymous*	practitioner	non-departmental public body (health & safety)	encouragement, regulation and enforcement of workplace health,	only organisation	**Y**	4	3	3	2	3	15	0.94	0.83	1.00	A
PHE	**Owen Landeg**	Principal Environmental Public Health Scientist	policy	public body (health)	government agency		N	1	3	1	2	3	10	0.63	0.83	0.57	B
CEH	**Steven Cole**	Head of Hydrological Forecasting Group	research	research institution	land and freshwater ecosystems and their interaction with the		N	1	3	1	2	3	10	0.63	0.83	0.57	B
Anglian Water	**Geoff Darch**		practitioner				N	1	2	1	1	1	6	0.38	0.33	0.43	K
Office for Nuclear Regulation	***Anonymous***	*Anonymous*	practitioner	public body (nuclear)	safety regulator for the civil nuclear industry in UK; independent	only organisation	**Y**	4	3	3	2	3	15	0.94	0.83	1.00	A
Yorkshire Water	**Amanda Crossfield**	Lead Advisor for Climate Change Adaptation	practitioner	private company	water supply and treatement utility company		N	1	2	1	1	1	6	0.38	0.33	0.43	K

Appendix 7 Ethics Policy

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E-mail	roxan@bgs.ac.uk

2nd October 2018

Dear Madam or Sir,

I am writing to invite you to participate in a research study commissioned by the **Natural Environment Research Council** (NERC) through UKRI (CR18075) and performed by a British Geological Survey (BGS) led consortium, supported by the Natural Hazard Partnership (NHP) partners (Health and Safety Executive (HSE), Centre for Ecology & Hydrology (CEH), Public Health England (PHE) and Met Office).

The study focuses on **reviewing multi-hazards research and risk assessment approaches**, with the aim of understanding what role NERC, alongside other funders, may have in promoting further research on the underlying processes and risks posed by multi-hazard events. The study requests a review of academic research and capability, industry and policy practice, as well as future research and innovation needs to inform multi-hazard risk assessment.

As part of this study, we would like to explore the understanding of multi-hazards of two key stakeholder groups: (i) industry practitioners and policy-makers, in areas such as, but not exclusive to, scientific research results and literature, operational processes and methods, policy guidelines and procedures.

Given your position as {*INSERT POSITION/ORGANISATION*}, I would like to request your assistance through answering some open-ended questions either in written form or by telephone to discuss in more detail the project and your views on this topic.

To ensure compliance with the UK ESRC (Economic and Social Research Council) Ethical Framework, I have attached herein an information sheet and consent form. You should only participate if you want to; choosing not to take part will not disadvantage you in any way. Before you decide whether you want to take part, it is important for you to understand, why the research is being done and what your participation will involve. Please take the time to read the attached information carefully and discuss it with others if you wish.

If you have any questions or require more information about this study, please contact the researcher using the contact details given above.

Yours sincerely,
Helen Reeves

1

INFORMATION SHEET FOR PARTICIPANTS

UKRI Project: **Review of multi-hazards research and risk assessment approaches**
Sourcing reference Number: CR18075

INDUSTRY, POLICY AND PRACTITIONERS' VIEW ON MULTI-HAZARDS

Extreme weather, earthquakes, landslides, pollution, diseases, all have a serious impact on people, supply chains and essential infrastructure in the UK and worldwide. Many such hazards are becoming more severe as our environment and socio-economic conditions change. It is now widely recognised that the combination and interaction of hazards (multi-hazards) can result in damages greater than by either hazard in isolation. Therefore, there is a growing need to better understand these processes and the associated risks posed to people, businesses and infrastructure.

In this study, information collected from the environmental multi-hazard literature across academia, industry and policy is complemented with evidence from interviews with industry and policy representatives. The interview questions are focused on identifying what approaches are being used to understand and assess the risk from multi-hazards, including how current risk assessments in different sectors are taking account of multi-hazards.

If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. You will then be invited to answer some questions in written form by **9th October 2018**. Subjected to your availability and interest, we will then arrange a telephone interview to discuss in more detail the project and your views on this topic. The interview will normally last for no longer than 45 minutes.

The interview will involve the discussion of multi-hazard processes relevant to your sector of activity. We understand that this can be distressful, and would encourage you not to take part if you think this may be the case.

The results of this questionnaire will form part of the project report submitted to the tender authority, UKRI NERC, at the end of the contract (**31st October 2018**).

Participants can choose whether to (i) remain anonymous, (ii) have only their organisation identified, (iii) have their name and organization identified. You can indicate this in the consent form. Should you later choose to change your status of anonymity, this can be done (by e-mailing roxan@bgs.ac.uk) before the submission of the study.

Participants can request to have their data removed (by e-mailing roxan@bgs.ac.uk) from the study up until **31st October 2018** before the submission of the research project to the contractor.

Interviews will be recorded, subject to your permission. Recordings of interviews will be deleted upon transcription.

The results of this research will be used to produce a report for NERC which will be published and available with date of publication to be confirmed. All those who take part in the study will have the opportunity to receive a copy of the final report by indicating this on the consent form (or e-mailing roxan@bgs.ac.uk).

Personal information about participants (including the consent forms, and other identifiable data) will not be kept after the completion of this research project, as indicated by the GDPR Regulations. Data from the investigation will be made available to other researchers and partners within the Consortium, but only in a fully anonymised form.

It is up to you to decide whether to take part or not. If you decide to take part you are still free to withdraw from the study at any time and without giving a reason.

If you have any questions or require more information about this study, please contact the researcher using the following contact details:

Dr. Roxana L Ciurean
WP Lead
Engineering Geology & Infrastructure Science Directorate
British Geological Survey
E-mail: roxan@bgs.ac.uk | Telephone: +44(0)115 9363004

If this study has harmed you in any way, you can contact the British Geological Survey using the details below for further advice and information:

Dr. Helen Reeves
Project Lead
Science Director of Engineering & Infrastructure Science Directorate
British Geological Survey
E-mail: hjre@bgs.ac.uk | Telephone: +44(0)115 9363381

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CONSENT FORM FOR PARTICIPANTS IN RESEARCH STUDIES

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study:
Review of multi-hazards research and risk assessment approaches (WP3 - Industry, policy and practitioners' view on multi-hazards)

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

- I understand that if I decide at any time during the research that I no longer wish to participate in this project, I can notify the researchers involved and withdraw from it immediately without giving any reason. Furthermore, I understand that I will be able to withdraw the data that I have contributed up until **31st October 2018** before the submission of the research report to the contractor. ☐
- I understand that anonymised data may be made available to other researchers at the end of this research project, but that no personal or identifiable information will be made available. ☐
- I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with the terms of the UK Data Protection Act 1998. ☐

Participants can choose whether to (*please tick one box below*):

(i) remain anonymous and non-identifiable in all publications ☐

(ii) have only their organisation identified ☐

(iii) have their name and organization identified ☐

FURTHER QUESTIONS	YES	NO
I would like to be contacted in order to participate at the telephone interview	☐	☐
I consent to my interview being audio/video recorded	☐	☐
I would like to receive a copy of the final report which will be published and available with date of publication to be confirmed	☐	☐

Participant's Statement:

I _______________________________________

agree that the research project named above has been explained to me to my satisfaction and I agree to take part in the study. I have read both the notes written above and the Information Sheet about the project, and understand what the research study involves.

Signed **Date**

If you opted to receive a copy of the report after submission, then please note your email address or postal address below:

Investigator's Statement:

I __Roxana L Ciurean______________________________

Confirm that I have carefully explained the nature, demands and any foreseeable risks (where applicable) of the proposed research to the participant.

Signed **Date**
Roxana Ciurean **2nd October 2018**

Appendix 8 Questionnaire

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Industry, Policy and Practitioners' views on Multi-Hazards

As part of a project commissioned by the **Natural Environment Research Council** (NERC), a British Geological Survey (BGS) led consortium, supported by the Natural Hazard Partnership (NHP) partners (Health and Safety Executive (HSE), Centre for Ecology & Hydrology (CEH), Public Health England (PHE) and Met Office), is reviewing multi-hazard research and risk assessment approaches amongst the stakeholders in academia, industry and policy. The project aims to enable better exploitation of the existing knowledge with respect to multi-hazard impacts and risk assessment in areas such as, but not exclusive to: scientific research results and literature, operational processes and methods, policy guidelines and procedures.

This questionnaire focuses on identifying what approaches are being used in industry and by policy-makers to understand and assess the risk from multi-hazards, including how existing risk assessments in different sectors are taking account of multi-hazards.

Definition of Multi-Hazard

In 2017, the United Nations Office for Disaster Risk Reduction (UNISDR) defined **multi-hazard** as "*(1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects*." (UNISDR, 2017). In this project, a thorough review of definitions existent in the academia (peer-review and grey literature) was performed; the results indicate that, although multiple taxonomies exist, there are strong commonalities between them with three emerging types of hazard relationship:

a) Hazard A causes hazard B to occur (*triggering*)
b) The occurrence of hazard A can change the likelihood and/or magnitude of hazard B in the future (*amplification effect*)
c) Hazard A and hazard B coincide in space and/or time with impacts greater than the sum of the two (*compound hazards*).

The consequence of hazard relationships occurring means that an impact is generated that is different to that of the individual hazards occurring in isolation.

References

UNISDR (2017) Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction, UNISDR, 41 p.

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Interview questions

Below are the questions that will form the basis of the interview.

A. **Self-assessment**
1. Given the multi-hazard definition stated earlier, what multi-hazard scenarios are most relevant to your sector?
2. On a scale of 1 to 5 (1 – no knowledge, 2 – some knowledge, 3 – fair knowledge, 4 – good knowledge, 5 – very good knowledge) what is the level of knowledge you have about multi-hazard processes and risk assessment methodologies used in (a) research, and (b) practice (industry and policy) within your sector?
3. What methodologies, approaches and procedures (including R&D) do you use in your organisation to understand the processes underlying multi-hazard events, their impacts, and to assess the risks?
4. What impact(s) do you believe multi-hazard processes have on your sector? Has this (or can this) been quantified in terms of economic costs? Are you aware of any evidence or best-practice guidance (e.g. reports) that support such an analysis?[1]

B. **State-of-the art**
5. In your experience, what are the advantages and pitfalls of current methodologies and approaches used to undertake multi-hazard risk assessments?
6. To what degree are the existing methodologies and approaches accessible, applicable and useful?

C. **Multi-hazard risk assessment**
7. Do existing risk assessments in your organisation take into account multi-hazards? If so, how?
8. What (if anything) hinders you from undertaking robust multi-hazard risk assessment within your sector?
9. What (if anything) enables you to develop robust multi-hazard risk assessment within your sector?

D. **Gaps in knowledge**
10. What are, in your experience, the current gaps in knowledge or skills for better understanding multi-hazard events and their impact?
11. In your experience, what are the current gaps in knowledge or skills for undertaking multi-hazard risk assessment within your sector?

Any other comments:

Contact Person:
Roxana Ciurean, Project WP Lead, Engineering Geology & Infrastructure Science Directorate, BGS;
Email: roxan@bgs.ac.uk, **Telephone: 0115 936 3004**

[1] If you have such evidence, would you be willing to share it within the framework on this project?

Appendix 9 Disciplines which could inform multi-hazard research and risk assessment

Natural Hazards Science. This community, focused on understanding Earth and environmental dynamics to characterise hazard processes (e.g., earthquakes, landslides, floods, volcanic eruptions) includes seismologists, engineering geologists, volcanologists, hydrologists, physical geographers and meteorologists. As well as characterising single hazards, a growing community of multi-hazard specialists focus on the relationships between multiple natural hazards.

Engineering. This community deal with the design, construction, and maintenance of the built environment, and includes many sub-disciplines that inform multi-hazard research and risk assessment (e.g., civil, engineering, coastal engineering, geotechnical engineering, transport engineering, mechanical and structural engineering). Understanding the impact of natural hazards on infrastructure (physical vulnerability) and the measures that are needed to build resilient infrastructure requires their engagement.

Social and Economic Sciences. Characterising multi-hazard *risk* also requires an understanding of social vulnerability, and the integration of economic analysis to determine the assets exposed to the multi-hazard environment. Helping to provide social/economic evidence to help aid the translation into policy

Ecology and Complexity Sciences. Multi-hazard risk involves complex interactions between multiple systems, and therefore the experience and insights of ecologists could inform this systems thinking. Research centres focused on complex systems exist (e.g., Centre for Complexity Science at the University of Warwick, Bristol Centre for Complexity Science) and could be a helpful contributing group.

Mathematics and Physics. Quantitatively characterising multi-hazard risk requires the application of probabilistic and statistical approaches. Developing these approaches, and understanding the uncertainties involved, will likely require those working on probability theory, statistics, game theory, and computation.

Computer Science and Modelling. The skills of computer scientists and mathematical modellers would allow modelling and simulation to advance multi-hazard analysis and risk assessment. The integration of single hazard models or the development of new physical models to characterise risk requires this set of skills.

Graphic Design, Communication Studies and the Visual Arts. The communication of information regarding multi-hazard risk may be through graphical user interfaces, cartography, or the visual arts. Helping decision makers to understand the complexity of multi-hazard environments and associated uncertainties is critical to ensuring research has impact.

Appendix 10 Relevant Initiatives, Forums, and Conferences

Here we outline some major networks and gatherings where discussion of multi-hazards research, and its application to support industry and practice, could be progressed.

Forums, Conferences and Workshops

Natural Hazards Partnership. The UK Natural Hazards Partnership provides authoritative and consistent information, research and analysis on natural hazards for the development of more effective policies, communications and services for civil contingencies, governments and the responder community across the UK.

Integrated Research on Disaster Risk (IRDR). The IRDR initiative is a decade-long research programme co-sponsored by the International Science Council (ISC) and the United Nations Office for Disaster Risk Reduction (UNISDR). It is a global, multi-disciplinary approach to dealing with the challenges brought by disasters, mitigating their impacts, and improving related policy-making mechanisms. As a network, it provides an opportunity for scientists from different disciplines to interact with each other, and with those coming from policy and practice perspectives.

European Geosciences Union (EGU). The EGU Natural Hazards Division brings together researchers from geology, hydrology, meteorology, and geography with an interest in natural hazards. The annual EGU General Assembly incudes a comprehensive programme of natural hazards science, and typically includes sessions linked to multi-hazards research, hazards and infrastructure, and the impacts of hazards on society. In 2018, a BGS-coordinated proposal was submitted to EGU to create a new multi-hazards sub-division within the EGU Natural Hazards division to facilitate greater dialogue on this theme.

American Geophysical Union (AGU). The AGU Natural Hazards Section focuses on geological hazards (e.g., droughts, earthquakes, fires, flooding, heat waves, landslides, space weather, storms, tsunamis, volcanoes, impact by near-Earth objects). The Section includes those working on fundamental research into dynamic Earth and space processes that can generate hazardous conditions and applied science and innovation through strategies and designs for hazard mitigation and disaster management worldwide. The AGU Fall Meeting gathers approximately 24,000 people each year.

INQUIMUS. This workshop series aims to provide knowledge exchange and catalyse dialogue on issues generally relating to disaster risk reduction and climate change adaptation. Their focus is on 'integrating quantitative and qualitative assessment methodologies for multi-dimensional phenomena'. The 2018 workshop focused on '*methods and tools to assess multi-hazard risk, vulnerability and resilience*'.

UK Alliance for Disaster Research. This forum brings together the UK's diverse disaster research community to facilitate collaboration and partnership, and to support representation of the research community at government level in the UK, and, where appropriate, help with the implementation of the Sendai Framework for Disaster Risk Reduction. They host an annual conference, with the 2018 theme being '*complex hazards, complex vulnerabilities*' aiming to bring together those working on disasters from the perspectives of the arts, social sciences, engineering, and physical sciences, as well as practitioners, academics and policy makers.

Multi-hazard Approaches to Civil Infrastructure Engineering. This 2016 book, published by Springer, is dedicated to the emerging critical issue of mitigating multi-hazards, from the perspective of the civil engineering community. While multiple volumes address single hazards, this collection relates to overall safety, sustainability and resilience of the built environment when subject to multiple hazards and different types of hazard relationships. While not a formal network, this volume gives a rapid overview of the key initiatives in the civil engineering community, and research groups working in this field.

Further Publications are noted in the references and Appendix 3.

Appendix 11 Transcripts

[See separate file A11_Transcripts.xls]

Stakeholder	Identification	Q1: Given the multi-hazard definition stated earlier, what multi-hazard scenarios are most relevant to your sector? – Primary
UKRI/BGS	identification info not provided	Landslides triggered by precipitation, earthquakes or volcanic unrest
Government department for transport	anonymous and non-identifiable	Scenarios involving hazards which could trigger power loss on a local or national level
Energy company	anonymous and non-identifiable	All types of these multi-hazards (and scenarios mentioned above) have the potential to impact the safety of infrastructure. At a practical level, often an important aspect concerns whether operatives can get out after the first hazard to make repairs before another hazard occurs; in this situation the time aspect is very important.
Environment Agency (Charles Pilling)	name and organisation identified	Various flood sources e.g. river and coastal coinciding
Environment Agency (David Hornby)	name and organisation identified	Weather events leading to flood. Fluvial flood event, combined with coastal/fluvial/surface water and any combination of them.
Environment Agency	identification info not provided	We warn of and respond to floods on the coast and in main rivers; Probably the main multi-hazard issue for us is floods in different places at the same time. We've done some work on the likelihood of this, but that was mainly to make sure people realise that it's not nearly as remote as they think. There's also an issue with floods in different places in close succession. One of the problems here is whether we've already deployed assets (e.g. demountable flood defences) but also the issue of having people who are available to respond.
Environment Agency (Paul Robinson)	name and organisation identified	The most appropriate multiple hazards of relevance would be scenarios where hazards interact to increase the magnitude of a single hazard. For example for a surface repository located on the coast, we would expect assessment of the impacts of storms events, flooding and tidal surges.
Historic Environment Scotland	identification info not provided	Combinations of different flooding sources (pluvial, fluvial, groundwater), rainfall plus wind/storm events (WDR), coastal flooding plus ground instability, etc
HSE	only organisation	All of the above [triggering, amplification effect and compound MH scenarios]
Independent consultant	anonymous and non-identifiable	Hazard A and B
Independent consultant (John Dora)	name and organisation identified	
Kings College London (Bruce Malamud)	name and organisation identified	All three examples [triggering, amplification effect and compound MH scenarios]
Met Office	only organisation	All three types above are relevant for our work – our customers are starting to become more interested in understanding multiple hazards. I'm not sure I can yet narrow it down to combinations of specific hazards, but our work is mostly on the hydrometeorological hazards side, plus space weather (given our operational responsibilities in both these areas and our responsibilities w.r.t. providing climate change information).
Met Office (Ian Lisk)	name and organisation identified	Strong winds, wind, rain, river-/coastal-/surface water-/groundwater- flooding and landslides; Thunderstorms, strong gusty winds, lightning, large hail, surface water- flooding and landslides; Strong winds, snow, ice and extreme cold; Heatwave, poor air quality, high pollen count; Heatwave, wildfires and poor air quality; Space weather impacts on power grid during period of extreme cold. Volcanic ash and poor air quality.
National Grid (Doug Dodds)	name and organisation identified	a. Weather hazards both direct and secondary impacts – Storms (wind), snow, ice, flooding (inland and coastal), extreme temperatures, drought, wildfires – weather (water) driven geohazards and erosion b. Space weather impacts leading to widespread electricity failure c. Effusive volcanic eruptions – pollutants particularly those where the particles are highly charged d. Other geohazards both natural and man-made earthquake, fracking e. Cyber-attacks, terrorist attacks f. Pandemics both human and animal
National Oceanography Centre (Mike Clare)	name and organisation identified	Multi-hazard scenarios most typically include triggering (e.g. submarine landslide triggers tsunami; tropical cyclone triggers turbidity current; earthquake (or compound small magnitude processes) triggers landslide etc) and amplification (e.g. particularly on volcanic islands where increased ash fall, or in fjord delta settings where increased meltwater related river run-off/flooding, provide enhanced sediment to offshore that does not directly trigger, but make turbidity current activity more likely)
Natural Resources Wales (identification info not provided)		Hazards that lead to inundation e.g. coastal, fluvial, surface water flooding, reservoir failure, landslide, impact on utilities, pollution
NCAS	identification info not provided	Most relevant would be those associated with interaction between air quality and meteorology, often under conditions where dispersion is limited. Examples include: a) Air quality and heat wave – conditions driving the heat wave also cause the air pollution event, the high temperatures also lead to higher ozone for the same meteorological conditions due to lower ozone stomatal uptake to vegetation when plants are under heat stress. May also then be linked with Drought – would bring increased dust component to particulate matter. Wildfire – emissions to air (presumably wildfire risk also linked to drought). b) Air quality and cold weather c) Volcanic eruption (effusive or explosive) – emissions to air.
Network Rail	only organisation	Extended periods of dry and hot weather. 'extreme' Dry weather leads to desiccation of earthworks and increased wildfire risk. Hot weather exacerbates this. Hot weather can lead to track deformation and desiccation exacerbates this. Storms can result in flooding, lightning strike, wind damage, coastal erosion and power loss. These may be in one location or geographically spread, but linked. Cold weather and rain/moisture can lead to icing.
Network Rail	identification info not provided	Amplification and compound hazards. Amplification hazards are in particular evident from natural slope failures where periods of increased activity can develop following an initial hazard. Operationally the railway can suffer from compound hazards during prolonged periods of wet weather where multiple routes may suffer restrictions / closures that reduce the capability of the network.

Stakeholder	Q1 – Secondary	Q1 – Notes	Q2 – Research	Q2 – Practice
UKRI/BGS	Groundwater flooding triggered by intense precipitation; surface flooding, triggered by landslide blockages	Geomagnetically induced currents triggered by magnetic (solar) storms	5	5
Government department for transport	Storm surge on the east coast – this would involve both storm and flooding, but we treat it as a single risk.		1 – No knowledge or very minimal knowledge of that used in research	2 – Some knowledge of that used in practice, but no clear understanding of best practice

Network Rail	identification info not provided	We deal with a number of weather events triggering geological events; specifically, extreme rainfall triggering flood events or ground movement, landslides	Very occasionally deal with earthquake events; whereas the flooding and landslide events occur 20 – 30 every year, earthquake (EQ) events, probably 1 in every 10 years.	Because we are transportation infrastructure owner, terrorism events are quite infrequent; we had the London Bridge event which was quite close by to one of our assets, but it wasn't directly involved in that event; although, there were some impacts on people using trains and using vulnerable stations as shelter; it had an emotional effect on people but no one was injured but members of staff were involved in that event. We don't deal with anything like pandemic, unless our staff is affected by it; we will just be taking guidance from the government. The data security, yes we are affected by that; we have a number of firewalls to prevent that happening, how to keep the data safe by using passwords, etc. but I don't think that's above any other government based organisation. Because we are transportation infrastructure owner, terrorism events are quite infrequent; we had the London Bridge event which was quite close by to one of our assets, but it [illegible]	3	4
ONR	only organisation	• One or more hazards that affect the plant and occur as the result of a separate event that also affects the plant. For example, an earthquake that causes a tsunami. • One or more hazards that affect the plant in the same time-frame due to persistence or similar causal factors. For example, meteorological conditions such as storms intrinsically involve the combination of several phenomena such as rainfall, wind, and storm surge. • One or more hazards may exacerbate other hazards. For example freezing conditions, drought or persistent rain can affect drainage conditions during subsequent rainfall. • One or more sequential hazards that affect the plant. For example if a wind hazard causes damage to building cladding, then any rainfall occurring during the period before the cladding [illegible]		Nuclear licensees need to take into account all combinations of external hazards that could reasonably be expected to occur at a given site. Categories of external hazards include seismic, geological, flooding and hydrological, meteorological, biological, man-made, fire, and other hazards including solar activity. More information is available in ONR's guidance, in particular Technical Assessment Guide TAG 13	4	4
Practical Action	name and organisation identified	All [triggering, amplification effect, compound hazards scenarios]			3	4
Scottish Government	only organisation	All natural hazard or non-malicious risk multi-hazards would be of relevance to our work.			2	2
Transport Scotland (Paul Mellon & Graham Edmond)	name and organisation identified	Multiple failures of Transport Network that could be triggered by a single failure, such as landslide, flood or major incident. This could be due to the diversion of the traffic to another unsuitable road or increase the stress of another mode –e.g. train to road or vice versa – alternative roads may be the responsibility of another roads (local) authority on which he have limited control or minimal information. There may also be cascading failures on utility supply to electrical railways for example.			3	3
University of Portsmouth	only organisation	All [triggering, amplification effect, compund hazards scenarios]		As an academic, I am interested in the processes and theory of multi-hazards, so all scenarios are relevant to me (and must be considered for a thorough multi-hazard risk assessment, even if only to be excluded from further analysis.)	3 to 4	For practice (I work with a range of stakeholders in urban Africa), I think there is good knowledge (4) of some specific multi hazard processes (e.g., storm > flooding) and very little knowledge (2) of others, particularly at a broader spatial [illegible]
UKWIR	identification info not provided	When you think about leakage for example, two of the environmental factors that influence leakage (freeze and thaw), cold weather isn't good and also drought as the soil around the pipes will shrink and move		Difficult to define MH; - the industry will plan for large climatic issue such as flooding, drought, deluge but in terms of MH, I was thinking more along the lines of things that are affected by; so if the weather affects power supplies or the roads network then, that can have an effect on the industry assets. I know the work the industry does on those single hazards, and they'll do a significant amount of contingency planning, but I was struggling with MH scenarios and I don't know for what specific things they might have planned for [cascading hazards vs cascading impacts]	2	4 to 5
Cabinet Office (EF)	name and organisation identified	A severe storm which happens at the same time as flooding; that can have multiple impacts over infrastructure with cascading effects towards multiple services and infrastructure; if there is a power outage on a regional or national basis then that can have cascading effects over a whole range of services; that can last several days, at which point there are huge amount of dependencies on that electricity supply	We look at endemic influenza, which has a huge amount of "slow-burn risk" i.e. it is spread over several months/years; the range of consequences that would have would result in a range of a whole set of other risks, in a similar way of power outage (e.g., impact on every day services); that would be difficult to predict	Another obvious example in terms of cumulative effect over time is climate change (CC); we don' really define CC as a risk in itself; it's more as a thematic trend; if you would do a long term trend analysis, you would be able to pinpoint the real life manifestation of various risk related to CC as a driver over time. On top of that, another example is cyber – although cyber in itself is not really a risk – but makes a whole area of risks more likely (e.g., fraud)	3	3
Cabinet Office	only organisation			At the moment, we don't specifically talk about MH, we just link to each weather/natural hazard scenarios that we've got and we'll also try to mention within the risk, another risk that isn't in the national risk assessment (NRA) that might be caused by it. Landslide is a good example but we are interested in any of them; but we're particularly interested in those that will tip one hazard into another one that isn't on the NRA at the moment.	3	4
CIRIA	identification info not provided	Each sector is different and how they identify hazards in that sector is different as well. In construction there is the social (e.g., buildings) and the linear infrastructure (e.g., energy, water); a variety of MH scenarios are relevant to those sector; e.g. flooding and secondary effects such as settlement with buildings, groundwater issues, landslide risks; landslides are certainly an issue for Network Rail, Highways England, Transport Scotland, etc. because they don't have control over these hazards. Some hazards they may have with their own assets, they can plan for those and manage the associated risks, whereas the other ones are beyond the boundary of their infrastructure; it depends on how they define the hazard and how they manage it – how far do you go? The hazard is the unknown; wind is one other hazard for the bridges and energy infrastructure (e.g. National Grid).		The most "talked about hazards" lean on the resilience aspect in the context of climate change	2 to 3	2 to 3
Geotechnics company	anonymous and non-identifiable	Rainfall events, landslides, and the interaction between them (rainfall triggers or increases the probability of a landslide). One of the big things is rainfall and actually surface water flow; we tend to think at landslides in relation with groundwater, but actually, our experience particularly in the last 10 yrs, is an increasing number of surface water flooding events that leads to wash-out type landslides or erosion of the toe of the slope that then causes a more "traditional" landslide	Warm winds causing snow packs to melt (Scotland) and potentially triggering landslides; people tend to think that rainfall melts the snow quickly, but actually warm wind even more, as it has a larger source of thermal energy for snow pack melting. - In terms of wind, probably the one that they come across most often is the effect on trees, and that has numerous knock-on effect; one of them is the movement of large trees which causes the roots to move and subsequent levering of blocks on rock faces ("root jacking"); the sail effect on the trees; we seem to be getting stronger winds during the parts of the year when the trees are in leaf - as an anecdotal; when the wind blows trees over you quite often get the release of soil or rock debris from the root ball; so, wind would definitely be a trigger lots of those things. On a soil type landslides you could have root induced loading of the slope – wouldn't say I can think of an example where this was the trigger or the cause but I can foresee that in some cases. In terms of dissolution, I think the management of surface water drainage with these high intensity rain cells that we have now is quite an issue; so there is probably more chance of existing drainage systems being topped and then water getting into the ground [currently working on a legal case where that kind of thing happened]. Where you've got sinkholes forming, I would've thought extreme dry and then extreme wet weather could lead to [illegible]	No scenario of the type: wildfire – intense rainfall – landslides was experienced by the UK operations; this is more relevant for Canada, Portugal, Australia; however, after the recent fires over the moorlands this summer in the Pennines, there might be a larger propensity for wash-out type of failures	3 to 4	4 to 5
Department for Communication, Media & Sport (Rob Willis)	name and organisation identified	Heatwave causes wildfires which can have implications for radio communications; severe winter weather (ice, snow) impacting overhead power lines, resulting in loss of power (another hazard); starting with a natural hazards but resulting in an anthropogenic hazard; [loss of power is considered a hazard in its own right]. The most frequent scenario would be the impact of weather-related hazards: ice and snow affecting the power lines resulting in another hazard which is loss of power; flooding (surface of fluvial) as a result of extreme rainfall; severe weather is the main issue (rain or snow and ice-related; winds affect the power as well but sometimes by themselves they can cause issue to the network)	Space weather – really big storms like solar storms (e.g., 1859 Carrington Event); they think this might happen at some stage and we don't know what the impact might be; likely, power gain (examples in Canada, US); TCs satellite might also be impacted by solar storm and this can cause terrestrial problems;	In TCs, it's more about the consequences; you can have a range of hazards that can have a knock-on effect that might have a multi-hazard effect but in the end it is the same sort of consequence i.e. the total network will get a loss of power. If there are MH happening it makes it more difficult for engineers to get out and about and to fix and repair things; e.g., if you got a storm, that might blow mobile phone down or cause wires to get loose; with severe weather and flooding it makes harder for people to reach those problematic areas [direct and indirect losses, in terms of intervention and mitigation]	2 to 3	2 to 3
SEPA (David Faichney)	name and organisation identified	Anything that has to do with floods: rainfall, surface and river flooding together, coastal flooding and fluvial flooding in lower reaches of rivers; when a prevailing flood warning comes, we endeavour to take the join probability of two processes happening together and see what the impact of the join probability of these two hazard happening together will be multi-variate models)	Snowmelt is an important component of MH; snow where interested in terms of maybe not road closure, etc. but accumulation of snow that can feed into the flood effect quickly. We are interested in snow in relation to wind in particular; where interested in storms (low pressure cells causing storm surge) which can lead to estuarine floods, and also wind associated with high sea level and wave action. Examples of multihazards along the coast: nuclear power plants that have no cooling water and get close to a criticality event. Another multi-hazard problem is in Scotland where there are 12 reservoirs that are cascades (chains of reservoirs)	SEPA is a regulator authority for reservoir safety; we're interested in when reservoirs maybe subjected to activity from the slopes – landslip action causing overtopping failure. There's definitely a gap in understanding how weather events can contribute to reservoir failure and that's a big deal. When we do our assessments for flood risk management purposes (every six years strategies), we can set up the impact of flooding on a number of things, and one of them is environmental impact (e.g. flood happening near a refinery which results in an environmental incident; other major incident induced by human factors as well); examples along the coast with very localized impacts (contamination with oil, asbestos, etc.). We have a responsibility as a CAT1 responder under the Civil Contingency Act, so we have to make our info and knowledge available to those who are acting under that. Over 600 m reservoirs (e.g. four reservoirs) – quite a few in [illegible]	2	3 to 4

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