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D1.3
Report on policies, policy-making processes, and governance for multi-hazard, multi-risk management

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D1.3 / Report on policies, policy-making processes, and governance for multi-hazard, multi-risk management

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Part 1: Review of policies, policy-making processes, and governance for multi-hazard, multi-risk management

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Part 2: Typologies of interdependencies between sectors

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Abstract

How can risks be better managed by considering interrelated effects of multiple hazards? How can we better account for dynamic feedbacks between risk drivers, and for trade-offs and synergies across sectors, regions, and hazards? These questions are central to the MYRIAD-EU project, which aims to support risk-informed management and decision-making in the EU. Initial diagnosis activities as part of MYRIAD-EU reflected upon terms and definitions (MYRIAD-EU D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts) and approaches for multi-hazard or multi-risk management (MYRIAD-EU D1.1 WIKI-style online platform of multi-hazard, multi-risk methods, models and tools). The development of long-term plans and strategic solutions from a multi-risk perspective requires a good understanding of the decision context and processes that govern multi-hazards and multi-risks.

Part 1 of this report investigates and reviews the current multi-risk governance practice in Europe. We analyze existing international and European policies and communications with regards to their consideration of key elements of multi-hazards and multi-risk. We present the national risk assessment process as an important avenue for risk governance practice in Europe; the assessment within this study concludes that the present embedding of a multi-risk perspective in the national risk assessments does not meet the ambition of the international and European policies. We present a selection of representative, promising and prominent approaches from the scientific multi-risk research to illustrate recent advancements from the academic community. Two main conclusions are: 1) multi-risk needs further consideration in existing (particularly sectoral) policies; and 2) the scientific community needs to embed the considerations of good governance principles into the development and testing of new tools for multi-risk identification, assessment, management and communication. Ultimately, we present barriers and opportunities to mainstream multi-risk governance into current practice, together with good practice examples. Part 1 of the report further reflects on the immediate implications for the upcoming activities in the scientific Work Packages of MYRIAD-EU and other projects.

Part 2 aims to classify sectoral dependencies and provides guidelines for the sectoral representatives on how to identify and navigate multi-sector risk. Sectoral interdependencies are first classified through the lens of undisturbed conditions: functional, spatial, financial, and societal. Combining this with analysis of hazard impact studies, four typologies of multi-sector risk are developed: spillover, co-dependent, interacting intersecting and interacting independent. Finally, part 2 of this report presents a set of questions for stakeholders (Table 2-3); these questions aim to facilitate future stakeholder discussions in the MYRIAD-EU project and the identification of sectoral inter-dependencies to promote more effective Disaster Risk Management strategies.

Dissemination level of the document

☒Public

☐Restricted to other programme participants (including the Commission Services)

☐Restricted to a group specified by the consortium (including the European Commission Services)

☐Confidential, only for members of the consortium (including the European Commission Services)

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1 Part 1: Review of policies, policy-making processes, and governance for multi-hazard, multi-risk management

Executive summary

Multi-risk assessment and governance are by their nature highly interdisciplinary pursuits, characterized by complex and interacting processes. This inherent complexity can pose difficulties for policy-makers and practitioners. Part 1 of this report aims to provide a first understanding of the governance landscape for the management of multi-risks in Europe: the review aims to highlight general guidelines, good practice examples, emerging conceptual work together with barriers and possible opportunities.

Multi-risk governance is an emerging topic. As such, limited information is readily available. For this analysis, three information pillars were considered: internal consultations with the project team, information retrieved from literature review and stakeholder semi-structured interviews.

Current considerations relevant for multi-risk governance have been partially embedded into European guidelines and regulations for Disaster Risk Management (DRM). Apart from critical infrastructure, the acknowledgement of the importance of multi-hazards or multi-risk in sectoral policies seems to be lacking entirely. The assessment of current management practice of natural hazard induced risks in Europe concludes that the National Risk Assessment (NRA) is the central avenue for national efforts for DRM governance in Europe. This report presents relevant considerations of NRA towards multi-risk governance, together with overarching differences in the national governance approaches. Additionally, a governance example from Italy (one of the MYRIAD-EU pilot countries) is presented as an illustrative example.

Existing literature was reviewed to map the landscape of working practices of national disaster (risk) management organizations for multi-hazards. However, despite extensive search, no systematically implemented multi-risk governance approaches could be found in working practice. The conducted semi-structured interviews with the MYRIAD-EU sectors (Infrastructure & Transport, Food & agriculture, Ecosystem & forestry, Energy, Finance, Tourism) and pilot leads also confirmed these trends in working practice and science. Nevertheless, we found calls for paradigm shifts of DRM towards multi-risk governance.

Given that scientific research often develops approaches that are ahead of the curve of working practice, we present a selection of promising, or prominent, representative approaches for the risk identification, risk assessment, risk management and risk communication illustrating general characteristics relevant for multi-risk governance. The review further includes examples of institutional partnerships and cross-agency collaborations that show initiatives towards the implementation of multi-risk approaches.

Transitioning towards multi-risk governance represents a complex process, and it requires a clear understanding of single risk approaches and systems thinking. The literature review resulted in the identification of multiple barriers & opportunities with regards to mainstreaming good multi-risk governance. The report concludes with reflections on lessons learned for the upcoming activities in the MYRIAD-EU project and other projects:

- Make the step from conceptual frameworks to testing and operationalizing approaches (Science)
- For new approaches, keep in mind the purpose and application context of these tools. A comprehensive overview of tools and methods will be available in the Disaster Risk Gateway wiki[1] developed in T1.2 (Science & Practice)
- Integrate processes of multi-risk assessment and management (Science)
- Make use of existing knowledge and link to existing processes (Science & Practice)
- Engage in projects and initiatives that consider multi-risks (Science & Practice)
- Integrate considerations of (multi-)risk governance in strategies and long-term planning (Practice)

[1] disasterriskgateway.net

1.1 Aim and objectives

Recent successive disasters show that there is an increasing need to recognize and assess interactions and interdependencies between multiple natural hazards and their impacts. The number of studies looking into the assessment of multi-hazard risk is steadily increasing; however little guidance exists with respect to the steps to be taken to include multi-hazard risks in policy and practice. A single agency or ministry often does not have all the funds, skills and mandates to address all aspects of disaster risk reduction and management. Further, single sectors (e.g. energy, transport) might have a good understanding of possible impacts of different natural hazards on their own sector but may overlook or underestimate dependencies to other sectors. A joint understanding of multi-hazard events, their impacts and options to mitigate the risks can be highly beneficial for a more efficient use of resources.

This report aims to provide a first understanding of the governance landscape for the management of multi-risks in Europe. The scope of the work is to understand existing multi-hazard management approaches, current developments and available (conceptual) approaches towards multi-risk governance. The review aims to highlight general guidelines, good practice examples, and emerging conceptual work. This report aims to:

- Map the landscape of working practices of national disaster (risk) management organizations for multi-hazards and multi-risks
- Review current developments and available (conceptual) approaches towards multi-risk governance
- Discuss gaps and opportunities to facilitate system thinking and progress on multi-risk governance
- Reflect on the immediate implications for the planned activities in the scientific Work Packages of MYRIAD-EU.

The outcomes of this report are relevant for the entire MYRIAD-EU consortium and for the broader academic community, policy makers and sectors. Important beneficiaries are the MYRIAD-EU pilots and sectoral representatives: this work aims to support them towards an improved understanding of multi-risk governance when proposing solutions for risk reduction.

This document aims at assessing the most up-to-date information, yet we acknowledge the variety of approaches and often country/region-specific governance of multi-risk management. Nonetheless, the recommendations made in the report are expected to be applicable to different countries and contexts.

1.2 Outline of the report

Following the introduction, **Section 1.3** explains the main information pillars considered for this analysis. **Section 1.4** introduces the most relevant terms and concepts, together with key concepts of the disaster risk management cycle and further describes principles of good governance. **Section 1.5** presents the main findings of the multi-risk governance review. This section is organized as follows: i) a synthesis of current management approaches for natural hazards induced risks in Europe (**Section 1.5.1** and **Section 1.5.2);** ii) preliminary findings from stakeholder interviews (**Section 1.5.3**), iii) a high level overview of available (conceptual) approaches towards multi-risk governance (**Section 1.5.4**); and iv) a discussion of knowledge gaps and opportunities to further facilitate multi-risk governance (**Section 1.6**). The key findings of the review are synthesized in **Section 1.7**.

1.3 Methodological approach

Multi-risk assessment and governance are by nature inter-disciplinary and characterized by complex interacting processes. This inherent complexity can pose difficulties to practitioners (policy makers and industry). This work aims to provide a first understanding of the governance landscape for the management of multi-risks in Europe: the review aims to highlight general guidelines, good practice examples, and emerging conceptual work. As such, this report is reflecting on the science of risk governance; although institutional arrangements and legislative regulations are highly relevant for any governance process, it is out of the scope of this study to investigate national policy coherence and organizational features.

Multi-risk governance is a recognized emerging topic. Therefore, limited information is readily available. To increase the portfolio of information that can be relevant for this work, three information pillars were considered: internal consultations with the project team, information retrieved from literature review, and stakeholder interviews. The three pillars are described in the following sections.

1.3.1 Internal consultation activities

Initial scans of available information on multi-risk governance (both at EU level and international) have shown that little information is available on this subject. During the project kick-off, an online tool (Mentimeter) was used to sense the level of knowledge of the consortium members with respect to policies, policy-making processes, and governance of multi-risks (Figure 1-1). This exercise suggested that the majority of the consortium members are not familiar with the policies, policy-making processes, and governance for multi-hazards and multi-risk management. The highest ranked perceived levels of maturity of multi-risk policies and governance processes are ‘agenda setting’, ‘problem emergence’ and ‘consideration of policy options’, as illustrated in the figure below.

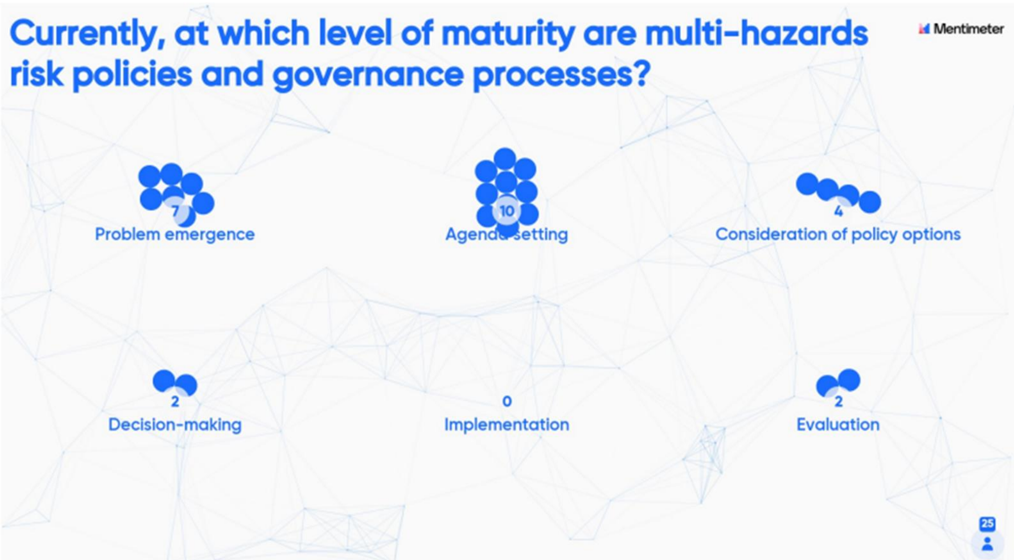

Figure 1-1: Perceived levels of maturity of multi-risk policies and governance processes during the MYRIAD_EU project kick-off (created using Mentimeter.com)

Among other questions, the consortium was also asked to share useful links and names of relevant projects on multi-risk governance. This has resulted in an initial collection of data sources, however the information provided was rather scarce.

Further engagement with the MYRIAD-EU consortium took place during the regular WP1 weekly meetings. A dedicated session for multi-risk governance was organized in December 2021, using the online collaborative tool ‘Padlet’. During this session, the consortium contributed to specific questions that aimed to expand the number of data sources that might inform the review of multi-risk governance:

- Examples of gray literature focused on policies, decision-making, and governance of multi-hazard risk (e.g., government documents and reports, working papers, guidelines, blogs, interviews, dissertations, thesis, etc.),
- Relevant scientific/practice-based networks that are relevant for multi risk governance,

- Groups/contacts that can help to better understand multi-hazard risk policy and governance within the pilot regions/sectors,
- Any other relevant info that can support the policy review.

The results of these internal consultations were used to inform the literature review.

1.3.2 Literature review

The literature review is based on the main conclusions and recommendations of multi-hazard policy analysis studies worldwide; due to the short time frame of the analysis and available resources, it is outside the scope of this work to perform detailed country-based institutional mapping and analysis of legislative documents, mostly available only in native languages.

Analysis of relevant policies for multi-risk governance

For the analysis of global and European policies the identified data sources provided during previous exercises as outlined in Section 1.3.1 were used as starting points. The list of relevant policies was later substantiated by suggestions provided by participants in the stakeholder interviews (see Section 1.3.3). The final list of policies considered can be found in Appendix 0. The analysis of these policies was conducted using search terms ("risk", "multi-hazard", "multi-risk", "cascading", "spillover", "compound", "dependence",...) to identify the relevance of a certain policy for this report.

Identification of relevant reports and gray literature

While a few reports and gray literature were identified during exercises as outlined in Section 1.3.1, additional relevant reports were identified using targeted research. For example, a search on Google using various key terms ("risk", "risk assessment", "risk management") in combination with institutions that were previously identified as potential relevant knowledge bearers (OECD, UNDRR, GCA, PIARC, WMO, C40, ...) resulted in approximately 50 relevant reports and other gray literature documents (see Appendix A1.b). These policies were screened for relevance based on search terms similar to the ones used for the analysis of policies.

Peer-reviewed literature

Scientific literature was identified using a combination of integrative literature review (Snyder, 2019) based on a search on GoogleScholar and a backwards snowballing (Wohlin, 2014) to synthesize existing knowledge from available scientific literature. Similar to Di Angeli et al. (2022), questions were identified to guide the search for relevant literature:

- What conclusions are drawn from analysis of existing risk governance in Europe in the available academic literature?
- What principles and elements have been identified as relevant in the context of risk governance?
- What local/regional/national/EU-wide good practices are available that consider multi-hazard interactions and multi-risk as part of a risk management approach?
- Are there any barriers or challenges policy-makers are facing in implementing multi-hazard, multi-risk management guidelines and policies in general and specific sectors?

For the integrative literature review, the following (combinations of) key search terms were used: "risk governance", "multi-risk governance", "multi-sector", "multi-hazard", "management", "governance". In this way, about 100 papers in the English language were identified that were used to inform the literature review; the research period spans from September 2021 to June 2022.

1.3.3 Stakeholder interviews

A survey was used as a triangulation tool complementing the literature review through semi-structured interviews (SSIs, Rubin & Rubin (2012)) with internal and external stakeholders. Semi-structured interviews were considered the most suitable approach of engagement; they are useful in cases where pre-existing work may be performed to inform the types of questions to ask, and flexibility is desired to adapt questions during the interviews and ask further probing questions. The main purpose of the SSIs was to inform the MYRIAD-EU team to better understand how decision-makers and practitioners consider and approach multi-hazard risk management and what policies and policy-making processes underpin the governance of natural multi-risks. The interviewees were representatives of the sectors targeted in the project (energy, finance, transport & infrastructure, food & agriculture, ecosystems & forestry, and tourism) and experts and practitioners from the DRR community. The interviews were prepared, conducted and evaluated in line with Hove & Anda (2005). The interview guide (questions) was developed iteratively, in consultation with MYRIAD-EU partners and aimed at exposing the interviewee to a few predetermined (general and specific) questions while also providing an opportunity to spontaneously explore other questions relevant for their role.

The set of ten guiding questions as well as the participant information sheet and example consent form shared with the interviewees can be found in Appendix A1.c. In total, twelve interviews were conducted.

The interviews were conducted in accordance with the Ethics Plan of MYRIAD-EU, meaning that: (1) the interviews were designed in a way that the tasks for participants were kept as short, simple and non-invasive as possible; (2) the collected personal data including perspectives, choices and preferences were handled with due care and in full compliance with national privacy and data protection laws (including, but not limited to, countries where research is conducted and where researchers operate); and (3) the interviews were approved by the BGS Ethics Review Board. All consent forms are transferred and saved on the BGS server. A note on this was saved on the MYRIAD_EU google drive.

Before the start of the interview, participants internal to the project consortium were invited to a one-hour webinar where questions and ambiguities regarding the purpose and content of the interviews were addressed. The interviewees received a document with the guiding questions at least two weeks in advance of the interview and were invited to share some first reflections in written form prior to the interviews. Those written responses were used to identify a set of follow-up questions that were addressed during the interview. The interviews were recorded subject to agreement with participants. Additionally, a third person was taking notes during the interviews in order to capture the main discussion points and provide a summary of the interview immediately after. For this deliverable, the notes formed the main source of data, selectively supported by recordings to address ambiguities or double-check for additional information provided in the interview.

We report that identifying a set of adequate, comprehensive guiding questions was a very challenging process. Not only did the MYRIAD-EU team have to account for the science-practice divide in terms of relevant topics, terminology and familiarity with the topic, but also that interviewees have diverse backgrounds where different terminology and concepts are applied. Enduring that participants understood the underlying intention and focus of the interviews was crucial for a meaningful interview. As such, the MYRIAD-EU team strived to reduce the knowledge/language barrier as much as possible, by organizing a preparatory meeting and inviting interviewees to provide responses prior to the interview in order to address potential clarifying questions and be able to adjust the approach during the actual interview.

1.3.4 WP1-WP2 Stakeholder workshop

In addition to the main data collection and generation activities (i.e., internal consultations and literature review), the topic of governance for multi-hazard, multi-risk management was addressed during the presentation of WP1 findings and breakout sessions with external experts at the WP1 - WP2 workshop at IIASA, Laxenburg (11 - 12 April 2022). During the WP1 breakout session, participants were asked to reflect on two questions: the first focused on current gaps in risk assessment and management in a multi-hazard, multi-scale, multi-sector context; the second addressed good practice that MYRIAD-EU can build upon in bringing together science, policy, and practice on risk assessment and management. To increase the potential for collaboration and co-learning, the session was organized as a Charrette style, with interactions between academics, practitioners, industry representatives, DRR and policy & governance experts taking place both online and in person.

1.4 Terms and Concepts

In this deliverable we use a variety of terms and concepts relevant for the governance of multi-hazard risk. The most relevant definitions are summarized in Table 1-1. A more comprehensive list of definitions can be found in the MYRIAD-EU D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts. While most of the definitions provided in the table below speak for themselves, more elaboration is provided regarding the different notions of risk and the concept of (risk) governance. This is to address the partners of the consortium coming from diverse backgrounds in order to build a common understanding about some of the central concepts relevant in this deliverable. Furthermore, the research field on multi-hazard, multi-risk is still rather novel. Thus, terms and concepts used in the literature do not always follow universal definitions. This section tries to ensure transparency and clarity on the understanding and used terminology. This was also necessary to help deal with the ambiguity/variety of the terminology used in the considered literature to describe similar/related concepts considered.

Table 1-1: Most relevant terms and definitions used in this report

Term	Definition	Source
Disaster	A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts.	UNDRR (2016)
Disaster Risk	The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society, or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.	UNDRR (2016)
Disaster Risk Assessment	A qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend.	UNDRR (2016)
Disaster Risk Governance	The system of institutions, mechanisms, policy and legal frameworks and other arrangements to guide, coordinate and oversee disaster risk reduction and related areas of policy.	UNDRR (2016)
Disaster Risk Management	The application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses.	UNDRR (2016)
Disaster Risk Reduction	Preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development.	UNDRR (2016)
Governance	The structures, processes, and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws, and procedures for deciding, managing, implementing, and monitoring policies and measures at any geographic or political scale, from global to local.	IPCC 6th Assessment Report, WG II Glossary

Term	Definition	Source
Hazard	A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation.	UNDRR (2016)
Hazards (Natural)	Hazards that are predominantly associated with natural processes and phenomena.	UNDRR (2016)
Multi-hazard	The selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects.	UNDRR (2016)
Multi-Hazard Risk	Risk generated from multiple hazards and the interrelationships between these hazards (but not considering interrelationships on the vulnerability level).	Zschau (2017)
Multi-Layer Single Hazards	More than one hazard is considered, but not the interrelationships between these (i.e., they are treated as discrete, independent).	Gill & Malamud (2014)
Multi-Risk	Risk generated from multiple hazards and the interrelationships between these hazards (and considering interrelationships on the vulnerability level).	Zschau (2017)
Policy	Policy is the development, enactment, and implementation of a plan or course of action carried out through a law, rule, code, or other mechanism in the public or private sector	Bogenschneider (2006)

1.4.1 Different perspectives on risk

As presented in Table 1-1 (disaster) risk is generally understood as a function of hazard, exposure, vulnerability and capacity (UNDRR, 2016). Here we limit the definition of hazard to natural hazards which are predominantly associated with natural processes and phenomena and "*may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation*" (UNDRR, 2016). Exposure means that elements at risk (people, infrastructure, housing, production capacities and other tangible human assets) are located in hazard-prone areas, while vulnerability is often defined as "*conditions determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards.*" (UNDRR, 2016)

In the past, risk has often been interpreted in a static manner. Therefore, a commonly used approach when accounting for multiple hazards is a multi-layer single hazard risk which is understood as "*more than one hazards are considered, but not the interrelationships between these (i.e., they are treated as discrete, independent)*" (Gill & Malamud, 2014). Conversely, multi-hazard risk determines the risk generated by multiple hazards, but also accounting for the interactions of these hazards (e.g. exacerbated impacts because a river flood and a storm surge hit the same region at the same time) (Zschau, 2017).

Yet, while multi-hazard risk accounts for interactions within the hazard domain, dynamic interactions also exist particularly regarding the vulnerability. A house might be more likely to be destroyed by a flood event, if it has been damaged (and not fully recovered yet) from a previous flood event. At the same time, if one element in a system might be vulnerable and thus impacted by a hazard, it could lead to cascading effects on other elements (e.g. disruption of transport services because of a pandemic limit the ability of farmers to deliver their food products in time to customers leading to financial losses which make their existence more vulnerable (less capable to recover) from a flood event resulting in an additional financial burden). These kinds of interactions in the regime of vulnerability are accounted for as part of multi-risk, defined as "risk generated from multiple hazards and the interrelationships between these hazards (and considering interrelationships on the vulnerability level)" (Zschau, 2017).

Many of these terms are still not unanimously used in research in practice. Conversely, they are interpreted conflicting to each other. For example, some reports use the term 'multi-risk' to refer to the consideration of multiple overlapping (but independent) risks caused by multiple hazards. The same holds for 'multi-hazard' neglecting the effects of interaction. This ambiguity has to be carefully considered when searching for and reviewing reports, policies and papers.

1.4.2 Governance in the context of risk

In this section, we set the basis for a broad understanding of governance including a set of good governance principles. We present the only multi-risk governance framework we identified from the literature to date to highlight the elements and phases deemed relevant in a multi-risk governance scheme.

According to the IPCC (2021), governance is defined as "*the structures, processes, and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws, and procedures for deciding, managing, implementing, and monitoring policies and measures at any geographic or political scale, from global to local*." UNDRR (2017) specifies that these societal goals are to "*coordinate and oversee disaster risk reduction and related areas of policy*" when addressing risks resulting from natural hazards. According to the International Risk Governance Council (IRGC, 2017), structures, processes and actions can be distinct in the following four pillars: identification, assessment, management and communication of risks.

Research on risk governance has focused on descriptive analysis (**How do actors currently interact to address a societal goal?**) as well as on normative discussions (**How should actors interact to address the societal goals?**) (IRGC, 2017). In both research directions, principles of good governance are used as benchmarks for the descriptive analysis or guidance to propose normative advancements. In the context of governance assessment frameworks of international development agencies, the following principles are included (Aven & Renn, 2010; Virtudes, 2016; IRGC, 2017; Chereni et al. 2020):

- **Effectiveness:** including efficiency, subsidiarity, and strategic vision
- **Equity**: including sustainability, gender equality and intergenerational equity
- **Accountability**: including transparency, rule of law and responsiveness
- **Participation:** including conflict resolution, human security
- **Environment safety**
- **Feasibility**: politically and legally
- **Public acceptance**

In the literature, many more sets of good governance principles are proposed (e.g. see Aven & Renn, 2020 for a list of examples). However, as Aven & Renn (2020) mention, they all revolve around similar concepts so that "*contours of a set of important principles*" can be identified. For the purpose of this report, the above set of principles is sufficient to illustrate the relevance of existing good practice examples (How do actors currently interact?) and promising approaches from science (How should actors interact?).

Inherent of the present understanding of risk governance is the inclusion of key integrative and adaptive capabilities. This means that risk governance "*becomes a dynamic process of continuous and gradual learning and adjustment"* (Klinke & Renn, 2021). As such it uses various resources from institutional arrangements (e.g. distribution of responsibilities, and transparent decision-making) over technical resources (e.g. databases, etc.) to human resources (e.g. expertise and willingness to participate). This so-called "*post-normal risk governance"* (Klinke & Renn, 2014) builds upon self-governing, democratic components involving not only those with the relevant authority but those affected and thus adds legitimacy, and effectiveness to the governance process (Klinke & Renn, 2021).

While a range of risk governance frameworks exist (e.g. IRGC, 2017; Renn & Klinke, 2014), only one framework explicitly addressing multi-risk governance has been found through our research. The framework designed by Scolobig et al. (2017) moves away from the intensive quantitative analysis, aiming to provide a bridge between the science and policy, thus overcoming barriers that will be explored in later sections of the report. Figure 1-2 schematically depicts the process described by the authors in the following four steps:

- Step 1: The observation of hazard and risk interrelationships as it is considered a starting point for understanding cascading events and interdependencies of both social and economic nature. A priority is given to identifying the most dangerous multi-risk environment at all levels, from local to national.
- Step 2: Social and institutional context analysis sees the mapping of stakeholders, with their corresponding tasks and responsibilities, at the single risk level and conceptualizes possible conflicts that may occur when scaling to the multi-risk level. This type of qualitative analysis aims to find the most suitable actors that could take the responsibility of multi-risk governance across institutional level. Some research in this area presents boundary organizations as useful for bridging the gap between experts and decision-makers and informed governance across levels
- Step 3: Multi-risk knowledge generation is a process that usually refers to tools that tackle both assessment and mitigation strategies. The ones that Scolobig et al. (2017) highlight from the literature are a hazard correlation matrix and subsequent risk mitigation matrix that guide the decision-making process through scenarios, followed by implementation of measures in a 'virtual city' for bettering the understanding of complex processes
- Step 4: Stakeholder processes is a step that builds on the previous societal involvement, arena creation and knowledge and designs the appropriate management options. The authors emphasize that the successful completion of previous steps should yield a thorough stakeholder and institutional analysis, as well as a variety of solutions for multi-risk reduction that take into account both social and technical options. Thus, this concluding step aims to find the middle-ground solution and focus on both the outcome and process of decision-making.

As presented by Scolobig et al. (2017) this is a cyclical process that should restart after the completion of the fourth step and prevention methods identified would be implemented after each cycle. Although, some financial limitations may hinder the continuation of the cycle.

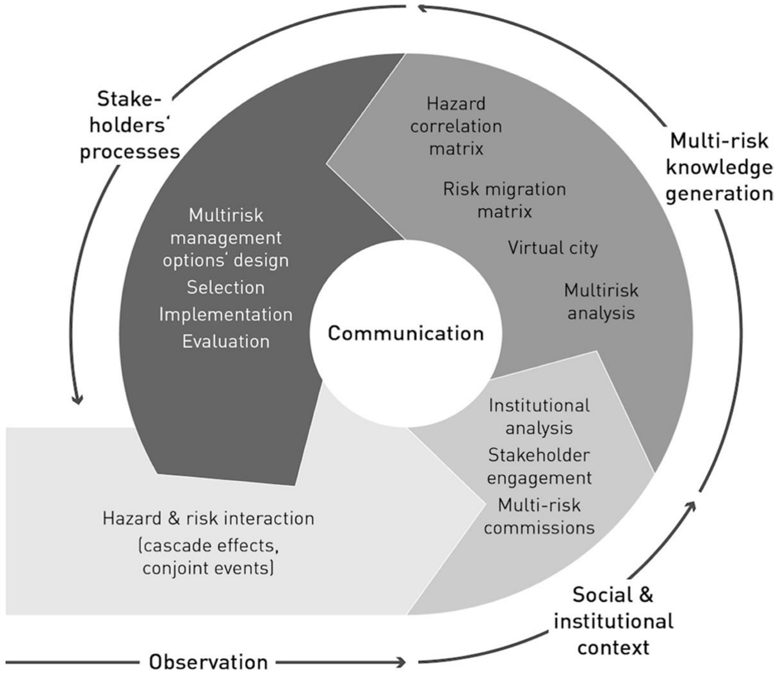

Figure 1-2: Multi-risk governance framework

Source: Scolobig et al. (2017) CC BY 4.0

Extensive stakeholder involvement is prioritized by Scolobig et al. (2017). The diverging views of the stakeholders are important for the diversity of multi-risk approaches developed. Meanwhile, experts in multi risk should provide multiple solutions and closely collaborate with stakeholders to find the technical solution to implement the results of qualitative research. The compromise between the two worlds should yield solutions. These should be further reinforced by a strong evaluation process which feeds back into the multi-risk governance co-production loop. At the same time, Scolobig et al. (2017) highlight that the effect of some of the elements proposed as part of the framework could have adverse effects jeopardizing the purpose. For example, multi-risk commissions (i.e. proposed in Scolobig et al. (2017): "*institutional arenas to discuss and take action on multi-risk issues with an interdisciplinary and multi sector character*") are proposed to enhance inter-agency cooperation.

1.5 Key findings on multi-risk governance

Existing literature was reviewed to map the landscape of working practices of national disaster (risk) management organizations for multi-hazards. However, despite extensive search, no systematically implemented multi-risk governance approaches could be found in policies or institutional frameworks. Nevertheless, we found calls for paradigm shifts of DRM towards multi-risk governance, and several good practice examples and promising scientific approaches implementing first steps necessary for a multi-risk governance. The conducted stakeholder semi-structured interviews also confirmed these trends in working practice and science.

As a result, key findings on multi-risk governance are split into two sections. First, we analyze how global or international policies call for a change in risk management practice in Europe (Section 1.5.1). Then, we analyze current management practice at national levels, based on available literature (Section 1.5.2). As we found that no systematic multi-risk governance approaches are used, we investigated scientific approaches and good practice examples that contribute to at least one of the steps of the multi-risk governance cycle as proposed by Scolobig et al. (2017) (Section 0). Finally, this chapter further reflects upon barriers that may inhibit the use of multi-risk governance approaches along with further illustration of opportunities and benefits of a multi-risk approach (Section 1.6).

1.5.1 The call for multi-risk governance

A set of representative policies have been reviewed to identify what concrete multi-sector, multi-hazard-specific considerations relevant for multi-risk governance are considered in overarching conventions and communications of transnational treaties and of the EU. These are summarized in Table 1-2. As we engaged in a first scanning of the multi-risk governance landscape, we do not claim completeness of the results.

Table 1-2: Summary of selected international and European initiatives and communications related to disaster risk calling for multi-risk governance approaches

Scale	Source	Considered multi-sector, multi-hazard specific elements	Legal status
Global	Agenda 21	Call for research on multi-hazard effects	Non-binding
Global	Hyogo Framework of Action	Developing and strengthening research methods and tools for multi-risk assessments and cost benefit analysis	Non-binding
Global	Sendai Framework (2015)	"All-of-society" approach on DRM, to identify synergies across stakeholders Long-term, multi-hazard and solution-driven research Including climate change scenarios when developing regional disaster risk assessment frameworks Mainstreaming and integrating disaster risk reduction within all sectors	Non-binding
EU	COMMISSION STAFF WORKING PAPER Risk Assessment and Mapping Guidelines for Disaster Management	Scope and methods for multi-risk assessment for risks in EU will be analyzed by Commission services Multi-risk scenarios should, where appropriate be considered as part of the national risk assessments	Non-binding
EU	Union Civil Protection Mechanism (UCPM)	Integrated approach to disaster management Member states should report frequently on their disaster risks accounting for multiple hazards, the so-called National Risk Assessments (NRA)	Binding
EU	Reporting Guidelines on Disaster Risk Management	Encourage accounting for future and emerging risks acknowledging climate change related dynamics Identify possible multi-risk scenarios, starting with a given event and evaluating the possibility that other risks or events may be triggered. Analysis for the interdependencies of hazards and vulnerabilities	Non-binding

Various international treaties and agreements call for advanced risk assessment encouraging multi-risk perspectives for DRM. As early as in the 1990s, the **Agenda 21**[2] already called for research on multi-hazard effects to account for implications of risk management strategies on exposure and vulnerability towards other hazards (United Nations Conference on Environment and Development, 1992). In 2005, the **Hyogo Framework of Action (HFA)**[3] was adopted. It sets five priorities for action, the first two being: governance and risk identification. As a part of this, HFA identified strategic and systematic approaches to reducing vulnerabilities and risks to hazards and

[2] https://sustainabledevelopment.un.org/outcomedocuments/agenda21

[3] https://www.preventionweb.net/sendai-framework/Hyogo-Framework-for-Action

emphasized the need for developing and strengthening research methods and tools for multi-risk assessments and cost benefit analysis (ISDR, 2008).

The succeeding **Sendai Framework** for Disaster Risk Reduction 2015-2030 identified four priorities, including(i) understanding disaster risk, and (ii) disaster risk governance at national, regional and global level (UNDRR, 2015). The Sendai Framework highlights that disaster risk reduction can only be efficient and effective if multi-hazard, and multi-sectoral perspectives are included. The Sendai Framework also recognises that knowledge in this context still needs to be advanced and therefore encourages to "*promote investments in innovation and technology development in long-term, multi-hazard and solution-driven research in disaster risk management*" (UNDRR, 2015). It also emphasizes integration across the global agendas by highlighting that climate change scenarios should be included when developing regional disaster risk assessment frameworks in the context of multi-hazards. In line with this, the Sendai Framework calls for adopting "*national and local disaster risk reduction strategies and plans, across different timescales, with targets, indicators and time frames"* aimed at preventing future risk, reducing present risk and enhancing resilience. At a more general level, the Sendai Framework calls for mainstreaming and integrating disaster risk reduction within all sectors and distributing clear roles and responsibilities, regulations and other guidance to ensure coherence and further development in the public and private domain on national or local level.

The recent Global Assessment Report on Disaster Risk Reduction 2022 (GAR2022) published by the United Nations Office for Disaster Risk Reduction also emphasizes the need to address systemic risk and "*reconfigure governance and financial systems to work across silos and design in consultation with affected people*". The report hereby mentions: "*to be effective for a systemic approach, risk reduction cannot be viewed as a competitive advantage or information to be protected"* and further concludes*: "governance arrangements need to be inclusive of all stakeholders affected by emerging systemic risk".* The call for multisectoral risk assessment builds upon the GAR2019 reports, hereby cited: '*we need to incentivize transdisciplinary integrated, multisectoral risk assessment and decision-making to improve efficiency, reduce duplication of effort and allow for connected, collective action*.'

Policy coherence: The concept of and debate around policy coherence for development (PCD) goes back to 1990s or earlier, largely focusing on low income developing countries designing and implementing comprehensive structural programs and policies. The **2030 Agenda for Sustainable Development** (UN, 2015) embraced universal goals applicable to all countries regardless of their level of development and moved the focus away from the symptoms only to addressing the underlying causes of economic, social, environmental and governance challenges (OECD, 2016). The Sustainable Development Goals (SDGs) and their operational targets are indivisible, universally applicable, and global priorities that incorporate economic, social and environmental aspects and recognise their inter-linkages in achieving sustainable development.

Policy coherence for sustainable development (PCSD) stands for coherence between policies addressing all dimensions of sustainable development. PCSD is important to (OECD, 2019):

- Foster synergies and maximising benefits across economic, social and environmental policy areas (e.g., climate change adaptation and disaster risk reduction),
- Balance domestic policy objectives with internationally recognised SDGs,
- Address the transboundary and long-term impacts of policies, including those likely to affect developing countries.

SDG target 17.14 (enhance policy coherence for sustainable development) calls on all countries to apply policy coherence as a key means of implementation of all seventeen Goals. The 2030 Agenda itself, however, does not provide guidance on how to ensure an integrated and coherent implementation of the SDGs (Soria Morales, 2018). According to the review of the Voluntary National Reviews (VNRs), enhancing policy coherence is one of the most difficult challenges to implementing the SDGs (Soria Morales, 2018).

These **calls from international agendas and agreements did not fully translate into the European context**. As an example, when evaluating the implementation of HFA in Europe, the development of tools for multi-risk assessment was prioritized the least within the 3rd priority for action of the HFA ("*Use knowledge, innovation and education to build a culture of safety and resilience at all levels*") (Scolobig et al. 2017). Nevertheless, various directives and communications exist on EU level that advocate for multi-risk considerations.

In 2010, the European Commission and member states developed guidelines for risk assessment and risk mapping for disaster risk management, "*based on a multi-hazard, multi-risk*[4] *approach*" (Directorate-General for European Civil Protection and Humanitarian Aid Operations, 2010) as part of their **Internal Security Strategy**. They use a similar definition of multi-risk as presented in A.1. As mentioned by Poljansek et al. (2021), similar calls for multi-risk approaches can be found in various other policy documents, including the EU Community framework on disaster prevention, and European disaster risk reduction strategy. Furthermore, the Union Civil Protection Mechanism (UCPM) acknowledges the increasing frequency, long-term consequences and interactions of multiple hazards calling for an "*integrated approach to disaster management*" (European Council, 2013). Moreover, the **UCPM requires its Member states to report frequently on their disaster risks accounting for multiple hazards, the so-called National Risk Assessments (NRA)**. However, as of now (for many reasons), hazards are still treated separately with limited or no integration into multi-hazard considerations in this reporting (Poljansek et al. 2021).

More recently, the **Reporting Guidelines on Disaster Risk Management**[5] propose an extended structure of the NRAs combining elements of: (1) national risk assessment (NRA); (2) risk management capability assessment (RMCA); and (3) information on the priority prevention and preparedness measures (including key risks with cross-border impacts, and, low probability risks with a high impact). Furthermore, the guidelines describe what a multi-risk scenario analysis could entail:

- Identification of possible multi-risk scenarios, starting with a given event and evaluating the possibility that other risks or events may be triggered.
- Exposure and vulnerability analysis for each individual risk within the different branches of the scenarios, as well as the interdependencies of hazards and vulnerabilities.
- Risk estimate for each adverse event and for multi-risk scenarios. Software tools such as Decision Support System (DSS) for mapping multiple risk scenarios can be used to help visualise, provide information on and run scenarios." (European Commission, 2019)

Countries are encouraged to specify if multi-risk approaches were used if appropriate (European Commission, 2019). In addition, the guidelines encourage accounting for future and emerging risks acknowledging climate change related dynamics in risk management (Poljansek et al., 2021). Those guidelines are non-binding, but **the acknowledgement of multi-risk elements in official communications of the European commission lend importance to it**.

Sector-specific EU-policies

While general directives addressing disaster risk management highlight the relevance of multi-risk perspectives, sector-specific directives differ in terms of the scope of risk definition. Multi-risk considerations for the sectors considered in MYRIAD-EU are explored here. In some sectors (e.g. tourism), no regulation touching upon risk governance could be found. For other sectors, the

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[4] "*A multi-risk approach entails a multi-hazard and a multi-vulnerability perspective (Carpaigno et al., 2009). Each risk assessment must incorporate possible amplifications due to the interaction with other hazards; in other words, one risk may increase as a consequence of the occurrence of another hazard, or because another kind of event has altered significantly the vulnerability of the system.*" (Directorate-General for European Civil Protection and Humanitarian Aid Operations, 2010)

[5] Commission Notice Reporting Guidelines on Disaster Risk Management, Art. 6(1)d of Decision No 1313/2013/EU2019/C 428/07 (OJ C, C/428, 20.12.2019, p. 8, CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019XC1220(01))

relevance of risk (management) is sometimes acknowledged but incorporated to different degrees as illustrated in Table 1-3.

Table 1-3: Examples of key calls in European regulations and communications related to sector-specific policies

Policy	Considered multi-sector, multi-hazard specific elements
Biodiversity Strategy for 2030	Acknowledges the accelerating risk to nature by droughts, flooding and wildfires No hazard-specific targets
Forest Strategy for 2030	Acknowledges the combined effect of climate change on changing the forest Objective to incorporate forest-related risk assessment and management in forest management plans Technical knowledge and information as well as targeted regulatory and financial incentives and support need to be developed
Directive 2008/114/EC	Directive on identification and designation of European critical infrastructures and the assessment of the need to improve their protection Importance of accounting for an "all-hazard approach"
Directive proposal to enhance resilience of critical entities providing essential services in the EU	Addressing the cross-border and cross-sectoral interdependencies Member States shall be obliged to account for risks arising from the dependencies between the sectors and disruptions in one sector might have Provide set of criteria to characterize the disruption
Common Agriculture Policy	Increase the support for risk management (specifically in terms of insurance premiums, and mutual funds) Calls for a "robust framework [...] to ensure appropriate risk management"

Regarding **ecosystems and forestry**, the EU has published the Biodiversity Strategy for 2030 as a comprehensive, ambitious and long-term plan to protect nature and reverse the degradation of ecosystems. While **the strategy acknowledges the accelerating risk to nature by droughts, flooding and wildfires caused by climate change, it does not provide hazard-specific targets** (European Commission, 2020a).The EU forest strategy for 2030 acknowledges the combined effect of climate change on changing the forest (vegetation) (European Commission, 2021), and whilst it sets the objective that forest-related risk assessment and management should be part of the forest management plans it does not specify what type of risk will be considered. Further it acknowledges that for that, "*technical knowledge and information as well as targeted regulatory and financial incentives and support need to be developed*" (European Commission, 2021).

Regarding procedures of **critical infrastructure** management, the Council directive 2008/114/EC highlights the importance of accounting for an "*all-hazard approach*" (European Council, 2008), which considers many different hazards but not the compounding or cascading effects of interactions. Furthermore, the European Commission has proposed a new directive to enhance the resilience of critical entities providing essential services in the EU, i.e. by addressing the cross-border and cross-sectoral interdependencies (European Commission, 2020b). It is proposed that a list of essential services is developed for each sector and an assessment of "all-hazard" risks might be regularly conducted to support management. For this risk assessment, Member States shall be obliged to account for risks arising from the dependencies between the sectors and disruptions one sector might have (European Commission, 2020b). The disruptions are meant to be characterized by the following criteria:

- the number of users relying on the service provided by the entity;

- the dependency of other sectors referred to in the Annex on that service;
- the impacts that incidents could have, in terms of degree and duration, on economic and societal activities, the environment and public safety;
- the market share of the entity in the market for such services;
- the geographic area that could be affected by an incident, including any cross-border impacts;
- the importance of the entity in maintaining a sufficient level of the service, taking into account the availability of alternative means for the provision of
- that service." (European Commission, 2020b)

It is noteworthy that risk plays a minor role even for planning processes in the context of the **energy sector**. The development of Ten-Year Network Development Plan (TYNDP) scenarios devising possible pathways for the development of the energy system in the European Union by 2050 acknowledge the influence of risk, but focus on other priorities, e.g. decarbonisation (CBS, 2021).

In the context of **food and agriculture**, a new common agricultural policy has very recently been adopted. It allows Member States to increase the support for risk management (Popp, 2019), specifically in terms of insurance premiums, and mutual funds, e.g. for income stabilization. Furthermore, it calls for a "robust framework [...] to ensure appropriate risk management" to be able to support farmers designing on-farm strategies and resilience farms in the context of "market exposure, climate change and associated frequency and severity of extreme weather events as well as sanitary and phytosanitary crises" (Regulation (EU) 2021/2115 (2021)). However, it does not account for any specification of multi-risk relevant components.

1.5.2 Current management practice of natural hazard induced risks in Europe

In the previous section it was demonstrated that current considerations relevant for multi-risk governance have been partially embedded into European guidelines and regulations for DRM. Apart from the critical infrastructure, the acknowledgement of importance of multi-hazard risk or multi-risk in sectoral policies seems to be lacking entirely. Based on the preceding analysis of EU policies, it appears that the process of National Risk Assessment is the central avenue for national efforts for DRM governance in Europe. This section investigates to what extent multi-risk approaches are included in the NRA. The main findings on the consideration of multi-risk approaches in the Veneto region of Italy are presented as an illustrative example.

Since 2015, the UCPM participating countries are compelled to conduct National Risk Assessments which address a wide range of relevant natural, technological and human-made hazards with national or supra-national significance periodically every three years and report summaries to the EU (Decision No. 1313/2013/EU). As mentioned before, NRA's have the ambition to be multi-hazard and multi-sectoral (Poljanšek et al., 2019). However, it is important to note that here they refer to multi-hazard as a comprehensive set of natural and human-made hazards. Furthermore, the cross-sectorial dimension is understood as covering all the sectors affected by the impacts (Poljanšek et al., 2021). As such, NRA is "trying to consider cascading events" (Poljanšek et al., 2021) but no further interactions between hazards or sectors.

NRAs have been identified as essential components of disaster risk management (DRM) by providing a holistic overview of all nationwide risks (Tomásson & Karlsson, 2020). According to a survey by OECD (2018), NRAs serve a multitude of objectives, slightly different for all member states as also shown in Figure 1-3: most NRA's are to communicate existing risk or to better understand the system, identify gaps in responsibilities of emergency and crisis management, but also to build consensus across ministries, or establish priorities. Only a few countries use NRAs to inform risk mapping or cross-boundary risk assessments. Furthermore, the survey showed that the main focus of the NRA so far is understanding risks better. Only few countries aim at using NRA for decision-support, requiring broader consultation and expert involvement to find consensus regarding taken measures/prioritization (OECD, 2018).

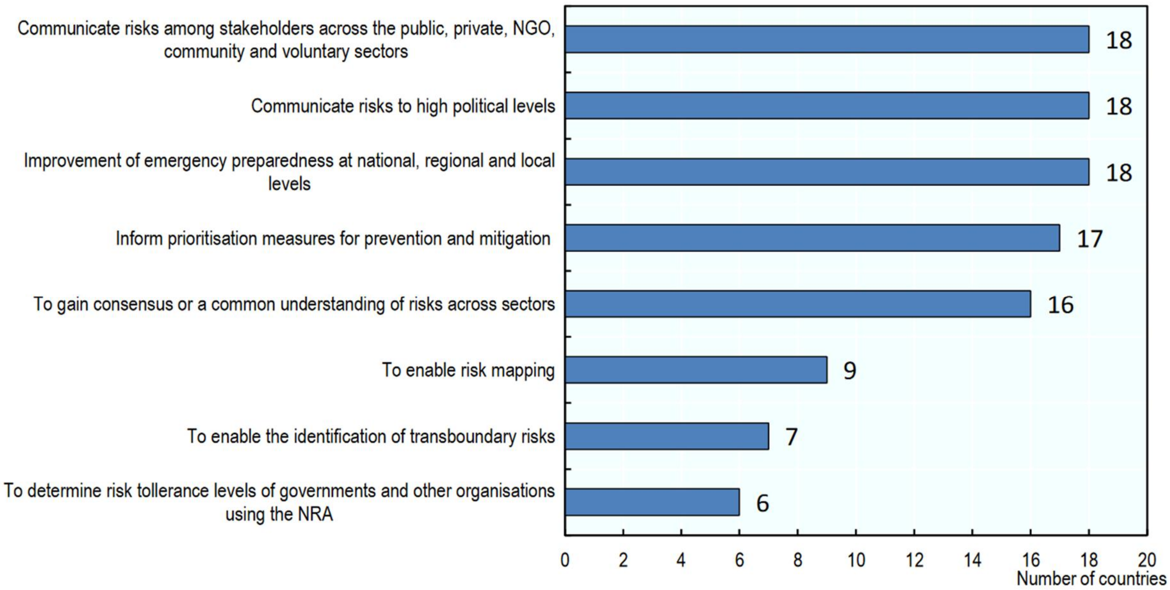


Figure 1-3: Objectives of the NRA process mentioned by surveyed Member states

Source: OECD (2018)

As the attention of DRM has shifted towards risk preparedness and prevention, NRA's present an important instrument to gather risk information and communicate them to respective stakeholders (OECD, 2015; OECD, 2018). According to Girgin et al. (2019), various international organizations have identified NRA as a good practice for cost-effective and efficient disaster risk management. Accepted good practice is to adopt an 'all-hazards' approach to risk assessment which includes all the risks of emergencies that countries might reasonably expect to face within the time horizon agreed to in the methodology (OECD, 2018). According to a survey by the OECD (2018), the majority of surveyed nations were interested in five-year timeframes, indicating a desire to include all types of events that were likely to occur in the near future, with reasonable confidence that the resources allocated, and risk management capabilities developed would not be wasted. A further goal of establishing a 5-year timeframe was to provide risk managers the flexibility to pace capability improvements and encourage a forward-thinking strategy that went beyond just historical risk analysis and reflected near-term risk drivers.

Compiling disaggregated hazard or risk data collected or produced by various stakeholders on various administrative levels, using non-uniform methodologies has caused significant challenges to Member States to produce the NRA (Roth et al. 2019). However, **experience of involved stakeholders and support in terms of Reporting Guidelines or shared best-practices has led to improved understanding** and iterative advancement of the assessment. It has been observed that with every new iteration, the set of considered disaster scenarios expanded (OECD, 2018). The methods of NRA include both qualitative and quantitative methods. Often, qualitative risk assessment is used as a first step to just screen relevant risks, identify objectives, and anticipate next possible steps. At the same time, OECD (2018b) suggests that fully quantitative methods are used thriftily:

> "*Countries used quantitative approaches to national risk assessment in two circumstances. First, where a government was considering the need for potentially high-cost risk treatment measures, quantifiable measurements were developed to increase confidence in the risk assessment. Second, a quantitative reassessment has been used to determine whether risk treatment measures had the intended impact of reducing a risk to meet a previously calculated level of risk tolerance.*"

The existing EU guidelines aim to reduce the impact of disasters by co-development of knowledge, linking actors throughout the management cycle, and improving effectiveness of existing policy instruments (Poljansek et al., 2021). Some of the key questions that are usually addressed are:

- Who takes the lead in prevention and mitigation planning?
- Who takes the lead in response and recovery actions?
- What roles do any coordinated agencies play?
- What must the lead agency and coordinated agencies budget for (OECD, 2018a)?

At the same time, it has been reported that due to the multi-disciplinary approach including various stakeholders from diverse hazard-contexts of the NRA processes, new national fora are created providing opportunities to interact and exchange knowledge amongst disciplines. A survey by OECD showed that about 75% of NRAs include the private sector to varying degrees in the assessment process, 60% include academia and 40% account for civil society (OECD, 2018b). **The engagement with stakeholders takes various forms, in OECD countries this happens mostly in the form of ad-hoc meetings with experts, national workshops with government officials, and conferences/workshops with participation from interest groups and NGOs (OECD, 2018a).** Some more inclusive NRA processes are more collaborative by "*help identify relationships among different types of risk scenarios [...] to designate responsibility for specific risks, and joint responsibility for complex risks that might otherwise 'fall between the cracks' of government silos*" (OECD, 2018b). Even though still far from a transdisciplinary process, **recent developments in the context of NRAs seem to streamline existing disaster assessment and management approaches into one combined one in various countries (Poljansek et al., 2021).**

It is important to mention that the NRA is a political process. As such, the national government set the methodologies and considered risk scenarios, but often invites non-governmental experts to contribute or conduct the assessments (OECD, 2018).

Different legal frameworks are used, leading to the involvement of different (types) of actors, and using different tools and practices, as evidenced by a comparison of civil security systems in 22 European countries (Kuipers et al., 2015). According to Roth et al. (2019), **risk governance involves three to four levels of administration in most of the countries** in the EU while integration of these levels is implemented differently in various countries. Furthermore, depending on the nature of the risk and the character of the government action to be taken, the extensive variety of critical risks, and multitude of competent actors raises the challenge of coordination between decision makers (OECD, 2018a). Generally, processes for risk analysis and assessment widely show strong integration of various levels, while **planning and budgeting is less integrated and operational responsibility usually is attributed to sub-national actors (e.g. civil protection agencies).**

Furthermore, it has been stressed that even within the constitutional framework of one country, limited homogeneity is observed in the application of governance across various sectors (van der Heijden, 2019). According to Wolf & Pfohl (2014), the highest degree of decentralization can be observed in Austria, Germany and Switzerland. Czech Republic, Finland, the Netherlands, Norway, Sweden are also rather decentrally organized but include some centralized elements (Bossong & Hegemann, 2015). On the opposite, Hungary, Latvia, Lithuania, Malta, Serbia, and Slovakia have the highest levels of centralization and Croatia, Estonia, France, Poland, and Romania are rather centralized but use some decentralized elements (Bossong & Hegemann, 2015). An analysis for the COVID-19 pandemic by Deubelli et al. (2022) shows that the amount of decentralization can have an influence on the crisis arrangements. For example, in Austria, decentralization required long rounds of negotiation across governance levels to ensure alignment of measures with legislation.

A governance example from Italy is further presented, following semi-structured interviews with five experts from various components of the civil protection system in Italy.

Risk management governance in Italy
Italy has one of the most advanced disaster risk management (DRM) systems in Europe, as testified by the OECD review in 2010 (OECD, 2010), developed and shaped while responding to a number of damaging disasters. The core of the DRM is the civil protection system, which operates under the direct authority of the Italian Prime Minister (OECD, 2010).

The national civil protection system is a partnership of various entities and first responders, including civil society organizations, which work together to safeguard the integrity of human lives, goods, settlements and the environment against the damage deriving from natural hazards. Part of this system is a network of multi-risk surveillance and early warning centers, which provide critical and timely information for disaster response operations (Mysiak et al, 2013).

As in few other countries, the modern multi-hazard/risk monitoring and surveillance systems have been seamlessly incorporated in disaster risk management. We have interviewed five experts from various components of the civil protection system – including the central civil protection agency, decentralized regional branches, early warning centers as well as academics and specialized consultancies. The common challenges of multi-risk governance identified through the interviews refer more frequently to risk prevention than risk responses and include:

- horizontal and vertical collaborations (or a lack thereof),
- fragmented and internally inconsistent normative framework punctuated with ad hoc and insufficiently coordinated pieces of legislations & regulations,
- institutional and cultural differences across DRR sectors and policy areas in how risks are understood, identified and coped with, management capabilities built up and organized, and societal groups engaged and mobilized,
- insufficient mainstreaming of climate adaptation and climate-proofing of essential infrastructure and services, and
- insufficient resources and capacity.

Good practice examples refer to bilateral or multilateral cooperation that rely on non-binding strategic alignment, and which take many forms such as joint risk assessment, contingency planning and exercises, financing and risk pooling arrangements, or technical cooperation.

1.5.3 Preliminary findings from stakeholder interviews

In the previous section we analyzed sector-specific EU policies on disaster risk assessment and management and how these regulatory frameworks (in the form of directives, communications, and recommendations) consider interactions between hazards and their combined effect. The limited representation of multi-hazard, multi-risk approaches in policy, decision-making processes, and governance also emerged from the stakeholder interviews, with the acknowledgement that knowledge and awareness of these processes varied depending on the scale (regional, national, international) and sector represented (energy, finance, food & agriculture, tourism, infrastructure & transport, ecosystems & forestry). Below, we provide a generalized summary of some preliminary observations from these interviews, highlighting sector specific examples where appropriate:

- Interactions between natural hazards are not considered across all sectors and most examples provided are focused on cascading impacts and interdependencies between sectors and sub-sectors (e.g., renewables on non-renewable energy sources) rather than interactions at the hazard level. Apart from the finance (insurance - reinsurance) sector, modelling of natural hazards that considers spatial and temporal correlation between events did not emerge during the interviews. However, an interesting finding was the consideration of multi-risks stemming from the amplifying effect of social or economic drivers that can exacerbate the impact of a natural hazard event (e.g., drought in combination with rising commodity or energy prices).

- Awareness of policies and governance processes that directly consider interrelationships between natural hazards and good practice is generally scarce. However, it is interesting to highlight an example from the ecosystems & forestry sector, where current national and regional legislative instruments (Law 5/2004, technical orders, and government action of private property) enforced by the Forest Fire Prevention and Extinction Service in Extremadura, Spain (INFOEX) are used to mitigate again multi-risks associated with forest fires (e.g., loss of biodiversity, loss of large agricultural areas, etc.). In the infrastructure & transport sector, the development of policies enhancing the integration of different national transportation systems (railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals) at EU level (Trans-European Transport Network, TEN-T). This policy action can be interpreted as a first step towards better understanding cascading effects from multiple interrelated hazards affecting the interdependency between exposed transportation networks.

- During the interviews, some barriers and challenges for the implementation of multi-hazard, multi-risk management guidelines and policies emerged. These were mainly related to (i) the lack of flexibility or adaptability of current risk assessment and management approaches due to, for example, a tendency to resist or implement changes slowly); (ii) disconnected governmental organizations with siloed legislative competences which reduce the capacity to prevent, mitigate, and respond to interrelated hazards and risks at sub-national, national and international level; and (iii) lack of support, resources, and competing interests between different sectors (e.g., agriculture and tourism).

Stakeholder interviews performed in T1.3 allowed a preliminary view on the state of knowledge and understanding of policy, policy-making processes and governance for multi-hazard, multi-risk management in MYRIAD-EU. It is expected that further insights from this activity will feed into other tasks associated with work packages 3, 4 and 6. It is anticipated that these initial interviews will be built upon through future stakeholder engagements (interviews and workshops) as the project progresses.

1.5.4 Available approaches towards multi-risk governance

Neither the literature review nor the stakeholder interviews provided indications that any multi-risk (or multi-hazard risk) governance frameworks are used in current practice. Nevertheless, the review and analysis process yielded scientific approaches and good practice examples that could be embedded and integrated into operational multi-risk governance frameworks. In the following section, we are presenting an illustrative set of approaches from science and practice to showcase how they can contribute to good multi-risk governance. Regarding the approaches proposed in academia, we present a selection of **promising, or prominent representative approaches** for the risk identification, institutional context analysis, knowledge generation for risk assessment, risk management and risk communication. We note that as part of activities of Task 1.2 of MYRIAD-EU (Duncan et al. (2022)), a wide range of platforms, frameworks, methods and tools applicable and relevant in the context of multi-hazard or multi-risk management were collected. The dedicated wiki developed within T1.2 (MYRIAD-EU D1.1 WIKI-style online platform of multi-hazard, multi-risk methods, models and tools) gathers a large portfolio of tools, methods and frameworks that can inform multi-risk governance, and will be launched shortly.

1.5.4.1 Towards hazard and risk interactions

In line with the first step of Scolobig et al.' s (2017) multi-risk governance framework, the observation and identification of potential multi-risks is the starting point for a broad system understanding. Multiple scholars have developed methods to identify multi-hazard events/characteristics for various natural hazard combinations. Here we present two methods to qualitatively and quantitatively identify multi-hazard events. Furthermore, two conceptual approaches are presented taking first steps to identify the interdependent drivers of multi-risk beyond hazard interactions.

Identifying multi-hazard scenarios

A prominent and widely used qualitative approach to investigate relevant multi-hazard interaction scenarios has been developed by Gill & Malamud (2014), see Figure 1-4. It follows the relationships occurring between 21 natural hazards. The interactions are identified as hazards triggering other hazards or increasing /decreasing the likelihood of occurrence respectively. Hazards were classified and special-temporal scales acknowledged. Gill & Malamud (2014) conceptualized two ways of visualizing these complex interactions, through matrices and network diagrams. The matrices represent a means for understanding which of the considered hazards has the potential to trigger a secondary hazard. The diagrams display hazards as nodes and the lines linking them as various occurring relationships. Concurrently, the authors argue for the conceptualisation of hazards through their potential to trigger or be triggered by other hazards. This is especially important in decision-making scenarios as it represents a tool for forecasting secondary hazard potential, spatial overlap and temporal likelihood based on the triggering event. Gill & Malamud (2014) explored only a multi-layer single hazard approach and mention steps to be taken for further understanding multi-hazard and, subsequently, multi-risk though accounting for further identification, comparison, analysis of interactions and coincidence, as well as dynamic vulnerability. This would then constitute a comprehensive way to conduct multi-risk assessment. This framework is intended to facilitate advancement in the field, be useful to practitioners and policymakers, as well as planners.

More recently, Gill et al. (2020) presented an updated, interdisciplinary version of the above presented framework to guide the comprehensive and systematic identification of potential multi-hazard scenarios applicable to different spatial scales by combining different evidence types: international literature, local (stakeholder) knowledge and field observations. Gill et al. (2020) apply it to the case study of Guatemala and demonstrate the usefulness of this qualitative approach to spark cross-institutional dialogue on multi-hazard interactions, and thus support knowledge co-production.

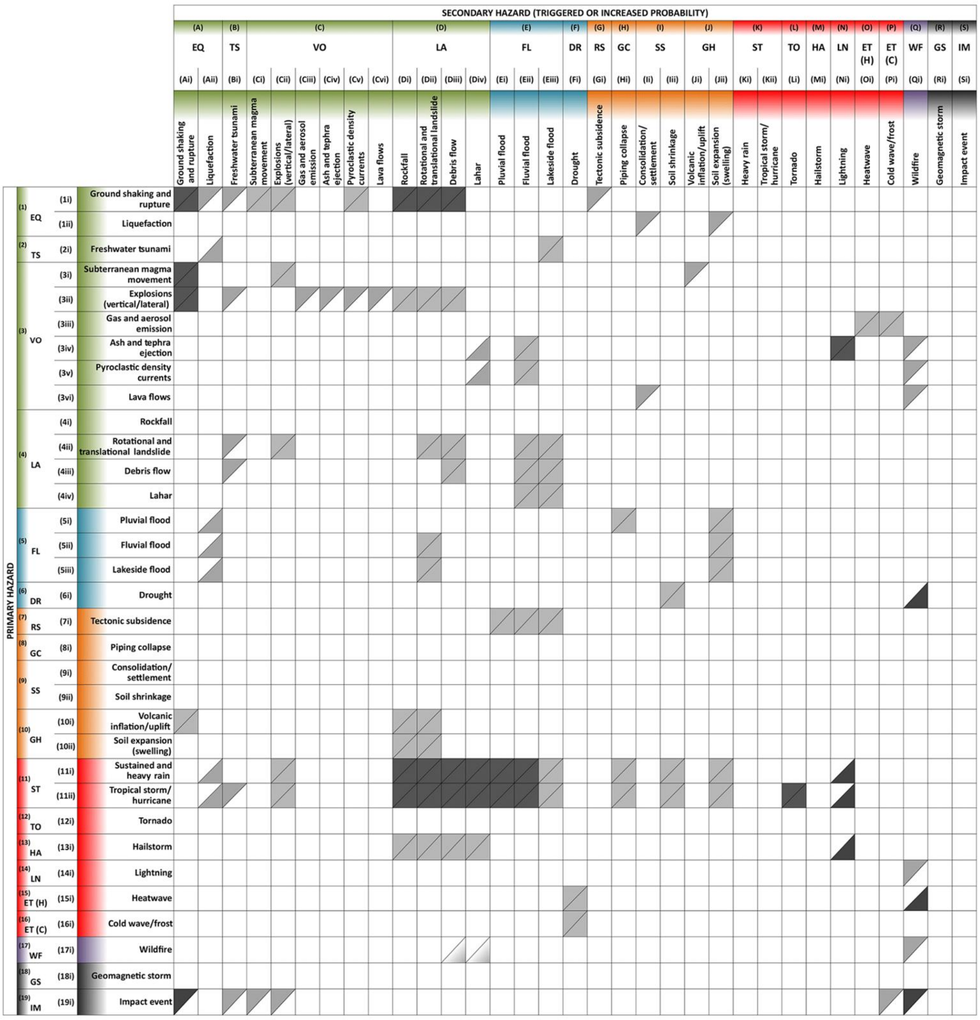


Figure 1-4: Multi-hazard interaction framework for the region of Southern Guatemala Highlands

Source: Gill et al. (2020) CC BY 4.0

On the other hand, a range of data-driven statistical, empirical or mechanistic approaches to identify and simulate hazard interactions have been developed in literature (Tilloy et al., 2019). Here, we use Bevacqua et al. (2021) as an example for data-driven, statistical approaches. Bevacqua et al. (2021) present guidelines for studying different types of compounding extreme weather events[6], namely preconditioned, multivariate, temporally compounding, and spatially compounding events. For each of the event types, Bevacqua et al. (2021) introduced a relevant case study as well as an appropriate tool to assess the compound hazard. For the **preconditioned type**, where a climate or weather background precondition can enhance the impact triggered by one or more hazards, a case study on crop impact caused by a hot and dry summer and exacerbated by an early dry and bright spring is used. Here, a linear regression has been applied to predict years with extremely low Leaf Area Index (LAI, a proxy for vegetation). They predict low vegetation considering only summertime meteorological conditions and test whether the prediction accuracy increases if springtime meteorological conditions are included. Next, the **multivariate type, when concurrent drivers and/or hazards at the same location lead to shared impacts**, is described by compound coastal flooding in Perth (Australia). Bavacqua et al. introduce a multivariate non-linear regression model to identify which flood element (such as sea levels or river discharge) is the key component of the resulting compound flood. Following this, the **temporally**

[6] Compound events are defined as the "combination of multiple drivers and/or hazards that contribute to societal or environmental risk" (IPCC, 2022). As such it is a definition used in climate science describing similar dynamics as the term multi-hazards, but with a narrowed perspective on weather and climate-related events.

compounding event, a sequence of hazards that lead to impact, are explained by a case study in Portugal where precipitation is followed by a landslide. Using local landslide and precipitation data, they tested if landslides were indeed preceded by a precipitation event. Finally, the **spatially compound event**, when impacts are aggregated as a result of hazards occurring in multiple connected locations, synchronous crop failure in Germany and France serves as a case study. Here, an Aggregate Exceedance Probability (AEP) curve is introduced in order to identify whether impacts of crop failure simultaneously are larger compared to when they occur on separate occasions.

The idea behind the separate case studies is that they serve as examples of how each compound hazard type can be studied, while the methods introduced can be applied to diverse compound event analysis across disciplines and sectors. However, Bevacqua et al. (2021) mention that collecting further methods for the identification and quantification of compound events as a useful scientific advancement. Furthermore, they acknowledge that their guidelines are depending on the selected case studies and specific questions addressed.

Identifying interactions between determinants of multi-risk

A recent attempt on conceptualizing interactions between determinants of complex risk[7] has been proposed by Simpson et al. (2021). It extends the current focus of interactions according to the IPCC (2022) by incorporating more interactions than just between hazard determinants. **Simpson et al. (2021) highlight that the broadening of understanding potential trade-offs and co-benefits for governance decisions is related to the response to risk**: decisions for certain response options are not only dependent on the (expected) benefits but also a question of robustness ("does the option perform well under a range of uncertainties?") and flexibility ("do we limit our future options in case we choose a certain response option now?"). Consequently, decision-taking is an inherent determinant of risk. Thus, the proposed analytical framework by Simpson et al. (2021) considers response as a risk determinant alongside hazard, vulnerability and exposure.

Ultimately, Simpson et al. (2021) propose an expanded assessment approach for complex risk. It includes not only elements to support the identification and characterization of various interactions (see Part B of this report for further elaboration and advancement of this approach in the context of multi-sector risk) but also introduces categories of complexity as visualized in Figure 1-5:

- The first category of complex risk considers that there is just one single driver for each determinant of risk.
- In the second category, the interaction between multiple drivers within and between the determinants of risk is accounted for.
- The third category of complex risk addresses interactions between different risks (for the same or different elements at risk).
- The last category aggregates the interactions between drivers of hazards, exposure, vulnerability, and response to risk interacting, which is different from the understanding of multi-risk.

For the definition of multi-risk, the interactions between multiple hazards and multi-vulnerability are made explicit and consequently also the importance of temporal and spatial dimensions of the interaction (see Part B for further elaboration).

[7] Simpson et al. (2021) use the term complexity "*to communicate the diversity of interactions among sectors and systems that can amplify or reduce climate change risk*". As such they use the term complex risk to refer to multiple different interactions in the context of risk (drivers) - all with their own definitions (e.g. compound risk, emergent risk, multi-risk, systemic risk). It is worth mentioning that the perspective of Simpson et al. (2021) is situated in climate research and thus uses slightly different terminology than in the disaster risk community (where MYRIAD_EU is mostly based). Thus, while the proposed two (overlapping, but still distinct) research communities currently address similar phenomena of system interactions and dynamics, overlapping, but still different concepts and approaches are developed.

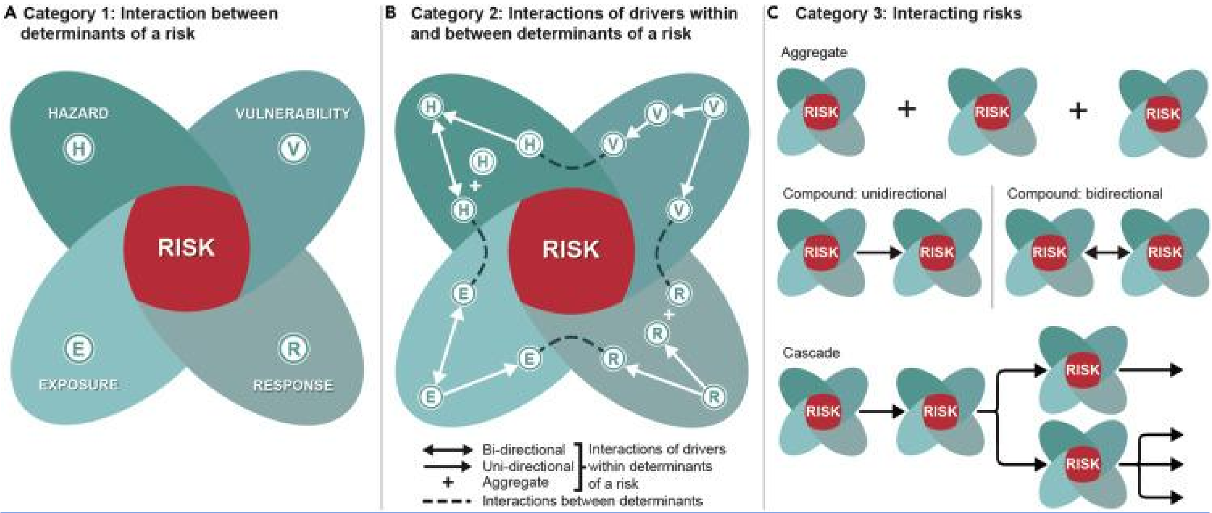


Figure 1-5: Three categories of increasingly complex risk.

(A) Category 1: interactions among single drivers (small circles) for each determinant of a risk, namely hazard, vulnerability, exposure, and response to climate change. (B) Category 2: interactions of multiple drivers (e.g., compounding vulnerabilities of education and income) within each determinant of risk, as well as among the determinants of a risk. (C) Category 3: interacting risks. Across categories 2 and 3, compounding and cascading interactions, together with aggregations, generate increasing complexity for risk assessment. We use ''determinant'' to refer to hazard, vulnerability, exposure, and response, within which the term ''driver'' refers to individual components, such as heavy precipitation (a driver within the hazard determinant) or access to shelter (a driver within the vulnerability determinant), that interact to affect the overall risk (e.g., flood mortality). Source: Simpson et al. (2021) CC BY 4.0

This conceptual framework as proposed by Simpson et al. (2021) is yet to be put in practice. The novelty of this approach rests on response being a dimension of risk. Effects of hazards impact different people in different ways, the case is similar for response strategies. According to the authors of the framework, the cross sectoral character of response represents a crucial step in thorough risk assessment, as **decision-makers tend to ignore impacts that go beyond their jurisdiction**. Response represents a feedback effect to risk exposure and vulnerability, as a response may entail specific action that may alter impact of possible future events. Navigating the interactions between all different aspects considered to influence risk by this framework may be aided by using other robust decision-making tools, such as deep uncertainty or systems thinking. The authors that developed this framework emphasize **the value of co-production for generating risk assessments, involving multiple stakeholders** that would, in turn, reflect through multi-level and polycentric governance of climate change risk.

Another not yet operational framework for the identification of interactions in the context of multi-risk is presented by Carter et al. (2021). They address the challenge to account for cross-border impacts resulting from (functionally) interconnected systems. The conceptual framework helps understanding the relation, dynamics and scales of initial impact, impact propagation through a transmission system and downstream consequences as visualized in Figure 1-6. As such, it also allows one to analyze the effects of response options and identify nodes along the transmission system where taking risk reduction measures could be most efficient and/or effective.

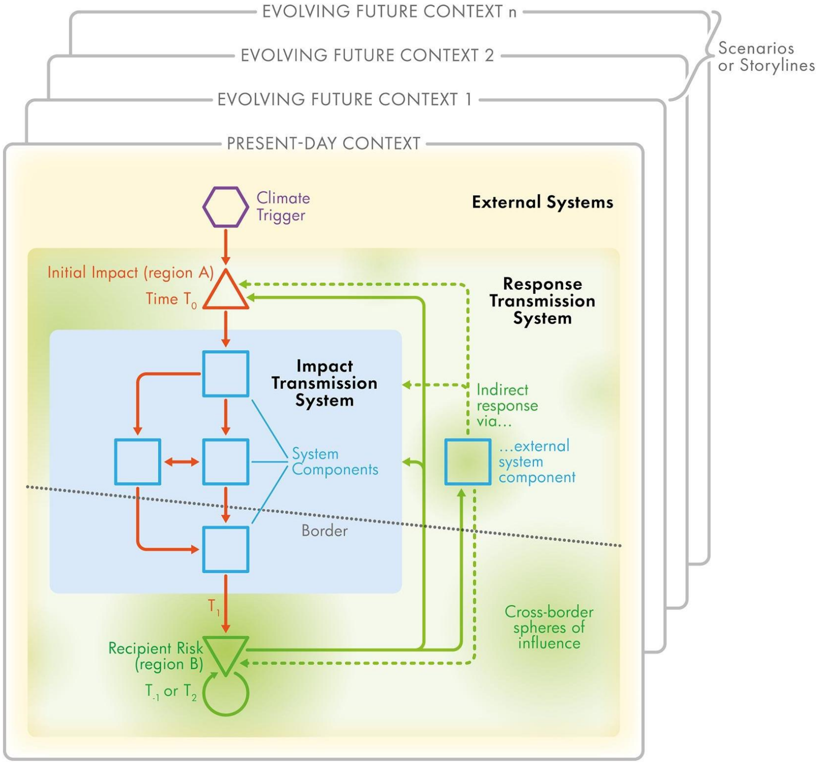


Figure 1-6: Conceptual framework for the transmission of cross-border impacts and responses.

An initial impact in one region due to a climate trigger is propagated (red arrows) via an impact transmission system (blue area) comprising impacts on interconnected system components of varied complexity, resulting in a recipient risk in a second region (location of the border is notional). Adaptive responses for ameliorating that risk (green arrows) can be targeted within a response transmission system (green area) directly at the recipient risk itself, at the impact transmission system and at the site of initial impact (solid arrows), and indirectly via system components external to the impact transmission system (dashed arrows). Responses can occur prior (T 1) or subsequent (T2) to the times of the initial impact (T0) and recipient risk (T1), to indicate anticipatory or reactive adaptation. The ability to respond can vary in terms of the sphere of influence exerted by the regional actor managing the recipient cross border risk (strength of background green shading tone). Note that a response with longer-term effectiveness, operating directly on the climate trigger and not shown here, would be greenhouse gas mitigation. Transmission systems are shown in relation to external systems that may include non-climate drivers of key importance in understanding both the propagating impacts and necessary responses. The present-day context in which the systems operate is coloured yellow and evolves into an uncertain future, depicted as stacked scenarios or storylines. Source: Carter et al. (2021) CC BY 4.0

1.5.4.2 Towards multi-risk partnerships

The literature review revealed several examples of institutional partnerships and cross-agency fora. These are reported to encourage the exchange of knowledge, and enhance the system understanding. This would overcome the single dimension of decisions taken into administrative siloes and promote coordination and co-management at the same time with strengthening inclusive communication channels (Deubelli et al. 2022).

In the context of National Risk Assessment processes, **National Platforms for Disaster Risk Reduction** have been recognized as a good example for "*coordination and policy guidance on [multi-sectoral and inter-disciplinary] disaster risk reduction*" (Poljansek et al. 2021). These provide not only a forum for the involvement of multiple stakeholders (as previously mentioned), but also a means to initiate integration of various expertise about risk assessment approaches, methodologies, risk metrics and data for various hazard scenarios, to be able to create a generic assessment framework that can be used as a first step towards multi-hazard or even multi-risk assessment. The Dutch National Steering Committee for National Safety and Security, in which ministries are represented along with other governmental bodies and organizations, is also considered a good governance practice.

National platforms play an important role for ensuring an all-of-government and all-of-society approach to reducing risk and building resilience (UNDRR, 2017). The platforms foster inter-relationships between DRR, sustainable development and climate change adaptation across sectors and across stakeholders. A recent inventory (UNDRR, 2020)[8] identified and described 37 Platforms in Europe, with heterogeneous structure but all aiming at multi-stakeholder cooperation and mainstreaming DRR into policies and practice.

Another good-practice example of multi-sectoral collaboration from the United Kingdom is the **Natural Hazards Partnership (NHP).** It focuses on preparedness and planning elements of the DRM cycle and is a collaboration between 17 public bodies: British Geological Survey, Cabinet Office, Centre for Ecology & Hydrology, Department for Environment Food and Rural Affairs, Environment Agency, Government Office for Science, Health & Safety Executive, Met Office, National Centre for Atmospheric Science, National Oceanography Centre, Natural Environment Research Council, Ordnance Survey, Public Health England, Scottish Environment Protection Agency, The Scottish Government, UK Space Agency and Welsh Government (GCA, 2021). Hemingway & Gunawan (2018) show that NHP is a model for multi-stakeholder collaboration and streamlining of scientific approaches to various natural hazards by developing a clear organizational structure (i.a. Hazard Advice and Service Group, Hazard impact modelling group, Science strategy Group, and Communications and Outreach group) overcoming coordinative challenges, disperse focus and geographic distribution of involved actors. The establishment of such novel partnerships could be conceptualized as an appropriate way to understand participation of parties in the governance process. As these interinstitutional spaces reinforced the efficiency of the already established institutions.

A recent study by Curt (2021) has shown that particularly cascade effects in critical infrastructure have been a key focus in scientific research on multi-hazard, multi-risk so far. The **Critical Infrastructure Partnership Advisory Council (CIPAC), established by the US Homeland Security Department**, represents an example of a forum that fosters partnerships between public administration and private entities to jointly engage in resilience efforts. As such, CIPAC supports the implementation of the National Infrastructure Protection Plan 2013, which highlights the need for enhancing understanding and awareness regarding cascading, cross-sectoral effects of risk (CISA, n.d.).

Another good practice example that was brought to attention during the interaction with stakeholders in MYRIAD-EU was the **EU Strategy for the Danube Region**. This macro-regional strategy has been active since 2011 and forms an avenue for EU, Danube Region countries and other stakeholders to closely cooperate regarding various relevant challenges and create synergies. It is organized in a rather informal structure and aims to promote regional, social and territorial cohesion by using creative/experimental ways of cooperating (e.g. networks). It accounts for risk management as a part of various thematic priority Environmental Risks (i.a. Flood risk management, promoting disaster resilience, managing droughts, anticipating regional and local impacts of climate change) and as components of other thematic priorities (e.g. Impact of risks & hazards on business environment, biodiversity, culture & tourism). While it does not explicitly mention multi-risk, its set-up as a forum for various actors, addressing specific thematic areas in light of risk management appears to be a promising, cross-country example to strengthen internal and external communication, enhance cross-boundary learning and understanding of a interconnected region (EUSDR, n.d.).

Also, citizen assemblies can help unlock more effective action and help solving intractable issues. A citizens' assembly (Aichholzer and Strauß, 2016; Bain and Bongiorno, 2020; Devaney et al.,

[8] https://www.preventionweb.net/publications/view/72289

2020b, 2020a; Howarth et al., 2020; McGovern and Thorne, 2021; Muradova et al., 2020; Niessen, 2019) is a group of people brought together to learn about and discuss issues and reach conclusions about what should be done. The citizens are chosen randomly, based on demographic criteria and attitudes. Participants interact with a range of experts, practitioners, stakeholders and campaigners. Climate Citizens' Assemblies were held in Ireland, France and the UK (Mellier-Wilson and Toy, 2020; Smith, 2020).

Community-Based Disaster Risk Reduction resulted as a top innovation in a recent survey of novel disaster risk reduction approaches and products (Izumi et al., 2019). As a bottom-up - and people-centered approach, community-based DRR is capable of harnessing local knowledge and resources and stimulating local ownership of the process and the developed solutions (Izumi et al., 2019). Most of the international projects include support to capacity building and community-based DRR.

1.5.4.3 Towards multi-risk assessment

Scolobig et al. (2017) acknowledge that additional tools for the multi-risk assessment are still required. As part of the NRA process, the siloed, single hazard disciplines are slowly integrated into interdisciplinary approaches with an ultimate goal to establish multi-risk assessment as a transdisciplinary process (Poljansek et al. 2021). However, practice is still far from this objective, and is currently in the phase of enhancing transparency and cross-discipline understanding regarding the different used approaches, required data (formats) (Poljansek et al., 2021; Ebrey et al., 2019). It has also been questioned, whether a simple integration of individual elements is satisfactory to address the challenges of complexity and uncertainty associated with multi-risk (Aven & Renn, 2020).

There are multiple scholars that have developed area or sector-specific assessment frameworks. Within the Disaster Risk Gateway wiki (MYRIAD-EU D1.1 WIKI-style online platform of multi-hazard, multi-risk methods, models and tools) a wide collection of methods and tools relevant for multi-risk assessment are presented. In this section, we illustrate one assessment framework for scenario-based multi-hazard impacts (di Angeli et al., 2022) and a quantitative multi-hazard risk assessment framework using Bayesian networks (Liu et al. 2015).
Di Angeli et al. (2022) propose a conceptual five-step multi-hazard impact framework as visualized in Figure 1-7 understood as a first step of formalizing a quantitative framework:

- The framework starts with the identification of hazards and their interactions to characterize the set of relevant hazards and mechanisms of their interaction.
- In a second step these multi-hazards are modelled. In a narrative-based case study using but adjusting an existing historic event of combined earthquake and extreme precipitation (leading to fluvial flooding) in the Po region, Italy, these interactions are modelled based on impacts that one hazard has on the physical properties of the system. This causal relation between the hazards is narrative-driven.
- In a third step, the spatial and temporal evolution of the impacts from the hazards are analysed to identify temporal and spatial overlap of the impacts.
- In a fourth step, it is analysed how these overlapping impacts are interacting to ultimately characterize the resulting multi-hazard impact.

For steps one, three and four, di Angeli et al. (2022) provide typologies for the characterization. For example, the analysis of impact interactions uses four instances of overlapping: 1) spatial-temporal overlapping impact; 2) temporal (but not spatial) overlapping impact; 3) spatial overlapping impact (with residual and subsequent damage); 4) independent single hazards impacts. **Conceptual implications of the different impact interactions are mentioned to guide the analytical process, but tools or methods to implement these steps are not provided and recognized as a critical knowledge gap.**

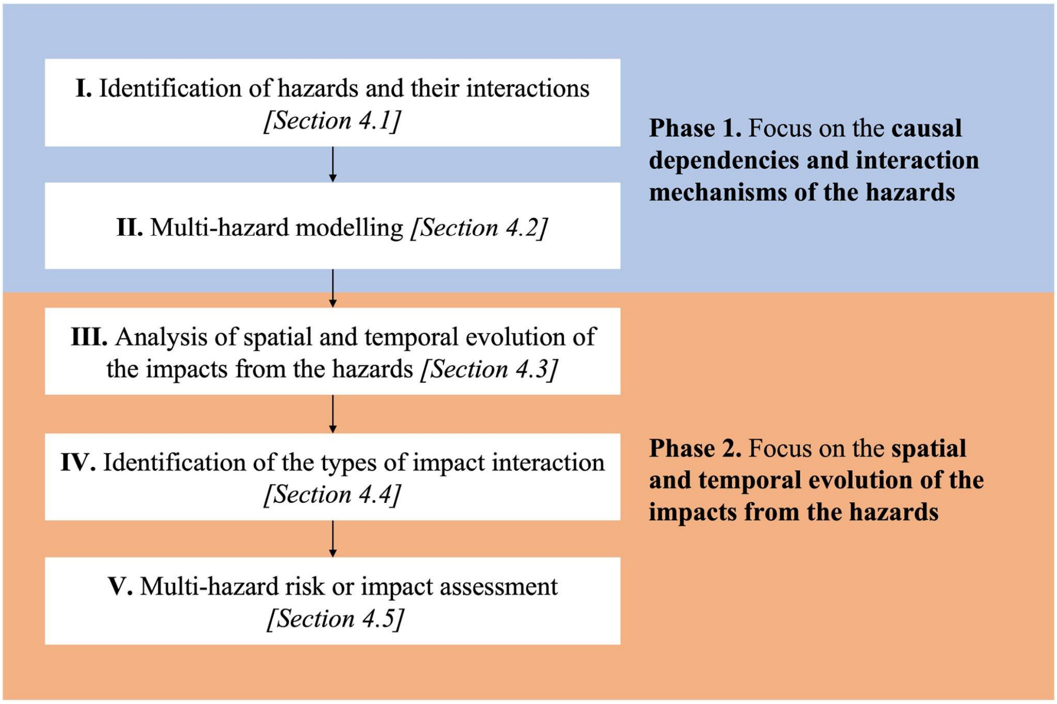


Figure 1-7: A five-step multi-hazard impact framework.

The arrows indicate that the five steps are consecutive. Steps I and II (blue box) refer to multi-hazard assessment and focus on causal dependencies among hazards. Steps III to V (orange box) allow researchers to perform a multi-hazard impact (or risk) assessment and focus on the spatial and temporal evolution of the impacts from the hazards. Each step is discussed in more detail in the section given in the corresponding box. Source: Di Angeli et al. (2022) CC BY 4.0

Liu et al. (2015) developed a three-level framework for multi-risk assessment to help decision-makers and risk analysts to identify relevant hazards and conduct a risk assessment on the required level of complexity. It provides a set of three methods to guide the implementation of each level of the multi-risk assessment. Starting point (precondition for the three-level framework) is the risk assessment for single hazards. By doing so, it sets out some additional harmonization requirements to be able to use information in the following stages: defining the target area and time window, quantifying the probability and intensity apart from the general element of hazard identification, and assessment of hazard and vulnerability.

A qualitative assessment of multi-risk is done as the first step. It uses the flow chart as visualized in Figure 1-8 to investigate potential characteristics of the multi-risk context. Additionally, it uses a scoping question to investigate the purpose of the risk assessment. In this way, it can be identified, if multi-hazard interactions and/or multi-vulnerability interactions are necessary to consider. This step concludes in a decision on which type of analysis is relevant (no multi-type assessment necessary, semi-quantitative (level 2) or fully quantitative (level 3)).

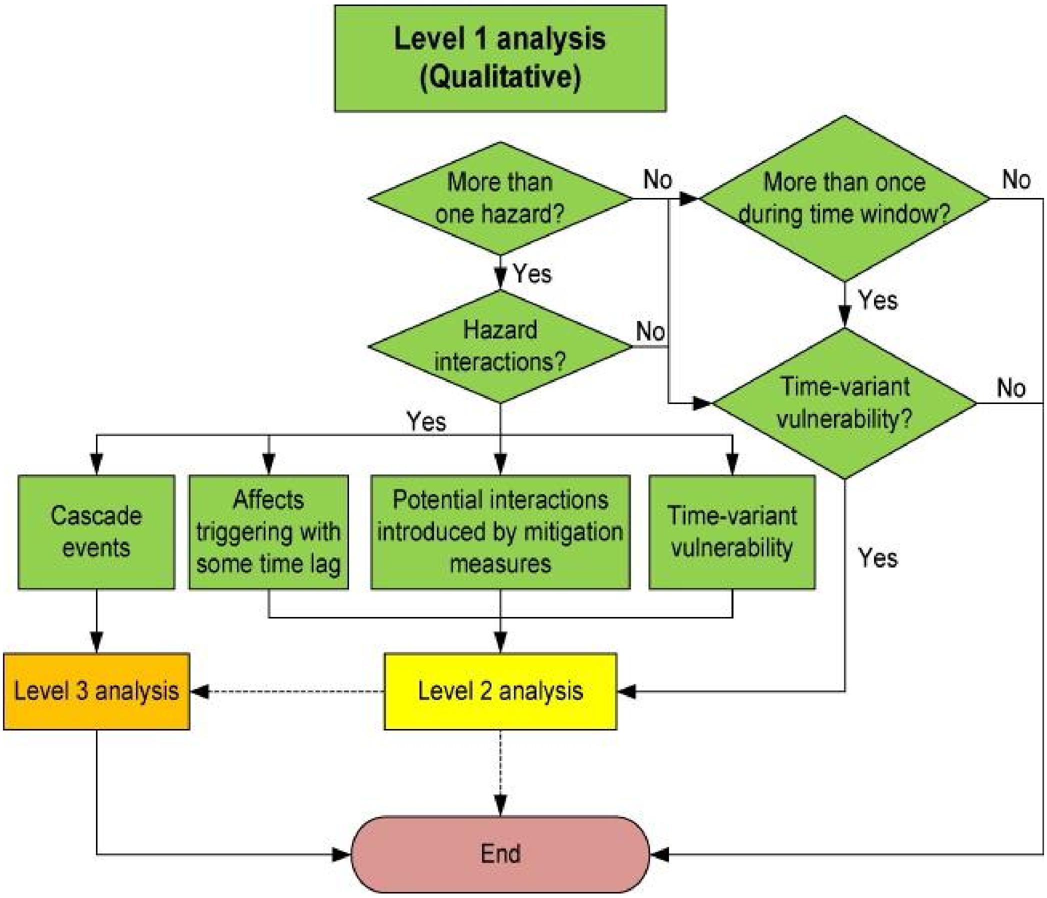


Figure 1-8: The steps involved in the Level 1 multi-risk analysis

Source: Liu et al. (2015) CC BY 3.0

In the level 2 analysis multi-hazard interactions and vulnerability dynamics are approximated using semi-quantitative methods by means of a matrix approach to investigate the level of interaction between different hazards and vulnerability elements. It uses a **scoring system based on the qualitative assessment of a specific interaction** (no, weak, medium, strong interaction) to identify the significance of interactions. In this way it can be identified whether a level 3 analysis adds additional accuracy from a detailed analysis compared to the uncertainty bounds.

Ultimately, a Bayesian network is used for the quantitative multi-risk assessment as visualized in Figure 1-9. This approach has been tested in an artificial case study. Multi-hazard interactions are only accounted for in terms of triggering and cascading effects. It uses the probability of occurrence of a primary event and the conditional probability of the impacted event to identify the probability of a multi-hazard event. Time-variant vulnerability[9] in terms of the probability of experiencing a certain level of damage given a certain hazard, is represented by a combination of time-variant fragility curves for possible experienced multi-hazard event combinations. To account for the time-variant probability of failure, the survival function for each individual hazard need to be combined[10]. Multi-risk is then calculated as the product of the probability of occurrence of a certain damage and the potential maximum loss.

[9] Note: multi-risk as used by Liu et al. (2015) considers only for time variant vulnerability of a specific element at risk and neglects interconnections of vulnerabilities between different elements at risk.

[10] Liu et al. (2015) only mention the probability of failure in case of full independence of the vulnerabilities (which is not necessarily the case for multi-risk considerations). This could lead to an under- or overestimation of the expected risk.

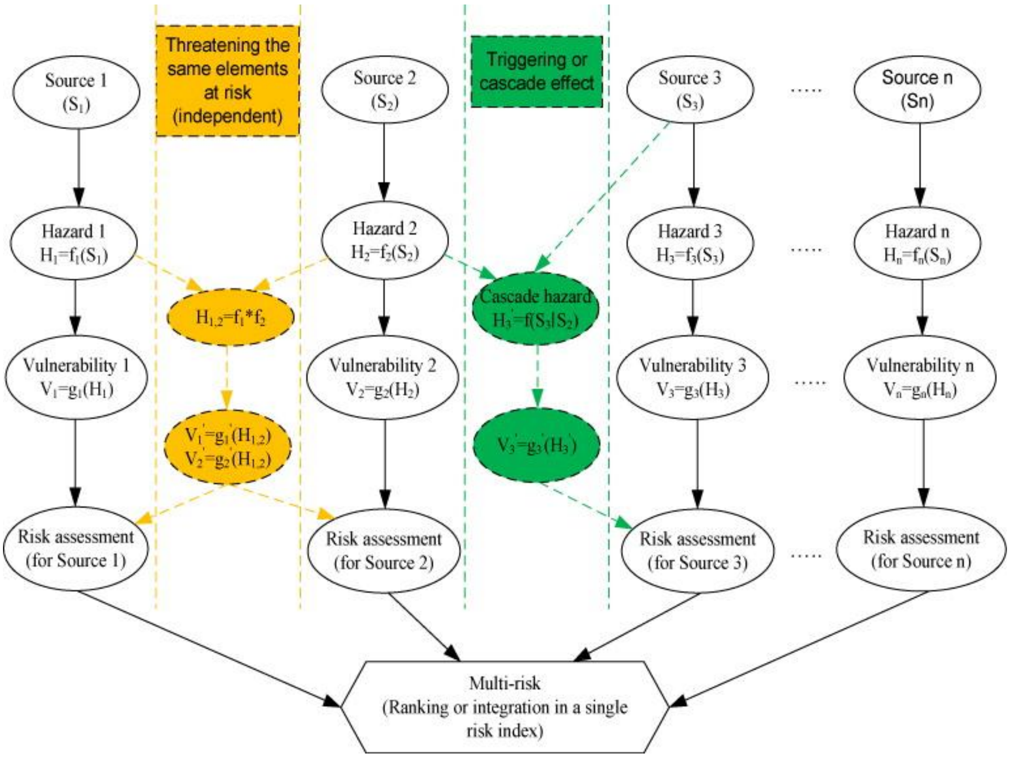


Figure 1-9: Bayesian network for quantitative multi-risk assessment

Source: Liu et al. (2015), CC BY 3.0

1.5.4.4 Towards multi-risk management

According to Scolobig et al. (2017), priority should be given to the design of multi-risk management options by using all information and existing collaborative spaces. It has been noted that research is biased towards approaches for the risk assessment. From the work of Task 1.2 for the development of the Disaster Risk Gateway wiki (MYRIAD-EU D1.1 WIKI-style online platform of multi-hazard, multi-risk methods, models and tools) an observation was made that research is biased towards approaches for the risk assessment. As such, only few approaches explicitly address multi-risk management. One promising approach is the 'Dynamic Adaptation Policy Pathways' (DAPP) developed by Haasnoot et al. (2013) as a tool to support decision-making under deep uncertainty. DAPP acknowledges that current decisions have to be taken under irreducible uncertainties (e.g. lack of predictive capability of the future development of the socioeconomic system or climate change) and offers a means to **explore future scenarios to identify policy options and long-term strategies that are robust and flexible**, thus capable to perform well under a wide range of uncertainties. As such, DAPP provides a framework for the analysis of policies to manage uncertain risks dynamically with long-term options in mind. The analytical framework is presented in Figure 1-10. DAPP has been applied in a variety of planning and risk management contexts, and therefore benefits from multiple lessons learned from the applied risk governance process. Relevant to multi-risk perspectives, DAPP may use a variety of criteria to evaluate promising measures and policies to reduce risk, representing different objectives, and requirements of the decision-making context. It is noteworthy that this approach has been translated into a British Standard (BS: 8631:2021; "Adaptation to climate change - using adaptation pathways for decision making - Guide") and thus received a special attention and more elaborate description of the specific steps and considerations to take into account.

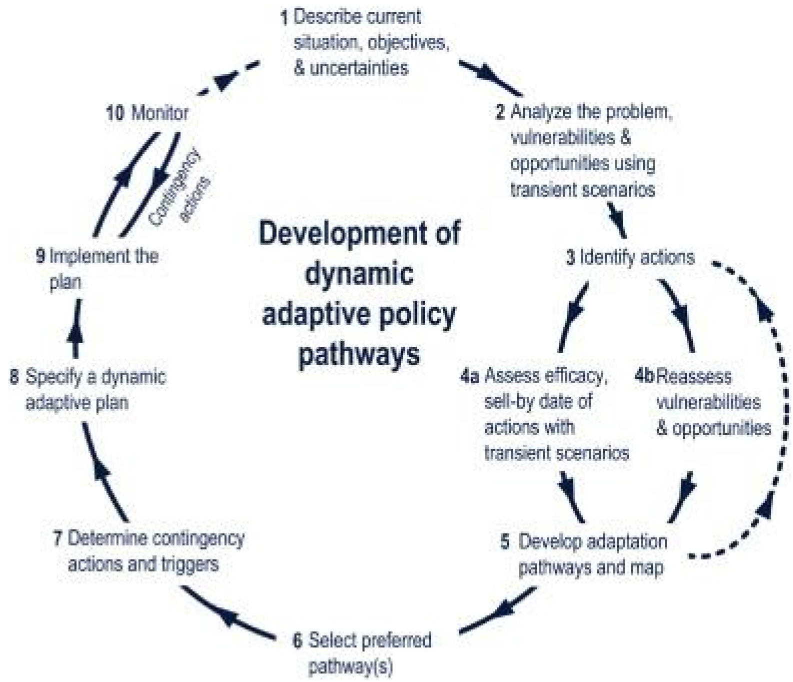


Figure 1-10: Dynamic Adaptive Policy Pathways approach

Source: Haasnoot at al. (2013), CC BY-NC-ND 3.0

DAPP makes decision-making over time explicit using the concept of adaptation tipping points. An adaptation tipping point specifies the conditions under which the status quo, a policy action or a portfolio of actions will fail. An adaptation tipping point is reached when the magnitude of external change is such that a policy no longer can meet its objectives, and new actions are needed to achieve the objectives (Deltares, n.a.). In this way **sequences of policies can be developed to manage risk over the relevant planning horizon**. An adaptive plan specifies actions to be taken immediately to be prepared for the near future and actions to be taken now to keep options open to adapt if needed in the future.

One of the key components and acknowledged strengths of DAPP is its visualization to simplify complexity and potential options. It uses metro map-like representations of pathways to present plausible combinations of management options and their relative timing of adaptation tipping points as shown in Figure 1-11. Each of the pathways can be evaluated, e.g. using scorecards to identify which short-term policy options pose low-regret alternatives and perform well regarding the identified objectives (beyond risk management).

While DAPP has been applied in a wide range of planning and risk management studies using various levels of complexity ranging from qualitative, narrative based pathways to computer-model-based, fully quantitative pathways, it is **not yet capable or lacks tools to manage the increased interdependencies of multi-risk in terms of system dynamics as well as complexity of decision-making processes** not only involving a large number of stakeholders, but particularly a large number of (contested) objectives (Bosomworth, 2017).

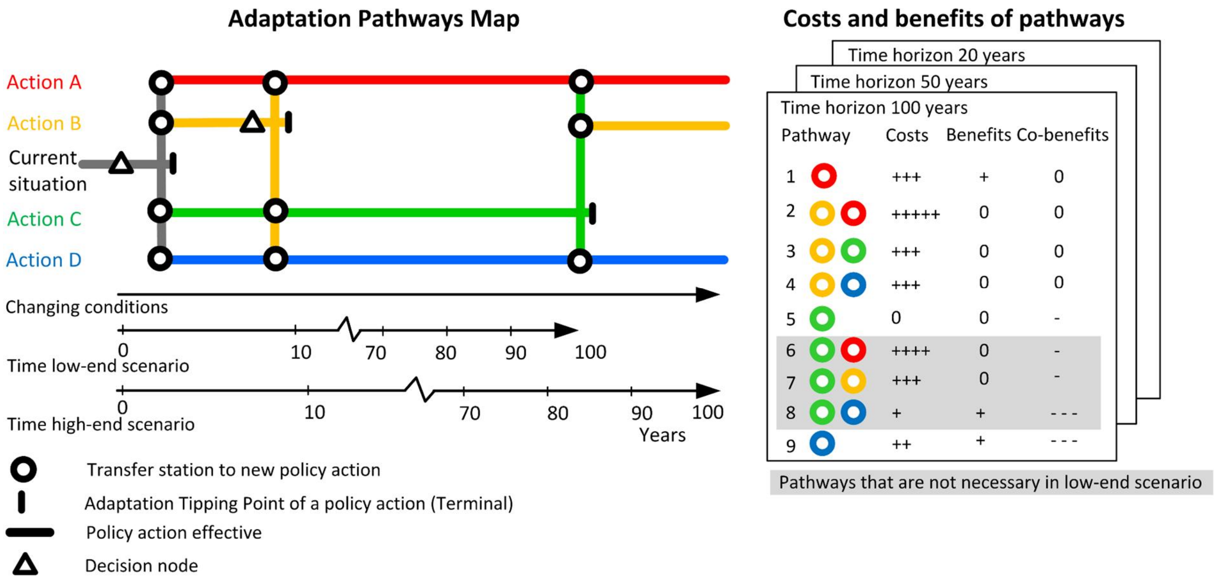


Figure 1-11: Example adaptation pathway map along with scorecard for qualitative analysis of costs and benefits of chosen pathways

The pathway map is indicating several possible routes to get to a desired point (target) in the future. The circles indicate a unidirectional transfer station (lines present a route through time). The blocks indicate a terminal station at which an adaptation tipping point is reached, and new policies need to be implemented. Source: Haasnoot at al. (2013), CC BY-NC-ND 3.0

1.5.4.5 Towards communication of multi-risk

The successful implementation of disaster risk reduction options and strategies demands not only comprehensive multi-risk assessment schemes, but also an appropriate mechanism to communicate and transfer knowledge on multiple risks and its underlying drivers to the various stakeholders involved in the decision-making process. The EU FP7 project New Multi-Hazard and Multi-Risk Assessment Methods for Europe (**MATRIX**), identified perceptions of civil defense stakeholders to the value of two complementary multi-risk communication tools:

- A generic probabilistic framework that implements hazard correlations in a comprehensive manner, and
- An evaluation methodology based on the concept of the risk matrix to incorporate expert knowledge through stakeholder interactions into multi-hazard scenario development.

The findings following the application of these two methods are discussed below.

Method 1: Generic multi-risk framework

Mignan et al., (2017) proposed a novel, 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. This approach was shown to be a very **effective way to communicate the role of multi-hazard to stakeholders**, regardless of their level of familiarity with the concepts of correlated chains of events and their impact on risk.

Considered hazard interactions are analogous to the ones observed in recent catastrophes, such as the 2005 hurricane Katrina or the 2011 Tohoku earthquake. The validation of this framework was made on a synthetic data set, based on the concept of a **virtual city within a virtual hazardous region** where generic data are defined heuristically (Mignan et al., 2017). Interaction between hazards considered were earthquakes (EQ), landslide (LS), hurricanes (HR) volcanic eruptions (VE), fluvial floods (FL), winds (WI) and sea submersions (SS). Other events considered include asteroid impacts (AI) and technological accidents (TK). (Figure 1-12).

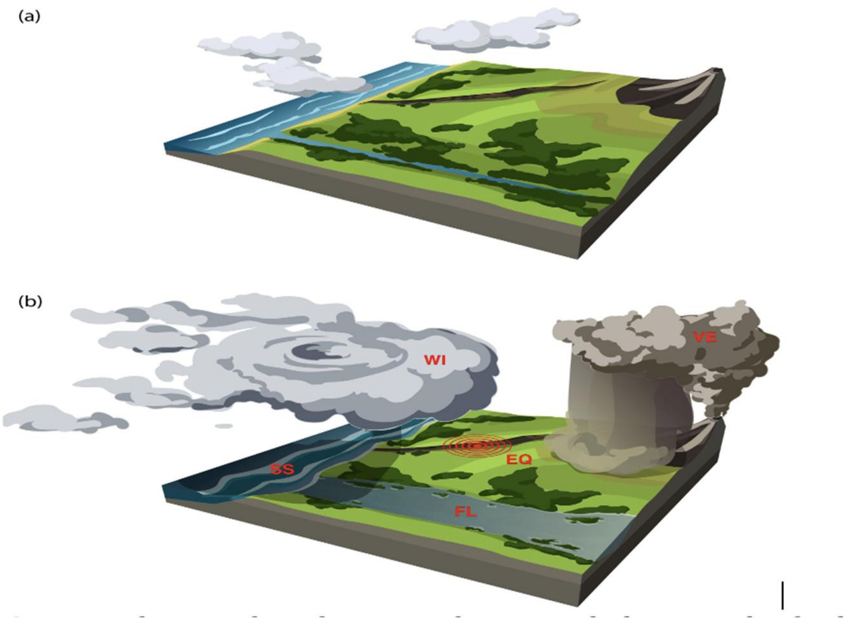


Figure 1-12: The virtual city layout used as a proof-of-concept for the framework of Mignan et al. (2017)

The figure shows the morphology of the 100 by 100 km region Source: Liu et al. (2015) CC BY 3.0

In Figure 1-13, the red arrows represent positive feedback and the blue arrows represent negative effects. The spatial distribution of the different hazards roughly follows the virtual region's constraints, as defined in Figure 1-13. Some events, referred to as independent events, are not influenced by the occurrence of other events (e.g., AI) but may occur simultaneously. Some interactions have analogues to recent catastrophes. For example, EQ-SS (tsunami)-TK is reminiscent of the Tohoku earthquake / Fukushima nuclear disaster of 2011, Japan. A negative effect represents the case when the occurrence of a second event becomes less likely or even impossible. For example, if a landslide occurs, a stable slope may be created, which hampers the occurrence of a new landslide at the same location. Again, if a technological accident occurs and the critical infrastructure is not repaired, the repeat of the same technological accident may be impossible. The heuristic strategy, that is the use of intuitive judgment and simple rules, allows for the solving of problems that are otherwise too difficult to consider.

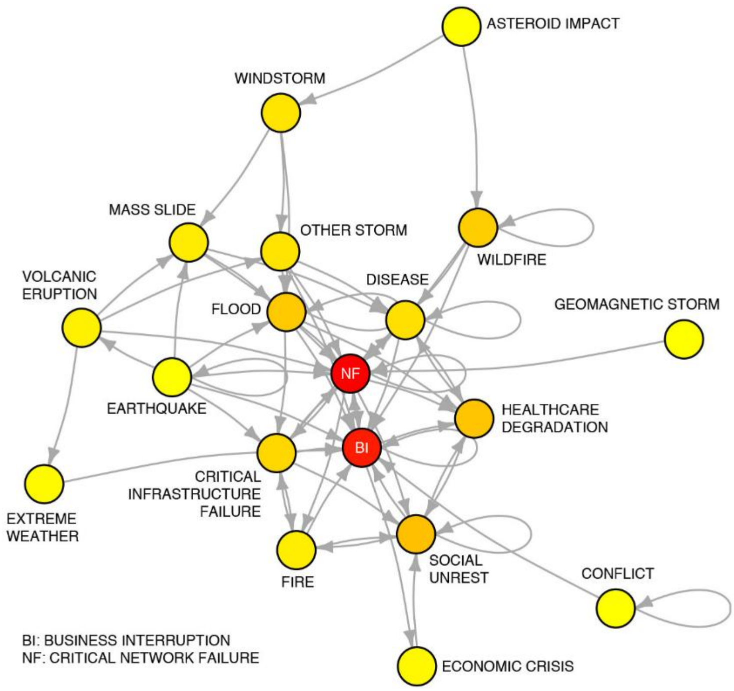


Figure 1-13: Network representation of the hazard interactions within the concept of the Virtual City.

Source: Mignan & Wang (2020) CC BY 4.0

Method 2: Decision-support tool

The methodology of the decision-support tool follows the definition of risk as a combination of the consequences of an event or hazard and the associated likelihood of its occurrence. Adapting the BBK framework (Bundesamt für Bevölkerungsschutz und Katastrophenhilfe 2010), consequences are expressed in terms of impacts in the following categories:

- people (expected casualties, homeless, affected persons),
- economy (expected financial losses, capital stock, business disruptions),
- environment (threat to ecosystem, groundwater, agricultural areas stability and sustainability),
- infrastructure (Interruption in freshwater, gas, energy, telecommunications, transportation systems) and
- intangibles (public security, political implications, psychological implications and loss to cultural values).

In this way, a risk matrix relating the two dimensions of likelihood (in terms of probabilities of occurrence) and impact (in terms of an ordinal category of loss which can be expressed as “catastrophic”, “large”, “moderate”, “small” and “irrelevant”) is a graphical representation of different risks in a comparative way, and can be used as a simple approach for setting priorities. Accordingly, the risk matrix presents a **visual two-dimensional display of the “ranking” of risk scenarios** in terms of a frequency and impact scale that is relevant to the region of interest and will help in interpreting historical experience and translating expert opinion in a consistent manner.

The risk matrix methodology was implemented into a decision-support software based on the principles of Multi-Criteria Decision Analysis (MCDA) and tested with a group of stakeholders to communicate and transfer the information contained for the different risk scenarios in the risk matrix to the various stakeholders involved. The decision-support tool allows the stakeholders to display the total risk index ranking of different risk scenarios (e.g., an extremely rare offshore earthquake which can trigger a tsunami, or a release of toxic material with severe impacts on the local environment, etc.) affecting a region in terms of expected losses that are quantitatively derived in different sectors (human, environment, economy, infrastructure, intangibles) for each scenario (Figure 1-14).

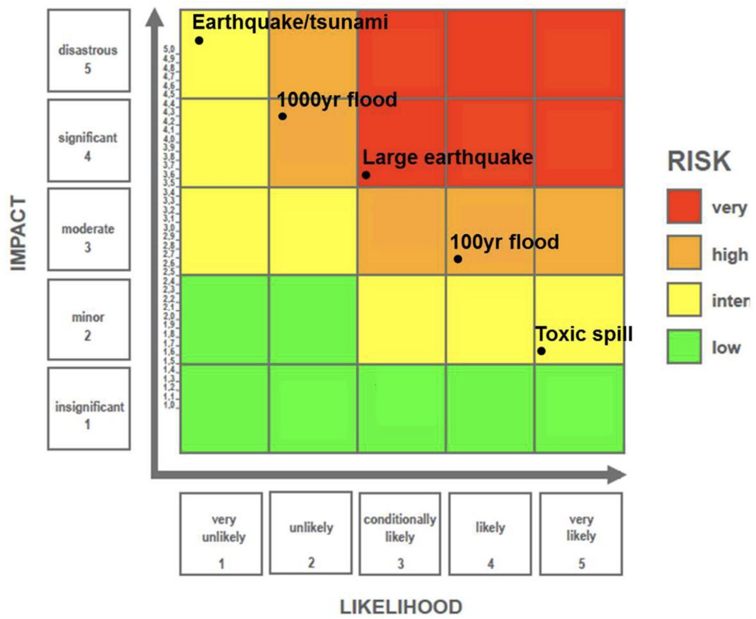


Figure 1-14: Example of how different scenarios fit within a risk matrix

Source: BBK (2010)

Interactions with stakeholders with regards to Method 2 identified differences in the perceptions between stakeholders from science and practitioners. From among the 14 stakeholders that responded, 6 represented the practice community, such as civil protection, emergency management, and policy making; and 8 represented various academic organizations. In the workshop the stakeholders were asked to rank the usefulness of the decision tool in terms of four categories (highly useful, moderately useful, slightly useful and not useful) for the following three areas: (i) understanding the distribution of losses for different sectors and comparing risk scenarios with each other (Figure 1-15, left); (ii)communicating multi-type risk parameters to different stakeholders and (iii) for developing strategies for risk management (Figure 1-15, right).

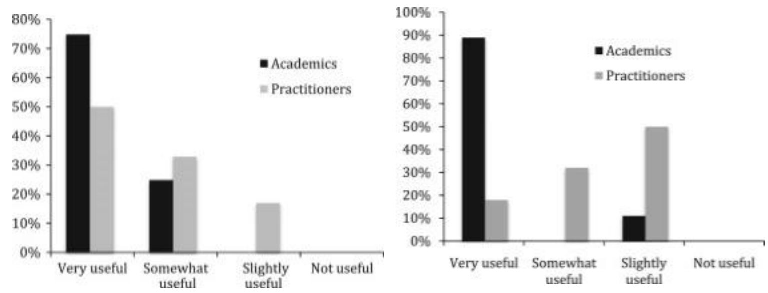


Figure 1-15: Differences in perceptions between stakeholders from science and practitioners

Left: The results of the survey in Method 2 tool helps with the understanding of losses and their contribution in a risk scenario (14 answers);
Right: how the Method 2 tool helps with communicating multi-type risk parameters to different stakeholders for developing risk management strategies (14 answers).
Source: Mignan et al. (2014)

It is interesting to note the variation in the perceptions between stakeholders in academia and those in the practice community in terms of the tool's usefulness. While both academic and practitioners agreed that the tool is useful for understanding losses and their contributions in a risk scenario (Figure 1-15 left), there is a difference between how practitioners viewed the usefulness of the tool when it comes to prioritizing risk and developing risk management strategies (Figure 1-15, right). In the case of the latter, most practitioners viewed the tools as being only slightly to somewhat useful, while academics believed it to be very useful for this purpose. In the discussion that followed with the stakeholders, it arose that a **precondition for the useful application of the tool is expert knowledge**, and thus the tool is ideally to be used by risk analysis experts. In this way, the tool brings added value by adding transparency and a rational breakdown of risk against a competing set of criteria. Furthermore, the stakeholders commented that the usefulness of the tool could only be gauged following an in-depth exercise with stakeholders for a region where the expertise and context (i.e., a case study with specific problem) is available (Komendantova et al., 2014).

The multi-risk communication tools presented above represent a fraction of the multitude of means of visualization present in the literature. The report produced by Ciurean et al. (2018) contains an extensive analysis of the choices scholars and practitioners made to represent multiple hazards. The identified approaches include: narrative descriptions, hazard wheels, hazard matrices, network diagrams, hazard maps, risk indices, physical modeling, probabilistic and statistical assessments.

1.6 Barriers & opportunities to further facilitate multi-risk governance

Barriers

In the previous sections we presented results from an analysis of the existing (multi-)risk governance landscape reaching from the global to the sub-national level. As part of this, we identified multiple barriers & opportunities with regards to mainstreaming good multi-risk governance as elaborated in the following section.

The **lack of binding regulations and policies** that require putting the consideration of multi-risk elements at their core can be seen as a major barrier for operational multi-risk governance. Naturally, practitioners are not systematically accounting for these if they are not required to. It also has been highlighted in the interviews that the required procedures by law need to be followed to ensure compliance and legal reliability of the process. Using alternative procedures for the assessment of risk for example would thus just be an additional assessment on top. The lack of legal consideration of multi-risk, also directly implies that **practitioners often lack the opportunity to deal with multi-risk issues** such as cascading impacts, increase of vulnerability during consecutive hazards because of lack of resources, available time or interactions available between people activating in different risk management fields (Schweizer & Renn, 2019). Furthermore, the **distribution of mandates/responsibilities across the different governance levels/sectors** and the different evolvement of risk assessment research between various hazard disciplines has been identified as an important limiting factor to cooperate to integrate single-hazard risks considerations (Scolobig et al. 2017; Mignan et al. 2017; Pursiainen and Rod, 2021). For instance, in case of an earthquake, levels of private responsibility are high, as property owners oversee vulnerability reduction, whereas, if flooding occurs, public authorities are expected to organize mitigation measures and to act on disaster relief. There is disagreement on cost distribution as well. For the former, the costs are covered by the individual, while for the latter, they are shared by the collective. In general, there are few opportunities for public-private responsibility sharing for households with exposure to multi-risks (Scolobig et al. 2022). Furthermore, it has been observed that interaction with other institutional responsibilities beyond risk management might be impeding the adoption of risk reduction measures (Raikes et al., 2019). As such, the management of floods and drought could happen in parallel, but other policy issues, e.g. economic growth, might be conflicting and inhibit proper DRM.

Depending on the hazard type, risk management is spread among different public organizations and may also be shared by the public society. This is being reflected by the existing endogenous institutional structure. There are different governance levels that tackle the same issue. This **lack of inter-institutional arenas** makes it harder even for the merging multi-risk frameworks to be systematically implemented (Mignan et al., 2017). Furthermore, the **lack of cross-border communication and collaboration** limits the ability for coordination across neighboring countries and thus might lead to unnecessarily high or even exacerbated risks - which raises a question of equity in DRM as well (Carter et al., 2021).

Apart from the above identified institutional barriers, barriers also arise in the context of methods and approaches. The previous analysis has shown that there is a lack of established approaches to foster interactive coordination and cooperation across administrative, or sectoral borders (Schweizer, 2021). As authorities are often using very **different approaches and tools** for the assessment and management of single risks, this poses multiple challenges to a multi-hazard integration (different risk reduction objectives, different timescales, different assessment tools). In terms of operationalisation of tools developed for single-layer risk assessment to integrate into a multi-risk assessment, Poljansek et al. (2020) identified some practical limitations. On the one hand, there could be struggles with (access to) data, its quality and the epistemic uncertainty. On the other hand, revising existing tools and management frameworks requires a certain reporting format, as well as more time, resources and expert knowledge exchange between different risk communities to be deployed (Scolobig et al. 2014; Aspinall et al. 2014). More generally, the respective approaches need to be tested to ensure that they are capable of addressing the increased complexity and uncertainty, which has been called in question repeatedly (Leveson, 2011; Aven & Renn, 2020).

Regardless, the methods vary across disciplines, and there is a need for common standards, even the definition of 'multi risk' requires consensus (Zschau, 2017). Furthermore, the quantitative scenarios that are predominantly used to navigate single risk assessment are generally lacking in multi-risk situations (Zschau, 2017).

As previously highlighted, the **suitability of available tools** to support good multi-risk governance is still a concern among scholars. Particularly quantitative methods have to face the question regarding the reliability of their results, which includes considerations whether the assessment itself complies with current standards or rules (Aven and Heide, 2009), but also to which extend the (lack of) knowledge is properly addressed (Aven and Renn, 2020).

Regardless of the abundance of tools there is a **rift between science and practice.** The interests and needs of practitioners often do not align with the research developments: practitioners need more reasoning for the benefits of using more complex methods, while researchers focus on the many possible aspects to improve the multi-risk assessment, like diversifying the tools available (Scolobig et al. 2017). The practitioners' needs can significantly vary, depending on the type of institution and their role in the disaster risk management cycle. However, there are domains in which practitioners do see benefits of joint multi-risk approaches. Areas that have been mentioned are land-use planning, emergency management and risk mitigation. One means of overcoming this rupture **is through informing policy decisions**, about both climate triggers and aspects not related to climate that could originate beyond the decision maker's jurisdiction (Carter et al., 2021). This could help reduce climate risks across systems, with Carter et al. (*ibid.*) mentioning the international agricultural system as an eloquent example.

Benefits & Opportunities

Transitioning towards multi-risk governance represents a complex process, and it requires a clear understanding of single risk approaches and systems thinking. However, the benefits of such a transition are well known. Ultimately, integrating the multi-risk viewpoints emerging from assessment brings certain benefits towards governance practice, such as **reducing loss of lives and property** and the potential to implement **tailored risk management strategies** increasing the efficiency of the intervention instead of causing trade-offs. Practitioners have acknowledged the potential trade-offs when managing different natural hazards individually leading to increased vulnerabilities (Scolobig et al. 2017; Månsson, 2019). Conversely, it could lead to an **improvement to land-use planning**, through building restrictions, which themselves may influence urban and economic planning, for example by regulating the construction of new houses and/or economic activities. Enhanced response capacity, because a multi-risk approach could account for potential damage to sectors from indirect impacts and consider precautionary measures. Furthermore, a **multi-risk perspective permits to account for the total risk which might be greater than the sum of the individual parts** because of the interactions of risk and sector dependencies when designing risk management strategies. It could furthermore be cost-efficient as spill-over effects on the disaster response and recovery costs could be avoided by **coordinated and tailored DRM strategies** (Zschau, 2022; Scolobig et al. 2014).

Scolobig et al. (2014) and Aspinall et al. (2014) make the case for the opportunities linked to the development of territorial platforms (for data exchange between researchers and practitioners), inter-agency environments and local/regional multi risk commissions. The **inter-agency environments** would represent an operational space for multiple levels of governance to exchange information, develop protocols and ease the process of offering information to relevant stakeholders across multiple governance levels. Introducing a platform for collaboration on disaster risk reduction could improve the coordination of both response and decision-making, connecting all concerned entities, amounting to a centralized governance approach (Poljansek et al., 2021). For example, it could support communication and knowledge co-production between risk managers, people at risk and decision makers. In that way, cooperation across agencies, and between private and public actors can be initiated. Particularly the collaboration across sectoral boundaries have been found to be important for co-designing innovative solutions and stimulating not only the learning process but also joint commitment (Head, 2019). At the same time, cooperation would support developing a common understanding of what multi-risk requirements are at the local level and what directions future research should orientate towards (Aspinall et al. 2014). As a result, co-benefits for different stakeholder groups could be identified and tailored risk management strategies could be implemented to seize synergies. This is particularly relevant for **cross-border coordination and preparedness** to make use of financial benefits of pre-event risk reduction and adaptation compared to the costs and human distress of post-event response. Knowledge about cascading hazards is particularly important for risk zoning and emergency response preparedness (Scolobig, et al 2017). Also, additional benefits could arise: **sharing and centralized management of resources** (e.g. data or tools) could enhance their (cost-)efficient use as well as enhance processes of exchanging and synthesizing information across administrative levels (Månsson, 2019).

Regardless of the reforms required on a case-by-case basis, the structure established must maintain high accountability standards, by having a transparent decision process and offer solutions in a timely manner. Simultaneously, at the local level commissions established could elaborate on the discussion on what risk assessment represents, necessary actions and priorities for future research. Involving thus local decision- and policy-makers, researchers and local natural advisors, the latter acting as the liaising bodies between local communities and practitioners, bridging sectors. Until recently effective participation has been deemed to be popular. Legitimacy has been offered to centralized institutions. However, the new values of participatory governance should reflect the blurring of lines needed for multi-risk decision-making.

1.7 Conclusions and way-forward

1.7.1 Conclusions

Multi-risk governance is by nature highly interdisciplinary, characterized by complex and interacting processes. This inherent complexity can pose difficulties for practitioners (policy makers and industry). This report aims to provide a first understanding of the governance landscape for the management of multi-risks in Europe: the review aims to highlight general guidelines, good practice examples, emerging conceptual work together with barriers and possible opportunities. This report reflects on the scientific approaches supporting risk governance; although institutional arrangements and legislative regulations are highly relevant for any governance process, it was out of the scope of this study to investigate national policy coherence and organizational features.

The review started with an overview of global and European directives, formal and informal agreements and communications outlining the political frame for multi-risk governance in Europe. We presented the national risk assessment as the main avenue of countries for initiating processes and taking actions to assess, manage and communicate risks. The analysis concludes with the observation that the embedding of a multi-risk perspective in the national risk assessments does not meet the ambition of the international and European policies. Institutional arrangements that specifically consider multi-risks are a critical factor in enhancing multi-hazard and multi-risk assessment and management. The inclusion of multi-risk considerations in sector specific policies was also investigated. Apart from the domain of critical infrastructures, the acknowledgement or importance of multi-hazard risk or multi-risk in sectoral policies seems to be lacking entirely.

Nevertheless, using the multi-risk governance framework developed by Scolobig et al. (2017), the analysis revealed that scientific approaches and good practice examples are available and could be used to advance practice towards multi-risk processes. We present approaches from the academic community that were identified as particularly **promising, or prominent representative approaches** for the risk identification, risk assessment, risk management and risk communication. The dedicated sections below summarize main findings and illustrate general characteristics relevant for multi-risk governance. We note that as part of activities of Task 1.2 of MYRIAD_EU, a wide range of platforms, frameworks, methods and tools applicable and relevant in the context of multi-hazard or multi-risk management have been collected. They can be accessed in the dedicated Disaster Risk Gateway wiki (MYRIAD-EU D1.1 WIKI-style online platform of multi-hazard, multi-risk methods, models and tools).

Towards hazard and risk interactions. The observation and identification of potential multi-risks is the starting point for a broad system understanding. Informed by the literature review, this report presents two selected methods to qualitatively and quantitatively identify multi-hazard events. Both presented approaches clearly show different strengths and challenges encountered when aiming to observe and identify potential multi-risks. While the approach by Gill & Malamud (2014) is much more directed towards stakeholder interaction and working with the information already available to qualitatively identify potential hazard interaction scenarios, data-driven processes such as those presented by Bevacqua et al. (2021), might be able to contribute a more accurate and quantitative characterisation of hazard interactions. At the same time, operational approaches for the identification and understanding of multi-risk are still in their infancy. The presented approaches by Simpson et al. (2021) and Carter et al. (2021) are still in a conceptual phase. As such they lack operationalization and therefore clearly can only contribute to the general understanding and awareness of relevant dynamics. They might be prerequisites for taking actions but are less helpful in the action itself. However, it confirms that multi-risk research is still in its infancy and the identified barrier regarding available tools is still present.

Towards multi-risk commissions. The literature review revealed several examples of local partnerships and cross-agency fora. Examples are: National Platforms for Disaster Risk Reduction, the Natural Hazards Partnership from the United Kingdom, the Critical Infrastructure Partnership Advisory Council (CIPAC) established by the US Homeland Security Department, the EU Strategy for the Danube Region. These initiatives illustrate the emerging recognition and benefits brought by the exchange of knowledge across country-borders and sector-boundaries. The integration of relevant stakeholders across country-borders and sector-boundaries is upcoming; such collaborations are often initiated for other regulatory processes but have the potential to yield useful dialogues for multi-risk governance as well. This is supported by the conclusion of OECD (2018) which reports that the experience of involved stakeholders has led to improved understanding and expansion of the disaster scenarios considered in the National Risk Assessments. Yet the number of multi-risk/multi-sector-oriented initiatives is rather limited. It appears that this element of multi-risk governance is the furthest accepted and used in practices compared to the other elements. It allows for the conclusion that the opportunities linked to cross-agency, cross-sectoral, and cross-boundary collaboration are increasingly exploited.

Towards multi-risk assessment. The research community has taken steps to respond to the call and need for guidelines for multi-hazard risk assessment. With illustration purposes, this report presents two recently published approaches from di Angeli et al., (2022) and Liu et al. (2015). While the framework by di Angeli et al. provides a comprehensive approach to address multi-risk (with the exception of indirect impacts), it again highlights the lack of tools and methods to support the application of the intended quantitative framework. Liu et al. (2015) provides a framework including tools which have at least been tested in a hypothetical case. However, their presented approach is highly data-driven and complex which might be a challenging entry point for stakeholders from policy-making or sectoral practice to understand, interact and participate in such assessment processes. Additionally, as this approach has also not been applied to an existing real-world case, its utility is a critical knowledge gap. As a result, it can be concluded that the present tools need to be further advanced or additional tools for multi-risk assessment are required (Scolobig et al. 2017).

Towards multi-risk management. In the past decade, risk governance practice has shifted towards a resilience-focused, "*people-centered*" approach (Scolobig et al. 2015; Roth et al. 2019). This means that risk governance is understood more and more as a holistic approach required to deal with the dynamic systems driven by climate change, urbanization, and combined effects of several hazards (Roth et al, 2019). Also, past large-scale events often resulted in public calls for further integration of responsibilities and actors, e.g. by means of new, centralized structures (Roth et al. 2019). From the literature review, an observation is made that research is biased towards approaches for the risk assessment. As such, only few approaches explicitly address multi-risk management. One of these few is the 'Dynamic Adaptation Policy Pathways' (DAPP) approach described in Haasnoot et al. (2013). DAPP has the valuable advantage of being a highly tested framework to explore future scenarios and identify policy options and long-term strategies that are robust and flexible. However, this approach is not yet capable or lacks tools to manage the increased interdependencies of multi-risk in terms of system dynamics as well as complexity of decision-making processes. While lessons learned from the multiple existing DAPP applications and other risk management approaches might have the potential to contribute the much-needed practical guidance towards multi-risk management in practice (Schlumberger et al., *in progress)*, more attention for the importance of supporting multi-risk management processes (with limited available knowledge) is needed.

Towards multi-risk communication. The successful implementation of disaster risk reduction options and strategies demands not only comprehensive multi-risk assessment schemes, but also an appropriate mechanism to communicate and transfer knowledge on multiple risks to the various stakeholders involved in the decision-making process. Good practice recommends that targeted information is developed for specific users. This will further enable a good basis for the dialogue with stakeholders on the possible measures and combination of measures to reduce risk. Another valuable tool is the setup of storylines describing the flood risk, either based on past events or on scenarios; these are much appreciated and facilitate "risk understanding". In this report the value of two complementary multi-risk communication tools is briefly described. Intuitive judgment and simple rules have proven to be very important for the communication of multi-hazard to stakeholders, regardless of their level of familiarity with the concepts of connected risk. Also, the feedback from stakeholders revealed that expert knowledge/relevant expertise is an important precondition for the useful application of a multi-risk exploring tool.

1.7.2 A way-forward

This section further presents a set of recommendations relevant for future MYRIAD-EU activities, and that can also inform general advancements towards multi-risk governance. Most recommendations are directed towards the scientific community, while some of them are relevant for practitioners as well.

Make the step from conceptual frameworks to testing and operationalizing approaches (Science)
It has been observed that within the scientific community, there is an increasing understanding of the expected dynamics and interdependencies within multi-risk systems. Testing and operational use of future multi-risk tools, methods and frameworks in real situations is an essential and much-needed step for practitioners to identify, assess, manage and communicate multi-risk.

For new approaches, keep in mind the purpose and application context of these tools (Science & Practice)
To specifically address the barrier caused by the rift between science and practice, it should be at the core of any new approach to be developed to specify how the developed approach makes best use of available resources (e.g. data, expertise and time) to address practice needs. For this, actively accounting for inputs from practice and the good governance principles (e.g. transparency, participation, feasibility, and, equity) to assure the uptake and the use of these tools in decision making processes is key. This also implies for practitioners that they should voice their needs repeatedly and clearly when involved in co-development processes.

Integrate processes of multi-risk assessment and management (Science)
When progressively accounting for the dynamics and interdependencies of considered systems, the implication of current management practice on future risk becomes increasingly important.

While risk assessment and management have traditionally been treated separately (institutionally), integration between both in early stages of any disaster risk reduction project could result in synergies to account for the complexity of multi-risk (Schweizer et al. 2019).

Make use of existing knowledge and link to existing processes (Science & Practice)
As illustrated with the scientific examples within this report, but much more clearly visible from the recently developed Disaster Risk Gateway wiki (MYRIAD-EU D1.1 WIKI-style online platform of multi-hazard, multi-risk methods, models and tools), many approaches, tools and methods are available. These tools address part of the required considerations relevant for multi-risk governance. It is vital to reflect on their strengths and limitations in order to effectively and efficiently advance any further development process. Similarly, as some processes (e.g. in the context of NRA) already contribute to overcome some of the barriers of mainstreaming multi-risk governance, engaging with these could be beneficial for MYRIAD-EU to feed into formal policy processes. The understanding of existing policy-making processes and collaboration initiatives will help practitioners build awareness, knowledge and understanding for the new fairly new subject of multi-risk governance.

Engage in projects and initiatives that consider multi-risks (Science & Practice)
For science, active engagement and collaboration across boundaries of projects can be expected to result in many synergies to make sure that developed approaches are complementary. For practice, it has been observed that sectors tend to ignore impacts that go beyond their domain. Further familiarization with perspectives on multi-risk might be useful to identify benefits to seize and barriers to overcome.

Integrate considerations of (multi-)risk governance in strategies and long-term planning (Practice)
The analysis within this report made visible that many sectors dedicate very limited awareness and attention to future strategies and long-term planning. Some sectors do start identifying the need for organized risk governance (often due to increased awareness of climate change). Options to account for long-term perspectives and multi-risk elements should be explored to allow for timely, precautionary, and effective risk governance structures to be put in place.

1.8 References

Aichholzer, G., Strauß, S., 2016. Collaborative Forms of Citizen (e-)Participation, in: Aichholzer, G., Kubicek, H., Torres, L. (Eds.), Evaluating E-Participation: Frameworks, Practice, Evidence, Public Administration and Information Technology. Springer International Publishing, Cham, pp. 109–122. https://doi.org/10.1007/978-3-319-25403-6_6

Aspinall, W., Bengoubou-Valerius, M., Desramaut, N., Ruocco, A.D., Fleming, K., Gasparini, P., Gehl, P., Khazai, B., Komendantova, N., Liu, Z., Marti, J., Marzocchi, W., Mignan, A., Monfort-Climent, D., Nadim, F., Parolai, S., Patt, A., Réveillère, A., Scolobig, A., Tyagunov, S., van Gelder, P., Vangelsten, B.V., Vinchon, C., Vorogushyn, S., Wang, J., Zschau, J., n.d. New Multi-Hazard and Multi-Risk Assessment Methods for Europe (Project Deliverable).

Aven, T., Heide, B., 2009. Reliability and validity of risk analysis. Reliab. Eng. Syst. Saf. 94, 1862–1868. https://doi.org/10.1016/j.ress.2009.06.003

Aven, T., Renn, O., 2020. Some foundational issues related to risk governance and different types of risks. J. Risk Res. 23, 1121–1134. https://doi.org/10.1080/13669877.2019.1569099

Aven, T., Renn, O., 2018. Improving government policy on risk: Eight key principles. Reliab. Eng. Syst. Saf. 176, 230–241. https://doi.org/10.1016/j.ress.2018.04.018

Aven, T., Renn, O., 2010. Risk Management and Governance: Concepts, Guidelines and Applications. Springer Science & Business Media.

Bain, P.G., Bongiorno, R., 2020. It's not too late to do the right thing: Moral motivations for climate change action. WIREs Clim. Change 11, e615. https://doi.org/10.1002/wcc.615

Bevacqua, E., De Michele, C., Manning, C., Couasnon, A., Ribeiro, A.F.S., Ramos, A.M., Vignotto, E., Bastos, A., Blesić, S., Durante, F., Hillier, J., Oliveira, S.C., Pinto, J.G., Ragno, E., Rivoire, P., Saunders, K., Wiel, K., Wu, W., Zhang, T., Zscheischler, J., 2021. Guidelines for Studying Diverse Types of Compound Weather and Climate Events. Earths Future 9. https://doi.org/10.1029/2021EF002340

Bogenschneider, K., Corbett, T.J., 2010. Evidence-Based Policymaking: Insights from Policy-Minded Researchers and Research-Minded Policymakers. Routledge, New York. https://doi.org/10.4324/9780203856390

Bosomworth, K., Leith, P., Harwood, A., Wallis, P.J., 2017. What's the problem in adaptation pathways planning? The potential of a diagnostic problem-structuring approach. Environ. Sci. Policy 76, 23–28. https://doi.org/10.1016/j.envsci.2017.06.007

Bossong, R., Hegemann, H., 2015. European Civil Security Governance: Diversity and Cooperation in Crisis and Disaster Management. Springer.

British Geological Survey & MYRIAD-EU, (in preparation). Disaster Risk Gateway. H2020 MYRIAD-EU Project, grant agreement number 101003276

BSI, 2021. BS 8631:2021 | 30 Apr 2021 | BSI Shop [WWW Document]. URL https://knowledge.bsigroup.com/products/adaptation-to-climate-change-using-adaptation-pathways-for-decision-making-guide/standard (accessed 7.18.22).

Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (Ed.), 2010. Methode für die Risikoanalyse im Bevölkerungsschutz, Wissenschaftsforum. Bonn.

Carter, T.R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., Reyer, C.P.O., West, C., 2021. A conceptual framework for cross-border impacts of climate change. Glob. Environ. Change 69, 102307. https://doi.org/10.1016/j.gloenvcha.2021.102307

Chereni, S., Sliuzas, R.V., Flacke, J., Maarseveen, M.V., 2020. The influence of governance rearrangements on flood risk management in Kampala, Uganda. Environ. Policy Gov. 30, 151–163. https://doi.org/10.1002/eet.1881

CISA, n.d. Critical Infrastructure Sector Partnerships | CISA [WWW Document]. URL https://www.cisa.gov/critical-infrastructure-sector-partnerships (accessed 6.29.22).

Ciurean, R., Gill, J., Reeves, H.J., O'Grady, S., Aldridge, T., 2018. Review of multi-hazards research and risk assessments [WWW Document]. URL https://nora.nerc.ac.uk/id/eprint/524399/ (last accessed 18 July 2022).

Copenhagen Business School (CBS), Copenhagen School of Energy Infrastructure (CSEI), Directorate-General for Energy (European Commission), 2021. TYNDP 2020 joint scenarios methodology: a CSEI assessment. Publications Office of the European Union, LU.
Curt, C., 2021. Multirisk: What trends in recent works? – A bibliometric analysis. Sci. Total Environ. 763, 142951. https://doi.org/10.1016/j.scitotenv.2020.142951
De Angeli, S., Malamud, B.D., Rossi, L., Taylor, F.E., Trasforini, E., Rudari, R., 2022. A multi-hazard framework for spatial-temporal impact analysis. Int. J. Disaster Risk Reduct. 73, 102829. https://doi.org/10.1016/j.ijdrr.2022.102829
Deubelli, T., Norton, R., Mechler, R., Venkateswaran, k, McClune, K., Stevance, A.-S., 2022. Boosting systemic risk governance: Perspectives and insights from understanding national systems approaches for dealing with disaster and climate risk. Contributing Paper. [WWW Document]. URL https://www.undrr.org/publication/boosting-systemic-risk-governance-perspectives-and-insights-understanding-national (accessed last accessed 16 June 2022).
Devaney, L., Brereton, P., Torney, D., Coleman, M., Boussalis, C., Coan, T.G., 2020a. Environmental literacy and deliberative democracy: a content analysis of written submissions to the Irish Citizens' Assembly on climate change. Clim. Change 162, 1965–1984. https://doi.org/10.1007/s10584-020-02707-4
Devaney, L., Torney, D., Brereton, P., Coleman, M., 2020b. Ireland's Citizens' Assembly on Climate Change: Lessons for Deliberative Public Engagement and Communication. Environ. Commun. 14, 141–146. https://doi.org/10.1080/17524032.2019.1708429
Directorate-General for European Civil Protection and Humanitarian Aid Operations (ECHO), 2010. COMMISSION STAFF WORKING PAPER Risk Assessment and Mapping Guidelines for Disaster Management. SEC(2010)1626.
Du, H., Triyanti, A., Hegger, D.L.T., Gilissen, H.K., Driessen, P.P.J., van Rijswick, H.F.M.W., 2022. Enriching the concept of solution space for climate adaptation by unfolding legal and governance dimensions. Environ. Sci. Policy 127, 253–262. https://doi.org/10.1016/j.envsci.2021.10.021
Duncan, M., Smale, L., Crummy, J., Ciurean, R., Napier, A., Chintham, S., Shelly, W., Gill, J., Schlumberger, J., Stuparu, D. … (in preparation). D1.1 WIKI-style online platform of multi-hazard, multi-risk methods, models and tools. H2020 MYRIAD-EU Project, grant agreement number 101003276, pp XX.
Ebrey, R., de Ruiter, M., Botzen, W., Koks, E., Aerts, J., Wens, M., Bloemendaal, N., Wouters, L., Robinson, P.J., Mol, J., Nirandjan, S., Tesselaar, M., Bosello, F., Mysiak, J., Scoccimarro, E., Mercogliano, P., 2021. STUDY ON ADAPTATION MODELLING: Comprehensive Desk Review: Climate Adaptation Models and Tools. Publications Office of the European Union, Luxembourg. https://doi.org/10.2834/280156
European Commission, 2021. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS New EU Forest Strategy for 2030.
European Commission, 2019. Commission Notice Reporting Guidelines on Disaster Risk Management, Art. 6(1)d of Decision No 1313/2013/EU2019/C 428/07.
European Commission, 2020b. The Commission proposes a new directive to enhance the resilience of critical entities providing essential services in the EU [WWW Document]. URL https://ec.europa.eu/home-affairs/news/commission-proposes-new-directive-enhance-resilience-critical-entities-providing-essential-services-2020-12-16_en (accessed last accessed 15 June 2022).
European Commission, 2020a. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU Biodiversity Strategy for 2030 Bringing nature back into our lives.
European Council, 2013. Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism Text with EEA relevance, OJ L.

European Council, 2008. Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection (Text with EEA relevance), OJ L.
EUSDR, n.d. Priority Areas. EUSDR - Danube Strategy Point. URL https://danube-region.eu/about/priority-areas/ (last accessed 29 June 2022).
GCA, 2021. Living with water: climate adaptation in the world's deltas [WWW Document]. Glob. Cent. Adapt. URL https://gca.org/reports/living-with-water-climate-adaptation-in-the-worlds-deltas/ (last accessed 25 January 2022).
Gill, J.C., Malamud, B.D., 2014. Reviewing and visualizing the interactions of natural hazards: Interactions of Natural Hazards. Rev. Geophys. 52, 680–722. https://doi.org/10.1002/2013RG000445
Gill, J.C., Malamud, B.D., Barillas, E.M., Guerra Noriega, A., 2020. Construction of regional multi-hazard interaction frameworks, with an application to Guatemala. Nat. Hazards Earth Syst. Sci. 20, 149–180. https://doi.org/10.5194/nhess-20-149-2020
Gill, J., Duncan, M., Ciurean, R., Smale, L., Stuparu, D., Schlumberger, J, de Ruiter M., Tiggeloven, T., Torresan, S., Gottardo, S., Mysiak, J., Harris, R., Petrescu, E. C., Girard, T., Khazai, B., Claassen, J., Dai, R., Champion, A., Daloz, A. S., ... Ward, P. 2022. MYRIAD-EU D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts. H2020 MYRIAD-EU Project, grant agreement number 101003276, pp 82.
Girgin, S., Necci, A., Krausmann, E., 2019. Dealing with cascading multi-hazard risks in national risk assessment: The case of Natech accidents. Int. J. Disaster Risk Reduct. 35, 101072. https://doi.org/10.1016/j.ijdrr.2019.101072
Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Change 23, 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006
Hemingway, R., Gunawan, O., 2018. The Natural Hazards Partnership: A public-sector collaboration across the UK for natural hazard disaster risk reduction. Int. J. Disaster Risk Reduct. 27, 499–511. https://doi.org/10.1016/j.ijdrr.2017.11.014
Hilhorst, D., Boersma, K., Raju, E., 2020. Research on Politics of Disaster Risk Governance: Where Are We Headed? Polit. Gov. 8, 214–219. https://doi.org/10.17645/pag.v8i4.3843
Hove, S.E., Anda, B., 2005. Experiences from conducting semi-structured interviews in empirical software engineering research, in: 11th IEEE International Software Metrics Symposium (METRICS'05). Presented at the 11th IEEE International Software Metrics Symposium (METRICS'05), p. 10 pp. – 23. https://doi.org/10.1109/METRICS.2005.24
Howarth, C., Bryant, P., Corner, A., Fankhauser, S., Gouldson, A., Whitmarsh, L., Willis, R., 2020. Building a Social Mandate for Climate Action: Lessons from COVID-19. Environ. Resour. Econ. 76, 1107–1115. https://doi.org/10.1007/s10640-020-00446-9
IRGC, 2018. Introduction to the IRGC Risk Governance Framework. https://doi.org/10.5075/EPFL-IRGC-233739
ISDR, 2005. Hyogo Framework for Action 2005-2015: Building the resilience of nations and communities to disasters: La FAO en situations d'urgence [WWW Document]. URL https://www.fao.org/emergencies/ressources/documents/ressources-detail/fr/c/169151/ (accessed 2.15.22).
Khazai, B., Merz, M., Schulz, C., Borst, D., 2013. An integrated indicator framework for spatial assessment of industrial and social vulnerability to indirect disaster losses. Nat. Hazards 67, 145–167. https://doi.org/10.1007/s11069-013-0551-z
Klinke, A., Renn, O., 2021. The Coming of Age of Risk Governance. Risk Anal. 41, 544–557. https://doi.org/10.1111/risa.13383
Klinke, A., Renn, O., 2014. Expertise and experience: a deliberative system of a functional division of labor for post-normal risk governance. Innov. Eur. J. Soc. Sci. Res. 27, 442–465. https://doi.org/10.1080/13511610.2014.943160
Komendantova, N., Mrzyglocki, R., Mignan, A., Khazai, B., Wenzel, F., Patt, A., Fleming, K., 2014. Multi-hazard and multi-risk decision-support tools as a part of participatory risk governance: Feedback from civil protection stakeholders. Int. J. Disaster Risk Reduct. 8, 50–67. https://doi.org/10.1016/j.ijdrr.2013.12.006

Kuipers, S., Boin, A., Bossong, R., Hegemann, H., 2015. Building Joint Crisis Management Capacity? Comparing Civil Security Systems in 22 European Countries. Risk Hazards Crisis Public Policy 6, 1–21. https://doi.org/10.1002/rhc3.12070
Leveson, N.G., 2011. Applying systems thinking to analyze and learn from events. Saf. Sci., The gift of failure: New approaches to analyzing and learning from events and near-misses - Honoring the contributions of Bernhard Wilpert 49, 55–64. https://doi.org/10.1016/j.ssci.2009.12.021
Liu, Z., Nadim, F., Garcia-Aristizabal, A., Mignan, A., Fleming, K., Luna, B.Q., 2015. A three-level framework for multi-risk assessment. Georisk Assess. Manag. Risk Eng. Syst. Geohazards 9, 59–74. https://doi.org/10.1080/17499518.2015.1041989
Månsson, P., 2019. Uncommon sense: A review of challenges and opportunities for aggregating disaster risk information. Int. J. Disaster Risk Reduct. 40, 101149. https://doi.org/10.1016/j.ijdrr.2019.101149
McGovern, R., Thorne, P., 2021. Citizens assemble: a study on the impact of climate reporting in the Irish media 'before', 'during' and 'after' the Citizens' Assembly on 'how the state can make Ireland a leader in tackling climate change.' Ir. Polit. Stud. 36, 214–234. https://doi.org/10.1080/07907184.2020.1811970
Mellier-Wilson, C., Toy, S., 2020. UK Climate Change Citizens' Assemblies & Citizens' Juries [WWW Document]. involve.org.uk. URL https://www.involve.org.uk/resources/case-studies/uk-climate-change-citizens-assemblies-citizens-juries (accessed 7.18.22).
Mignan, A., Komendantova, N., Scolobig, A., Fleming, K., 2017. Handbook of Disaster Risk Reduction & Management. WORLD SCIENTIFIC. https://doi.org/10.1142/10392
Mignan, A., Komendantova, N., Scolobig, A., Fleming, K., 2016. Multi-Risk Assessment and Governance, in: Handbook of Disaster Risk Reduction & Management. WORLD SCIENTIFIC, pp. 357–381. https://doi.org/10.1142/9789813207950_0014
Mignan, A., Wang, Z., 2020. Exploring the Space of Possibilities in Cascading Disasters with Catastrophe Dynamics. Int. J. Environ. Res. Public. Health 17, 7317. https://doi.org/10.3390/ijerph17197317
Muradova, L., Walker, H., Colli, F., 2020. Climate change communication and public engagement in interpersonal deliberative settings: evidence from the Irish citizens' assembly. Clim. Policy 20, 1322–1335. https://doi.org/10.1080/14693062.2020.1777928
Mysiak, J., Testella, F., Bonaiuto, M., Carrus, G., De Dominicis, S., Ganucci Cancellieri, U., Firus, K., Grifoni, P., 2013. Flood risk management in Italy: challenges and opportunities for the implementation of the EU Floods Directive (2007/60/EC). Nat. Hazards Earth Syst. Sci. 13, 2883–2890. https://doi.org/10.5194/nhess-13-2883-2013
Niessen, C., 2019. When citizen deliberation enters real politics: how politicians and stakeholders envision the place of a deliberative mini-public in political decision-making. Policy Sci. 52, 481–503. https://doi.org/10.1007/s11077-018-09346-8
OECD, 2019. Policy Coherence for Sustainable Development 2019: Empowering People and Ensuring Inclusiveness and Equality. OECD. https://doi.org/10.1787/a90f851f-en
OECD (Ed.), 2018a. Assessing global progress in the governance of critical risks, OECD reviews of risk management policies. OECD Publishing, Paris. https://doi.org/10.1787/9789264309272-en
OECD, 2018b. National Risk Assessments: A Cross Country Perspective. OECD. https://doi.org/10.1787/9789264287532-en
OECD, 2016. Development Co-operation Report 2016 - The Sustainable Development Goals as Business Opportunities - OECD [WWW Document]. URL https://www.oecd.org/dac/development-co-operation-report-2016.htm (accessed 7.18.22).
OECD, 2015. The Changing Face of Strategic Crisis Management. Organisation for Economic Co-operation and Development, Paris.
OECD, 2014. OECD Recommendation on the Governance of Critical Risks - OECD.
Poljanšek, K., Casajus Valles, A., Marín Ferrer, M., De Jager, A., Dottori, F., Galbusera, L., García Puerta, B., Giannopoulos, G., Girgin, S., Hernandez Ceballos, M.A., Iurlaro, G., Karlos, V., Krausmann, E., Larcher, M., Lequarre, A.S., Theocharidou, M., Montero Prieto,

M., Naumann, G., Necci, A., Salamon, P., Sangiorgi, M., Sousa, M.L., Trueba Alonso, C., Tsionis, G., Vogt, J.V., Wood, M., 2019. Recommendations for national risk assessment for disaster risk management in EU: approaches for identifying, analysing and evaluating risks : version 0. Publications Office of the European Union, LU.

Poljansek, K., Casajus Valles, A., Mar??n Ferrer, M., Artes-Vivancos, T., Boca, R., Bonadonna, C., Branco, A., Campanharo, W., De Jager, A., Rigo, D. de, Dottori, F., Durrant Houston, T., Galbusera, L., Garc??a Puerta, B., Giannopoulos, G., Girgin, S., Gowland, R., Grecchi, R., Estreguil, C., Ferrari, D., Frischknecht, C., Hernandez Ceballos, M.A., Iurlaro, G., Kambourakis, G., Karlos, V., Krausmann, E., Larcher, M., Lequarre, A.S., Liberta, G., Loughlin, S.C., Maianti, P., Mangione, D., Marques, A., Menoni, S., Montero Prieto, M., Naumann, G., Necci, A., Oom, D., Pfieffer, H., Robuchon, M., Salamon, P., Sangiorgi, M., San-Miguel-Ayanz, J., Sousa, M.L., Theocharidou, M., Theodoridis, G., Trueba Alonso, C., Tsionis, G., Vogt, J.V., Wood, M., European Commission, Joint Research Centre, 2021. Recommendations for national risk assessment for disaster risk management in EU: where science and policy meet: version 1.

Popp, T.R., 2021. Explaining Policy Convergence and Divergence through Policy Paradigm Shifts: A Comparative Analysis of Agricultural Risk Governance in OECD Countries. J. Comp. Policy Anal. Res. Pract. 23, 310–327. https://doi.org/10.1080/13876988.2019.1674623

Pursiainen, C., Rød, B., 2021. National disaster risk assessments in Europe. How comparable are they and why? Risk Hazards Crisis Public Policy 12, 194–214. https://doi.org/10.1002/rhc3.12215

Raikes, J., Smith, T.F., Jacobson, C., Baldwin, C., 2019. Pre-disaster planning and preparedness for floods and droughts: A systematic review. Int. J. Disaster Risk Reduct. 38, 101207. https://doi.org/10.1016/j.ijdrr.2019.101207

Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013, 2021. , OJ L.

Roth, F., Prior, T., Käser, M., 2019. Natural Hazards Governance in Western Europe [WWW Document]. Oxf. Res. Encycl. Nat. Hazard Sci. https://doi.org/10.1093/acrefore/9780199389407.013.225

Rubin, H.J., Rubin, I.S., 2011. Qualitative Interviewing: The Art of Hearing Data. SAGE.

Schweizer, P.-J., 2021. Systemic risks – concepts and challenges for risk governance. J. Risk Res. 24, 78–93. https://doi.org/10.1080/13669877.2019.1687574

Schweizer, P.-J., Renn, O., 2019. Governance of systemic risks for disaster prevention and mitigation. Disaster Prev. Manag. Int. J. 28, 862–874. https://doi.org/10.1108/DPM-09-2019-0282

Scolobig, A., Garcia-Aristizabal, A., Komendantova, N., Patt, A., 2014. Chapter 3-20: From multi-risk assessment to multi-risk governance: Recommendations for future directions, in: GFDRR (Ed.), . International Bank for Reconstruction and Development, Washington.

Scolobig, A., Komendantova, N., Mignan, A., 2017. Mainstreaming Multi-Risk Approaches into Policy. Geosciences 7, 129. https://doi.org/10.3390/geosciences7040129

Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., New, M.G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D.N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E., Trisos, C.H., 2021. A framework for complex climate change risk assessment. One Earth 4, 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

Smith, G., 2020. Enhancing the Legitimacy of Offices for Future Generations: The Case for Public Participation. Polit. Stud. 68, 996–1013. https://doi.org/10.1177/0032321719885100

Snyder, H., 2019. Literature review as a research methodology: An overview and guidelines. J. Bus. Res. 104, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Soria Morales, E., 2019. Building Integrated Approaches to Sustainable Development Implementation: How to Enhance Policy Coherence for Sustainable Development. https://stg-wedocs.unep.org/handle/20.500.11822/30559 (last access: 07.18.2022)
Tilloy, A., Malamud, B.D., Winter, H., Joly-Laugel, A., 2019. A review of quantification methodologies for multi-hazard interrelationships. Earth-Sci. Rev. 196, 102881. https://doi.org/10.1016/j.earscirev.2019.102881
Tómasson, B., Karlsson, B., 2020. The role of households in Nordic national risk assessments. Int. J. Disaster Risk Reduct. 45, 101495. https://doi.org/10.1016/j.ijdrr.2020.101495
UN, 2015. Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs [WWW Document]. URL https://sdgs.un.org/2030agenda (last accessed 18 July 2022).
UNDRR, 2020. National Platforms for Disaster Risk Reduction - UNDRR Regional Office for Europe and Central Asia Overview [WWW Document]. URL https://www.undrr.org/publication/national-platforms-disaster-risk-reduction-undrr-regional-office-europe-and-central (last accessed 18 July 2022).
UNDRR (2016). Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. Terminology available at: https://www.undrr.org/terminology (last accessed 18 July 2022).
United Nations Conference on Environment and Development, 1992. AGENDA 21.
United Nations Office for Disaster Risk Reduction (2022). Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future. Geneva.
United Nations International Strategy for Disaster Reduction (2019). Global Assessment Report on Disaster Risk Reduction (GAR)
van der Heijden, J., 2019. Risk Governance and Risk-Based Regulation: A Review of the International Academic Literature (SSRN Scholarly Paper No. ID 3406998). Social Science Research Network, Rochester, NY. https://doi.org/10.2139/ssrn.3406998
Virtudes, A., 2016. 'Good' Governance Principles in Spatial Planning at Local Scale. Procedia Eng., World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium 2016, WMCAUS 2016 161, 1710–1714. https://doi.org/10.1016/j.proeng.2016.08.650
Wohlin, C., 2014. Guidelines for snowballing in systematic literature studies and a replication in software engineering, in: Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering. pp. 1–10.
Wolf, F., Pfohl, T., 2014. Protecting the population in a multilevel system: horizontal and vertical informal governance patterns in Germany, in: Bröchler, S., Lauth, H.-J. (Eds.), Von Government zu Governance: Informales Regieren im Vergleich. Springer Fachmedien, Wiesbaden, pp. 259–285. https://doi.org/10.1007/978-3-658-06145-6_11
Zschau, J., 2017. Where are we with multihazards, multirisks assessment capacities? 30.

2 Part 2: Typologies of interdependencies between sectors

Executive Summary

The field of multi-sector risk is highly complex and relatively understudied. Understanding the dynamic interaction of systems and inherent systemic risk is a considerable scientific challenge but is one that needs to be addressed to effectively identify and prepare for hazard events. This report aims to classify interdependencies between sectors and multi-sector risk into generic typologies. Typologies are classes (types) of multi-sector risk which aim to make it easier for sector representatives to understand multi-sector systems and the types of risks which can occur.

Impacts of natural hazards on interconnected multi-sector systems are difficult to quantify. By defining typologies for different types of risk, it is hoped that this process becomes easier. Through a stakeholder question table, this report aims to facilitate the understanding and identification of the different types of multi-sector risk present in sectors' systems and make Disaster Risk Management planning more effective. Risk-reduction interventions can be targeted towards most relevant risk drivers and at the most vulnerable areas. The main sectors considered are those in the MYRIAD-EU project which include Ecosystems and Forestry, Energy, Finance, Food and Agriculture, Infrastructure and Transport and Tourism. This report highlights four main drivers/channels of inter-sectoral dependence between sectors:

- *Functional interdependence* – where one system relies on the function of another to operate
- *Spatial interdependence* – where sectors are spatially proximate such that an impact in one can lead to correlated responses in multiple systems due to this proximity.
- *Financial interdependence*– where sectors are financially closely coupled, and thus a financial impact in one can have an impact on another.
- *Societal interdependence*- where the societal and government context, level of preparation and long-term planning impacts the way in which sectors are interconnected

The report further proposes four multi-sector risk typologies:

- *Spillover* – a situation in which one event triggers others in a uni-directional fashion.
- *Co-dependent* – a situation where there are two mutually reliant functions, leading to a 'cancelling out' of both if one is negatively affected.
- *Interacting intersecting* – a situation where two or more different risks interact in a bidirectional fashion to create an exacerbated impact
- *Independent intersecting* – a situation where two or more different risks in different sectors are added together to create an exacerbated risk elsewhere.

Other factors that are important to consider when thinking about multi-sector risk are time and space. Considering temporality is vital when understanding cross-sectoral risk, as some risks can be immediate (directly following a hazard event), some emergent (occurring in the hours and days following the occurrence of natural hazards), and others are delayed (occurring in the months and years after an event). Furthermore, considering spatiality is also of concern, as due to globalisation, many sectoral systems now cross-borders. There are therefore also cross-border risks that need to be accounted for in assessments of multi-sector risk.

The multi-sector risk typologies can be explained to some degree by the interdependency drivers between sectors. For example, spillover effects are most likely to be triggered by functional interdependencies. This report proposes a standardized comparison table to explore the relation between relevant drivers of inter-dependence and multi-sector risk typologies. A stakeholder question table (see Figure 2-1 for a summary and Table 2-3 for the full version) is designed to help determine which of the risk typologies a sector may be experiencing and in what way. The table proposes prompting questions such as 'How reliant are sector services on specific critical infrastructure?'. This intends to facilitate the identification of drivers of sectoral interdependence and multi-sector risk typologies relevant to their hazard context and system. In doing so, sectors will be able to develop more effective DRM that targets vulnerable elements in their systems.

	Functional	Spatial	Financial	Societal
Spillover	How reliant are my services/machinery on specific critical infrastructure? If a particular piece of this infrastructure stopped functioning, how affected would my system's functionality be?	How close is my infrastructure to a potential hazard? How proximate is my infrastructure to other infrastructure that could inflict damage in a hazard event? What other sectors or stakeholders are likely exposed to the same impacts and therefore might be willing partners to cooperate regarding risk reduction measures?	How interlinked is my sector with the global financial markets? How sensitive is my sector's financial position to oil price changes? Are fixed prices built into my supply chain contracts to buffer cascading impacts of price spikes? (Carter et al, 2021). How likely are consumers to panic buy products in my sector?	What potential regions might a failure in my sector reach? What actors would be particularly affected and in what capacities? In what ways does my disaster risk planning account for potential spill-over effects? Is disaster planning adaptable and able to deal with dynamic hazards? i.e., does it use dynamic adaptive pathways?
Co-dependent	Are my services highly coupled with other systems, whereby they are mutually dependent on each other's functionality?	Are there proximate system services which are highly inter-dependent with each other, which if fail, could threaten the functioning of the system?	Are the financial systems of my sector highly coupled with financial wellbeing of another, such that if one experiences financial shock, so would mine? With which sectors are mine tightly coupled to?	Are there particular groups that are co-dependent for disaster management?
Interacting Intersecting	Does my sector rely on multiple functions that on failure, intersect to compound the overall impact?	Are there sectors operating in the same location and what are their interacting aspects? What is the geographical area that could be affected by an incident and are there cross-border impacts?	How far does my sector interact with others financially?	What adaptive capacity is there at the interaction location? Do we have contingency plans for long-term compounding hazards?
Independent intersecting	What sectors do we rely on in terms of their functionality, for ours to also function? (i.e., Do we depend on transport service functionality for our services?)	What is the geographical area that could be affected by an incident and what independent sectors could be impacted?	What potential impacts in other sectors, when combined could impact the financial security of our sector?	What is the adaptive capacity to deal with risks that occur together? Do we have contingency plans for the long-term effects of natural hazards?

Figure 2-1: Table of sector stakeholder questions aiming to facilitate investigation of the most relevant drivers of sectoral interdependencies and risk typologies to a sector

2.1 Introduction

The Sendai Framework for Disaster Risk Reduction 2015-30 (SFDRR) stresses that "disaster risk reduction practices need to be multi-hazard and multi-sectoral-based, inclusive and accessible in order to be efficient and effective" (UNDRR, 2015). This call for change has arisen out of growing evidence that traditional, single-hazard, single-sector approaches to risk management can lead to an overall underestimation of risk, inappropriate risk reduction strategies and enhanced vulnerabilities in the system (Simpson et al, 2021, Reed et al, 2022). This is because risk has previously been understood as a static representation of hazard, exposure and vulnerability which does not account for the complexities and dynamics of system components, networks, and feedbacks (Simpson et al., 2021). The need for such approaches is now more apparent than ever, given the expected effects of climate change on the frequency and magnitude of weather-related hazards (Cegan et al., 2022; Ciurean et al., 2018; Schipper, 2020; Laurien, Martin and Mehryar 2022, Venkateswaran & MacClune, 2020). As Kachali et al (2018) point out, a reduction in siloed thinking and an improved understanding of the interconnectedness between sectors will help mitigate the impact of natural hazards. The aim of this report therefore is to develop typologies of multi-sector risk, enabling stakeholders to better understand the types of risk in their system, and resultingly apply this to DRM planning.

In network science (the study of complex networks), societal risk has been characterized under the concepts of interconnected and cascading risk to define the consequences of natural hazards in tightly coupled socio-technological systems (Pescaroli & Alexander, 2018). However, despite increasing recognition of systemic risk, little research has attempted to analyze the specific interactions between sectors. A multi-sector approach to risk recognises that direct impacts in one sector caused by a hazard could result in indirect effects in another (Kachali et al., 2018).

Understanding the complexity of multi-hazard and multi-sector interactions is a significant scientific challenge, but there have been some recent attempts to create frameworks to identify these interactions and how they translate into risk. Simpson et al (2021) argue that there are three levels of risk complexity, 1) single drivers for each determinant of risk (that is: hazard, exposure, vulnerability), 2) multiple interacting drivers within determinants of risk, 3) interacting risks as shown in Figure 2-2. Simpson et al (2021) further argue that interacting risk is inherently cross sectoral and is a reality that needs to be managed if risk is not to be underestimated. This work builds on the work of Simpson et al (2021) by characterizing the multi-sectoral relations that you can expect in a system.

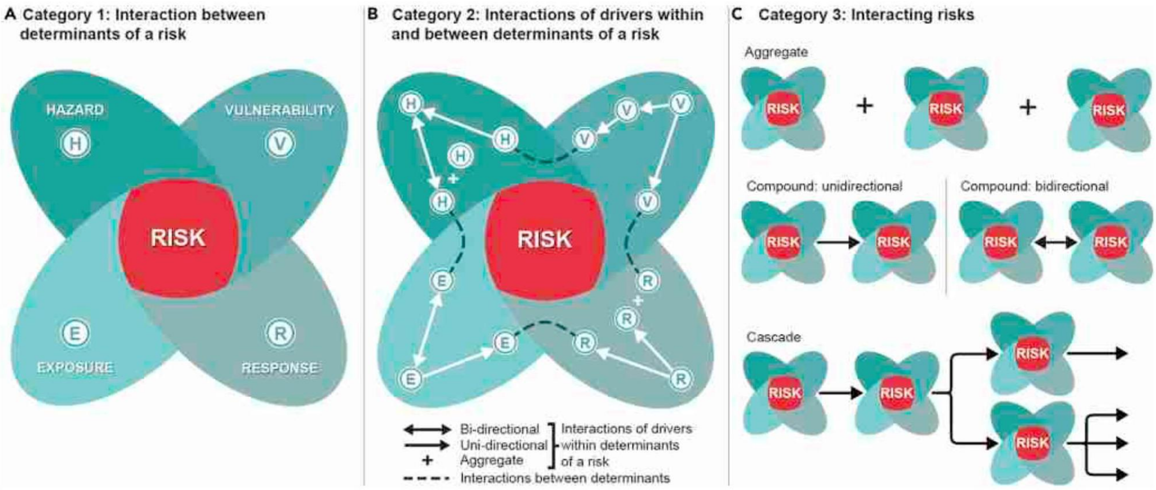


Figure 2-2: Three categories of increasingly complex climate change risk.

(A) Category 1: interactions among single drivers (small circles) for each determinant of a risk, namely hazard, vulnerability, exposure and response to climate change. (B) Category 2: Interactions of multiple drives (e.g. compounding vulnerabilities of education and income) within each determinant of risk, as well as among the determinants of risk. (C) Category 3: Interacting risks. Across categories 2 and 3, compounding and cascading interactions, together with aggregations, generate increasing complexity for risk assessment. We use "determinant" to refer to hazard, vulnerability, exposure and response, within which the term "driver" refers to individual components, such as heavy precipitation (a driver within the hazard determinant) or access to shelter (a driver within the vulnerability determinant), that interact to affect the overall risk (e.g. flood mortality). Source: Simpson et al. (2021) CC BY 4.0

Therefore, the focus of this study is to develop typologies (i.e. general types) of multi-sector risk to better understand complex systems, and in doing so, promote more effective system-focused DRM strategies. The following report attempts to classify types of inter-sectoral dependence and develop typologies of inter-sectoral risk. Firstly, what is meant by a multi-sector system is presented. Secondly, an extensive literature review of hazard impact literature, multi-sector dynamics (MSD) and multi-risk literature is carried out to identify sector interaction drivers, develop multi-risk typologies and identify other factors that are important to consider when thinking about multi-sector risk. In the discussion the sector interaction drivers are compared to the identified multi-risk typologies in a comparison table to analyze the extent to which they are interlinked. A second table presents questions for sectoral stakeholders which aim to help sectoral representatives understand how the types of sectoral interdependencies that they have in their systems, relate to different types of multi-sector risk, enabling them to implement more effective DRM strategies that address the most relevant interdependencies and multi-sector risk types within their sector. In using the presented typologies and stakeholder question table it is hoped that sectoral representatives and stakeholders will be able to better understand the types of multi-risk present in their system and apply this to DRM planning.

2.2 Terminology and concepts

In this study, and in the field of hazard risk, many terms and definitions are used. The most prominent ones are summarized in Table 2-1. A more extensive list of relevant terminology can be found in the glossary provided in the MYRIAD-EU D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts.

Table 2-1: Table of definitions

Term	Definition	Source
Direct impact	These relate to direct losses, triggered directly by the event and include all physical damages, or other degradation to assets.	(Khazai et al, 2013).
Indirect impact	Losses that are a consequence of the direct losses.	(Khazai et al., 2013)
Risk	Risk is the probability of an outcome having a negative effect on people, systems or assets. Risk is expressed as being a function of the effects of hazards, the assets of people exposed to hazards, and the vulnerability of those exposed elements.	(UNDRR, 2016)
Impact	The total effect, including negative effects (e.g., economic losses) and positive effects (e.g., economic gains), of a hazardous event or a disaster. The term includes economic, human and environmental impacts	(UNDRR, 2016)
Multi-hazard	The selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascading or cumulatively over time, and taking into account the potential interrelated effects.	(UNDRR, 2016)
Multi-hazard approach	An approach that considers more than one hazard and the interrelations between these hazards, including their simultaneous or cumulative occurrence and their potential interactions.	(Gill & Malamud, 2014)
Multi-hazard risk	Risk generated from multiple hazards and the interrelationships between these hazards (but not considering the interrelationships on a vulnerability level).	Zschau (2017)
Multi-risk	Risk generated from multiple hazards and the interrelationships between these hazards (and considering interrelationships on the vulnerability level).	(Zschau, 2017)
Multi-Sector Dynamics	Complex systems of systems that deliver services, amenities and products to society	Reed et al (2022)
Multi-sector risk	Risk generated from the interrelationships between sectors (in a hazard event).	n/a
Risk typology	A classification according to a general type of risk.	n/a
Sector	The services and products that emerge from the interdependent dynamics of the underlying systems-of-systems that shape resources, demands, and impacts from global to local scales.	Reed et al (2022)
Systemic risk	Understands that individual elements of a system or sub-system do not act in isolation, but rather interact with each other.	(Sillmann et al., 2022)

2.2.1 Conceptualising multi-sector risk

Within single-hazard approaches to risk, risk is commonly defined as a function of hazard, exposure and vulnerability (UNDRR, 2017). Accounting for multi-hazard risk on the other hand, means considering the interrelations between hazards in space and time, and the ways in which they can impact one another. This is possible in two ways; the first is in the instance that the event of one hazard occurring changes the probability of a second hazard occurring, for example, a flood increases the likelihood of a landslide. Secondly, the level of damage could be increased because of the co-occurrence of hazards, or because the first hazard left the system more (or less) exposed to the second hazard (de Ruiter et al., 2020; Wang et al., 2020).

Differing again from multi-hazard approaches, multi-risk accounts for the temporal and spatial dynamics of vulnerability, meaning the pre-disposition of a certain element of risk to be adversely affected, as well. It is defined as "risk generated from multiple hazards and the interrelationships between these hazards (and considering interrelationships on the vulnerability level)" (Zschau, 2017). Multi-risk considers that the vulnerability of a certain element at risk varies over time, depending on previous hazards, or other developments (e.g. socio-economic or political changes) (de Ruiter and van Loon, 2022). For example, consecutive hazards can exacerbate impacts as one hazard may change the exposure to a future hazard (de Ruiter et al, 2020). Multiple storms in one week can exacerbate disaster losses, as the soil is already saturated, increasing the risk of trees falling and damaging property or increasing fatalities (Wicki et al., 2020). Furthermore, different elements at risk can depend on each other due to interrelation. As a result, if one element at risk suffers impacts, another element at risk could be impacted as well. Hence, multi-risk accounts not only for the dynamics of direct impacts but also the dynamics of indirect impacts (Zschau, 2017). Moving from a purely multi-hazard perspective to a multi-risk approach (which includes sectoral interactions) is therefore inherent to understanding systemic risk and its impacts (Reed et al., 2022; Simpson et al., 2021).

This study looks specifically at multi-sector risk, which has limited definitions in the literature. Multi-sector risk is generated from the interrelationships between sectors (in a hazard event). It is based on an understanding of multi-risk but makes explicit that the interconnections between vulnerabilities and indirect impacts are cross-sectoral (which is not necessarily the case for multi-risk). Sectors can be defined by "the services and products that emerge from the interdependent dynamics of the underlying systems-of-systems that shape resources, demands, and impacts from global to local scales" (Reed et al., 2022). A multi-sector approach to DRM therefore looks specifically at the impact side of multi-risk, considering the interactions and interrelationships between sectors, and the dynamics of the inter-sectoral system in the event of a shock.

2.2.2 Conceptualisation of a multi-sector system

Given the complexity of human-Earth systems, and the ways in which sectors interlink and react dynamically to one another, there is a need to rethink our traditional disciplinary approaches and think in terms of multi-sector systems. Sectors are defined as groups of services that are impacted by system dynamics, but also interact with broader global systems, and Reed et al (2022) define multi-sector dynamics (MSD) as "*complex systems of systems that deliver services, amenities and products to society*".

A System of Systems is a system where the individual elements of the system are treated again as systems (Gill et al., 2022). As Maier (1998) highlights, within a System of Systems,

> "*the constituent elements are collaborating systems that exhibit the properties of operational independence (each constituent system operates to achieve a useful purpose independent of its' participation in the system of systems) and managerial independence (each constituent system is managed and evolved, at least in part, to achieve its' own goals rather than the system of systems goals)*"

A sector is therefore a system of elements (e.g., stakeholders), where every element could be potentially complex and comprising various sub-elements. The grouping of elements into a system is driven by the understanding that those elements together produce something that could not be provided if all elements would operate individually (Klein & van Vliet, 2013). Consequently, the system-of-systems of multi-sector considerations consists of a set of subsystems (stakeholders) within each sectoral system, which are interconnected beyond the sector boundaries, within (and beyond) the boundaries of the existing spatial system at stake.

This system thinking has been widely applied in multi-sector literature and is increasingly being used to understand global connectivity between sectors, countries, continents and individuals (Gaupp, 2020). System dynamics seeks to better understand the interconnected nature of cause and effect (Lawrence et al., 2020). Whilst the concept is several decades old, it gained popularity in dealing with ‘wicked problems’ and risk because of the 2007/2008 financial crisis, and recently the COVID-19 pandemic, clear examples of systemic risk (Sillmann et al., 2022). The interconnectedness of systems can be both, a driver of strength, resilience and control in the system (Reed et al. 2022), as well as a driver of cascading impacts within the system ultimately affecting the risk of the system as a whole (Sillmann et al. 2022). Understanding interactions within the system is therefore necessary for identifying dynamic behavior, and thus, systemic risk (see tab.1) (Reed et al, 2022).

If enough sub-systems are impacted, the performance of the system can be influenced, which can in turn have impacts on other systems, leading to impacts on the system of systems level. Systemic risk therefore results from connections between risks, where localized initial failure could have disastrous effects because of inter-related system components (Simpson et al., 2021). If these impacts exceed a threshold, other subsystems could feel the indirect impacts (because of dependence), leading to impact on a system of systems level. Individual events can therefore trigger systemic risk in complex systems. However, individual, and systemic risk are often treated separately, rather than as a continuum (Hochrainer-Stigler et al., 2020).

Verschuur et al (2022) visualize this in Figure 2-3, Depicting the multi-scale systems-of-systems approach to understanding local, regional and global port networks, using the example of ports in global supply chain networks. Ports are strategic local-global hubs, connecting local critical infrastructure, to regional transport networks and global maritime transport. Because of the inter-connectivity of different system levels, local events may trigger impacts in other system components. Disruptions to any of the network components that link to ports, or a disruption at the port itself can disrupt supply chains. Using a systems-of-systems approach therefore shows the way in which different scales and sectors interact and are linked with broader, global scales (Hochrainer-Stigler et al, 2020).

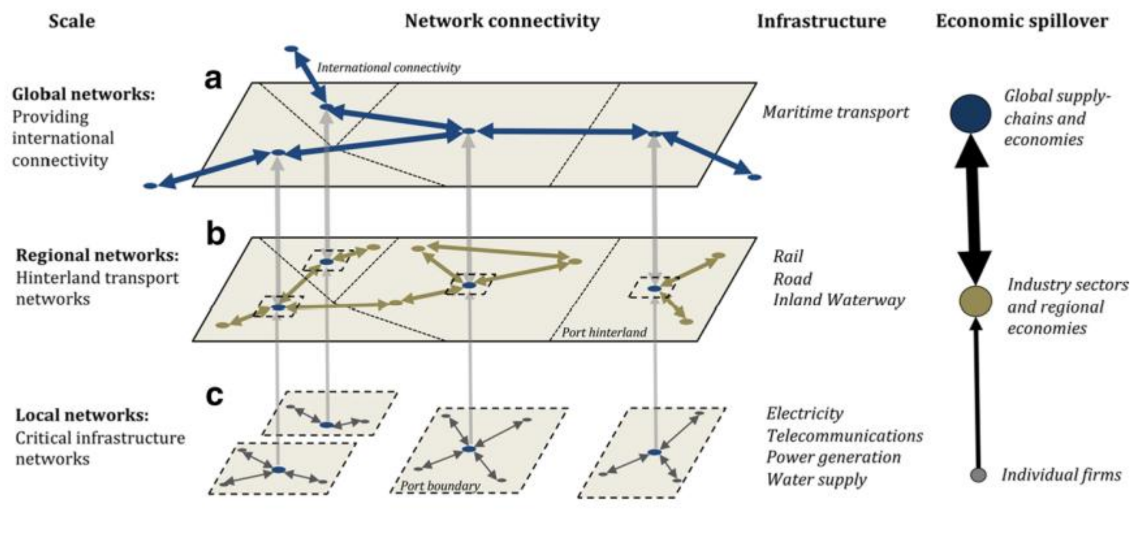


Figure 2-3: Multi-scale systems-of-systems approach to understanding local, regional and global port networks

Source: Verschuur et al. (2022). Used with permission from the lead author of the paper (personal communication, Jasper Verschuur, 20 July May 2022)

2.3 Methods

As de Angeli et al (2022) state, multi-hazard risk evaluation is a relatively new field, and mature methods have not yet been developed. A literature review was chosen because of the 'systems thinking' approach and conceptual nature of this report, which needed to understand the complexity of MSD and multi-risk, to identify types of multi-sector risk. Given the lack of consolidated literature on multi-sector risk, an iterative approach was taken to the literature review (Snyder, 2019). Firstly, relevant studies were identified through searching academic databases such as Google Scholar and Web of Science, and gray literature sources were searched to review relevant case studies (Snyder, 2019). The key search terms used were 'multi-sector risk', 'sectoral dependencies', 'sectoral interactions in disaster risk management', 'interactions between sectors', 'cascading disasters', 'indirect impacts', 'spillover effects' and 'compounding impacts'. The literature search involved firstly discovering the current state of multi-hazard risk research and understanding current multi-hazard risk frameworks. This uncovered the relative lack of research on multi-sector approaches to risk, but also the relative complexity of multi-risk and the need for a framework of clearer understanding (de Angeli et al, 2022). Given the lack of research on sectoral interactions in hazard events, secondly, case studies of past hazard events involving sectoral analysis were reviewed for patterns of impact interactions between sectors. Search terms which helped uncover further literature included those which have had more research, i.e. 'critical infrastructure' and 'impact cascades'.

The current approaches for understanding multi- risk (the majority of which are focused on hazard (rather than sector) interactions) were reviewed. These were analyzed in the context of the impact case studies and were used as 'evidence' to determine and develop sectoral dependency types and typologies of multi-sector risk. Some typologies were developed from current multi-hazard and multi-risk studies. However, it was determined that current literature does not cover the broad possible range of multi-sector risk types. Looking at different driver types of impact, and the different spatial and temporal evolution of impacts, highlighted a broader range than simply risk 'cascades'. Resultantly, four multi-risk typologies were identified. Further, through literature review, other important factors to think about when determining multi-hazard risk were identified and are outlined in the report.

2.4 Results

The following sections present the results of a detailed literature review to collect current knowledge on sector interdependencies and impact interactions in the context of natural hazards. The author attempts to categorize the described examples of interrelationships into typologies (general types) and reflect on the importance of temporality and spatiality to multi-risk typologies.

2.4.1 Drivers (types) of intersectoral interdependence

To better understand the ways in which sectors can interact with each other, the types of inter-sectoral interdependencies are detailed below. Based on the literature it was observed that different sector interdependencies exist (under undisturbed conditions). We propose a set of four types of sector interdependencies: functional interdependence, spatial interdependence, financial interdependence, and societal interdependence. The four interdependencies were identified from a scientific literature review of hazard impacts and sectoral systems-thinking literature and outline the main ways in which sectoral interdependencies occur. These four types are briefly characterized and implications of each type in light of systems thinking are discussed below.

2.4.1.1 Functional interdependence

Functional interdependence relates to situations where one system is connected to and relies on another system to operate. According to Rinaldi (2004), critical infrastructures may have physical, informational and logical dependencies. A failure in one sector may affect the operation of other sectors as a result, creating closely coupled dependencies (Stergiopoulos et al., 2016). In a highly functionally interdependent system, a failure in a very small fraction of nodes can lead to a complete system failure (Buldyrev et al., 2010). Galbusera et al (2020) describe these concepts as 'functional integrity loss' defined as affecting the intrinsic ability of a node to deliver a service as well as 'inoperability' describes the limitation to a node's supply capacity deriving from insufficient service levels. Examples often include IT-related interdependencies, whereby many services rely on IT communication services to function. This is exacerbated in a system which relies on one type of function, enhancing vulnerability of or even creating a new hazard for the system relying on the function.

Little research has explored the micro level impact of natural hazards on individual elements of critical infrastructure, or nodes and hubs in a network that may influence the system (Meyer et al, 2013). However, research on hazard events has shown that the electricity sector is the key sector to propagate risk to other sectors in terms of functionality failures (Haraguchi & Kim, 2016).

Functional examples

In the 2003 North American electrical blackout, the shutdown of power stations led to failure of nodes in the internet communication network, causing further breakdowns of power stations (Rosato et al., 2008).

Additionally, cases where there is a high reliance on one function or service, i.e. the low cost of inland water transport compared to road and rail in Europe, means that during an extreme drought, substitution to rail and road is limited (Verschuur et al., 2022).

However, whilst some literature argues that high infrastructure interconnectivity increases risk of failure, it is also possible to reduce function failure risk by increasing infrastructure network interdependence. A 'smart' power network coupled to a communication system suggests that increased power-communication coupling decreases vulnerability. This highlights that interconnected infrastructure with complementary capabilities increases robustness if modes of inter-network failure propagation are constrained (Korkali et al., 2017). A study on electrical grids, (as shown in Figure 2-4) highlights that in 'ideal' and 'intermediate' grid models, where there are limiting mechanisms for 'failures' to propagate between the two networks, increased coupling was more beneficial than detrimental. In these cases, as connectivity increases, robustness increases. Therefore, resilience in a networked system is present when the loss in function is easily recoverable *or* replaced by a different function that does that same job *and* when there is a mechanism to limit the effect of the failure between different parts of the system.

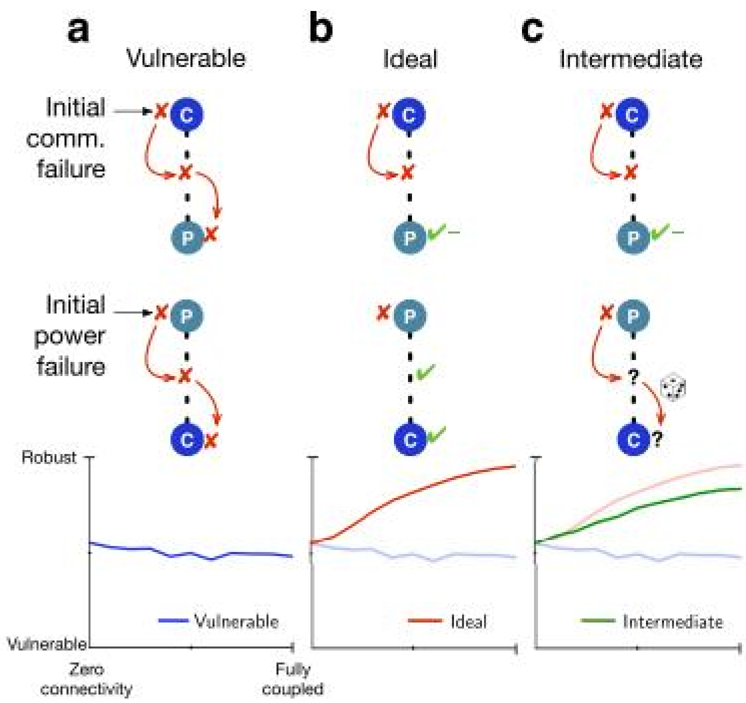


Figure 2-4: Illustration of the three smart grid models.

a) communication failures cause grid failures, and power failures cause communication failures, both with probability one. As the connectivity between the power grid and the *communication network increases, the robustness of the network decreases. In the Ideal model (b) communication failures can degrade the ability to monitor and control power nodes, but power failures cannot return to cause additional communication failures. In this case, as connectivity increases, robustness increases. In the Intermediate model (c), communication failures degrade control performance as before, and power failures trigger communication failures probabilistically. Robustness is degraded but still increases monotonically with connectivity. Source: Korkali et al (2017) CC BY 4.0)*

2.4.1.2 Spatial interdependence

Spatial interdependencies refer to where proximity leads to a correlated response in multiple systems (Dawson, 2015). An example would include floods that have impact on local surrounding roads or a bridge collapsing leading to a failure of ICT cables over the bridge (Dawson, 2015). Spatial interdependencies often trigger cascading effects, whereby the proximity of infrastructure to one hazard results in the function of that infrastructure being disrupted, which then goes on to have domino effects. These relate to direct losses, triggered directly by the event, and include all physical damages, or other degradation to assets (Khazai et al., 2013).

Having said this, spatial interactions and interdependencies can be bidirectional (meaning feedbacks going in both directions between two components or systems in nature as sectors overlap in space, and thus impacts on one, will most likely affect the other by way of proximity (Depellegrin et al., 2021). This is especially true of multi-use spaces in which many sectors are present in one common space.

> *Spatial examples*
>
> The North Sea is an example of a multi-use space, where space and resources are in high demand, and different sectors including shipping aquaculture and energy are all operating in the same space. This can create spatial risk, as seen in the example of the Julietta, a freight ship with 18 crew on board, which lost anchor and resultingly crashed into an oil and chemicals tanker west of the port of Ijmuiden (Aljazeera, 2022).
>
> Multiple use platforms (MUPs) are being used increasingly in the North Sea to try and create synergies between the different sectors. However, this can create more risk in disaster scenarios as sectors become more reliant on each other (Depellegrin et al, 2021).

2.4.1.3 Financial interdependence

Most financial interdependencies between sectors result from top-down economic relationships (Dawson, 2015). For example, shared markets result in sectors interacting through the same economic system. This influences investments, share prices, and availability of credit, creating top-down economic interdependencies (Dawson, 2015). The global financial system is hierarchical with a small number of global financial centers that most countries are connected to and exhibits rising heterogeneity in banking regulation. Complex interdependence in the global financial system is therefore characterized by a persistent structure of connectivity and rising heterogeneity (Bauerle Danzman et al., 2017). Therefore, if an economy experiences a banking crisis, it is more to do with developments in the center of the global financial system, than with domestic politics (Bauerle Danzman et al., 2017). In this sense, financial interdependence between sectors is to some extent unavoidable due to the interconnectedness of the global financial system.

Whilst top-down economic dependencies tend to control the workings of the financial system at large, there are also bottom-up economic interdependencies for example in the event of a disaster, demand for services such as energy can change, influencing overall financial markets (Dawson, 2015). Panic behaviors by customers in response to risk-based signals can occur quickly and affect people's lives or asset values, and thus affect people who are least able to avoid the consequences (Lawrence et al., 2020). However, in general there is little understanding of the interactions between economic dynamics and external shocks (Meyer et al, 2013). Furthermore, there is likely to be business interruption costs following a disaster, for example if people are not able to carry out their work because their workplace is damaged or inaccessible (et al., 2013). Losses also occur if industrial or agricultural production is reduced due to water scarcity. These are referred to as *primary indirect damages* because the losses do not result from direct physical damage but from the interruption of economic processes (Smith and Ward, 1998).

The most devastating economic disruptions, however, are likely to occur from spillover effects (those that have domino effects in other system components). As Verschuur et al (2022) argue given the dependence of global shipping on a few strategic routes, (e.g., Suez Canal and Panama Canal), and reliance on a few global ports, the potential for widespread economic spillover effects is high. Similarly, the shock of the COVID-19 pandemic on the transport industry led to a collapse in energy prices. Inter-industry financial flows and the reliance on energy and commodities such as oil, may spread idiosyncratic shocks, spreading what was initially a sector-specific shock through the entire economy (Sillman et al, 2022, see Appendix A2.b *Example of global interdependency with oil price change*).

Financial examples

The 2008 financial crisis was a result of high financial interconnectedness and had more severe effects in economies that use financial instruments and had a high debt ratio. It also had a large impact on the energy and agriculture sectors, because of the financialisation of commodities (Zhu et al., 2021).
The financial crisis driven by the COVID-19 pandemic, however, was due to measures in place to prevent the spread of the pandemic, which were mostly physical. The impacts of the COVID-19 pandemic were therefore a result of spatial/physical disruptions to interconnections, rather than financial (Zhu et al., 2021). Having said this, the financial impacts from the disruption to physical networks, resulted from high financial interdependence between sectors and the highly complex global financial systems. Therefore, whilst the physical COVID-19 measures were the trigger, the scale of the financial crises was a result of a highly interconnected financial system.

2.4.1.4 Societal interdependence

Social interdependence relates to the level of preparation and long-term planning by a community to face a natural hazard and relates to the concept of vulnerability, adaptive capacity, and resilience within a society, before the disaster has occurred. Individuals and communities act and interact locally to communicate risk and deal with an evolving disaster (Dawson, 2015). These interactions affect the effectiveness of response and recovery efforts and thus the extent and severity of impacts. For example, a community that has large social capital, is more likely to be resilient to disaster events. This was shown in a study on the Haor region of Bangladesh, which showed that groups of farmers with strong mutual trust had higher motivation to take action to prevent potential disaster (Rana et al., 2020).

Socio-economic factors also intermediate the relationship between hazardous events and the physical, social, economic and political contexts in which hazard events interact with citizens. Lower-income countries face challenges in organizing resources to support DRR, exacerbating the losses in lower-income countries (Ali et al., 2021). On the other hand, a community that has a well-planned and thorough emergency response system and citizens that are well informed, is likely to be more resilient to impacts (Rana et al., 2020). There is, however, a continuing lack of recognition of the importance of local coping capacities in DRM (Rana et al., 2020).

In this sense governance plays a key role in system interdependence. Hierarchical, top-down governance systems which fail to decentralize DRR at the community level fail to address local vulnerabilities and adaptive capacities. Such is often the case for indigenous communities, who due to ongoing neo-colonialism, have had many parts of their indigenous lives suppressed (Ali et al., 2021). However, research is suggesting that lessons can be learned from indigenous DRR knowledge which has been built on generations of knowledge and adaptation to the changing environment.

Societal examples

In the 2004 Indian Ocean Tsunami, local vulnerabilities and adaptive capacities were not considered in the Indian islands of Andaman and Nicobar, as they are remotely governed by the government in Delhi. The designs of shelter housing using galvanized iron sheets proposed by government officials were unsuitable, and the government response was too slow (Gupta & Sharma, 2006). This highlights the need for effective social capital and local governance mechanisms to be put in place in preparedness for disaster risk.

2.4.2 Typology of multi-hazard impact interrelations in multi-sector systems

Multi-hazard risk evaluation is a new field, and whilst there has been some literature addressing multi-hazard interactions in earth sciences which has attempted to characterize the types of interactions, including the impacts of multiple compound, consecutive, cascading hazards on the same exposed element at risk (de Ruiter et al., 2020), there has been little complexity science addressing multi-sectoral impact (Pescaroli & Alexander, 2018).

The following section outlines the types of interactions between sectors in the event that a natural hazard would occur, and thus are referred to as risk typologies. As previously mentioned, multi-hazards accounts for the spatial and temporal interrelationships of hazards. Natural hazards can alter the physical properties of the system (leading to altered spatial extent, severity and probability of another hazard), which can trigger additional natural hazard events (which again cause impacts) or occur simultaneously at a certain location leading to exacerbated impact drivers. In a multi-sector system, however, the following temporal and spatial considerations are relevant when considering sectoral impacts of natural hazards:

- Systems in the multi-sector system could be located at the same location, thus directly affected by the same set of multi-hazards.
- Direct impacts in a certain location in the system of systems could cause indirect effects at: a) the same location, again exacerbating the overall impacts; or b) other locations not exposed to the natural hazard.
- The temporal scales of cascading impacts (at the same location or beyond the boundaries of the exposed location) could have effects in terms of altered vulnerability (or exposure) in case of consecutive events occurring.

Here, we summarize findings from literature that mention impact interactions between sectors and propose a set of four categories that can be used to describe how impacts are interrelated in a multi-sector system. The four categories attempt to cover most interaction types found in the literature and were chosen by reviewing the different ways in which risk manifests itself in a multi-sector system in the event of a natural hazard.

2.4.2.1 Spillover effects

A multitude of terms (cascading, spillover, domino) have been used in the literature to describe the same phenomenon of one event triggering others in a uni-directional fashion. We use these terms interchangeably but title them 'spillover effects' for clarity.

The 'spillover effects' of natural hazards is an emerging field of research that has come out of the increasing complexity of functional networks that can create large-scale disruptions in the event of disaster (Pescaroli and Alexander, 2016). Simpson et al (2021, p.491) highlight those cascading interrelations "can be one way (e.g., domino or contagion effects) but can also have feedbacks; cascading risk is often associated with the vulnerability component of risk, such as critical infrastructure". Here, criticality is defined as the contribution of the infrastructure to the society in maintaining the minimum quality level of vital societal functions, health, safety, security, economic or social well-being of people (Theoharidou et al., 2010, p. 463).

A spillover effect starts with a primary 'trigger' or 'failure point', which 'sets off' a multitude of domino effects. Spillover effects can be linear with a single cause and multiple, stepwise effects, or can be non-linear, with certain effects triggering a new 'secondary' cause and a new line of cascades (see

Figure 2-5) (Pescaroli & Alexander, 2018). Additionally, Pescaroli and Alexander (2016) have described an escalation point as a critical juncture in cascades at which the interaction of vulnerabilities and the concatenation of influences lead to a bigger impact than mere reaction to the primary factor/failure would suggest. Spillover effects should therefore be understood as dynamic in nature, multi-dimensional and are constantly evolving based on new effects and responses.

Spillover effects also often result in spatially distant impacts due to domino triggering effects. The potential for spillover risk increases when going from local to global, for example in the case of a critical infrastructure disruption at a major global port which has the potential to have widespread economic implications (Verschuur et al, 2022). Carter et al (2021) have highlighted that there are different types of possible cascades, such as an ‘escalating cascade’, ‘diminishing cascade’ and ‘feedback cascade’. An escalating cascade can occur in a supply chain where a rise in price provokes an overreaction such as stockpiling or market intervention that drives up the price of that commodity even further. Therefore, considering the type of spillover is also useful in determining multi-risk.

Helbing (2013) further comments that three aspects should be considered in understanding cascading or spillover effects, those being the interactions in the system, the context, and a triggering effect. As shown in Figure 2-6, two hazards occurring at the same time can cause multiple ‘triggers’ which trigger more chains of impact, and result in a broader impact. Spillover impacts are therefore a result of interplay between hazards, risks, and vulnerabilities, and it has been suggested that a paradigm shift in preparedness could look further at escalation points and critical infrastructure trigger points to strengthen societies against cascading risk (Pescaroli and Alexander, 2018).

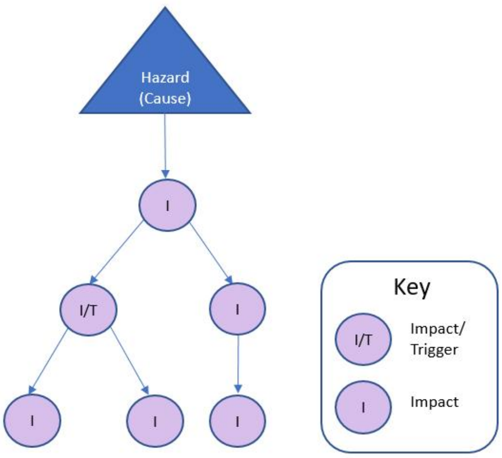


Figure 2-5: Diagram of spillover effects from a single hazard highlighting chains of trigger and impact. I/T is used where the impact also becomes a trigger for further impacts.

The cause is exchangeable with the ‘trigger’ for further effects, i.e. a tree falling on power lines, resulting in a disruption to power supply.

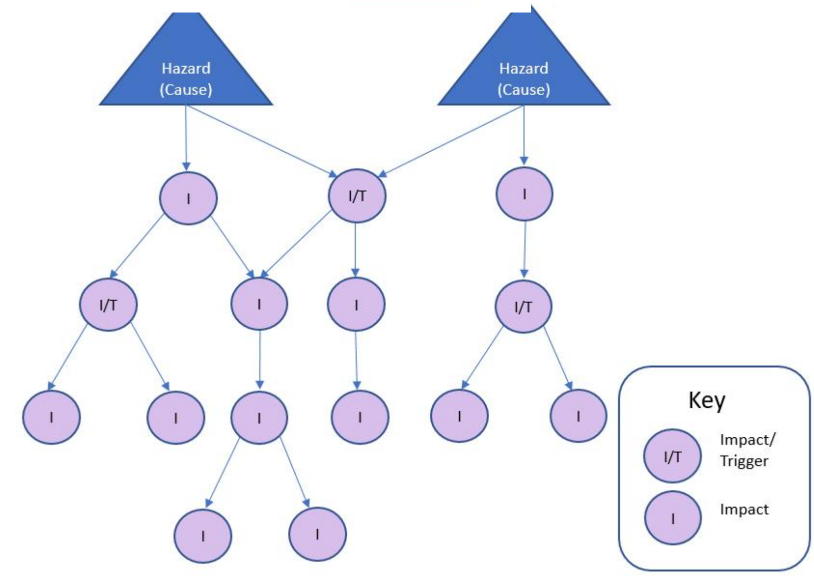


Figure 2-6: Example of spillover effects from a multi-hazard event where the two hazards interact causing more lines of spillover.

Spillover examples
Examples include IT and telecommunication system outages that (due to heavy reliance by modern-day services on these functions), have spillover impacts on a multitude of other functions, services, and sectors). A study has shown that the energy sector accounts for 60% of all cascades, with 28% originating in the telecommunication and Internet sectors, 5% from the transportation sector, and 3% in the water sector (Luiijf et al., 2009, p. 305). This type of interdependence is becoming increasingly common as society relies further on electricity and IT for the running of critical infrastructure and services (Reed et al, 2022).

An example in the context of a natural hazard event includes the Eyjafjallajokull volcano in April 2010 which affected civil aviation, leading to effects on business and travel, tourism, and food trade across Europe (Pescaroli and Alexander, 2018). Hurricane Harvey in 2017 on the other hand caused flooding evacuations, power outages, spread dangerous pathogens from overrun wastewater treatment plants, and shut down ¼ US oil production in the Gulf of Mexico raising petrol prices (Sneed, 2018). As producers in modern economies are strongly interconnected, initially localized production shortfalls can ripple through upstream supply chain networks and affect national economies.

2.4.2.2 Co-dependent risks

Co-dependent risks are mutually dependent functions leading to a 'canceling out' of both if one is negatively impacted. This occurs where sectors are mutually reliant on one another to complete their function. An example would be where water is needed to cool power stations to generate electricity, but energy is needed to pump water through the distribution infrastructure (Dawson, 2015). In this case the functionality of both is co-dependent, and therefore when one capacity is damaged, the other is also unable to operate. It is necessary to identify these relationships as they embody a particularly vulnerable point in the system, which if prevented, could prevent further cascading impacts because of two elements failing at the same time.

Co-dependent example
An example of co-dependent risk is often featured in water and electricity systems, which are often highly interlinked and mutually reliant. However, vulnerabilities and adaptations within the water-energy system are often studied in isolation without considering how risks might interlink with one another (Szinai et al., 2020). This is an issue for regions such as California where the energy sector demands of water sector climate adaptations could significantly impact California's future electricity needs (Szinai et al., 2020). For example, in an extreme drought and water shortage event, water conserving adaptation measures can provide large energy saving-co benefits, however, energy-intensive water adaptations could double impacts on California's electricity sector by the end of the century (Szinai et al., 2020). Cross-sectoral planning between the water and energy sectors can ensure reliable service in both sectors and improve resilience between water and electricity systems worldwide (Szinai et al., 2020).

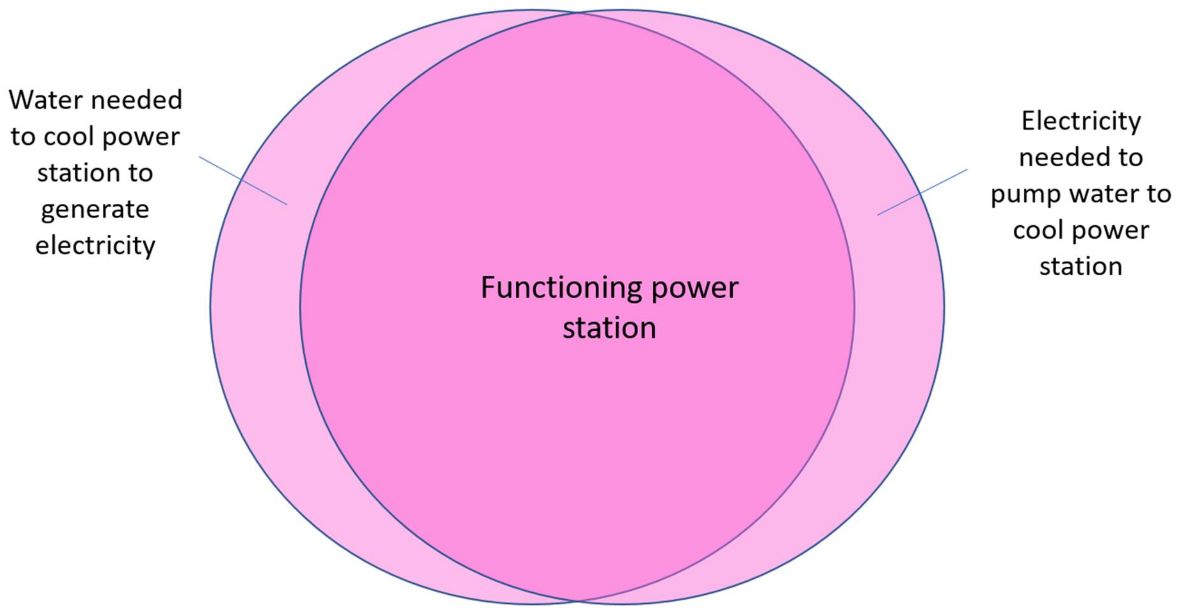


Figure 2-7: Diagram of co-dependent multi-sector risk typology,

The figure highlights the example of a co-dependent relationship as seen in water-electricity networks in power stations. The rings are closely overlapping to demonstrate that the functionality of one depends on the functionality of the other.

2.4.2.3 Intersecting

Intersecting risk types represents all inter-sectoral risks that are the result of risks that interact or are bidirectional in some way (i.e. not unidirectional as in spill-over effects, and do not 'cancel out', as in co-dependent). It differs from co-dependent interactions as two or more risks need to be present. There are two types, *interacting* and *independent.*

2.4.2.3.1 Interacting Intersecting

Interacting intersecting risks are bidirectional and result from the intersection of two or more different risks (Figure 2-8). Many examples of this can be seen during the COVID-19 pandemic that collides with other social or environmental shocks, leading to increased compound hazards (Kruczkiewicz et al., 2021). Interacting risk can therefore be thought of as the intersection of different risks, to create an effect that is greater than their sum. For example, the combination of drought and the COVID-19 pandemic creates an amplified impact on food supply, as droughts reduce crop yields and farm revenues and COVID-19 disrupts food distribution (Mishra et al., 2021). The post-disaster processes and disaster context can also compound losses, for example in the Indian Island communities of Andaman and Nicobar after the Indian Ocean Tsunami. Here, response efforts were too late and slow, and were also designed by experts from abroad and thus not well adapted to the local context (Gupta and Sharma, 2006). This highlights that interacting response factors are also able to exacerbate resulting risk in a disaster context.

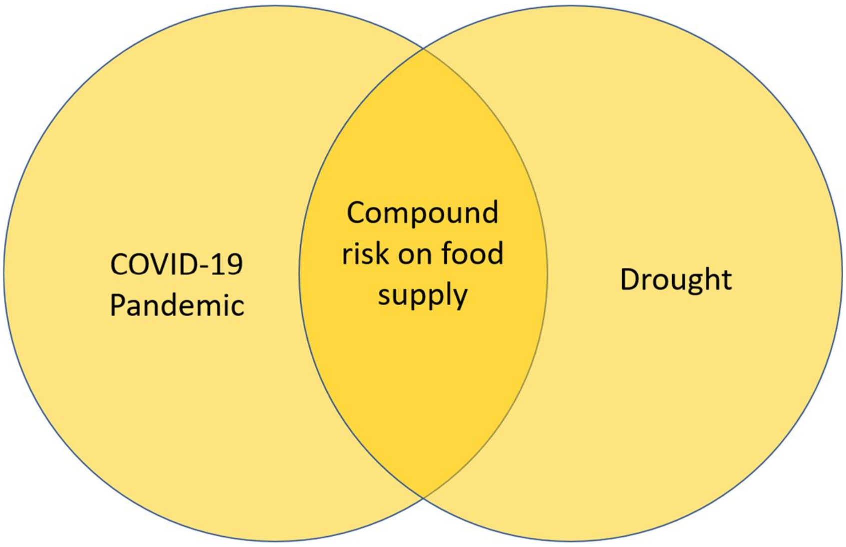


Figure 2-8: The interacting factors of a drought and the COVID-19 pandemic

The figure illustrated the compound risk on food supply due to the travel restrictions due to COVID-19 and additional crop yield reduction due to drought.

2.4.2.3.2 Independent Intersecting

Independent intersecting risks are those that result from an aggregation of multiple different impacts that when added together, have impacts that converge to create an accumulated risk elsewhere. Simpson et al (2021, 491) names this aggregated risk as "The accumulation of independent determinants of risk". An example would involve two separate impacts that converge to create a disruption elsewhere. For example, a disruption to transport services and lack of power supply can result in a disruption to healthcare services, as nurses and doctors are unable to go to work and healthcare machinery will not function. Whilst a disruption to transport and a lack of power supply might be two separate risks, the occurrence of both together can create an entirely separate risk in a different sector. Neither disruption to transport nor lack of power supply interlink to exacerbate risk, yet added together, they create significant risk to the functioning of another sector (Figure 2-9).

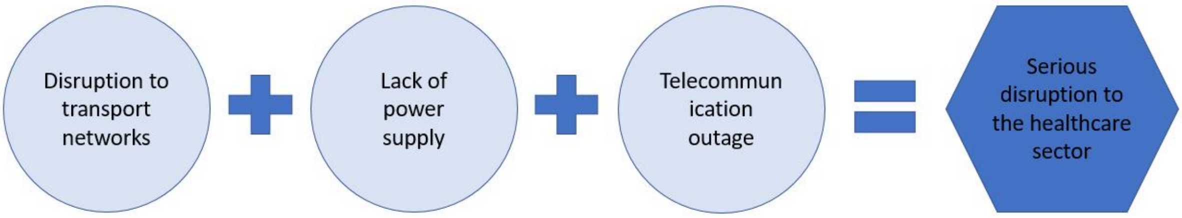


Figure 2-9: Independent intersecting risk whereby three separate sectoral risks aggregate to create an exacerbated impact in a separate sector.

The combination of disruption to transport, lack of power supply and telecommunication outage, results in nurses being unable to get to work, healthcare machinery not working and inability of operating systems to function.

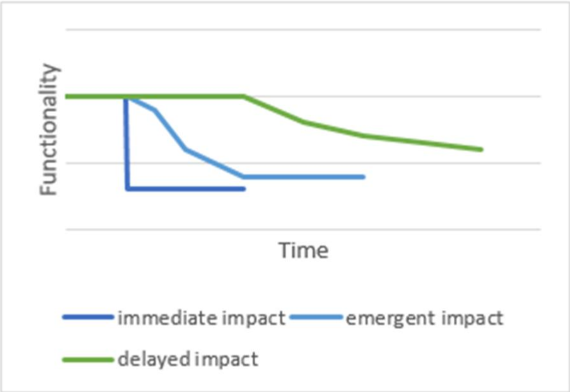
2.4.3 Other drivers of multi-sector impact interrelations

There are other factors that need to be considered when thinking about systemic, multi-sector risk, and its impacts, and these include the temporality of the impact and the scale of impact.

2.4.3.1 Importance of temporality

Considering the temporality of cross-sectoral risk is vital, as some impacts directly follow the hazard whilst others create an increased risk over time, requiring different disaster risk management strategies. Temporality can have relevance for multi-risk considerations in terms of time until first impact, maximum impact, duration of impact and duration of recovery (De Angeli et al., 2022). Depending on when multiple impacts or indirect effects occur relative to the current state of previous impacts, resulting damages could be different depending on the type of interrelation. To be able to distinguish and understand the temporality of the complex impact interactions, we propose the use of three categories defined as immediate, emergent, and delayed impacts.

The following Figure 2-10 attempts to visualize the relationship between the temporal dimension of disaster impacts and service functionality over time. The first figure shows that an immediate impact is likely to be a result of direct damage from the hazard, and thus reduces functionality of the service/product fully (as in the case of destruction of critical infrastructure). Delayed impacts on the other hand, can happen years after the hazard event and thus have a less severe impact on functionality, yet can make the system more vulnerable to future events (de Ruiter et al., 2020).



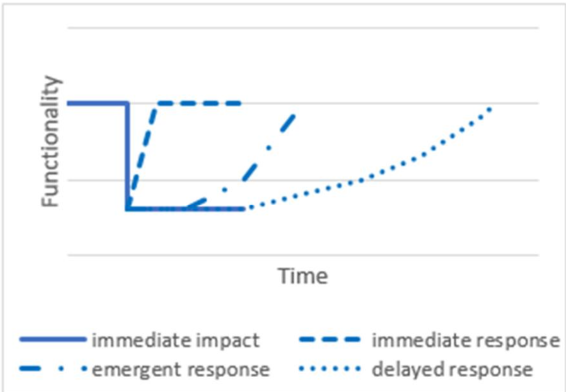


Figure 2-10: The relationship between functionality and time at different hazard impact timelines (immediate, emergent and delated) (left) and response time (immediate, emergent and delayed) (right).

Immediate: Immediate impacts are those arising directly following the hazard (seconds, minutes, hours). An example would involve damage to a road, or damage to telecommunication lines in the event of a storm. These immediate impacts are usually a direct result of the hazard itself.

Emergent: Arising over time through the combination of complex interactions and resulting actions (days and weeks). An example would include rising fuel prices. Whilst fuel prices would not rise hours after a storm, it takes days for fuel supply to run low and this to affect financial markets.

Delayed: Delayed impacts are defined as those that increase risk in the long-term (years). An example would be the erosion of topsoil in the event of a flash flood, reducing the ability of plant growth, eroding the topsoil, increasing surface runoff in future storm events. Delayed risk may not be apparent in the post-disaster impact and recovery assessments but create more vulnerability and therefore risk in future hazard events.

2.4.3.2 Importance of scales

Scales of impacts can be local, regional, national and cross-border (Carter et al, 2021), but can also be multi-regional or multi-local. Scale plays a role in temporality, as the more widespread effects in general are less immediate. Having said this, there are tightly coupled systems, such as financial markets, in which the time between local impact and global impact is very short. Scale of impact is therefore likely to be highest in spillover impacts as changes in the system trigger more widespread impacts elsewhere. Hazard impact studies tend to confine their attention to impacts within the same region. However, this approach ignores cross-border climate impacts (Carter et al., 2021). Cross-border climate impacts can be defined as consequences of hazard events that occur remotely from their initial impact, requiring a response from that impacted region (Carter et al., 2021). Both international and domestic factors influence transboundary and trans-sector climate risk transmission (Figure 2-11).

The cross-border impacts of the 2011 Thailand 158-day flooding event involved enormous economic losses in the automobile and electronic industries, due to inundation of plants supplying key components (Carter et al., 2021). Therefore, hazards at critical nodes in supply chains lead to impacts that go far beyond the borders of the country of origin. It is imperative therefore that resilience is built into these nodes, such that cross-border impacts are reduced. A device for exploring the possible examples or frameworks could be through the analysis of climate event storylines. This would involve mapping complex cross-border impacts that have been observed before now, and projecting what could happen in the future.

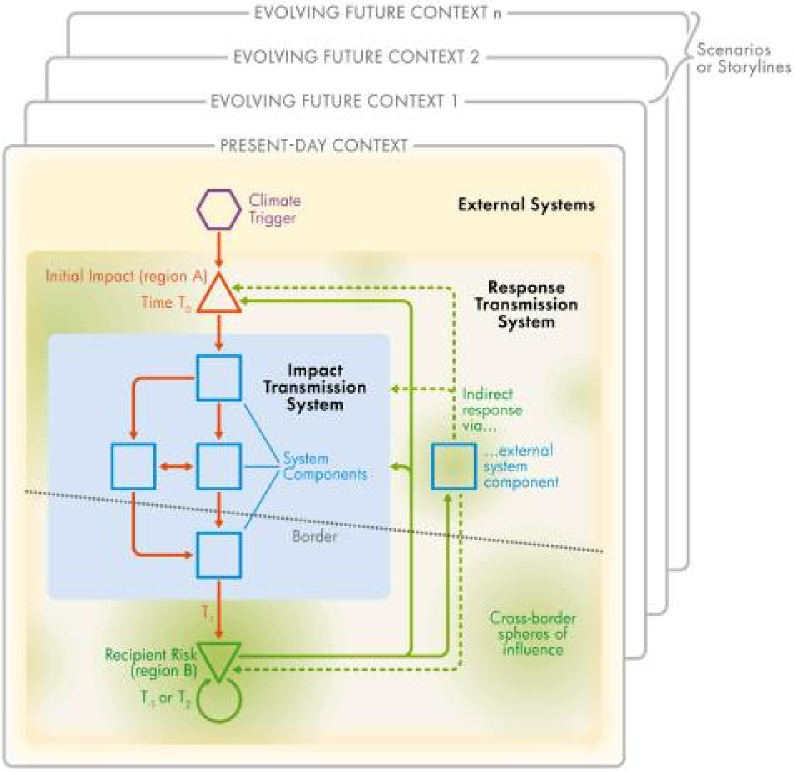


Figure 2-11: Conceptual framework for transmission of cross-border impacts and responses.

An initial impact in one region due to a climate risk is propagated (red arrows) via an impact transmission system (blue area) comprising impacts on interconnected system components, resulting in a recipient risk in a second region (location of the border is not national). Source: Carter et al. (2021) CC BY 4.0

2.5 Discussion

2.5.1 Overview of multi-sector risk typologies

Despite the four types of risk typologies having their own definition, in practice, they often can occur together. Figure 2-12 below presents a conceptual overview of the different risk typologies and dimensions that should be considered when thinking about multi-sector risk. The diagram is illustrative of one possible system experiencing all four risk typologies in the event of a hazard. In reality, the risk types and possible impacts experienced would change entirely based on the hazard(s) and system context. For example, a second hazard may create new lines of spillover impacts, and thus impact more sectors as shown in Figure 2-13.

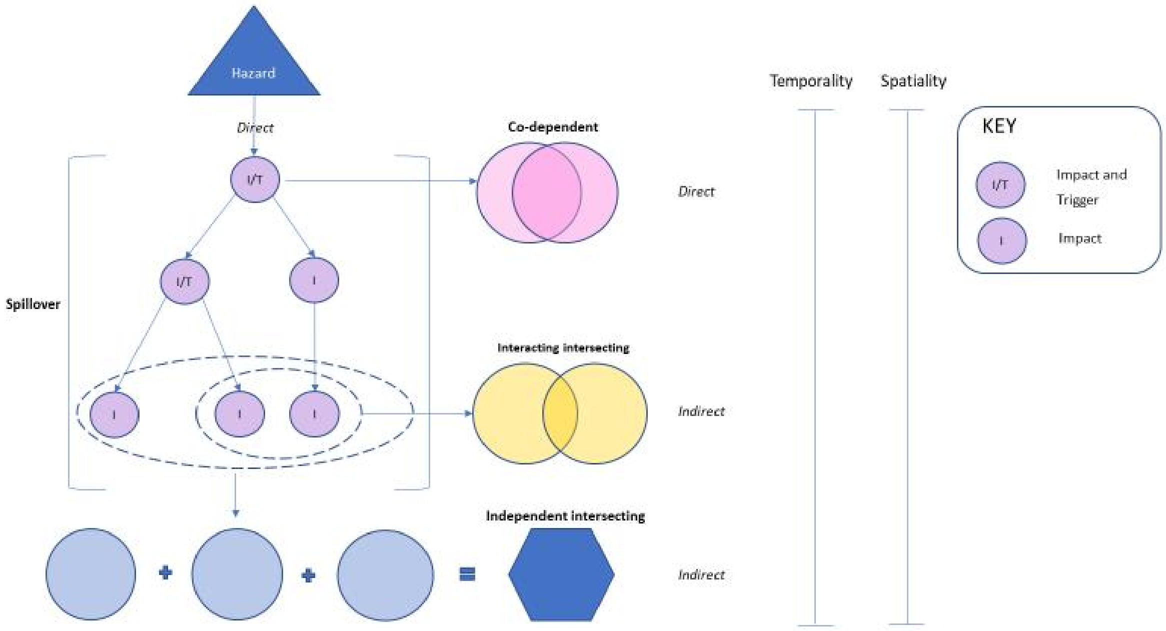


Figure 2-12: Illustrative conceptualization of the 4 risk typologies and other dimensions influencing impact interrelations.

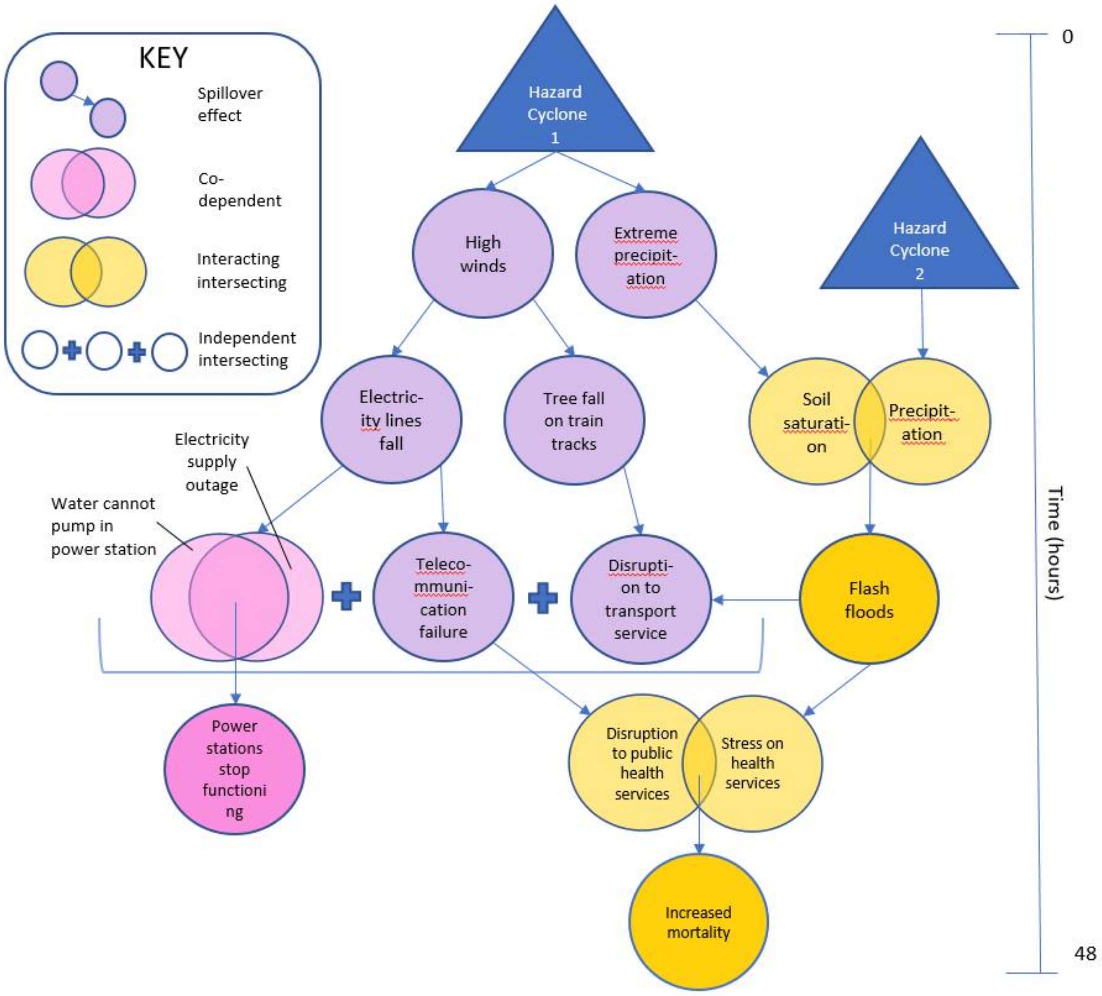


Figure 2-13: A worked example of a multi-hazard scenario (2 cyclones one after another), including spillover, co-dependent, independent intersecting and interacting intersecting risk typology types.

2.5.2 Relation between multi-hazard impact interrelations & inter-sectoral interrelations

The following Table 2-2 represents a qualitative assessment of a possible way in which inter-sectoral interdependence types are interconnected with typologies of inter-sectoral risk. It assesses the relevance between the interdependence types and risk typologies using the scale, low, medium and high. This will be followed by a discussion of the table, explaining the interlinkages between type of interdependence and risk typology. As such this section presents a set of attributes a sector should evaluate when assessing risks involved with their systems. Sector stakeholders will then be able to better categorize the main types of risk that a sector may be facing and attributes that sectors should consider when assessing risk.

Table 2-2: Comparison of the relevance of sector interaction drivers with multi-risk typologies.

The relationships are classed by relevance; high (+++, dark purple), medium (++, medium purple), low (+, light purple), uncertain (?) and none (empty cell). High relevance implies that the risk typology (i.e. spillover, co-dependent, interacting intersecting and independent intersecting) are highly interlinked with the interdependence driver.

	Functional	Spatial	Financial	Societal
Spillover	+++	++	+++	+
Co-dependent	+++	++	+	?
Interacting intersecting	+	+	+	++
Independent intersecting	+		+	?

As shown in Table 2-2, and by use of examples, the typologies of risk can be explained to some degree by the type of inter-sectoral dependence. Spillover effects and co-dependent relationships are more likely to be a result of functional and/or spatial interdependencies between sectors due to the nature of their risk type being a result of a direct trigger or cause (Pescaroli and Alexander, 2016; Simpson et al, 2021, Carter et al, 2021). A spill-over effect is often started by failure of critical infrastructure, which by its nature has domino effects elsewhere. Similarly, co-dependent risk typologies are almost exclusively related to functional interdependencies as these risks occur where one relies on the functionality of another. Therefore, spillover and co-dependent risk typologies are triggered by direct impacts, i.e., a direct result of the physical effects of the natural hazards, whereas interacting intersecting and independent intersecting tend to be a result of indirect impacts and emerge in the longer-term. It is often the case therefore that multi-sector risk starts with a direct impact, i.e., the start of a spill-over effect or co-dependent risk type and transforms into an intersecting risk type as more impacts overlap and compound (see Figure 2-12).

Considering that many widespread sectoral impacts emerge from functional relationships between critical infrastructure for multiple sectors, it is therefore vital for a sector to understand what are the likely direct or triggering impacts that it may experience in a hazard event, and how these can propagate into larger risks. Spillover and co-dependent relationships result from clear vulnerabilities in the system, due to high levels of dependency on certain functions. It is therefore important to review the critical infrastructure that a sector relies on to function and assess the vulnerability of that infrastructure to disruption. By reducing the reliance on one type of function, or ensuring 'backup' options, the sector will become more resilient to most types of inter-sectoral risk.

Due to the financialization of sectors, the financial interdependence channel will always have some relevance in determining risk typologies (Table 2-2). However, financial interdependencies are most related to spillover effects due to the extreme interconnectedness of the global financial system (Allegret et al 2015; Verschuur et al, 2022). The impacts of these can be immediate, in the case of stock prices dropping after an extreme hazard event, or take longer, through a decline in economic growth as seen in the COVID-19 pandemic. Conversely, co-dependent risk typologies are less directly related to financial interdependencies because it is rare that one sector is entirely co-dependent on another sector for its functioning and financial position, due to the complexity of the financial system. Whilst adapting financial interdependencies is very difficult given the complexity of the global financial system, sectors can think about the sectors that they have significant financial connections with, and also review their reliance on price volatile commodities such as oil. An understanding of these financial ties will allow better awareness and preparedness in the event of a disaster.

Societal impact is relevant to all risk categories because it relates to the ability of a society to plan for, respond to, and recover from the different types of risk. To account for societal interdependence between sectors across all types of risk, a focus on contingency planning and adaptive capacity building is needed. This does not vary significantly according to the type of risk typology however, for spillover and co-dependent risk, this needs to be in the form of emergency response, and for intersecting risks, in the form of longer-term planning. It is more applicable to the effects of intersecting risk types, as whereas spillover and co-dependent risk types are more related to short term functional vulnerabilities as a direct impact of a hazard, intersecting risk types often emerge from vulnerabilities on a societal level. Utilizing methods such as dynamic adaptive pathways (DAPP) can help to overcome the inherent unpredictability and uncertainty related to multi-hazard, multi-sector risk. By looking at possible scenarios and planning for different possible spillover effects or intersecting risks, sectors can be prepared to react to dynamic systems quickly (Lawrence & Haasnoot, 2017).

Table 2-2 shows that the relevance between risk drivers and multi-risk typologies is higher for functional and spatial drivers and less strong for interacting intersecting and independent intersecting. However, it is possible that the reason for this is related to the fact that functional and spatial drivers are more observable and co-dependent and spillover effects are more immediate. Conversely, financial and societal drivers are more challenging to observe, and interacting risk types tend to be more delayed and a result of multiple impacts and contexts. There is no link between spatial and independent intersecting because independent intersecting risk results from separate risks coming together in one sector (at the same time) and is not influenced by physical proximation. These findings highlight that more research is needed on sectoral interactions, specifically for intersecting (indirect) impacts, to better understand the relationships between drivers and risk typologies.

Whilst Table 2-2 presents an overview of relevance between risk drivers and risk typologies, there are limitations to the usefulness of this table for actionable risk management strategies. As such the section below aims to facilitate sector stakeholders understanding of their sector-system and the types of risk that they might be most exposed to.

2.5.3 Guiding questions to investigate multi-sector risk

Whilst this report attempts to address the typologies of inter-sectoral risk, it is vital to recognize that every disaster context will involve different systems, thus every hazard event will have a unique set of impacts, and each sector will have its own unique system of interdependencies. Therefore, the following table (Table 2-3) aims to ask questions that will help sectoral actors understand the relevant interdependency drivers and multi-risk typologies that are most relevant to them and their hazard context.

In asking these questions, sector stakeholders will identify, for example, what pieces of critical infrastructure or services it relies most heavily on, and how impacted its own services would be if these failed. Looking at its spatial interdependencies will encourage assessment of the vulnerability context of its infrastructure, and the hazard environment in which it is located. In doing so, they will be more easily able to understand their system and links with other sectoral systems, informing better DRM strategies. However, it must be kept in mind that implementing a multi-sector risk investigation method such as the one above (Table 2-3), would produce answers that represent participants' understanding of reality rather than reality itself (Menk et al., 2022). Having said this, the involvement of stakeholders in risk management results in increased understanding of the system and adaptation measures to be actioned. Furthermore, engaging diverse stakeholders will enable the exploration of synergies of knowledge, experience and data between sectors, which is currently severely lacking (Menk et al., 2022).

It is another question however, to understand who should have responsibility for compounding impacts. Should sectors be aware of the risks that will affect them or also risks that they can propagate onto other sectors? This is a challenging question, but the following Table 2-3 assumes that sectors are mainly interested in understanding the impacts that they will experience, but also challenges thinking regarding the types of impacts that might result from an impact in their own sector. Ultimately, a multi-sector approach to governance will bridge this problem of responsibility through the understanding that all sectors have much to gain, if they work together (Onyango et al, 2020).

	Functional	Spatial	Financial	Societal
Spillover	How reliant are my services/machinery on specific critical infrastructure? If a particular piece of this infrastructure stopped functioning, how affected would my system's functionality be?	How close is my infrastructure to a potential hazard? How proximate is my infrastructure to other infrastructure that could inflict damage in a hazard event? What other sectors or stakeholders are likely exposed to the same impacts and therefore might be willing partners to cooperate regarding risk reduction measures?	How interlinked is my sector with the global financial markets? How sensitive is my sector's financial position to oil price changes? Are fixed prices built into my supply chain contracts to buffer cascading impacts of price spikes? (Carter et al, 2021). How likely are consumers to panic buy products in my sector?	What potential regions might a failure in my sector reach? What actors would be particularly affected and in what capacities? In what ways does my disaster risk planning account for potential spill-over effects? Is disaster planning adaptable and able to deal with dynamic hazards? i.e., does it use dynamic adaptive pathways?
Co-dependent	Are my services highly coupled with other systems, whereby they are mutually dependent on each other's functionality?	Are there proximate system services which are highly inter-dependent with each other, which if fail, could threaten the functioning of the system?	Are the financial systems of my sector highly coupled with financial wellbeing of another, such that if one experiences financial shock, so would mine? With which sectors are mine tightly coupled to?	Are there particular groups that are co-dependent for disaster management?
Interacting Intersecting	Does my sector rely on multiple functions that on failure, intersect to compound the overall impact?	Are there sectors operating in the same location and what are their interacting aspects? What is the geographical area that could be affected by an incident and are there cross-border impacts?	How far does my sector interact with others financially?	What adaptive capacity is there at the interaction location? Do we have contingency plans for long-term compounding hazards?
Independent intersecting	What sectors do we rely on in terms of their functionality, for ours to also function? (i.e., Do we depend on transport service functionality for our services?)	What is the geographical area that could be affected by an incident and what independent sectors could be impacted?	What potential impacts in other sectors, when combined could impact the financial security of our sector?	What is the adaptive capacity to deal with risks that occur together? Do we have contingency plans for the long-term effects of natural hazards?

Table 2-3: Table of questions to facilitate investigation of the most relevant drivers of sectoral interdependencies and risk typologies to a sector

2.6 Conclusion

Current single-sector approaches to risk management and linear thinking about impacts, does not account for all potential hazard damage, leading to DRM policies that may not be fully effective in reducing disaster losses. There is a need to take a systems-thinking and MSD approach to better understand systemic risk. However, bar some literature on the role of critical infrastructure in inter-sectoral systems, there is limited research regarding sectoral interactions or types of multi-sector risk. Taking a multi-risk approach which involves looking at sectoral interactions will aid the comprehension of the complexity, temporality, and scales of effective risk.

Understanding sectoral interdependence types and looking at the dynamics of risk playing out in hazard events, we can better understand multi-sector risk typologies. Looking at sectoral dependence types in combination with inter-sectoral risk highlights that there are certain 'channels' through which certain types of risk typologies move. Four main interdependence drivers were found, those being, *functional, spatial, financial, and societal* and four multi-sector risk typologies can occur: *spillover, co-dependent, interacting intersecting, independent intersecting.* The multi-sector risk typologies are to some extent related to the interdependence drivers, for instance, spillover effects are caused by a trigger or failure point in critical infrastructure (functional), but often transform into much broader economic spillover impacts (financial).

Defining typologies is a useful approach for sectors to understand the types of interactions and potential risks that they might be involved in, simplify what is an otherwise very complex system and help to encourage system-based response.

2.6.1 Recommendations

Given the role of functionality relationships in multi-sector risk it is recommended that sectors gauge a fuller understanding of their function failure points and integrate operational thresholds and uncertainties into decision making to reduce spillover effects. Further to this, assessment needs to be widened to not only consider 'domino effects' but also intersecting risks, which can combine to cause exacerbated risk in the long-term. DRM planning therefore needs to think not only about immediate impacts and shorter-term solutions, but also impacts in the long-term. DRM strategies should also be adaptable and dynamic as the trajectory of spillover effects for example, are highly unpredictable.

Additionally, further attention should be brought to the local societal context, and its adaptive capacity to shocks. Previous research has shown that local governance systems and participatory response processes are the only way that vulnerable communities can mitigate and recover quickly from shocks (Gupta and Sharma, 2006). It is further possible that as infrastructure and sectors become more connected, more inter-sectoral governance structures will be needed. With better management there is potential for inter-sectoral management to encourage synergies rather than an increase in risk.

2.6.2 Limitations

It is recognized that interaction strength, spatial scale, and the local socio-economic context are all factors that need to be considered to fully address sectoral interdependence in terms of risk assessment and management. Such detailed and locally specific conditions cannot be addressed by a report such as this, however, the stakeholder question Table 2-3 presents a method by which these more sector/ stakeholder specific risks could be identified. It is recommended that this report is used by sectors to understand what types of interdependency drivers and risk typologies apply to them and use these findings to concentrate further investigation into contextually specific risk research.

2.6.3 Future research

There has been a previous lack of consideration of the scale of sectoral interactions, and the extent to which hazard events can create risk elsewhere. Therefore, future research should aim to model the scale of different types of interactions further. One way to do this would be to create hazard impact storylines (Shepherd et al., 2018), which would involve looking at past events and analyzing their impact. Additionally, the temporality and spatial scales of impact and the ways in which this can vary based on the typology of risk and the relevant sectors needs to be further investigated.

Additionally, risk reduction and adaptation responses that deal with multi-sector risk have the capacity to have both positive and adverse consequences, and future efforts should be aware of possible trade-offs and co-benefits with other sectors (Simpson et al, 2021). For example, urban greening reduces the need for air conditioning, which in turn reduces the need for energy generation and GHG emissions (Simpson et al, 2021). Therefore, system dynamics and interactions between sectors should be considered in adaptation responses as well as in risk mitigation.

Finally, to deal with such multi-hazard, multi-sector complexity in DRM, a multi-stakeholder approach will be required to mitigate against systemic risk (Booth et al., 2020). However, there is currently an implementation gap between discussions surrounding a multi-hazard, multi-sector approach because of institutional barriers, political barriers, inter-sectoral misperceptions, and unequal funding (Booth et al., 2020). Strengthening inter-sectoral knowledge generation will better inform mitigation planning and further research should explore ways to effectively integrate sectors and sector stakeholders in DRM.

2.7 References

About ISIMIP. (2022). ISIMP. https://www.isimip.org/about/

Ali, T., Paton, D., Buergelt, P. T., Smith, J. A., Jehan, N., & Siddique, A. (2021). Integrating Indigenous perspectives and community-based disaster risk reduction: A pathway for sustainable Indigenous development in Northern Pakistan. International Journal of Disaster Risk Reduction, 59, 102263. https://doi.org/10.1016/j.ijdrr.2021.102263

Aljazeera, (2022) All crew evaculated after two ships collide off Dutch coast. Aljazeera. https://www.aljazeera.com/news/2022/1/31/evacuation-under-way-after-two-ships-collide-off-dutch-coast.

Allegret, J.-P., Mignon, V., & Sallenave, A. (2015). Oil price shocks and global imbalances: Lessons from a model with trade and financial interdependencies. Economic Modelling, 49, 232–247. https://doi.org/10.1016/j.econmod.2015.04.009

Bauerle Danzman, S., Winecoff, W. K., & Oatley, T. (2017). All Crises are Global: Capital Cycles in an Imbalanced International Political Economy. International Studies Quarterly, 61(4), 907–923. https://doi.org/10.1093/isq/sqx054

Booth, L., Schueller, L. A., Scolobig, A., & Marx, S. (2020). Stakeholder solutions for building interdisciplinary and international synergies between Climate Change Adaptation and Disaster Risk Reduction. International Journal of Disaster Risk Reduction, 46, 101616. https://doi.org/10.1016/j.ijdrr.2020.101616

British Geological Survey & MYRIAD-EU, (in preparation). Disaster Risk Gateway. H2020 MYRIAD-EU Project, grant agreement number 101003276

Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. Nature, 464(7291), 1025–1028. https://doi.org/10.1038/nature08932

Carter, T. R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., Reyer, C. P. O., & West, C. (2021). A conceptual framework for cross-border impacts of climate change. Global Environmental Change, 69, 102307. https://doi.org/10.1016/j.gloenvcha.2021.102307

Castle, C. J. E., & Crooks, A. T. (2006, September). Principles and Concepts of Agent-Based Modelling for Developing Geospatial Simulations (Working / Discussion Paper No. 110). (CASA Working Papers 110). Centre for Advanced Spatial Analysis (UCL), UCL (University College London), Centre for Advanced Spatial Analysis (UCL): London, UK. (2006); Centre for Advanced Spatial Analysis (UCL), UCL (University College London), Centre for Advanced Spatial Analysis (UCL). https://discovery.ucl.ac.uk/id/eprint/3342/

Cegan, J. C., Golan, M. S., Joyner, M. D., & Linkov, I. (2022). The importance of compounding threats to hurricane evacuation modeling. Npj Urban Sustainability, 2(1), 2. https://doi.org/10.1038/s42949-021-00045-7

Ciurean, R., Gill, J., Reeves, H. J., O'Grady, S., & Aldridge, T. (2018). Review of multi-hazards research and risk assessments [Publication - Report]. British Geological Survey. https://nora.nerc.ac.uk/id/eprint/524399/

Dawson, R. J. (2015). Handling Interdependencies in Climate Change Risk Assessment. Climate, 3(4), 1079–1096. https://doi.org/10.3390/cli3041079

De Angeli, S., Malamud, B. D., Rossi, L., Taylor, F. E., Trasforini, E., & Rudari, R. (2022). A multi-hazard framework for spatial-temporal impact analysis. International Journal of Disaster Risk Reduction, 73, 102829. https://doi.org/10.1016/j.ijdrr.2022.102829

de Ruiter, M. C., Couasnon, A., van den Homberg, M. J. C., Daniell, J. E., Gill, J. C., & Ward, P. J. (2020). Why We Can No Longer Ignore Consecutive Disasters. Earth's Future, 8(3), e2019EF001425. https://doi.org/10.1029/2019EF001425

de Ruiter, M. C., & van Loon, A. F. (2022). The challenges of dynamic vulnerability and how to assess it. IScience, 25(8), 104720. https://doi.org/10.1016/j.isci.2022.104720

Depellegrin, D., Hansen, H. S., Schrøder, L., Bergström, L., Romagnoni, G., Steenbeek, J., Gonçalves, M., Carneiro, G., Hammar, L., Pålsson, J., Crona, J. S., Hume, D., Kotta, J., Fetissov, M., Miloš, A., Kaitaranta, J., & Menegon, S. (2021). Current status, advancements and development needs of geospatial decision support tools for marine spatial planning in European seas. Ocean & Coastal Management, 209, 105644. https://doi.org/10.1016/j.ocecoaman.2021.105644

Duncan, M., Smale, L., Crummy, J., Ciurean, R., Napier, A., Chintham, S., Shelly, W., Gill, J., Schlumberger, J., Stuparu, D. ... (in preparation). D1.1 WIKI-style online platform of multi-hazard, multi-risk methods, models and tools. H2020 MYRIAD-EU Project, grant agreement number 101003276, pp XX.

Galbusera, L., Trucco, P., & Giannopoulos, G. (2020). Modeling interdependencies in multi-sectoral critical infrastructure systems: Evolving the DMCI approach. Reliability Engineering & System Safety, 203, 107072. https://doi.org/10.1016/j.ress.2020.107072

Gaupp, F. (2020). Extreme Events in a Globalized Food System. One Earth, 2(6), 518–521. https://doi.org/10.1016/j.oneear.2020.06.001

Gill, J. C., & Malamud, B. D. (2014). Reviewing and visualizing the interactions of natural hazards. Reviews of Geophysics, 52(4), 680–722. https://doi.org/10.1002/2013RG000445

Gill, J., Duncan, M., Ciurean, R., Smale, L., Stuparu, D., Schlumberger, J, de Ruiter M., Tiggeloven, T., Torresan, S., Gottardo, S., Mysiak, J., Harris, R., Petrescu, E. C., Girard, T., Khazai, B., Claassen, J., Dai, R., Champion, A., Daloz, A. S., ... Ward, P. 2022. MYRIAD-EU D1.2 Handbook of Multi-hazard, Multi-Risk Definitions and Concepts. H2020 MYRIAD-EU Project, grant agreement number 101003276, pp 82.

Gupta, M., & Sharma, A. (2006). Compounded loss: The post tsunami recovery experience of Indian island communities. Disaster Prevention and Management: An International Journal, 15(1), 67–78. https://doi.org/10.1108/09653560610654248

Haraguchi, M., & Kim, S. (2016). Critical infrastructure interdependence in New York City during Hurricane Sandy. International Journal of Disaster Resilience in the Built Environment, 7(2), 133–143. https://doi.org/10.1108/IJDRBE-03-2015-0015

Hazeleger, W., van den Hurk, B. J. J. M., Min, E., van Oldenborgh, G. J., Petersen, A. C., Stainforth, D. A., Vasileiadou, E., & Smith, L. A. (2015). Tales of future weather. Nature Climate Change, 5(2), 107–113. https://doi.org/10.1038/nclimate2450

Helbing, D. (2013). Globally networked risks and how to respond. Nature, 497(7447), 51–59.

Hochrainer-Stigler, S., Colon, C., Boza, G., Poledna, S., Rovenskaya, E., & Dieckmann, U. (2020). Enhancing resilience of systems to individual and systemic risk: Steps toward an integrative framework. International Journal of Disaster Risk Reduction, 51, 101868. https://doi.org/10.1016/j.ijdrr.2020.101868

Inoue, H., & Todo, Y. (2020). The propagation of economic impacts through supply chains: The case of a mega-city lockdown to prevent the spread of COVID-19. PLOS ONE, 15(9), e0239251. https://doi.org/10.1371/journal.pone.0239251

Kachali, H., Storsjö, I., Haavisto, I., & Kovács, G. (2018). Inter-sectoral preparedness and mitigation for networked risks and cascading effects. International Journal of Disaster Risk Reduction, 30, 281–291. https://doi.org/10.1016/j.ijdrr.2018.01.029

Khazai, B., Merz, M., Schulz, C., & Borst, D. (2013). An integrated indicator framework for spatial assessment of industrial and social vulnerability to indirect disaster losses. Natural Hazards, 67(2), 145–167. https://doi.org/10.1007/s11069-013-0551-z

Klein, J., & van Vliet, H. (2013). A systematic review of system-of-systems architecture research. Proceedings of the 9th International ACM Sigsoft Conference on Quality of Software Architectures - QoSA '13, 13. https://doi.org/10.1145/2465478.2465490

Korkali, M., Veneman, J. G., Tivnan, B. F., Bagrow, J. P., & Hines, P. D. H. (2017). Reducing Cascading Failure Risk by Increasing Infrastructure Network Interdependence. Scientific Reports, 7(1), 44499. https://doi.org/10.1038/srep44499

Kruczkiewicz, A., Klopp, J., Fisher, J., Mason, S., McClain, S., Sheekh, N. M., Moss, R., Parks, R. M., & Braneon, C. (2021). Compound risks and complex emergencies require new approaches to preparedness. Proceedings of the National Academy of Sciences, 118(19), e2106795118. https://doi.org/10.1073/pnas.2106795118

Laurien, F., Martin, J. G. C., & Mehryar, S. (2022). Climate and disaster resilience measurement: Persistent gaps in multiple hazards, methods, and practicability. Climate Risk Management, 100443. https://doi.org/10.1016/j.crm.2022.100443

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. Climate Risk Management, 29, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lawrence, J., & Haasnoot, M. (2017). What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. Environmental Science & Policy, 68, 47–57. https://doi.org/10.1016/j.envsci.2016.12.003

Leontief, W. (1986). Input-Output Economics. Oxford University Press.

Luiijf, E., Nieuwenhuijs, A., Klaver, M., van Eeten, M., & Cruz, E. (2009). Empirical Findings on Critical Infrastructure Dependencies in Europe. In R. Setola & S. Geretshuber (Eds.), Critical Information Infrastructure Security (pp. 302–310). Springer. https://doi.org/10.1007/978-3-642-03552-4_28

Maier, M. W. (1998). Architecting principles for systems-of-systems. Systems Engineering, 1(4), 267–284. https://doi.org/10.1002/(SICI)1520-6858(1998) 1:4<267::AID-SYS3>3.0.CO;2-D

Menk, L., Terzi, S., Zebisch, M., Rome, E., Lückerath, D., Milde, K., & Kienberger, S. (2022). Climate Change Impact Chains: A Review of Applications, Challenges, and Opportunities for Climate Risk and Vulnerability Assessments. Weather, Climate, and Society, 1(aop). https://doi.org/10.1175/WCAS-D-21-0014.1

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A. H., & Viavattene, C. (2013). Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps. Natural Hazards and Earth System Sciences, 13(5), 1351–1373. https://doi.org/10.5194/nhess-13-1351-2013

Mishra, A., Bruno, E., & Zilberman, D. (2021). Compound natural and human disasters: Managing drought and COVID-19 to sustain global agriculture and food sectors. Science of The Total Environment, 754, 142210. https://doi.org/10.1016/j.scitotenv.2020.142210

Onyango, V., Papaioannou, E., Schupp, M. F., Zaucha, J., Przedzymirska, J., Lukic, I., ... & van de Velde, I. (2020). Is demonstrating the concept of multi-use too soon for the North Sea? Barriers and opportunities from a stakeholder perspective. Coastal Management, 48(2), 77-95.

Pescaroli, G., & Alexander, D. (2016). Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. Natural Hazards, 82(1), 175–192. https://doi.org/10.1007/s11069-016-2186-3

Pescaroli, G., & Alexander, D. (2018). Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework. Risk Analysis, 38(11), 2245–2257. https://doi.org/10.1111/risa.13128

Rana, S., Kiminami, L., & Furuzawa, S. (2020). Analysis on the factors affecting farmers' performance in disaster risk management at community level: Focusing on a Haor locality in Bangladesh. Asia-Pacific Journal of Regional Science, 4(3), 737–757. https://doi.org/10.1007/s41685-020-00171-7

Reed, P. M., Hadjimichael, A., Moss, R. H., Brelsford, C., Burleyson, C. D., Cohen, S., Dyreson, A., Gold, D. F., Gupta, R. S., Keller, K., Konar, M., Monier, E., Morris, J., Srikrishnan, V., Voisin, N., & Yoon, J. (2022). Multisector Dynamics: Advancing the Science of Complex Adaptive Human-Earth Systems. Earth's Future, 10(3), e2021EF002621. https://doi.org/10.1029/2021EF002621

Rinaldi, S. M. (2004). Modeling and simulating critical infrastructures and their interdependencies. 37th Annual Hawaii International Conference on System Sciences, 2004. Proceedings of The, 8 pp.-. https://doi.org/10.1109/HICSS.2004.1265180

Rosato, V., Issacharoff, L., Tiriticco, F., Meloni, S., Porcellinis, S., & Setola, R. (2008). Modelling interdependent infrastructures using interacting dynamical models. IJCIS, 4, 63–79. https://doi.org/10.1504/IJCIS.2008.016092

Rosenzweig, C., Arnell, N. W., Ebi, K. L., Lotze-Campen, H., Raes, F., Rapley, C., Smith, M. S., Cramer, W., Frieler, K., Reyer, C. P. O., Schewe, J., Vuuren, D. van, & Warszawski, L. (2017). Assessing inter-sectoral climate change risks: The role of ISIMIP. Environmental Research Letters, 12(1), 010301. https://iopscience.iop.org/article/10.1088/1748-9326/12/1/0103011
Schipper, E. L. F. (2020). Maladaptation: When Adaptation to Climate Change Goes Very Wrong. One Earth, 3(4), 409–414. https://doi.org/10.1016/j.oneear.2020.09.014
Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., Reichstein, M., Ruane, A. C., Schweizer, P.-J., & Williams, S. (2022). ISC-UNDRR-RISK KAN Briefing note on systemic risk [Other]. International Science Council. https://doi.org/10.24948/2022.01
Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., … Trisos, C. H. (2021). A framework for complex climate change risk assessment. One Earth, 4(4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005
Sneed, A. (2018). The Next Climate Frontier: Predicting a Complex Domino Effect. Scientific American. https://www.scientificamerican.com/article/the-next-climate-frontier-predicting-a-complex-domino-effect/
Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. Journal of Business Research, 104, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039
Stergiopoulos, G., Kotzanikolaou, P., Theocharidou, M., Lykou, G., & Gritzalis, D. (2016). Time-based critical infrastructure dependency analysis for large-scale and cross-sectoral failures. International Journal of Critical Infrastructure Protection, 12, 46–60. https://doi.org/10.1016/j.ijcip.2015.12.002
Szinai, J. K., Deshmukh, R., Kammen, D. M., & Jones, A. D. (2020). Evaluating cross-sectoral impacts of climate change and adaptations on the energy-water nexus: A framework and California case study. Environmental Research Letters, 15(12), 124065. https://doi.org/10.1088/1748-9326/abc378
Theoharidou, M., Kotzanikolaou, P., & Gritzalis, D. (2010). A multi-layer Criticality Assessment methodology based on interdependencies. Computers & Security, 29(6), 643–658. https://doi.org/10.1016/j.cose.2010.02.003
UNDRR. (2015). Sendai Framework for Disaster Risk Reduction 2015-2030. UNDRR.
UNDRR (2016). Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. Terminology available at: https://www.undrr.org/terminology
Venkateswaran, K., & MacClune, K. (2020). Building the Evidence Base to Achieve the Sendai Framework for DRR Goals. In M. Yokomatsu & S. Hochrainer-Stigler (Eds.), Disaster Risk Reduction and Resilience (pp. 191–211). Springer. https://doi.org/10.1007/978-981-15-4320-3_10
Verschuur, J., Pant, R., Koks, E., & Hall, J. (2022). A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards. Maritime Economics & Logistics. https://doi.org/10.1057/s41278-021-00204-8
Wang, J., He, Z., & Weng, W. (2020). A review of the research into the relations between hazards in multi-hazard risk analysis. Natural Hazards, 104(3), 2003–2026. https://doi.org/10.1007/s11069-020-04259-3
Ward, P. J., Daniell, J., Duncan, M., Dunne, A., Hananel, C., Hochrainer-Stigler, S., Tijssen, A., Torresan, S., Ciurean, R., Gill, J. C., Sillmann, J., Couasnon, A., Koks, E., Padrón-Fumero, N., Tatman, S., Tronstad Lund, M., Adesiyun, A., Aerts, J. C. J. H., Alabaster, A., … de Ruiter, M. C. (2022). Invited perspectives: A research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment. Natural Hazards and Earth System Sciences, 22(4), 1487–1497. https://doi.org/10.5194/nhess-22-1487-2022
Wicki, A., Lehmann, P., Hauck, C., Seneviratne, S. I., Waldner, P., & Stähli, M. (2020). Assessing the potential of soil moisture measurements for regional landslide early

warning. Landslides, 17(8), 1881–1896. https://doi.org/10.1007/s10346-020-01400-y
Zhu, B., Lin, R., Deng, Y., Chen, P., & Chevallier, J. (2021). Intersectoral systemic risk spillovers between energy and agriculture under the financial and COVID-19 crises. Economic Modelling, 105, 105651. https://doi.org/10.1016/j.econmod.2021.105651
Zschau, J. (2017). 2.5 Where are we with multihazards, multirisks assessment capacities?

Appendix

A1 Appendix regarding Part 1

A1.a Considered Policies

Scope	Organisation	Name
regional	EU	EU Flood Directive (Directive 2007/60/EC)
regional	EU	EU Water Framework Directive (Directive 2000/60/EC)
regional	EU	EU Seveso III Directive (Directive 2012/18/EU) (involving dangerous substances)
regional	EU	EU Critical Infrastructure Directive (Directive 2008/114/EC)
regional	EU	EU Solidarity Fund (Council Regulation (EC) No 2012/2002)
regional	EU	EU strategy on adaptation to climate change (COM(2013)216)
regional	EU	Directive on serious cross-border threats to health (Decision No 1082/2013/EU)
regional	EU	Council Directive 2013/59/Euratom laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation
regional	EU	Council Directive 2014/87/EURATOM amending Directive 2009/71/Euratom establishing a Community framework for the nuclear safety of nuclear installations
regional	EU	EU Commission Notice – Reporting Guidelines on Disaster Risk Management, Art. 6(1)d of Decision No 1313/2013/EU
regional	EU	Commission Staff Working Paper - Risk Assessment and Mapping Guidelines for Disaster Management, SEC(2010) 1626 final, Brussels, 21 Dec 2010
regional	EU	Decision No 1313/2013/EU on a Union Civil Protection Mechanism (with ammendments: Decision (EU) 2019/420, Regulation (EU) 2021/836)

A1.b List of gray literature considered

Organisation	Title
Adaptation Committee (UNFCCC)	Synthesis report on how developing countries are addressing hazards, focusing on relevant lessons learned and good practices
American Society of Civil Engineers	Diverse
APRU (Association of Pacific Rim Universities)	Science & Technology in Disaster Risk Reduction in Asia 2018
APRU (Association of Pacific Rim Universities)	30 innovations for DRR
C40	How to conduct a climate change risk assessment
C40	How to strengthen climate governance for an effective climate action plan
C40	C40 Infrastructure Interdependencies and Climate Risks report
Climate Adapt	ICZM Database
DRMKC	Gaps explorer
ECHO	Overview of Natural and Man-made Disaster Risks the European Union May Face
FERMA	The European Risk Manager Profile 2020 – European Map and results per country

FERMA	The European Risk Manager Report 2020: key findings
FERMA	COVID-19: FERMA survey shows risk managers' contributions to response and resilience
FERMA	Our priorities for the EU Institutions – Manifesto 2019-2024
GAR 2019	United Nations International Strategy for Disaster Reduction (2019). Global Assessment Report on Disaster Risk Reduction (GAR)
GAR 2022	United Nations Office for Disaster Risk Reduction (2022). Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future. Geneva.
GFDRR	A Work Plan For The Global Facility For Disaster Reduction and Recovery 2016 – 2018
Global Center on Adaptation	Living with water: climate adaptation in the world's deltas
Global Center on Adaptation	Stocktake of Climate-resilient Infrastructure Standards
Global Center on Adaptation	Persistent Business Blind Spots on Climate Risk and Adaptation
Global Center on Adaptation	Adaptation Metrics Current Landscape and Evolving Practices
Global Center on Adaptation	Climate-Resilient Infrastructure Officer Handbook
Government Office for Science (UK)	Reducing Risks of Future Disasters Priorities for Decision Makers
Groupe Caisse Centrale de Reassurance (FR)	compensation scheme for natural disasters arising in France
IRGC	Involving Stakeholders in the Risk Governance Process
IRGC	IRGC guidelines for the governance of systemic risks
IRGC	Cricical infrastructure resilience – Lessons from insurance
IRGC	IRGC Risk Governance Framework
ISO	ISO 31000 Risk Management standard
ISO	ISO IEC 31010:2019 Risk management — Risk assessment techniques
ISO	ISO 31000:2018 Risk management. Guidelines
OECD	Assessing Global Progress in the Governance of Critical Risks
OECD	National Risk Assessments: a cross-country perspective
OECD	OECD Recommendation on the Governance of Critical Risks
OECD	Methodological Framework for Disaster Risk Assessment and Risk Financing
OECD	Recommendation of the Council on the Governance of Critical Risks
PIARC (World Road Association)	Evaluation of organizational approaches to risk
PIARC (World Road Association)	Methodologies and tools for risk assessment and management applied to road operations
PIARC (World Road Association)	Risks associated with natural disasters, climate change, man-made disasters and security threats
PIARC (World Road Association)	Project risk catalog

PIARC (World Road Association)	Increasing Resilience of Earth Structures to Natural Hazards
Review by the Royal Academy of Engineering (UK)	Safer Complex Systems strategy
Review by the Royal Academy of Engineering (UK)	Critical capabilities: strengthening UK resilience
UN-DESA	Sustainable development goals
UN-HABITAT	New Urban Agenda
UN-ISDR	Hyogo framework for action 2005–1015: Building the resilience of nations and communities to disasters
UNDRR	Recommendations for national risk assessment for disaster risk management in EU (2021)
UNDRR	Sendai Framework
WMO	2020 State of Climate Services: Risk Information and Early Warning Systems
WMO	WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services (WMO-No. 1150), Part II: Putting Multi-Hazard IBFWS into Practice
WMO	Multi-hazard Early Warning Systems: A Checklist : Outcome of the first Multi-hazard Early Warning Conference

A1.c Additional information regarding Interviews

Guiding Interview Question

WP1 Diagnosis, Task 1.3: Review of policies, policy-making processes, and governance for multi-hazard, multi-risk management

Work Package Lead: UKRI BGS **Work Package Co-Lead:** Deltares, **Email:** Dana.Stuparu@deltares.nl

Interviewee/ Organisation				
Background/Role				
Facilitation				
Date/Time		Recorded	Yes	No

Brief intro

The number of people affected by natural hazards is growing, as many regions of the world become subject to multiple hazards. Recent scientific evidence shows that decision-makers are increasingly facing the challenge of not only mitigating against single hazards and risks but also multiple risks, which must include the consideration of their interrelations. Traditionally, natural hazards and risks are separately managed; agencies, ministries or businesses often have funds, skills, and mandates to address risk and implement risk reduction measures for single hazards only. However, a joint understanding of multiple hazards, their impacts, and interactions may lead to a more efficient use of resources by identifying measures that reduce impacts across hazards.

In MYRIAD-EU (WP1, Task 1.1), an extensive review of multi-hazard, multi-risk concepts, definitions, and indicators showed that, while there are small differences between definitions of 'multi-hazard', they have in common that they all refer to the (threat of) the occurrence of more than one hazard. Some of these definitions explicitly include hazard interactions, account for varying spatial and/or temporal scales, or include the context in which multiple hazards take place. The definition proposed by the UNDRR (2017) appears to capture these different elements: "*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*."

The MYRIAD-EU project team aims to better understand how decision-makers and practitioners consider and approach multi-hazard risk management and what policies and policy-making processes underpin the governance of natural multi-risks (natural hazards considered in this project are floods, heatwaves, snow, fires, drought, storms, volcanic activity, tornadoes, extreme wind, thunder/hail, biological hazards, earthquake, tsunami, and landslides). We recognize this a non-exhaustive study and the questions below cannot cover all possible multi-hazard, multi-risk scenarios. The questions guiding this interview are designed to stimulate the discussion about existing frameworks and good practice and identify knowledge gaps and opportunities to further facilitate the inclusion of multi-hazards, multi-risks in policy guidelines and sectoral operations.

Generic questions (where applicable, please state if the reflection or perspective presented is that of your organization or your wider network)

1	With which **types of natural hazards** are you dealing with on a regular basis in your role/organisation, if any?
2	Given the definition stated earlier (UNDRR, 2017), what is your **understanding of** and **experience with multi-hazards, multi-risks**? Could you give some examples?
3.	In your organization and/or network, are natural hazards and risks considered individually or in interaction in the disaster risk management cycle (response, recovery, mitigation, preparedness)? For example, think about the following scenarios: an earthquake triggers multiple landslides or intense rainfall and storm surges occurring simultaneously result in extensive inland and coastal flooding.
4.	a) Are you aware of any **policies** or **governance processes** taking into account interactions between natural hazards? b) What **specific benefits** and **opportunities** do they bring, if any?
5.	Can you share **examples of** (local/regional/national/EU-wide) **good practices** that consider multi-hazard interactions and multi-risk as part of a risk management strategy? *For example, think about the institutions that have responsibility for assessing, warning for, and managing different hazards, and the procedures and processes in place for managing multi-risk events.*
6.	Are there any barriers or challenges you think decision-makers are facing in implementing multi-hazard, multi-risk management guidelines and policies in sectors/areas you are familiar with? Can you give some examples?
7.	What **potential trade-offs** or **synergies** do you anticipate or have experienced in the development or implementation of policies and guidelines that take into account multi-hazard, multi-risk in DRM[11] actions?

[11] Disaster Risk Management (DRM)

Sector-specific questions, in addition to the general questions above (where applicable, please state if the reflection or perspective presented is that of your organization or your wider network)

1.	a) In your **sectoral policies** and **strategy plans**, do you consider **dependencies** or linkages **between different sectors** and if so, b) do these policies and plans take into account potential interactions between natural hazards? Please give some examples, if possible.
2.	To your knowledge, what **tools**, **models**, and **frameworks**[12] are **used in your sector** to support multi-hazard, multi-risk assessment and management? If possible, please give some examples keeping in mind their potential inclusion in a Wiki-style platform (WP1, Task 1.2).
3.	Is there any **further information** or **knowledge** you would like to share with regards to policy, policy-making processes and governance for multi-hazard, multi-risk management?

Pilot-specific questions, in addition to the general questions above (where applicable, please state if the reflection or perspective presented is that of your organization or your wider network)

1.	To your knowledge, what **tools**, **models**, and **frameworks** are **used in your pilot region** to support multi-hazard, multi-risk assessment and management? If possible, please give some examples keeping in mind their potential inclusion in a Wiki-style platform (WP1, Task 1.2).
2.	Which **institutions** in your pilot region have **roles** and **responsibilities (mandates) for monitoring/forecasting/managing** (preparing for, responding to, and supporting recovery from) **natural hazards**?
3.	Is there any **further information** or **knowledge** you would like to share with regards to policy, policy-making processes and governance for multi-hazard, multi-risk management?

[*Please feel free to use this document to prepare and share your answers in advance of the interview, where possible. Thank you!*]

The MYRIAD-EU WP1 Team

[12] In MYRIAD-EU, we generally define a *tool* as a resource to help you meet an objective or to generate new knowledge or information. A *model* is a representation of the real-world or potential scenario or system; and a *framework* is a conceptual organization of terms, principles or components.

Consent Form Interviewees

Project title: Multi-hazard and sYstemic framework for enhancing Risk-Informed mAnagement and Decision making in the E.U. (MYRIAD-EU): *WP1 Diagnosis, Task 1.3* **Review of policies, policy-making processes, and governance for multi-hazard, multi-risk management (M1 – 9)**

Work Package Lead: UKRI BGS **Address:** Nicker Hill, Keyworth, Nottingham NG12 5GG, UK. **Work Package Co-Lead:** Deltares, **Email:** Dana.Stuparu@deltares.nl

Principal Investigator: Professor Philip Ward. **Address:** Institute for Environmental Studies (IVM), De Boelelaan 1111, 1081 HV Amsterdam, Netherlands. **Email:** philip.ward@vu.nl

Before taking part in this interview, please review the statements below. If you wish to participate, please tick the box to confirm your consent.

In giving my consent to participate in this study, I confirm that:

I understand that this study is designed to further scientific knowledge, and that all procedures adhere to the MYRIAD-EU ethics framework.
I have read and understood the participant information sheet.
I understand that I can ask questions, using the email address above, about this research before participating.
I understand that I am under no obligation to take part in the study, have the right to stop my participation at any point for any reason, or decide not to answer a particular question, and will not be required to explain my reasons for any of these actions.
I understand that I can withdraw my consent to participation and request my data is extracted from the study and destroyed, at any point up until the publication of research outputs.

Use of Information

I agree to any personal information I choose to provide being processed in accordance with the General Data Protection Regulations (further information can be found here: https://gdpr-info.eu/).
I understand that my personal information will be stored in a secure location for no more than 12 months after the completion of the project.
I understand that personal information will only be accessible to the project team, unless (under the statutory obligations of the agencies which the researchers are working with) it is judged that confidentiality will have to be breached for the safety of the participant.
I understand that anonymised data may be used in research outputs (e.g., publications, reports, web pages).

I agree to take part in this study.	YES	NO
If Yes, I agree to anonymised quotes being used in research outputs	YES	NO

Name:	Signature:	Date:

If you would like to receive copies of outputs (reports, academic journal articles) resulting from your participation, please provide your email address:

This proposed research has been reviewed by UKRI BGS, and was approved on 14th October 2021 (Reference number: BGSREC-2021-009).

If you are worried about this research, or if you are concerned about how it is being conducted, you can contact Dr Louise Ander, Chair of the BGS Research Ethics Committee, British Geological Survey, Keyworth, Nottingham, UK, NG12 5GG or by emailing BGSEthics@bgs.ac.uk.

A2 Appendix regarding Part 2

A2.a Methods for accounting for system behavior (systems of systems computing/ understanding)

Systems maps are one method for highlighting the interdependencies, feedback loops and cascades across different elements in a system which show how cascades move across the system because of tightly linked elements, policy decisions or concurrent impacts (Lawrence et al., 2020). However, there are continuing attempts to use climate models in order to make sense of risk, however, they are not necessarily a reliable quantity for risk assessment as the 'mean' response tends to underestimate the associated risk (Hazeleger et al., 2015). Storyline approaches can be useful to allow a system to be stress-tested by considering several different plausible outcomes (Sillman et al, 2022).

Due to the complexity of systems-of-systems dynamics, several computer modelling methods been applied to attempt to quantify this complexity. Input-output (IO analysis) for example, is capable of interrogating economic data on inter industry transactions, final consumption and value added to trace economic activity throughout complex supply chain networks and determine immediate and indirect effects of system shocks (Leontief, 1986) In terms of multi-sector risk, the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) are aiming to provide a framework for the intercomparison of global and regional-scale risk models within and across multiple sectors and to enable coordinated multi-sectoral assessments of different risks and their aggregated effects. ISIMIP uses community-agreed sets of scenarios with standardized climate variables and socio-economic projections as inputs for projecting future risks and associated uncertainties, within and across sectors (Rosenzweig et al., 2017) Using these scenarios, the ISIMIP creates impact models for sectors such as water, fisheries and marine ecosystems, coastal infrastructure, energy, agriculture and health (*About ISIMIP*, 2022).

It has been suggested however, that agent-based modelling and general systems modelling may better help to understand the impacts of a shock on an economic system (Castle & Crooks, 2006). One study used an agent-based model to simulate what would happen in the case of a possible lockdown of Tokyo to prevent COVID-19 spreading. The study found that the indirect effect on other regions would be twice as large as the direct effect on Tokyo (Inoue & Todo, 2020). This highlights that economic shocks due to disasters propagate to non-disaster regions and result in a large total loss for the entire country economy (Inoue & Todo, 2020).

A2.b Example of global financial interdependency with oil price change

Changes in energy prices impact worldwide current-account imbalances and, thus countries' net foreign asset positions, as an increase in energy prices is considered as a transfer of wealth from importing to exporting countries (Allegret et al., 2015). Considering the energy price–current account imbalances relationship, two main transmission channels can be highlighted. The first refers to the trade channel that focuses on the dynamics of energy exports and imports for exporting and importing countries. The second is related to international capital flows linked to the increase in energy prices (Allegret et al., 2015)

As oil is so heavily relied upon as an energy source, the gap between supply and demand has the ability to affect the macroeconomy, as well as economic growth (Allegret et al., 2015). This is because an increase in the oil price is passed on to the price of petroleum products, leading to a rise in energy bills for consumers and costs for producers (Allegret et al., 2015) Yet, an increase in the oil price causes a drop in productivity, which is passed on to (i) real wages and employment; (ii) selling prices and core inflation; (iii) profits and investment, as well as stock market capitalization (see fig 5). Therefore, fully understanding the effects of oil shocks on global balances requires consideration of both the trade channel and international capital flow (Allegret et al., 2015)

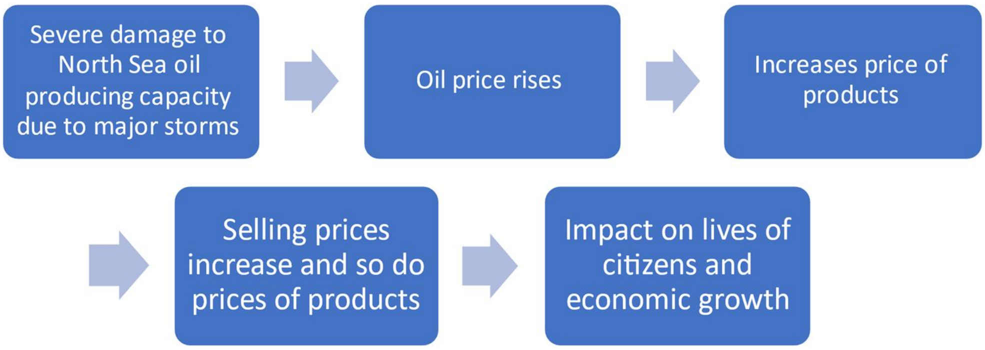


Figure 0-1: Visualization of the spillover impacts of a storm on North Sea oil.