# 2.1

# Risk assessment

## Lead Author:

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| ***Michael Hagenlocher*** | *United Nations University, Germany* |

## Contributing Authors:

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| ***Annegret Thieken*** | *University of Potsdam, Germany* |
| ***Stefan Schneiderbauer*** | *United Nations University, Germany / Eurac Research, Italy* |
| ***Ignacio Aguirre Ayerbe*** | *IHCantabria, Spain* |
| ***Pavel Dobes*** | *Technical University of Ostrava, Czechia* |
| ***Amy Donovan*** | *University of Cambridge, United Kingdom* |
| ***Claudia Morsut*** | *University of Stavanger, Norway* |
| ***Nicholas Paris*** | *Cyprus Civil Defense, Cyprus* |
| ***Lydia Pedoth*** | *Eurac Research, Italy* |
| ***Fahim Tonmoy*** | *Griffith University, Australia* |

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# 1 Introduction

*Disaster risk management and adaptation policies, strategies and plans should be based on a common understanding, assessment and monitoring of the risks associated with natural and human-induced hazards based on a multi-hazard risk approach..*

Causing damage to human well-being, ecosystems, infrastructure and disrupting entire economies, disasters continue to undermine sustainable development. Reducing the impacts of natural hazards and identifying pathways towards resilient societies hence remains a global priority. Understanding and assessing the drivers, patterns and dynamics of risk associated with single or multiple hazards is a necessary precondition for the identification, planning and implementation of targeted disaster risk reduction (DRR), risk transfer and climate change adaptation (CCA) policies, strategies and solutions. This realisation is reflected in key international agreements of the post-2015 agenda (e.g. the Sendai Framework for Disaster Risk Reduction 2015–2030, the 2030 Agenda for Sustainable Development, and the Paris Agreement) as well as the European Union's Civil Protection Mechanism and the European Agenda on Security – all of which include an explicit or implicit call for risk assessments. This subchapter provides an overview of current risk assessment concepts (Section 2), highlights the relevance of a transdisciplinary perspective when assessing risk (Section 3) and presents approaches to tackle the complex nature of risk (Section 4). Furthermore, it emphasises the need to analyse and communicate uncertainties as part of the risk assessment process as well as the essential role of risk communication to support disaster risk management.

# 2 Understanding risk: key elements and conceptual foundations

*Risk is the potential for adverse consequences or impacts due to the interaction between one or more natural or human-induced hazards, exposure of humans, infrastructure and ecosystems, and systems' vulnerabilities.*

Over the past few decades, conceptual approaches to understanding risk have undergone considerable paradigm shifts. Early conceptualisations drew on environmentally deterministic approaches, which focused primarily on understanding and assessing key characteristics of the hazard (e.g. floods, droughts, storms), such as their frequency, intensity, duration or extent (White, 1973). The choice and frequent use of the term 'natural disasters' reflects the thinking of that time that disasters are to be understood as being random, exceptional events, or purely natural phenomena (Hewitt, 1983; Burton, 2005). Criticising this hazard-driven view, a number of scholars in the early 1970s and 1980s started to call for the consideration of vulnerability as a key driver of risk (O'Keefe et al., 1976; Hewitt, 1983; Blaikie et al., 1994; Lewis, 1999; Wisner et al., 2004) emphasising the role of agency (i.e. the action people take to reduce their vulnerability) and structure (i.e. the social, economic or political structures that place people in vulnerable conditions). Building on these developments, more holistic risk concepts have been put forward that integrate environmental, social, economic, political, infrastructural and governance-related drivers of disaster risk (Turner et al., 2003; Birkmann et al., 2013; IPCC, 2014; UNDRR, 2019). As a result, a multitude of conceptual foundations and frameworks on how to define disaster risk coexist (see Box 1). While vulnerability and risk were conceptualised differently by the DRR and CCA communities for a long period of time, recent developments, such as the Special Report on Extreme Events (SREX) (IPCC, 2012) or the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014), have made a significant contribution to reconciling contrasting definitions (Giupponi and Biscaro, 2015). Although a commonly accepted definition of risk is still lacking, it is widely acknowledged today that risk (i.e. the potential for adverse consequences) is more than just the likelihood and severity of hazardous events and potential impacts. Rather, it results from the interaction of hazardous events with exposure of humans, infrastructure and ecosystems, and systems' vulnerabilities (IPCC, 2014, 2019; UNDRR, 2015, 2019). Evidence has shown that the impacts of hazards are not equally distributed within society (UNDRR, 2018), but largely linked to the question of how vulnerable an individual, community, infrastructure, society, asset or (eco)system is to such events (Schneiderbauer et al., 2017). Consequently, the following components should be considered when assessing risk.

**Hazard**, i.e. the process, phenomenon or human activity that carries the potential to cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards can be natural (e.g. earthquakes, droughts, floods) or anthropogenic (e.g. oil spills, terrorist attacks) in origin and can be characterised by their location, likelihood of occurrence, intensity or magnitude, duration, and extent. Hazards can be sudden onset events (e.g. flash floods, storms, mudflows, landslides, earthquakes) or creeping processes (e.g. droughts, salinisation) (IPCC, 2014; UNDRR, 2016).

**Exposure**, i.e. the presence of people, infrastructure, housing, production capacities, species or ecosystems, and other tangible human assets in places and settings that could be adversely affected by one or multiple hazards (IPCC, 2014; UNDRR, 2016). Exposure may vary in space and time, for example, as people commute between their work place and their home.

**BOX 1**

## Current risk assessment frameworks: similarities and differences

Several risk assessment frameworks have been formulated to capture the multi-dimensional, dynamic nature of risk. Such frameworks can serve as (1) a heuristic for characterising risk (e.g. how to frame and link its key drivers and components), (2) 'thinking tools' for the assessment of risk, as well as (3) policy guidance (e.g. providing entry points for risk management and adaptation). Here, similarities and differences of relevant risk assessment frameworks are presented:

- Risk as a result of the interaction of hazard(s), exposure and vulnerability (e.g. IPCC AR5 (IPCC, 2014), ISO 14091, or the Global Risk Assessment Framework (GRAF, UNDRR, 2019)). Although the AR5 and ISO 14091 illustrate risk related to climate impacts, these frameworks may be applied to other non-climatic hazards. The GRAF emphasises the systemic nature of risk across sectors and scales and promotes a multi-hazard and multi-risk approach.

- Risk is expressed in terms of risk sources, potential events, their consequences and their likelihood (e.g. ISO 31000: 2009). ISO 31000: 2018 builds on the same concept and proposes a three-step approach of risk identification, risk analysis, and risk evaluation. The risk framework of the World Economic Forum (WEF) follows the same logic.

**Vulnerability**, i.e. the propensity or predisposition of an individual, a community, infrastructure, assets or systems (incl. ecosystems) to be adversely affected (UNDRR, 2016). Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (Birkmann et al., 2013; IPCC, 2014).

Hence risk is different from impacts, which can be seen as the manifestation of risk in the form of materialised effects on human and natural systems (IPCC, 2019, 2014)

## 3 The need for a transdisciplinary perspective

*The integration of experts from natural and social sciences, as well as relevant stakeholders (including state and non-state actors), is needed to tackle the complexity of risk and facilitate the mainstreaming of risk information into policy and practice.*

Given its complex multidimensional nature, risk cannot be adequately characterised or assessed by a single discipline (e.g. geosciences) alone. Instead, it requires the involvement of experts from both natural and social sciences (multi- or interdisciplinary perspective), and ideally should go one step further and involve relevant stakeholders (taking a transdisciplinary perspective). The interaction between scientists, policy- and decision-makers, practitioners, the private sector and citizens is critical to ensure knowledge is co-created, to increase trust in the outcomes of risk assessments, and to mainstream co-produced risk information into evidence-based policy- and decision-making for DRR and CCA (Ismail-Zadeh et al., 2017; Brown et al., 2018).

While this might sound like an easy task, a number of challenges persist that make it difficult to move from traditional multidisciplinary (i.e. working within disciplinary silos) or interdisciplinary approaches (i.e. working across disciplinary silos but using disciplinary methods) of risk assessment to integrated transdisciplinary approaches (Donovan, 2019). Examples include a lack of common understanding of what constitutes risk, limited awareness of the potential methodological contributions different disciplines can make to risk assessments, the willingness and capacity of stakeholders to engage with opposing views, power relations or simply the choice of the 'right' stakeholders (Ismail-Zadeh et al., 2017). However, such approaches have significant potential to address some of the communication challenges around risk assessments, as well as ensuring that all relevant knowledge is incorporated ( Donovan and Oppenheimer, 2015).

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# 4 Risk assessment: approaches, opportunities and challenges

*Research is increasingly engaged in monitoring, assessing, and understanding risk by developing concepts, methods and approaches. However, several challenges persist when it comes to unravelling the complexity and dynamics of risk in assessments.*

Over recent decades, there has been a major increase in the number of risk assessments, drawing on a multitude of conceptual foundations and methodological approaches (Preston et al., 2011; de Sherbinin et al., 2019; Hagenlocher et al., 2019). As a result, a bewildering variety of risk assessment methods and approaches exists. Independent of the approach that is chosen, common steps in risk assessment include (1) scoping (i.e. understanding the context, scope, objectives and expected outcomes of the risk assessment) and definition of the methodological approach, (2) identification of the root causes/drivers(1) of risk through expert and/or community consultation and literature reviews, (3) data acquisition, (4) integrated analysis and evaluation of hazard, exposure and vulnerability, (5) validation and (6) visualisation and communication of the results (Zebisch et al., 2018). For semi-quantitative or purely quantitative approaches, the evaluation of uncertainties and confidence levels represents another key step that should be part of the validation process (Zebisch et al., 2018). Furthermore, the entire risk assessment should undergo a verification process to identify if it was developed in a sound and correct way. As risk assessment should not be an end in itself, every risk assessment should ideally include the identification and evaluation of possible risk reduction, risk transfer (e.g. through insurance mechanisms) or adaptation options (Hagenlocher et al., 2018a).

Despite major advances in terms of understanding risk and developing methods for its assessment, several challenges persist. These include issues such as how to best (1) integrate local knowledge and intangible factors (e.g. risk perception, behaviour, values, norms and beliefs) into risk assessments (UNDRR, 2015, Hagenlocher et al., 2018b) or (2) capture and represent dynamics (including future scenarios) of risk (Jurgilevich et al., 2017), non-linearities, human–environmental and cross-scale interactions, and compound or cascading effects (EC, 2017; Ford et al., 2018; Adger et al., 2018; UNDRR, 2019). The following sections reflect on these challenges by outlining the current state of the science, existing solutions and good practices as well as potential ways forward.

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## 4.1 Integrating qualitatitative and quantitative approaches to tackle complexity

Risk assessments have to deal with an increasing diversity of possible adverse events and increasing complexity and interdependency of the drivers of risk (see Box 2). To address these challenges, a number of qualitative, semi-quantitative and quantitative methodologies have been developed. The selection of the most appropriate approach depends on the scope of the assessment, the level of quantification and spatial differentiation demanded within the context of each assessment, and its defined objectives. These demands may vary among the three main assessment phases: (1) risk identification, (2) risk analysis and (3) risk evaluation (ISO 31000:2009).

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*(1) For indicator-based approaches (see Section 4.1), this step may also include the identification of valid, reliable, understandable, comparable and measurable indicators.*

In many circumstances a combination of methods is necessary to tackle the complexity and systemic nature of risk. To support the identification of risks it is useful to start with an investigation of past events and associated impacts. Such information can be either found in appropriate inventories at national, regional or global level (e.g. the EU Risk Data Hub(2), the Emergency Events Database (EM-DAT)(3) or the Sendai Monitor(4) or drawn from traditional and/or expert knowledge. Records of past events need to be augmented by a comprehensive list of additional potential hazards and risks that should be compiled based on the knowledge and experience of relevant experts. The output of the risk identification process is in most cases conceptual and qualitative. Within the context of global warming it is of crucial importance to consider the modification of past risks not yet reflected in event databases as well as the emergence of new risks due to changing environmental (including climatic) and societal conditions.

The objective of risk analysis is to understand possible risks and their drivers, patterns, dynamics and potential consequences. Techniques used for this task differ depending on context and the complexity of the types of risks in question. In the case of risks related to accidents in technical production processes, relevant analytical steps can rigidly follow potential failure causal chains, as applied, for example, in failure mode and effect analysis or event tree analysis (US Department of Health and Human Services Food and Drug Administration, 2006). The identification of risks associated with natural hazards or climate-related extreme events requires a more flexible approach that allows for systemic perspectives that explicitly scrutinise exposure and vulnerability factors in addition to the hazardous events themselves, for example when developing impact chains (Hagenlocher et al., 2018b; Schneiderbauer et al., 2013) or influence diagrams (McDaniels et al., 2012).

To get a full picture of the risk situation, and to understand related drivers as well as possible consequences, qualitative information embedded in storylines and narratives is crucially important (Jasanoff, 1999). Many aspects relevant to understanding complex risks – particularly those of an intangible nature – cannot be found in databases, statistics or the outputs of equations and models. These are often linked to issues such as governance (e.g. the role of traditional or informal governance systems that exist in parallel to official administrative structures) and culture (e.g. the role of religion/beliefs in shaping risk perception and behaviour). Nonetheless, quantification is vital when risk analyses aim to determine frequencies and probabilities of consequences, particularly when a comparison in time or space is requested. There are many available methods and tools for this assessment step, such as stochastic modelling/Monte Carlo simulations (e.g. Musson, 2000), system dynamics modelling (e.g. Simonovic, 2011), sensitivity analysis (e.g. Glas et al., 2016), event tree analysis (e.g. Tang et al., 2018) or composite indicators (e.g. De Groeve et al., 2016). A specific challenge concerns risk analysis questions that require spatially explicit investigations, such as assessments that aim to inform the spatial planning of DRR and adaptation options, or the allocation of funds to high-risk regions. Such spatial analysis also requires quantitative assessment approaches. In this case, data paucity and time required for data collection and data processing can be restricting factors. However, the ever-increasing availability and resolution of remote sensing data as well as citizen-generated data also provide new opportunities. Figure 1 illustrates a number of existing platforms that provide access to risk data of EU relevance. Consistent population (e.g. Global Human Settlement project[5]), land use (e.g. the Copernicus Land Monitoring Service(6) or socioeconomic data (e.g. Eurostat(7), as well as spatial information on hazards (e.g. Copernicus Emergency Management Service(8), exposure and impacts (e.g. Risk Data Hub(2), are available for EU countries.

Furthermore, depending on the scale of the analysis, participatory mapping or primary data collection (e.g. through household surveys) may also enhance data availability. Semi-quantitative risk analyses represent a structured

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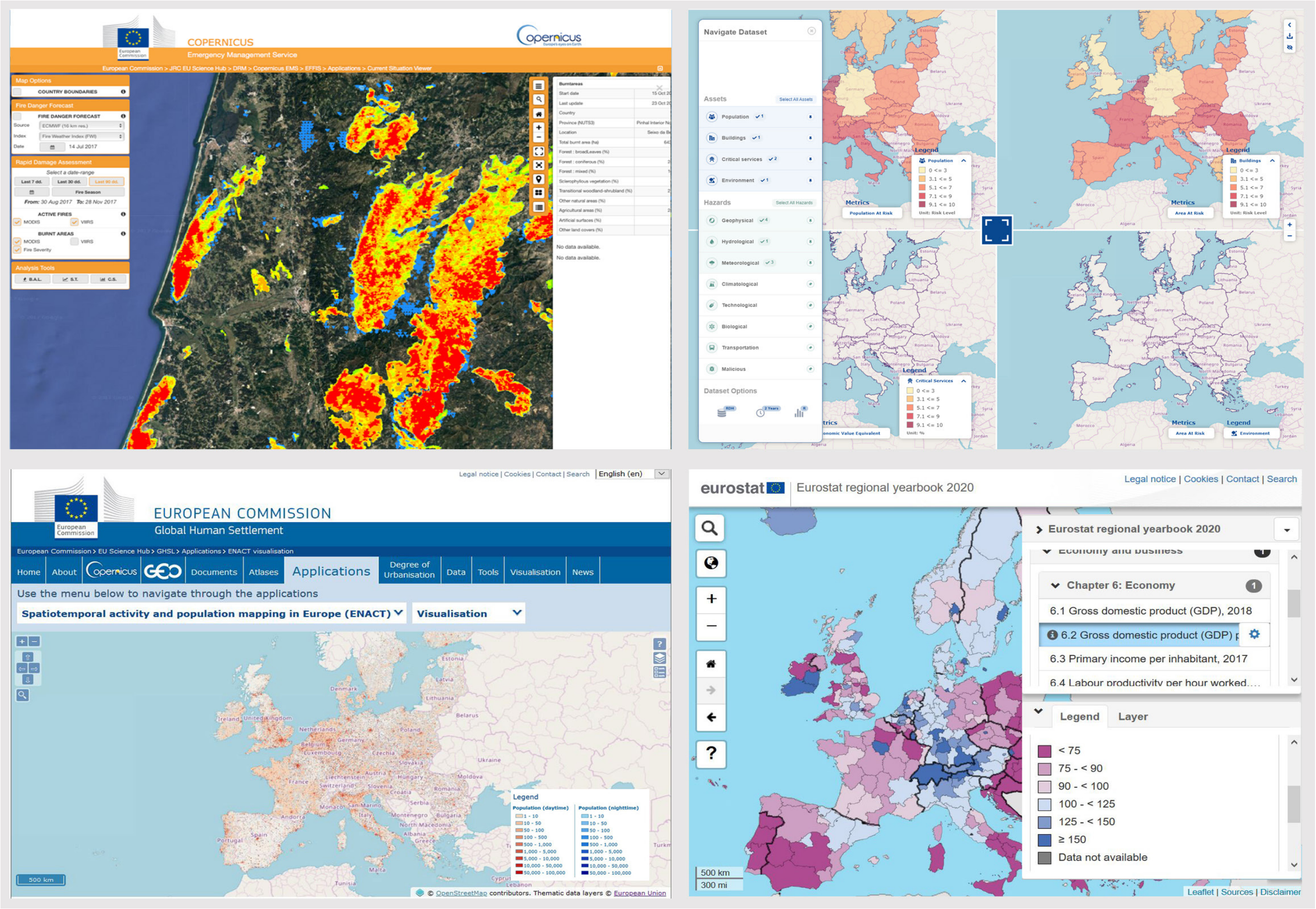
*(2) https://drmkc.jrc.ec.europa.eu/risk-data-hub/*
*(3) https://www.emdat.be*
*(4) https://sendaimonitor.unisdr.org*
*(5) https://ghsl.jrc.ec.europa.eu/*
*(6) https://www.copernicus.eu/en/services/land*
*(7) https://ec.europa.eu/eurostat*
*(8) https://emergency.copernicus.eu/*

way to rank risks by applying comparative scores. This procedure often applies participatory indicator-based approaches (e.g. Simmons et al., 2017; Aguirre-Ayerbe et al., 2018). When data and resources are limited, qualitative methods (e.g. interviews, focus group discussions) allow an estimation of risk levels in a descriptive manner. Risk evaluation is the final assessment step with a direct link to supporting decision-making. In this step, the risk analysis results are verified regarding context-specific criteria, which strongly depend on actors' risk perception and awareness. The methods of risk evaluation mainly comprise techniques for the acquisition of expert knowledge and the engagement of relevant actors

***Figure 1**. Illustrative examples of risk data platforms for Europe: the COPERNICUS EMS Fire Danger Forecast (top left), the EU Risk Data Hub (top right), the Global Human Settlement platform (bottom left), and EUROSTAT (bottom right). **Source**: Authors.*



## 4.2 Single hazard risk, multi-hazard risk, and multi-risk

Quantitative risk assessments are commonly performed hazard by hazard as single-hazard risk assessments. However, to make informed decisions on priorities in risk management, spatial planning or risk communication, it is necessary to consider all hazards and know all risks relevant to the area under investigation (Durham, 2003). Multi-hazard assessments have not been standardised up to now and are thus distinguished by the level of interaction and interdependencies between different risk components. If no interaction between hazard processes is considered in the hazard models or in the vulnerability models, Zschau (2017) refers to this type of assessment as multi-layer single-risk assessment, for which Kappes et al. (2012) distinguish three basic approaches: indices, matrices and curves. Any of them can address single components of the risk equation or the total risk (see, for example, Kappes et al., 2012; Zschau, 2017). One example of an index-based approach is the Index for Risk Management (INFORM) Global Risk Index (IASC and EC, 2019), which assesses risk at the global level. Early examples of a matrix approach are the Switzerland-wide all-hazard risk assessment Katastrophen und Notlagen in der Schweiz (KATANOS and its successor KataRisk (BABS, 2003; BZS, 1995). Grünthal et al. (2006) presented one of the first examples of risk curves using the City of Cologne in Germany as a case study to compare earthquakes, storms and floods. One key challenge with risk curves is to use a comparable and consistent methodology across different hazards.

To assess risk more realistically, it is necessary to account for interactions between hazards and vulnerabilities. Three types of hazard interactions can be distinguished: compound, interacting and cascading events (Pescaroli and Alexander, 2018). Compound events are described as (1) simultaneous or successively occurring events, such as a heatwave that is accompanied by dry conditions leading to wildfires that cause – among other things – heavy air pollution (Zscheischler et al., 2018), (2) events combined with background conditions that augment their impacts, e.g. sea level rise and coastal storms, and (3) a combination of (several) average values that result in an extreme event (IPCC, 2012; Pescaroli and Alexander, 2018). For example, the power outage caused by heavy snowfall in Münsterland, Germany, in November 2005 could be traced back to a combination of heavy wet snowfall, a temperature range around 0 °C, moderate to strong wind and the type of steel used in the constructions (Klinger et al., 2011). Importantly, this last type of compound events calls for new, bottom-up modelling approaches that start with a forensic analysis of damaging events to identify the root causes of damage and failure (Zscheischler et al., 2018). The European Cooperation in Science and Technology (COST) action DAMOCLES (Understanding and modelling compound climate and weather events) focuses on understanding and modelling compound events.

In contrast to compound events, interacting events are predominantly addressed by earth scientists investigating 'how physical dynamics develop through the existence of a widespread network of causes and effects' (Pescaroli and Alexander, 2018, p. 2248). In this regard, mechanisms and combinations of hazards in their temporal and spatial domains are often the focus. Gill and Malamud (2014) systematically analysed the interaction of 21 hazards, revealing that geophysical (e.g. landslides and avalanches) and hydrological hazards are most often triggered by other hazards (i.e. they are secondary events), and atmospheric and geophysical hazards (in particular earthquakes and eruptions) are the most common triggers (i.e. primary events). Understanding and modelling these interactions is of great importance for improving forecasting, early warning and emergency management (Pescaroli and Alexander, 2018), but is still hampered by the complexity of the processes (Komendantova et al., 2014).

If there is a clear link between the primary and secondary hazards, this chain is also often referred to as a cascading event. Pescaroli and Alexander (2018), however, argue that cascading events are associated with uncontrolled chain losses involving critical infrastructures. In their view, cascading events can also be the result of cumulative vulnerabilities, not necessarily a chain of different hazards (Pescaroli and Alexander, 2016). If interactions between vulnerabilities are included in the risk analysis, Zschau (2017) calls them multi-risk assessments.

Currently, there is no systematic application of multi-risk assessments in Europe, owing to different methodological approaches and databases and ambiguous terminology (Tilloy et al., 2019; Zschau, 2017). Insufficient cooperation and long-term partnerships between institutions, lack of funding, data or an overarching communication strategy are further challenges (Zschau, 2017). However, recently progress has been achieved regarding the mapping of relevant terminologies (e.g. by the EU project Platform for Climate Adaptation and Risk Reduction, PLACARD), clarifying modelling approaches for different hazard interrelations (Tilloy et al., 2019), the development and assessment of multi-sector/stakeholder partnerships (Aerts and Mysiak, 2016) and the development of guidelines for enhanced (multi-hazard) risk management (Lauta et al., 2018).

**BOX 1**

## Interdependencies and cascading effects: operationalisation in risk assessments for policy guidance

When considering multiple hazards and their interactions it is possible that the total risk estimated can be greater than the sum of their individual parts. This is mainly because risk can emerge from the interconnections that occur at the hazard level where an initial hazard may trigger other events, such as a tsunami triggered by an earthquake, or when several events occur simultaneously such as a bushfire starting during a heatwave. Risk can also emerge from the interactions that occur at the vulnerability level (i.e. a system's vulnerability), where the first hazard event can make the affected system or community more prone to the negative consequences of a second hazard event. Moreover, slow-onset phenomena, such as climate change, act as 'threat multipliers' by exacerbating other hazards (e.g. temperature increase leading to more wildfires), but may also lead to exceeding the adaptive (coping) capacities of a population or system. Therefore, the emergence of complexities and unprecedented threats needs sound principles, innovative thinking, advanced databases, models, methods and simulations to capture the cascading effects of hazards and the interdependencies between drivers of vulnerability. In addition, infrastructure systems are also interdependent, as they use each other's output and operate together to provide joint services to communities (Fu et al., 2014; Hasan et al., 2015). A single hazard event can trigger a cascading failure in these systems (Pescaroli and Alexander, 2016) with cascading impacts on people and societies. Therefore, management strategies for one infrastructure network (e.g. telecommunications, water, gas, electricity or transportation) often rely on the functionality of other networks, so all components should be considered part of an overall 'system of systems' (Helbing, 2013).

An all-hazards and multi-risk approach requires that risk assessments take account of these cascading effects and interdependencies across risk components, sectors, scales and borders (EC, 2017). Modelling approaches for understanding interdependencies, cascading effects and the systemic nature of risk include empirical approaches that use historical failure data and expert judgement (Luiijf et al., 2008), agent-based simulation (Rome et al., 2009), system dynamics (Stergiopoulos et al., 2016) or network-based approaches (Ulieru, 2007). All of these modelling approaches can also be supplemented by expert judgement (EFSA, 2014).

## 4.3 Space-time dynamics and future risk scenarios

Risk is not static, but rather dynamic in both space and time. Dynamics are a key property of all three components of risk: hazard, exposure and vulnerability.

For example, flooding in a downstream area of a catchment might not only result from heavy rainfall in the catchment area, but can also be exacerbated by deforestation and erosion processes upstream. Capturing these dynamics in hazard models is common practice (e.g. Metin et al., 2018; Merz et al., 2014). Similarly, exposure to hazards can be highly dynamic (Birkmann et al., 2013; Jurgilevich et al., 2017) as people move through space in time or as a result of seasonal hazard variability. While exposure assessments still tend to be quite static in their nature, technological advances in remote sensing and the ever-increasing availability and accessibility of geolocated data (e.g. mobile phone data, Twitter) have led to advances in spatiotemporal exposure assessments from local to pan-European scales. For example, Renner et al. (2017) analysed the changes in population distribution and associated exposure to river floods during a work day and night in the city of Bolzano, Italy, for different months of the year. The ENACT (Spatiotemporal activity and population mapping in Europe) project produced population density grids for Europe considering daily and seasonal variations, and Batista e Silva et al. (2018) also analysed space–time patterns of tourism in the EU at high resolution.

Vulnerability also exhibits a dynamic and non-linear nature (Wisner et al., 2004; Birkmann et al., 2013; IPCC, 2014; Jurgilevich et al., 2017; Ford et al., 2018), for example driven by changes in social, economic, physical or natural capital, and/or as a result of human–environmental interaction. Particularly in rural, natural-resource-dependent settings, where livelihoods rely on ecosystems and their services, a social-ecological systems perspective that also considers the vulnerability of ecosystems and their interlinkages with the vulnerability of the communities depending on them is necessary (Sebesvari et al., 2016; IPCC, 2019). Recent reviews of vulnerability and risk assessments, however, have revealed that, although the number of studies that include dynamics is growing, the focus is still mostly placed on assessing biophysical dynamics linked to hazard and exposure patterns, rather than dynamics in vulnerability (Tonmoy et al., 2014; Jurgilevich et al., 2017; Ford et al., 2018; Hagenlocher et al., 2019; de Sherbinin et al., 2019).

Furthermore, the dynamics of risk are also directly linked to global environmental change (e.g. land use and climate change), development trends and societal transformation (Peduzzi, 2019). This calls for assessments that capture potential changes in risk over time. Future risk scenarios are useful tools to (1) illustrate different potential development pathways and associated risk trends, and (2) help to identify policies and measures to prepare for a range of possible futures (Birkmann et al., 2015). The representative concentration pathways (RCPs) (Moss et al., 2010) and the shared socioeconomic pathways (SSPs) (Kriegler et al., 2012; O'Neill et al., 2014) provide substantial guidance for the assessment of future risks and options for their management (van Ruijven et al., 2013). However, existing future-oriented risk assessments still tend to focus on future hazard and exposure scenarios (e.g. combining urban growth simulations with future hazard trends; Güneralp et al., 2015; Hallegatte et al., 2013; Jongman et al., 2012; Neumann et al., 2015), while scenarios of vulnerability remain an underdeveloped field (Birkmann et al., 2015; Jurgilevich et al., 2017). To date, only a few studies have simulated future vulnerability (e.g. Rohat et al., 2018) and risk scenarios (e.g. Rohat et al., 2019) in Europe based on RCPs and SSPs.

## 4.4 Uncertainty

Sound decision-making should be based on up-to-date and reliable information on current and possible future risks, including associated probabilities and uncertainties as well as the full range of possible consequences. Information on extreme events and associated uncertainties about their occurrence is especially important when assessing the risk associated with low-probability but potentially high-impact events. In the context of risk assessments, uncertainties can arise from the given variability of the physical environment (random or aleatory uncertainty), as well as from limited knowledge, measurement or modelling capabilities (epistemic uncertainty) (Swart et al., 2009). Uncertainty is inherent in all steps of the risk assessment, from the conceptualisation of risk (conceptual model uncertainty), through the acquisition of data (uncertainty in data), to the actual analysis of risk (expert bias, uncertainty in risk perception, model uncertainty) (Sword-Daniels et al., 2018; Donovan, 2019). Uncertainties should therefore be explicitly considered at each step of the assessment and, together with their impacts on the results, documented and communicated in a transparent manner (Manning et al., 2004). The analysis and expression of uncertainty may be qualitative (e.g. expert-based) or quantitative (i.e. based on statistical models). While assessing and communicating uncertainties associated with hazardous events has become standard practice (e.g. Merz and Thieken, 2009), the analysis of inherent uncertainties in the assessment of vulnerability and risk (e.g. Feizizadeh and Kienberger, 2017) is still an emerging field.

# 5 Communicating risk information to support disaster risk management

*Risk communication is key to link risk perception to risk awareness and any subsequent decision making*

Effective communication of knowledge and results generated by risk assessments is crucial for efficient disaster risk management (DRM). All steps of risk assessments should tackle the question of how the findings can be transferred from theory to practice and policy while ensuring that the science is useful, usable and used (Boaz and Hayden, 2002). The communication of risks should go far beyond a unidirectional flow of information. Particularly, it should represent a dialogue-oriented process as a precondition for developing compromises among actors with different values, norms and interests. It may follow different goals, which might focus on aspects such as information exchange, awareness building or legitimisation of decision-making (Renn, 1992; Höppner et al., 2010). Risk communication is strongly connected to risk awareness. Only if policy-makers perceive certain risks will they communicate them, which in turn has a direct influence on their perception among stakeholders and the population (Hagemeier-Klose and Wagner, 2009).

There are a variety of tools for communicating knowledge generated from risk assessments. Hazard, exposure, vulnerability and risk maps, in digital or analogue form, are a core instrument for informing policy-makers, relevant stakeholders and the general public about possible risks. However, map-based risk communication poses various challenges, since it is limited by the amount of information visualised and can being interpreted differently depending on a user's capacity to comprehend its meaning. Therefore, Meyer et al. (2012) recommend creating user-specific maps. In order to be useful in DRM, it is therefore necessary to integrate map-based instruments into a complementary communication strategy (Hagemeier-Klose and Wagner, 2009; Wenk et al., 2018). Such a strategy should, depending on the target group, translate knowledge from risk assessments into activities such as school campaigns, exhibitions, radio programmes, blogs, public consultations and hearings, opinion polls and much more (Höppner et al., 2018; see also Chapter 4 of this report).

# 6 Conclusions and key messages

Disaster risk management and adaptation to climate change are increasingly prioritised in policy debates. In response there has been a rapid rise in the number of risk assessments at different spatial and temporal scales aiming to inform the identification, prioritisation and (spatial) planning of risk reduction, risk transfer and adaptation options. Evidence shows that the impacts of hazards are not equally distributed within society, and that risk assessments need to consider relevant hazards, exposure and vulnerability as well as the interactions between them. Going beyond the assessment of current risks, future risk scenarios are useful to anticipate and prepare for future challenges. Since risk is accompanied by a degree of uncertainty, special care should be given to evaluating and communicating uncertainties.

## Policymakers

Policies tackling issues of land use, settlement or infrastructure planning as well as sustainable development should be risk-informed to reduce future loss and damage. Risk assessments, co-designed with relevant stakeholders (including state and non-state actors), can provide baselines for preventative and adaptive decision-making.

## Practitioners

A great variety of risk assessment approaches exists. The participation of a wide range of disciplines and actors, such as scientists from the social and natural sciences, policy-makers, practitioners, the private sector and citizens, is key for the acceptance of the outputs and outcomes. Risk assessments should include the identification and evaluation of possible risk reduction, risk transfer or adaptation options. Outcomes of risk assessments, as well as associated uncertainties, should be communicated in an understandable and actionable manner.

## Citizens

Traditional and/or local knowledge is a vital source of information in the process of assessing risk. Participation of citizens in risk assessments, particularly at local level, raises the awareness of the public, and increases the acceptance of the outcomes of risk assessments and associated recommendations of how to reduce existing and prevent future risk.

## Scientists

Further research is needed on how to better integrate local/traditional knowledge and intangible factors (e.g. risk perception, values, norms and beliefs) into risk assessments, and how to capture the dynamic and systemic nature of risk in assessments. The analysis of inherent uncertainties in the assessment of risk is an additional area that requires further research.