Chapter 2

Understanding disaster risk: risk assessment methodologies and examples

David C. Simmons
Coordinating lead author

David C. Simmons
Lead author 2.1

Rudi Dauwe
Richard Gowland
Zsuzsanna Gyenes
Alan G. King
Durk Riedstra
Stefan Schneiderbauer

Christina Corbane
Lead author 2.2

Paolo Gamba
Martino Pesaresi
Massimiliano Pittore
Marc Wieland

Stefan Schneiderbauer
Lead author 2.3

Elisa Calliari
Unni Eidsvig
Michael Hagenlocher

Scira Menoni
Lead author 2.4

Costanza Bonadonna
Mariano García-Fernández
Reimund Schwarze

Jochen Zschau
Lead author 2.5

2 Understanding disaster risk: risk assessment methodologies and examples

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Introduction

Definition of risk

There is no commonly accepted definition of risk. According to the United Kingdom's Royal Society (1992), risk is 'the probability that a particular adverse event occurs during a stated period of time, or results from a particular challenge'. By contrast, the latest UNISDR's definition (2017) of disaster risk is 'the potential loss of life, injury, 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'.

Disaster risk is not just about the likelihood and severity of the hazard event but also about what is exposed to that hazard and how vulnerable that exposure is. A severe earthquake in a relatively uninhabited region can be of far less consequence than a relatively minor one near a large conurbation. Similarly, a severe earthquake in an area known to be prone to earthquakes and so with strict design and construction standards can cause fewer fatalities and less damage than an unexpected, much smaller one in an unprepared area with poor building standards.

Following the Sendai disaster risk definition, we may consider risk to comprise of three elements.

1. Hazard: the adverse event causing the loss.
2. Exposure: the property, people, plant or environment that are threatened by the event.
3. Vulnerability: how the exposure at risk is vulnerable to an adverse event of that kind.

Note that the forth Sendai element; capacity, the ability of the system to respond after the event to mitigate the loss, is generally considered to be a component of vulnerability. Loss suffered, that is the damage caused to the exposure at risk to a defined hazardous event, will depend upon these elements.

Risk complexity and dependency

Single events may have no one single cause. For example a major flood could be caused by a combination of one or more of heavy rain, unseasonably high temperatures causing snow to melt fast, baked land from a prior dry spell or conversely saturated soil from earlier continuous rains, which both increase run-off, high tides and storm surge.

Whilst it is sometimes difficult to consider risks from a single hazard, what of their combinations? The major cause of death and damage following the Great Kantō earthquake affecting Tokyo in 1923, an event that left more than

140 000 people dead or missing, was not from building collapse due to ground shaking but from fire storms provoked by cooking equipment knocked over in the event. Similarly, earthquakes may cause tsunamis, landslides, dam failures or avalanches and windstorms may cause landslides, storm surge, floods or flash floods. Vetere Arellano et al. (2004) includes a fascinating example of cascading risk following an earthquake in Turkey in 1999.

Human action can also affect the loss. For example, canalising rivers or building on historical floodplains can give excess flood water nowhere to go; wide-scale concreting over gardens to provide hard standing for motor cars prevents water absorption, perhaps exacerbated by inadequate or poorly maintained drains. What historically would have been a benign event can now become a calamitous one.

Uncertainty and subjectivity

Risk includes elements of the scientific and the subjective. In some hazards or sectors, risk can be clearly defined. For example in the insurance industry, the 'risk business' defines property or people who are normally insured against defined hazards with payment made upon financial loss suffered. As we will discuss later, this has led to an explosion in risk analytics over the last 30 years, leading to a far more technically sophisticated but also financially secure insurance industry.

However, even here there are limits in what we know. We may feel we know how well a particular building will react to an earthquake of a certain intensity, but do we know it was built to the right standard or correctly maintained? We may feel we can reasonably estimate the damage that a flood with a depth of 1 metre can do to an industrial plant, but how well can we estimate the firm's economic loss related to this damage, which will depend on how quickly the plant may be repaired or replaced, on whether it has any other factories available to take some of the strain and on whether business temporarily lost can ever be fully regained.

There is an inherent uncertainty, as by definition catastrophes are rare events; data to describe their effects may be partial, at best. However, as we will discuss later on, the process to understand and model risk sheds light on areas where data are lacking and therefore where additional focus is required. Subjective assumptions, perhaps currently unstated, must be made explicit and so held up for discussion.

Risk is not static but rather dynamic and dependent upon changes to hazard, exposure and vulnerability. Anthropogenic climate change is accepted as scientific fact, but its consequences on a local level and for a particular hazard may not be clear. Historical observations are often limited, partial and contaminated with natural variation and underlying factors that may not be fully understood. But clearly there is a public and therefore political pressure for governments

to protect their populations against the impacts of climate change. In practice, though, the risk as it is now is very often not properly understood, and still less how it may worsen (or conversely improve) under different climate change assumptions in 30 years' time; understanding current risk is fundamental to understanding how that risk may change in the future.

Risk perception

When we begin to move into exposure, such as the preservation of habitat and/or animal population, it may be harder to place an agreed value on preservation or qualification of damage if either is impaired, even where there is common acceptance of the importance of the risk to society. A common risk metric must be agreed in order to allow, for example, the relative social and environmental cost of sacrificing an important ecological habitat to protect the human population of a city.

Humans have short memories; current risk concerns may be driven by recent experience rather than underlying loss potential. Few were concerned with tsunami risk until the tragic events of 2004 and 2011 — the risks were theoretically known but were rare, and crucially as no significant tsunami had been filmed until 2004, the risk was difficult to relate to and was often overlooked.

Indeed, perception of risk drives policy (Klinke and Renn 2002). For example, many more die on the road than in train crashes, but these deaths tend to come in ones and twos at any time, rather than several casualties, as in rail crashes. Post-loss this may lead to calls to improve the already relatively safe rail system when a similar amount spent on the road network may save more lives.

The public purse is not unlimited. Should the politician react to the public perception of risk by spending on risk prevention in areas of known public concern or try to assess the range of risks the population face and prioritise spending on a more rational cost/benefit approach? In the short term, pre-event, the former will be more electorally advantageous but the post-event failure to react to an unrecognised hazardous eventcould have enormous political as well as human consequences. It is vital to consider not just what has happened but what could happen; taking action to minimise loss in advance and not just reacting to events as they occur.

Recognising risk may also have its consequences. Many societies have a pressure on housing. Flood plains offer an easy solution, the land drained, defences constructed and houses built, which is popular as people like living near water. But how robust are the new properties in a changing climate? Can risk be overlooked if there is a social need? Certainly before the event, but what about after? What if the properties become uninsurable and so unsaleable?

The importance of understanding disaster risk

Risk is complicated, but understanding risk is vital to the proper protection

of society and the environment. Without proper risk analysis, can appropriate policy decisions be made?

In an increasingly litigious society, could governments and officials not have a proper risk assessment methodology? It is vital to understand and use the best science, but ultimately policymakers will also necessarily react to stakeholder perception. It is hoped that scientific fact, properly presented, will drive perception, but ultimately risk management decisions are necessarily political.

Those decisions need to be made in a transparent manner; open to scrutiny, challenge and debate. It is impossible to completely eliminate risk, even with an unlimited public purse. In reality, budgets are under pressure, with many calls upon limited funds: spending money on preparing for an event that will probably not even occur within a politician's period of office may not be as high a priority as trying to address an immediate social need.

However, there is a duty of care to protect the citizens and the natural environment of Europe. Modern risk assessment, coupled with risk and financial modelling, provides the framework to make the right decisions for both now and the future.

2.1 Qualitative and quantitative approaches to risk assessment

***David C. Simmons**, Rudi Dauwe, Richard Gowland, Zsuzsanna Gyenes, Alan G. King, Durk Riedstra, Stefan Schneiderbauer*

2.1.1 Risk assessment

2.1.1.1 The importance of risk assessment

Risk assessment is a means not only to understand the risks that society (or a family or business) faces, with their potential probabilities and impacts, but also to provide a framework to determine the effectiveness of disaster risk management, risk prevention and/or risk mitigation.

It would be spurious to pretend that we fully understand all the hazards that society faces and their potential consequences. The process of risk assessment requires a structured approach. Without such a process, risks may be overlooked or implicit assumptions may be made. A risk assessment process requires transparency, opening up assumptions and options to challenge, discussion and review.

A structured approach is required to understand all the hazards that society faces and their potential consequences. This requires transparency, opening up assumptions to challenge, discussion and review.

Risk assessment and mapping guidelines for disaster management (European Commission, 2010) and Overview of natural and man-made disaster risks in the EU (European Commission, 2014), provide a solid outline of the issues in a European context. The first outlines 'the processes and methods of national risk assessments and mapping in the prevention, preparedness and planning stages, as carried out within the broader framework of disaster risk management', whereas the second paper analyses 18 national contributions, identifying 25 hazards, both natural and man-made (malicious and non-malicious).

However, as an example of the importance of risk assessment, the experience of the insurance industry is presented, an industry that has been transformed by the adoption of an increasingly rigorous risk assessment and modelling process over the last 30 years. The lessons learnt are relevant to policymakers and practitioners in government.

2.1.1.2 Example: catastrophe risk and the insurance industry

As recently as the 1980s, the insurance industry's catastrophe risk assessment was almost entirely based on historical experience or 'rule of thumb' assumptions. Catastrophes are, by definition, rare events. It is very unlikely that a mega event will have occurred in recent years and, even if that were

the case, it may have had unique features that may not reoccur. If we had a historical event, would it cause similar damage if it reoccurred? The global population is growing and getting wealthier, with the majority now concentrated in cities. Pressure of population growth has created the need to build on land that was wisely avoided by our forefathers. Growth may be unplanned with infrastructure, such as drainage not keeping up with the rate of development. People like living close to water, potential loss may be more than just scaling the historical loss by population change and wealth.

The need for a better approach was clear. In 1984 Don Friedman published a paper that would form the template for modelling insurance catastrophe risk over the following 30 years, breaking the process into hazard, exposure, vulnerability and financial loss. The first United States hurricane model to this template was produced by the reinsurance broker E.W. Blanch in 1987 (White and Budde, 2001), followed by the United States earthquake in 1988. Reinsurance brokers and reinsurers also lead the field in Europe; however, the early 1990s saw the rise of three major catastrophe modelling firms, which still dominated the industry in 2016.

These models were stochastic models — based not on a few historic hazard events but rather on a synthetic event made of many thousands of events that attempt to represent the range of possible events with their associated probabilities. The models required knowledge not only of what properties were insured and their value but also of their location, construction type and occupation. Engineering principles augmented by historical loss analysis attempted to understand the relationship between the event's manifestation at a particular location (e.g., peak ground acceleration, peak gust speed and maximum flood depth) and its likely damage. From this an overall damage estimate for any given property portfolio for each of the synthetic events could be calculated. If the probability of each synthetic event is then applied, we could understand the distribution off loss to the overall portfolio, for example what the annual average loss is and how big a loss from that hazard type can be expected every 5, 10, 20, 50 and 100 years.

The process of modelling catastrophe risk has transformed the reinsurance industry by increasing knowledge, scientific engagement, technical competence and, most importantly, the resilience of the industry — its ability to pay claims.

Decisions could be made based on 'objective fact', not subjective opinion. Underwriters now had much more information to appropriately rate individual policies and to decide how much total risk they could accept across their portfolio and how much to off lay. The concept of risk/return entered the market. Firms began to clearly define their risk appetite to ensure appropriate levels of financial security and then seek to maximise return within that appetite.

It has not been a painless process. Initially, many saw the models as a panacea to the market's problems. There was a tendency by those unaware of the complexity of the models to believe the results. Arguably, the models were oversold and overbought: the vendors sold the models on their technical capabilities and the buyers bought them seeking certainty, but neither publically faced up to the inherent uncertainty within the models, despite growing pains in the process. However, this information has transformed the industry. Twenty years ago the most technical reinsurance broker had perhaps 3 % of staff engaged in risk analytics, whereas now this has become 25 % to 30 %. Chief risk officers were virtually unknown in the insurance industry 20 years ago; now they are embedded.

The models became a mechanism to raise debate above vague opinion to a discussion of the veracity of assumptions within the model. The models' data requirements led to a massive increase in the quality and quantity of data captured, leading in turn to improved models. Knowledge of catastrophe risk has grown immeasurably; firms have become smarter, more financially robust and therefore more likely to meet their claim obligations.

Whilst such modelling originally applied to catastrophe risk only, it has been extended to cover man-made hazards such as terrorism and more esoteric risk such as pandemic. Indeed, the EU's solvency II (Directive

2009/138/EC) an insurance regulatory regime, requires firms to understand all the risk they face, insurance and non-insurance (e.g., market risk, counterparty risk and operational risk), with the carrot that if they can demonstrate that they can adequately model their risks, then they may be allowed to use the capital requirement implied by their model rather than the standard formula. Regulators rather smartly realise that any firm willing and able to demonstrate such capacity and understanding is less likely to fail.

2.1.1.3 The key elements of risk assessment

Whilst the insurance industry is a special case, others are noticing that the same methods can be used to manage risks to governments, cities and communities. They can drive not only a better understanding of the risks that society faces but also a means to determine and justify appropriate risk planning, risk management strategies as well as public and investment decisions.

Risk assessment requires the identification of potential hazards as well as a knowledge of those hazard including their probability, what is exposed to that hazard and the vulnerability of that exposure to the hazard.

Indeed, it can be argued that the process of risk assessment and modelling is more important than the results obtained. Risk assessment does not need to be as complex as a full stochastic model to add real value. Similarly, it is a common misunderstanding that a lack of good-quality, homogeneous data invalidates risk assessment. Any risk assessment methodology requires assumptions to be brought to light and so opened to challenge. Assumptions can then be reviewed, compared and stressed, identifying areas of inconsistency, illogicality, sensitivity and where further research should be concentrated.

The key steps in risk assessment are the following.

- Identify the hazards which might affect the system or environment being studied A brain-storming session to identify all potential hazards should be done at an initial stage. It is important to think beyond events or combinations of events that have occurred in order to consider those that may occur.

- Assess the likelihood or probability that hazards might occur: inputs to this process include history, modelling, experience, corporate memory, science, experimentation and testing. In practice, events with a very, very low probability (e.g. meteor strike) are ignored, focussing on ones more likely to occur and can be either prevented, managed or mitigated.

- Determine the exposure to the hazard, i.e. who or what is at risk.

- Estimate the vulnerability of that hazard to the entity exposed in order to calculate the physical or financial impact upon that entity should the event occur. This may be obtained by a review of historical events, engineering approaches and/or expert opinion and may include the ability of the system to respond after the event so as to mitigate the loss.

- Estimate the potential financial and/or social consequences of events of different magnitudes.

2.1.1.4 Risk tolerance

The likelihood of the hazard and its consequences needs to be compared with the norms of tolerability/acceptability criteria that society or an organisation has formulated. If these criteria are met, the next step would be to manage the risk so that it is at least kept within these criteria and ideally lowered with continuous improvement.

If the risk criteria are not met, the next step would be risk reduction by either reducing exposure to the hazard or by reducing vulnerability by preventative measures or financial hedging, typically through traditional indemnity insurance that pays upon proof of loss, but also increasingly through parametric insurance that pays upon proof of a defined event occurring. Insurance-like products can also be obtained from the financial markets by means of catastrophe or resilience bonds.

In industry, reducing event likelihood is normally the preferred method, since this dimension is amenable to improving reliability and enhancing

the protective measures available. In many cases, these can be tested, so are therefore often a dominant feature of risk reduction. Estimating the potential severity of the hazard is harder and often leaves much to expert opinion. If risk cannot be credibly reduced in industry, it may lead to the cessation of an activity. Ideally, a hazard would be completely avoided: a fundamental step in the design of inherently safer processes.

However, for natural hazards and climate risk, where hazard likelihood reduction is often impossible, it is required to work on exposure and vulnerability. Building codes, for example the EU standard Eurocodes, encourage appropriate resilience in design and construction and can include 'build back better' after an event. Spatial planning and the delineation of hazard zones of various levels can promote development in areas less exposed to risk.

Risks can never be eliminated but they can be managed and their consequences reduced, at a cost. Defining risk tolerance allows informed, cost-effective risk management decisions.

The insurance mechanism can be used to encourage appropriate risk behaviours, penalising poor construction, maintenance or location by reduced cover or higher premiums and rewarding mitigation measures, e.g. retro-fitting roof ties in tropical cyclone-exposed areas or installing irrigation systems for crops by premium reductions.

2.1.2 Risk identification process

2.1.2.1 The importance of risk identification

It is necessary to identify unwanted hazardous events (i.e., atypical scenarios) and their consequences. It is very important to include all these in a study. If a possible hazard is overlooked, it will never be assessed. Unfortunately, there are many examples of this failure (Gowland, 2012).

In all risk assessment methods, the failure to include these 'atypical' scenarios will present problems. Examples include the major fire and explosion at Buncefield (December 2005) and the tsunami that inundated the Fukushima nuclear power station (March 2011). Identification of all potential hazards is absolutely fundamental in ensuring success.

The United Kingdom Health and Safety Executive has identified and reviewed almost 40 hazard identification methods.

The scope and depth of study is important and relevant to purpose and the needs of users of the assessment. It is necessary to identify all hazards so that a proper risk assessment may be made. When we are open to considering potential deviations we need to make sure that we are open-minded enough to consider all possibilities even when they may seem to be remote.

It is important to consider all potential hazards, natural and man-made, and their possible interactions and consequences. The process should not be limited to events known to have happened in the past, but also to consider what could happen.

Methods in use greatly depend on the experience of the persons carrying out the study. This is normally a team activity, and how it is made up is important and should be drawn from persons familiar with the technology or natural phenomena and the location being considered. Techniques adopted range from relatively unstructured 'brainstorming' through to the more structured 'what if' analysis.

Potential risks may not be obvious and may not have occurred in the past. It is vital to seek to identify what could occur as well as the consequences.

Other more formalised processes exist in industry, though, including failure mode and effect analysis (FMEA) and the highly structured hazard and operability (HAZOP) study, both of which look to identify hazardous events and to locate causes, consequences and the existing preventive measures. FMEA was developed for the automobile industry and HAZOP

was developed for the chemical and process industry. However, similar studies can be applied to any field of risk. For example, the HAZOP (Tyler et al., 2015) use of guide words and deviations, which might seem to be limited to the industry where first applied, can be adjusted or replaced with those relevant to the field being studied; this has been demonstrated in the mining industry in Australia, where modified chemical industry methods have proved useful.

2.1.2.2 What if

This is a form of structured team brainstorming. Once the team understands the process or system being assessed and the kind of risks (potential exposures and vulnerabilities), each discreet part or step is examined to identify things that can go wrong and to estimate their possible consequences.

A team of experts brainstorming is one way to flush out potential risks, but it is important to use a panel of experts whose experience covers all aspects of risk.

In order to carry this out successfully, we must stress the need for the team to be properly qualified and to have a full set of data relating to the system being studied. This would include operating instructions, process flow sheets, physical and hazardous properties of the materials involved, potentially exposed persons, environment or assets, protective systems. Most users will simply estimate the likelihood and severity of consequences in a similar way to that used in risk matrix applications.

A brainstorming exercise has the side benefit of encouraging a wide participation in the risk identification and assessment process, increasing ownership of the ultimate conclusions.

2.1.2.3 Failure mode and effect analysis (FMEA)

FMEA is a rigorous, step-by-step process to discover everything that could go wrong in a task or process, the potential consequences of those failures and what can be done to prevent them from happening. In this way, it can be used in risk assessment in industry. As shown in Figure 2.1, it comprises a systemised group of activities designed to:

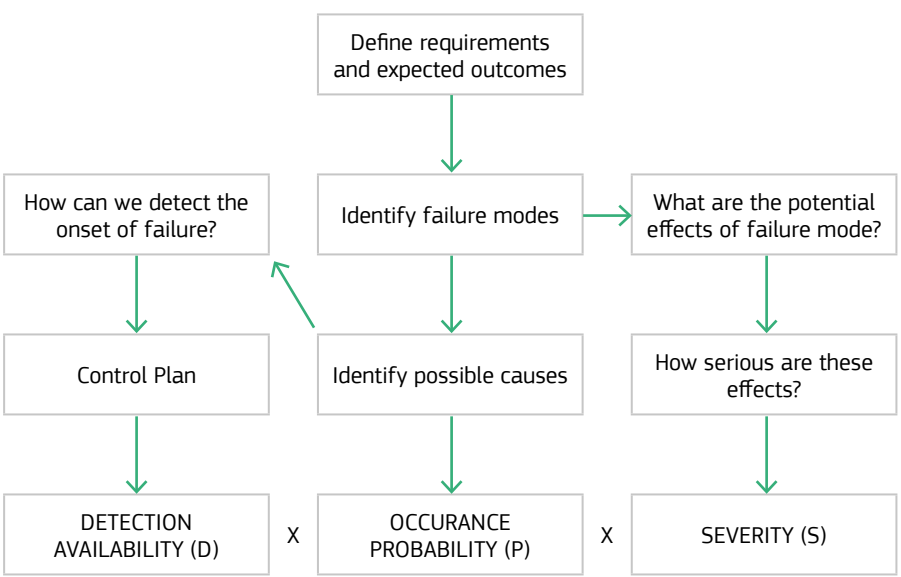
- recognise and evaluate the potential failure of a process or equipment and their effects;
- identify actions which could eliminate or reduce the chance of potential failure;
- document the process.

It captures:

- the failure mode, i.e., what could go wrong;
- the effect analysis, i.e., how it would happen, how likely it is to go wrong and how bad it would be.

FIGURE 2.1

A graphic illustration of the FMEA process.
Source: courtesy of authors



A very good example of a high-risk and high-priority project is the space shuttle where we put fragile human lives in a tin can and send them to space, hoping to get them home safely. Considering the complexity of the shuttle, there are many possible items which can fail, and they all have individual failure modes and effects. Lives are at risk and space shuttles are expensive. FMEA is a tool used to provide a structured process to understand and thereby minimise risk.

FMEA is a structured what-if process widely used in the process industries and provides a template for other potential applications.

The three distinct assessments for each of the three strands of this methodology, detection availability, occurrence probability and severity, are each given a rating: D, P and D, respectively. Risk ranking is calculated by multiplying these factors to give a single rating D x P x S. A risk matrix may be used to illustrate this process (see Chapter 2.1.4.3.).

2.1.2.4 Hazard and operability study (HAZOP)

The technique of HAZOP has been used and developed since the 1970s for identifying potential hazards and operability problems caused by 'deviations' from the design intent of a part of a production process or a procedure for new and existing operations. The technique is most associated with identifying hazardous deviations from the desired state, but it also greatly assists the operability of a process. In this mode it is very helpful when writing operating procedures and job safety analysis (Tyler et al., 2015).

Processes and procedures all have a design intent which is the desired normal state where operations proceed in a good way to make products in a safe way.

With this in mind, equipment is designed and constructed, which, when it is all assembled and working together, will achieve the desired state. In order to achieve this, each item of equipment will need to consistently function as designed. This is known as the 'design intent' for that particular item or section of the process.

HAZOP is a what-if process identifying potential hazards caused by 'deviations' from the design intent of a part of a production process or procedures.

Each part of this design intent specifies a 'parameter' of interest. For example, for a pump this could be flow, temperature or pressure. With a list of 'parameters' of interest, we can then apply 'guide words' to show deviations from the design intent. Interesting deviations from the design intent in the case of our cooling facility could include less or no flow of water, high temperature or low (or high) pressure. When these deviations are agreed, all the causes associated with them are listed. For example, for no or less flow, causes will include pump failure, power failure, line blockage, etc.

The possible hazardous consequences can now be addressed, usually in a qualitative manner without significant calculation or modelling. In the example, these might be, for example, for line blockage pump overheats or loss of cooling to process, leading to high temperature problems with product.

These simple principles of the method are part of the study normally carried out by a team that includes designers, production engineers, technology specialists and, very importantly, operators. The study is recorded in a chart as in the study record. A decision can then be made about any available safeguards or extra ones that might be needed — based on the severity or importance of the consequence.

It is believed that the HAZOP methodology is perhaps the most widely used aid to loss prevention in industry. The reason for this can be summarised as follows:

- it is easy to learn;
- it can be easily adapted to almost all the operations that are carried out within process industries;
- no special level of academic qualification is required.

2.1.3 Risk analysis methodologies

2.1.3.1 Types of risk analysis

Risk analysis is a complex field requiring specialist knowledge and expertise but also common sense. It is not just a pure scientific field but will necessarily include judgements over issues such as risk appetite and risk management strategy. It is vital that the process be as comprehensive, consistent, transparent and accessible as possible. If a risk cannot be properly understood or explained, then it is difficult if not impossible for policymakers, companies and individuals to make rational choices.

The appropriate form of risk analysis will depend on the purpose and the data available from simple scenarios to full probabilistic analysis, but all can lead to better decision-making.

Currently, there is no universally agreed risk analysis method applied to all phenomena and uses, but the methods used rather are determined by a variety of users, such as industrial and transport companies, regulators and insurers. They are selected on the basis of their perceived relevance, utility and available resources. For example, a method adopted in industry may not be suitable in the field of natural hazards. Legal requirements may also dictate the degree of study as well as such factors as the 'allowable' threat to the community. This last matter is common in 'deterministic' risk analysis where the requirement may be that there is no credible risk for a community in the location of an industrial operation.

Deterministic methods consider the consequences of defined events or combinations of events but do not necessarily consider the probability of these events or guarantee that all possible events are captured within the deterministic event set. Often this is the starting point for risk analysis. At the other extreme, stochastic or probabilistic analysis attempts to capture all possible outcomes with their probabilities; clearly coming with a much higher data and analytical requirement and, if correct, forming the basis for a sophisticated risk assessment process.

2.1.3.2 Deterministic methods

Deterministic methods seek to consider the impact of defined risk events and thereby prove that consequences are either manageable or capable of being managed. They may be appropriate where a full stochastic model is impossible due to a lack of data; providing real value whilst a more robust framework is constructed.

Risk standards may be set at national and international level and, if fully complied with, are believed to prevent a hazard that could impact the community. This is akin to the managing of risk in the aviation industry, where adherence to strict rules on the design and operation of aircraft and flights has produced a very safe industry. The same approach to rule- based operations exists in some countries and companies.

How are deterministic events framed? For example, to check the safety of an installation against a severe flood, severity is assessed according to the worst recently seen, the worst seen in the last 20 years or the worst that may be expected every 100 years based on current climatic conditions and current upstream land use. A different choice of event will have a different outcome and potentially a very different conclusion about manageability. Can we ensure that all deterministic events used in risk assessment across hazards are broadly equivalent in probability? If not, assessments and conclusions may be skewed.

Deterministic methods seek to consider the impact of defined risk events and thereby prove that consequences are either manageable or capable of being managed.

In recent times there has been a shift from a totally rule- based system to one where an element of qualitative, semi- quantitative and quantitative risk assessment (QRA) may influence decisions. But deterministic risk assessment is also carried out as a reali-

ty check for more complex stochastic models and to test factors that may not be adequately modelled within these models.

For example, over the past 20 years the insurance industry has enthusiastically embraced advances risk assessment techniques, but deterministic assessment of the form 'if this happens, this is the consequence' is still required by regulators. They may be referred to as:

- a scenario test, where a defined event or series of events is postulated and the consequences assessed;
- a stress test, where pre-agreed assumptions of risk, for example implied within a business plan (e.g. interest rate assumptions), are stressed and challenged to determine their impact on results and company sustainability;
- a reverse stress test, where events or combinations of events are postulated that could cause insolvency of the firm if unhedged.

Scenario, stress and reverse stress tests may be informed by science and modelling or expert opinion, or both, and often an assessment of probability will be estimated. Insurance regulators often focus on a 0.5 % probability level as a benchmark, i.e. the worse that may be expected every 200 years. If stress and scenario tests give numbers for an estimated 1 in 200 events that the stochastic model says could happen, say, every 10 years, then it casts doubt on the assumptions within the model or the test itself — they could be assessed and challenged. Similarly, the framing of multievent reverse stress tests may challenge assumptions about dependency and correlation within the model.

Realistically, deterministic methods are not 100 % reliable, taking as they do only a subset of potential events, but their practical performance in preventing hazard -impacting communities is as good and in some cases even better than other methods. If properly presented they can be clear, transparent and understandable. The process of developing deterministic stress and scenario sets can also be a means to engage a range of experts and stakeholders in the risk analysis process, gaining buy-in to the process.

Whether rules and standards derived from such tests work may depend on the risk culture of the region or firm where the risk is managed. Some risk cultures have a highly disciplined approach to rules, whereas others allow or apparently tolerate a degree of flexibility. Furthermore, the effort required to create, maintain and check for compliance where technical standards are concerned is considerable and may be beyond the capacity of those entrusted with enforcement.

2.1.3.3 Semi-quantitative risk analysis

Semi-quantitative risk analysis seeks to categorise risks by comparative scores rather than by explicit probability and financial or other measurable consequences. It is thus more rigorous than a purely qualitative approach but falls short of a full comprehensive quantitative risk analysis. But rather like deterministic methods, it can complement a full stochastic risk analysis by inserting a reality check. Semi-quantitative methods can be used to illustrate comparative risk and consequences in an accessible way to users of the information. Indeed, some output from complex stochastic models may be presented in forms similar to that used in semi-quantitative risk analysis, e.g., risk matrices and traffic light rating systems (for example where red is severe risk, orange is medium risk, yellow is low risk and green is very low risk).

Semi-quantitative risk analysis seeks to categorise risks by comparative scores rather than by explicit probability and financial or other measurable consequences.

A risk matrix is a means to communicate a semi-quantitative risk assessment: a combination of two dimensions of risk, severity and likelihood, which allows a simple visual comparison of different risks.

Severity can be considered for any unwanted consequence such as fire, explosion, toxic release, impact of natural hazards (e.g. floods and tsunamis) with their effects on workers and the community, environmental damage, property damage or asset loss. A severity scale from minor to catastrophic can be estimated or calculated, perhaps informed by some form of model. Normal risk matri-

ces usually have between four and six levels of severity covering this range with a similar number of probability scales. There is no universally adopted set of descriptions for these levels, so stakeholders can make a logical selection based on the purpose of the risk assessment being carried out. The example depicted in Figure 2.2, below, is designed for risk assessment by a chemical production company and is based on effects on people. Similar matrices can be produced for environmental damage, property or capital loss. See also Chapter 2.5, Figure 2.21 for the risk matrix suggested by European Commission (2010).

In this illustrative example the severity scale is defined as:

- insignificant: minor injury quick recovery;
- minor: disabling injury;
- moderate: single fatality;
- major: 2 -10 fatalities;
- severe: more than 11 fatalities.

Similarly, the likelihood scale is defined as:

- rare: no globally reported event of this scale — all industries and technologies;
- unlikely: has occurred but not related to this industry sector;
- possible: has occurred in this company but not in this technology;
- likely: has occurred in this location — specific protection identified and applied;
- almost certain: has occurred in this location — no specific protection identified and applied.

When plotted in the matrix (Figure 2.2), a link may be provided to rank particular risks or to categorise them into tolerable (in green), intermediate (in yellow and orange) or intolerable (in red) bands. A risk which has severe consequences and is estimated to be 'likely' would clearly fall into the intolerable band. A risk which has minor consequences would be intermediate and 'very rare' in likelihood would be in the tolerable band. For risks which appear in the intolerable band, the user will need to decide what is done with the result.

There are choices to be made, either to reduce the severity of the consequence or the receptor vulnerability and/or to reduce the event's likelihood. All may require changes to the hazardous process. Many users would also require intermediate risks to be investigated and reduced if practicable.

Some users apply numerical values to the likelihood and/or severity axes of the matrix. This produces a 'calibrated' matrix.

The following matrix, in Figure 2.3 is derived from the Health and Safety Executive's publication Reducing risks, protecting people (2001) as well as from its final report on the

FIGURE 2.2

A risk matrix
Source: courtesy of authors

LIKELIHOOD	CONSEQUENCES				
	Insignificant	Minor	Moderate	Major	Severe
Almost Certain	M	H	H	E	E
Likely	M	M	H	H	E
Possible	L	M	M	H	E
Unlikely	L	M	M	M	H
Rare	L	L	M	M	H

FIGURE 2.3

A calibrated risk matrix
Source: Health and Safety Executive (2001, 2009)

FREQUENCY/ LIKELIHOOD		SINGLE FATALITY	2 - 10 FATALITIES	11 - 50 FATALITIES	51 - 100 FATALITIES	101+ FATALITIES
Likely	$>10^{-2}$/yr	Intolerable	Intolerable	Intolerable	Intolerable	Intolerable
Unlikely	$>10^{-4}$/yr but $<10^{-2}$/yr	Tolerable (but intolerable if individual risk of fatality $>10^{-3}$/yr)	Tolerable (but intolerable if individual risk of fatality $>10^{-3}$/yr)	Intolerable	Intolerable	Intolerable
Very unlikely	$>10^{-6}$/yr but $<10^{-4}$/yr	Tolerable	Tolerable	Tolerable	Tolerable	Intolerable
Remote	$>10^{-8}$/yr but $<10^{-6}$/yr	Broadly Acceptible	Broadly Acceptible	Tolerable	Tolerable	Tolerable

Buncefield fire and explosion, Safety and environmental standards for fuel storage sites (2009).

Sometimes matrices are used to compare different risk types as per this example from the United Kingdom's National risk register of civil emergencies report (2015). Such matrices are intuitively attractive, but in practice they can be misleading (Cox, 2008).

Very often an assessment of both frequency and severity is highly subjective and so can greatly differ , even when produced by two people with similar experiences; the impact of expert judgement can be profound (Skjong and Wentworth, 2001). It is vital for reasoning to be given for any

FIGURE 2.4

A comparative risk matrix
Source: United Kingdom Cabinet Office (2015)

OVERALL RELATIVE IMPACT SCORE	Between 1 in 20,000 and 1 in 2,000	Between 1 in 2,000 and 1 in 200	Between 1 in 200 and 1 in 20	Between 1 in 20 and 1 in 2	Greater than 1 in 2
5				Pandemic Influenza	
4			Coastal Flooding Widespread electricty failure		
3		Major transport accidents Major industrial accidents	Effusive volcanic eruptions Emerging infectuaous diseases Inland flooding	Severe space weather Low temperatures/heavy snow Heatwaves Poor air quality events	
2		Public disorder Severe wildfires	Animal diseases Drought	Explosive volcanic eruption Storms and gales	
1			Disruptive industrial action		

RELATIVE LIKELIHOOD OF OCCURING IN NEXT 5 YEARS

assessment, therefore allowing debate and challenge.

If subject to a full probabilistic modelling exercise, we would not just have one value for coastal flooding but rather a complete distribution of coastal floods from frequent but very low severity to rare but very high severity.

Which point of the curve should be picked for each peril? Different selections will give very different impressions of comparative risk.

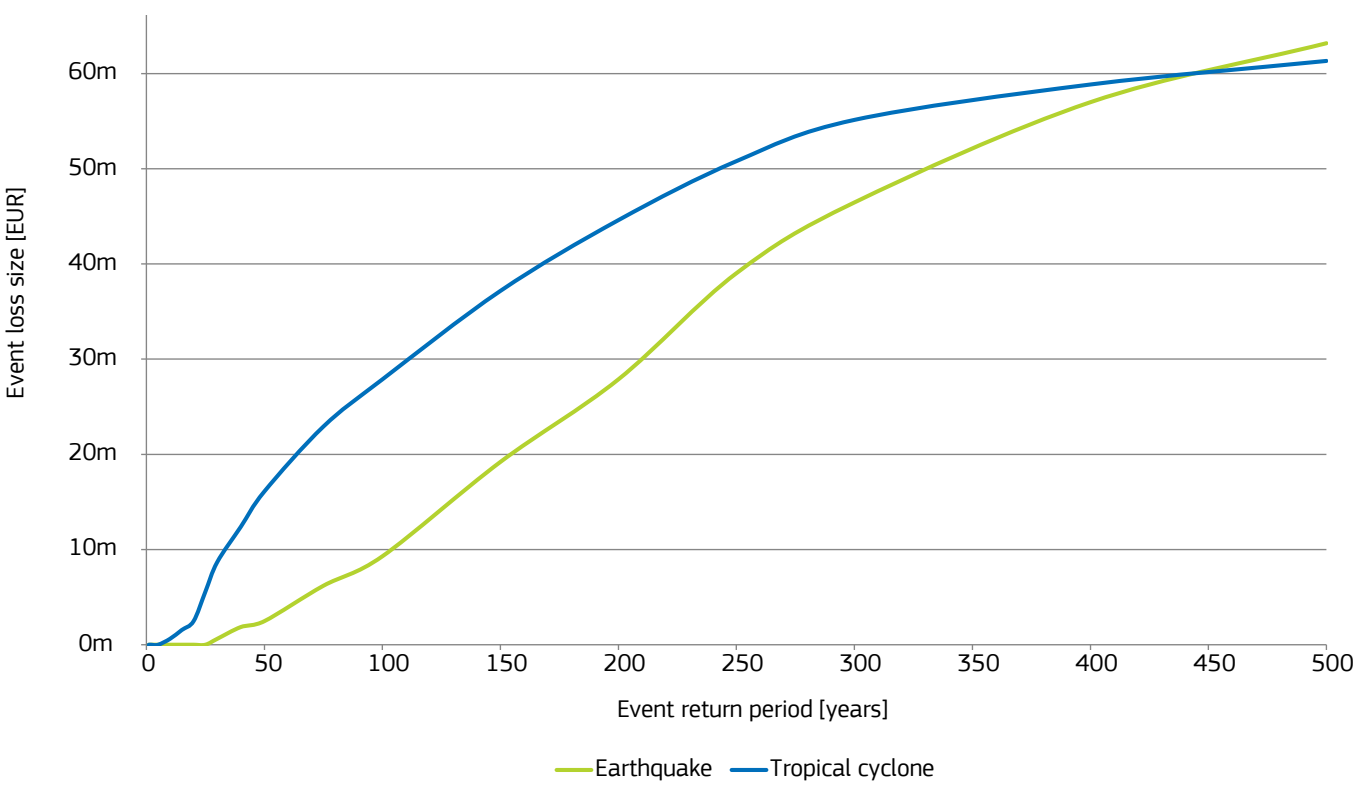
Semi-quantitative methods can be a useful stepping stone towards a full quantitative system, particularly where detailed data are lacking, and can be used as a means to capture subjective opinion and hold it up to challenge, opening debate and becoming a framework to identify where additional analytical effort is required.

2.1.3.4 Probabilistic risk analysis

This method originated in the Cold War nuclear arms race, later adopted by the civil nuclear industry. It typically attempts to associate probability distributions to frequency and severity elements of hazards and then run many thousands of simulated events or years in order to assess the likelihood of loss at different levels. The method is often called Monte Carlo modelling after the gaming tables of the principality's casinos. These methods have been widely adopted by the insurance industry, particularly where problems are too complicated to be represented by simple formulae, including catastrophic natural hazard risks.

FIGURE 2.5

Anonymised insurer comparative event exceedence curve
Source: Willis Towers Watson



A commonly used generic term for these methods is QRA or probabilistic or stochastic risk modelling. Today it is frequently used by industry and regulators to determine individual and societal risks from industries which present a severe hazard consequence to workers, the community and the environment. EU legislation such as the Seveso III directive (Directive 2012/18/EU) requires risks to be mapped and managed to a tolerable level. These industrial requirements have resulted in the emergence of organisations, specialists and consultants who typically use specially designed software models. The use of probabilistic methods is spreading from the industrial field to others, for example the Netherlands flood defence planning.

Probabilistic or stochastic risk analysis seeks to understand and model all potential events with their associated probabilities and outcomes, allowing a sophisticated cost/benefit analysis of different risk management strategies.

Stochastic risk modelling has been wholeheartedly embraced by the re/insurance industry over the past 30 years, particularly for natural catastrophes, though increasingly for all types of risks. EU solvency II regulation (Directive 2009/138/EC), a manifestation of the advisory insurance core principles for regulators set by the International Association of Insurance Supervisors in Basel (IAIS, 2015), allows companies to substitute some or all of their regulatory capital calculation with their own risk models if approved by their regulatory and subject to common European rules.

The main advantage of a quantitative method is that it considers frequency and severity together in a more comprehensive and complex way than other methods. The main problem is that it can be very difficult to obtain data on risks: hazard, exposure, vulnerability and consequential severity. If it is difficult to understand and represent the characteristics of a single risk then it is even harder to understand their interdependencies. There is inevitably a high level of subjectivity in the assumptions driving an 'objective' quantitative analysis. A paper by Apostolakis (2004) on QRA gives a coherent argument for appropriate review and critique of model assumptions. The level of uncertainty inherent in the model may not always be apparent or appreciated by the ultimate user, but the results of a fully quantitative analysis, if properly presented, enhance risk understanding for all stakeholders.

Often the process of building a probabilistic model is as valuable as the results of the model, forcing a structured view of what is known, unknown and uncertain and bringing assumptions that may otherwise be unspoken into the open and thereby challenging them.

Typically for a full stochastic model, severities for each peril would be compared for different probability levels, often expressed as a return period; the inverse of annual probability, i.e. how many years would be expected to pass before a loss of a given size occurred.

Figure 5 gives an example of output of such a model, here showing the size of individual loss for two different perils with return periods of up to the worst that may be expected every 500 years. Note that a return period is a commonly used form of probability notation. A 1-in-200 year loss is the worst loss that can be expected every 200 years, i.e. a loss with a return period of 200 years. A return period is the inverse of probability; a 1- in -200 year event has a 0.5 % probability (1/200).

We can see that, for example, every 100 years the worst tropical cyclone loss we can expect is over EUR 28 million compared to the worst earthquake loss we can expect every 100 years of EUR 10 million.

In fact, a tropical cyclone gives rise to significantly higher economic loss than an earthquake, up until the 1 -in-450-year probability level. But which is the most dangerous? A more likely event probabilities tropical cyclone is much more damaging, but at very remote probabilities it is earthquake. Notice too the very significant differences in loss estimate for the probability buckets used in the National risk register for civil emergencies report (United Kingdom Cabinet Office 2015) risk matrix example in Figure 2.4. The national risk register looks at the probability of an event occurring in a 5-year period, but compares the 1-in-40-year loss to the 1-in-400-year loss, broadly equivalent to the 1-in-200 to 1-in-2 000 5-year bucket: the

loss for both perils at these probability levels is very different.

Terms like '1-in-100 storm' or '1-in -100 flood' are often used in the popular press, but it is important to define what is meant by these terms. Is this the worst flood that can be expected every 100 years in that town, valley, region or country? It is also important not just to look at the probability of single events as per Figure 2.5, an occurrence exceedance probability curve, but also annual aggregate loss from hazards of that type, i.e. an annual aggregate exceedance probability curve. For a given return period the aggregate exceedance probability value will clearly be greater or at least equal to the occurrence exceedance probability — the 1 in 200 worst aggregate exceedance probability could be a year of one mega event or a year of five smaller ones that are individually unexceptional but cumulatively significant.

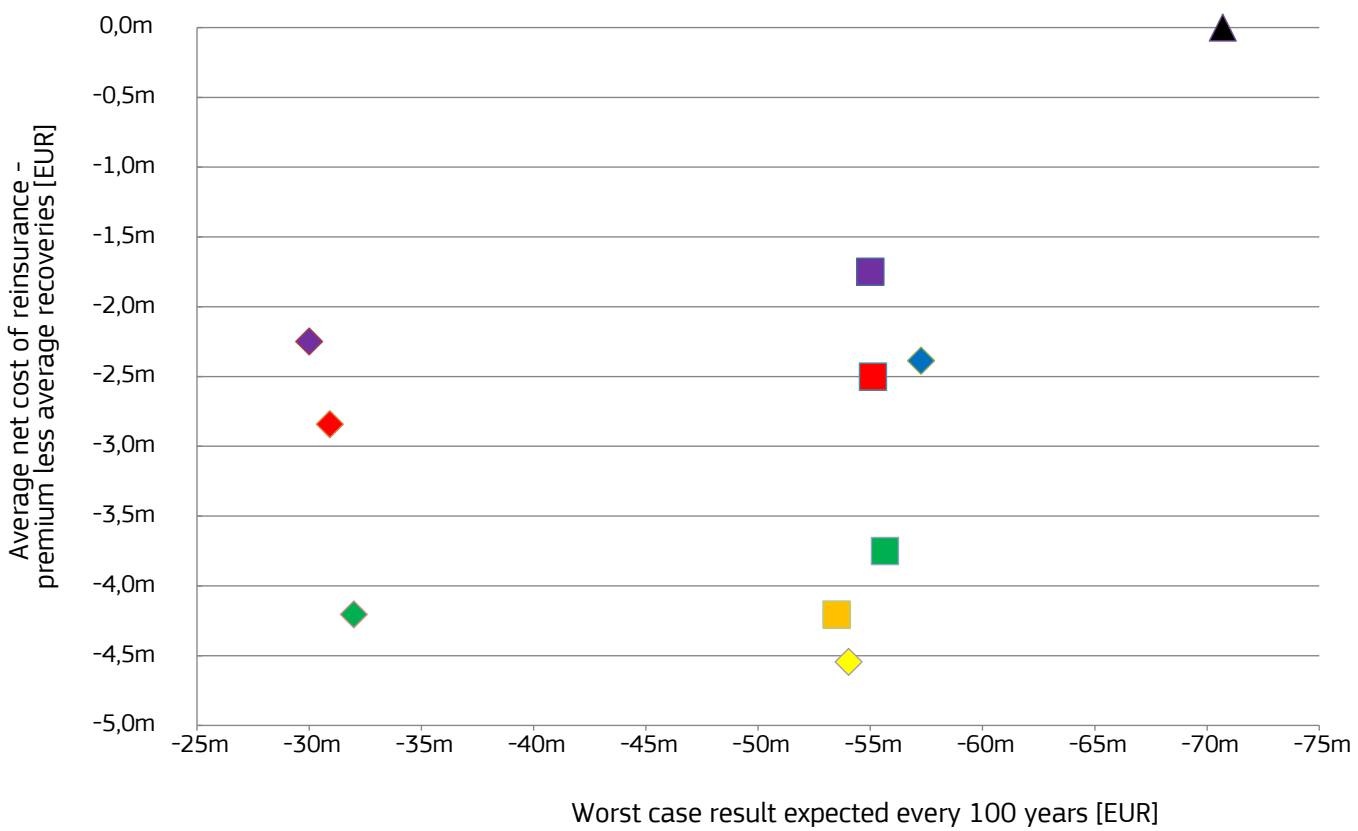
The models can be used to compare the outcome of different strategies to manage and mitigate risk. The cost and benefit of different solutions can be compared, and so an optimal strategy rationalised. An anonymised insurance example is shown in Figure 2.6.

Figure 2.6 compares 10 reinsurance hedging options to manage insurance risk against two measures, one of risk and one of return. On the horizontal axis we have the risk measure: the worse result that we may expect every 100 years, while on the vertical axis we have the return measure, or rather its inverse here, the cost of each hedging option.

Ideally we would be to the top left

FIGURE 2.6

An anonymised example of a risk return analysis
Source: Willis Towers Watson



of the chart: low risk but low cost. The 'do nothing' option is the black triangle at the top right: high risk (a EUR 70 million 1-in-100 year loss) but zero additional cost. The nine reinsurance hedging options fall into two clusters on the chart.

The purple diamond option to the extreme left has the least risk, reducing the 1-in-100 loss to EUR 30 million, but at an annual cost of EUR 2.25 million. The other two options in that cluster cost more and offer less benefit so can be ignored. The best opinion of the middle group is the purple square, reducing the 1-in-100 loss to EUR 55 million but at an annual average cost of EUR 1.75 million. Again, this option clearly offers the best risk return characteristics of all the others in the middle group, so the others in that group may be discounted.

Therefore, from 10 options including the 'do nothing', option we have a shortlist of three:

- black triangle: high risk (EUR 70 million 1-in-100 loss), zero cost;
- purple square: medium risk (EUR 55 million 1-in-100 loss), medium cost (EUR1.75million);
- purple diamond: lowest risk (EUR 30 million 1-in-100 loss), highest cost (EUR2.25million).

Which to pick depends on the risk appetite of the firm. If they are uncomfortable with the unhedged risk then the purple diamond seems to offer much better protection than the purple square option for comparatively little additional cost.

Similar methods can be used to compare options for, say, managing flood risk in a particular location and/or process risk for a particular plant. The same metrics can be used to look at and compare different perils and combinations of perils. The methods make no moral judgements but allowing the cost of a particular strategy to be compared against the reduction is a risk as defined by a specific risk measure. It is at this point that more subjective, political decisions can be made on an informed, objective basis.

An example of a comparative peril analysis for a European city is outlined in a paper by Grünthal et al. (2006) on the city of Cologne.

It must always be remembered that models advise, not decide. Such charts and analyses should not be considered definitive assessments; like any model they are based upon a set of defined assumptions.

2.1.4 Conclusions and key messages

Partnership

The process of risk assessment acts as a catalyst to improve risk understanding and so to encourage a process of proactive risk management. An early adapter of these methods, the global catastrophe insurance and reinsurance industry has been transformed by the process and has become more technically adept, more engaged with science and more financially secure, providing more resilience for society. Similarly, the manufacturing and process industries have embraced structured risk identification and assessment techniques to improve the safety of the manufacturing process and the safety of the consumer.

Disaster risk assessment requires a combination of skills, knowledge and data that will not be held within one firm, one industry, one institution, one discipline, one country, or necessarily one region. Risk assessment requires input from a variety of experts in order to identify potential hazards, those that could occur as well as those in the historical record.

Rigorous approaches to risk assessment require scientific modelling and a precise understanding of risk and probability. Scientific models can be compared in order to challenge the underlying assumptions of each and lead to better, more transparent decisions.

As risk assessments get more quantitative, scientific, and technical, it is important that policymakers are able to interpret them. The assumptions within models must be transparent, and qualitative risk assessment (such as deterministic scenario impacts or risk matrixes) can be useful and complementary to stochastic modelling. It is important that policymakers can demonstrate that appropriate expertise and rigor has been engaged to found risk management decisions firmly.

The practitioner lies in the centre of the many opportunities for partnerships in disaster risk assessment. In order to think beyond accepted ways of working and challenge ingrained assumptions, links between other practitioners in familiar fields as well as other sectors and industries and academia are extremely valuable.

Knowledge

The risk assessment process is structured and covers risk identification, hazard assessment, determining exposure and understanding vulnerability.

Depending on the objective of risk assessment and data availability, risk assessment methods can range in formalization and rigor. There are more subjective scenario based deterministic models, semi quantitative risk analyses such as risk matrixes, and fully quantitative risk assessment; probabilistic or stochastic risk modelling. The more qualitative approaches to risk add value through the process of developing a framework to capture subjective risk perception and serve as a starting point for a discussion about assumptions and risk recognition engaging a wide variety of experts and stakeholders in the process. They also provide a means to reality check more theoretical models. Probabilistic and stochastic analyses provide the potential to perform cost/benefit or risk/return analysis, creating an objective basis for decision making.

Rigorous quantitative approaches to risk assessment and probabilistic analysis raise awareness of the need for further scientific input and the requirement to transfer of knowledge and engagement between science and practitioners.

Risk assessment and analysis provides a framework to weigh decisions, and risk models provide an objective basis against which policy decisions can be made and justified. However, it is important that the limitations of modelling are recognized and inherent uncertainty is understood. Having the ability to compare and challenge assumptions, as well as requiring evidence based analysis, is required.

Risk perception is subjective, but practitioners have valuable information in the fields of data, methodologies and models that further solidify frameworks through which hazards can be understood and compared in an objective fashion.

Innovation

Innovation is required to meet the challenges of lack of data and partial information in risk identification and modelling. Creative approaches can be made to capture and challenges assumptions implicitly or explicitly made and so test them against available data and defined stresses.

Risk analysis creates a framework; a starting point for debate about policy, risk and what we know and cannot know. This leads to greater understanding and better, more transparent decision-making.

No model is perfect. New scientific input can improve and challenge models – testing sensitivity to prior assumption, so leading to a greater understanding of disaster events which in turn leads to safer companies, communities and countries A deeper understanding of the quantitative and qualitative approaches to risk management can help innovate ways of thinking about subjective public risk perception, and risk assessment frameworks can develop a more objective understanding of risk and risk-informed decision making.

Risk assessment and associated modelling contain inherent uncertainty and are not fully complete. It is important to innovate in areas where hazards are less known and capable of anticipation; truly "unknown unknowns" and "known unknowns" must be considered. Similarly assumptions held for "known knowns" should be continuously challenged and tested as new information arises.

2.2 Current and innovative methods to define exposure

***Christina Corbane**, Paolo Gamba, Martino Pesaresi, Massimiliano Pittore, Marc Wieland*

2.2.1 What is exposure?

Exposure with vulnerability (see Chapter 2.3) and hazard (see Chapter 3) is used to measure disaster risk (see Chapter 2.3). It is reported that exposure has been trending upwards over the past several decades, resulting in an overall increase in risk observed worldwide, and that trends need to be better quantified to be able to address risk reduction measures. Particular attention to understanding exposure is required for the formulation of policies and actions to reduce disaster risk (UNISDR, 2015a), as highlighted by the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015b): 'Policies and practices for disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can be leveraged for the purpose of pre -disaster risk assessment, for prevention and mitigation and for the development and implementation of appropriate preparedness and effective response to disasters.

Exposure is a necessary, but not sufficient, determinant of risk (Cardona et al., 2012) (see Chapter 2.1). According to available global statistics, least developed countries represent 11 % of the population exposed to hazards but account for 53 % of casualties, while the most developed countries account for 1.8 % of all victims (Peduzzi et al., 2009) with a population exposure of 15 %. These figures show that similar exposures with contrasting levels of development, of land- use planning and of mitigation measures lead to drastically different tolls of casualties. Hence it is possible to be exposed, but not vulnerable; however, it is necessary to also be exposed to be vulnerable to an extreme event (Cardona et al., 2012).

Due to its multidimensional nature, exposure is highly dynamic, varying across spatial and temporal scales: depending on the spatial basic units at which the risk assessment is performed, exposure can be characterised at different spatial scales (e.g. at the level of individual buildings or administrative units).

Exposure represents the people and assets at risk of potential loss or that may suffer damage to hazard impact. It covers several dimensions like the physical (e.g. building stock and infrastructure), the social (e.g. humans and communities) and the economic dimensions.

Population demographic and mobility, economic development and structural changes in the society transform exposure over time. The quantification of

exposure is challenging because of its interdependent and dynamic dimensions. The tools and methods for defining exposure need to consider the dynamic nature of exposure, which evolves over time as a result of often unplanned urbanisation, demographic changes, modifications in building practice and other socioeconomic, institutional and environmental factors (World Bank, GFDRR, 2014). Various alternative or complementary tools and methods are followed to collect exposure-related data; they include rolling census and digital in situ field surveys. When the amount, spatial coverage and/or quality of the information collected in the ground is insufficient for populating exposure databases, the common practice is then to infer characteristics on exposed assets from several indicators, called proxies. Exposure modelling also has a key role to play in risk assessment, especially for large- scale disaster risk models (regional to global risk modelling (De Bono and Chatenoux, 2015; De Bono and Mora ,2014)). Among the different tools for collecting information on exposure, Earth observation represents an invaluable source of up-to-date information on the extent and nature of the built-up environments, ranging from the city level (using very high spatial resolution data) to the global level (using global coverage of satellite data) (Deichmann et al., 2011; Dell'Acqua et al. ,2013; Ehrlich and Tenerelli, 2013). Besides, change -detection techniques based on satellite images can provide timely information about changes to the built-up environment (Bouziani et al., 2010).The choice of the approach determines the resolution (spatial detail) and the extent (spatial coverage) of the collected exposure data. It also influences the quality of the collected information.

Despite the general conceptual and theoretical understanding of disaster exposure and the drivers for its dynamic variability, few countries have developed multihazard exposure databases to support policy formulation and disaster risk- reduction research. Existing exposure databases are often hazard specific (earthquakes, floods and cyclones), sector specific (infrastructure and economic) or target specific (social, ecosystems and cultural) (Basher et al., 2015). They are often static, offering one-time views of the baseline situation, and cannot be easily integrated with vulnerability analysis.

This chapter reviews the current initiatives for defining and mapping exposure at the EU and global levels. It places emphasis on remote sensing-based products developed for physical and population exposure mapping. Innovative approaches based on probabilistic models for generating dynamic exposure databases are also presented together with a number of concrete recommendations for priority areas in exposure research. The broader aspects of exposure, including environment (e.g. ecosystem services) and agriculture (e.g. crops, supply chains and infrastructures), deserve to be addressed in a dedicated future chapter and will not be covered by the current review.

2.2.2 Why do we need exposure?

There is a high demand for exposure data by the communities that address disaster risk reduction (DRR). National governments and local authorities need to implement DRR programmes; the insurance community needs to set premiums and manage their aggregate exposures; civil society and the aid community need to identify the regions of the world that most urgently require DRR measures (Ehrlich and Tenerelli, 2013). Effective adaptation and disaster risk management (DRM) strategies and practices depend on a rigorous understanding of the dimensions of exposure (i.e. physical and economic) as well as a proper assessment of changes and uncertainties in those dimensions (Cardona et al., 2012).

Both the scope and the scale of the natural hazard impact assessment determine the type of exposure data to be collected.

Risk models require detailed exposure data (e.g. with information on buildings, roads and other public assets) to produce as outputs risk metrics such as the annual expected loss and the probable maximum loss (see Chapter 2.4). For instance, catastrophe models commonly used by the insurance industry include an exposure module, which represents either a building of specific interest, a dwelling representative of the average construction type in a given area or an entire portfolio of buildings with different characteristics

(e.g. an entire city). The characteristics may include physical characteristics like building height, occupancy rate, usage (private, public like commercial, industrial, etc.), construction type (e.g. wood or concrete) and age, and also non-physical characteristics like the replacement cost which is needed for calculating the loss at a certain location (Michel-Kerjan et al., 2013). Besides, insurance companies need to assess and model the business interruption that represents a major part of the total economic loss. To quantify loss due to business interruption, exposure databases need to include information on building contents and business information for different types of properties (Rose and Huyck 2016). These industry exposure databases are often proprietary and use heterogeneous taxonomies and classification systems which hinder efforts of merging independently developed datasets (GFDRR, 2014). However, the Oasis (OASIS, 2016) community and the recently established Insurance Development Forum are dedicating special efforts to exposure data harmonisation, sourcing, structuring and maintenance at the global levels. Moreover, an initiative lead by Perils is offering de facto standard industry exposure databases for property across Europe at an aggregated spatial level (PERILS, 2016).

If the aim is to know whether a particular feature is likely to be affected or not by a certain level of hazard, then it is enough to simply identify the location of that feature (e.g. building location and building footprint) or group of features (e.g. building stock). Whereas if the purpose is to understand the potential economic impacts or human loss, then other attributes of the feature or group of features need to described (e.g. the type of construction materials, population density and the replacement value). Exposure databases detailed to single building units are seldom available for disaster modellers. Instead, the exposure data are more often available in an aggregated level for larger spatial units related to arbitrary areal subdivision of the settlements, census block, postal codes, city blocks or more regular gridded subdivision. A spatial unit may contain a statistic summary of building information such as average size and average height, density or even relative distribution of building types (Ehrlich and Tenerelli, 2013). For optimal results the choice of the attribute and its granularity should be aligned with the scale and the purpose of the risk assessment. To a certain extent, the requirements in terms of granularity also depend on the peril being modelled: e.g. flood models require detailed information on the location and building type. By contrast, windstorm models arguably need to be less precise. Detailed gust speeds will not be known at a precise location level but rather estimated on a broader spatial scale. There are clearly many attributes that can be attached to exposure data. Developing such databases requires a multidisciplinary team of construction engineers, economists, demographers and statisticians.

In recent years, several exposure datasets with regional or global coverage have attempted to generate detailed building inventories and compile exposure data despite the challenges related to the heterogeneous mapping schemas, the different typologies and the varying resolutions. In the following sections, we review the existing initiatives at EU and global levels that have made a first step in overcoming these obstacles either i) by using exposure proxies such as land -use and land- cover products, ii) by using Earth observation technologies for mapping human settlements and population or iii) by integrating existing information from different acquisition techniques, scales and accuracies for characterising the assets at risk and for describing the building stock. We purposely limit the review here to large -scale exposure datasets that have a spatial component (i.e. associated with a geographic location) and that are open, hence ensuring replicability and a better understanding of risk (World Bank, 2014).

2.2.3 Land-cover and land-use products as proxies to exposure

These products outline areas with different uses, including 'industrial', 'commercial' and 'residential' classes, as well as non-impervious areas (e.g. green spaces).

Land- use and land-cover (LU/LC) information products that are usually derived from remote sensing data may provide information on buildings and thus on exposure.

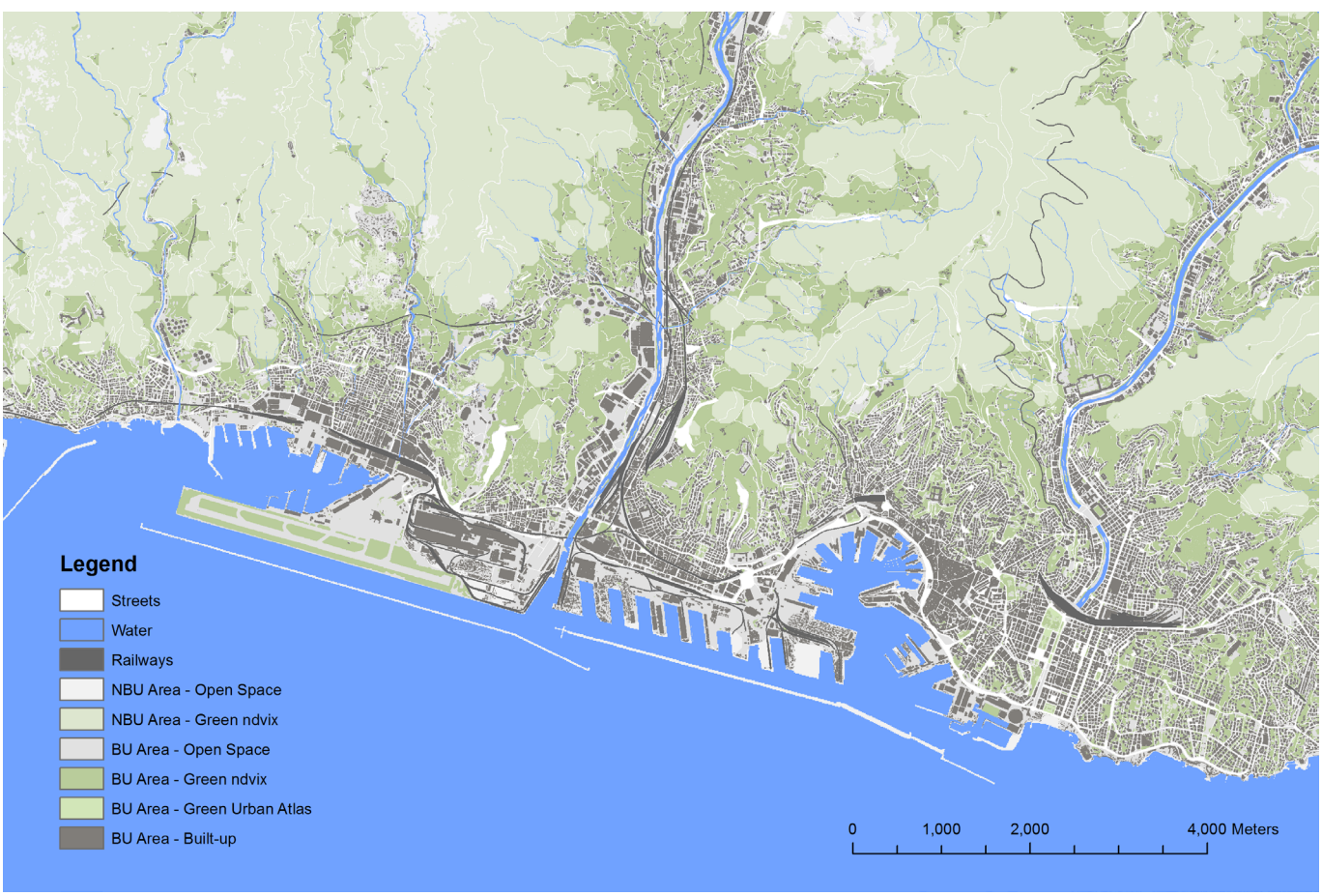
Some products may also describe the building density. LU/LC maps provide valuable information on infrastructure such as roads. The spatial characteristics of LU/LC maps are influenced by the minimum mapping units , which refer to the smallest size area entity to be mapped.

2.2.3.1 European land-use and land-cover (LU/LC) products

The currently available EU-wide and global LU/LC products have minimum mapping units ranging between 0.01 ha (e.g. the European Settlement Map (ESM)) to 100 ha (e.g. MODIS land cover). At the EU level, the Corine Land Cover is the only harmonised European land cover data available since 1990. It comprises 44 thematic classes with units of 25 ha and 5 ha for changes, respectively. From 1990 until 2012, four of such inventories were produced and completed by change layers, and it has been used for several applications like indicator development, LU/LC change analysis (Manakos and Braun, 2014) and flood risk assessment within the EU context (Lugeri et al., 2010). However, its limitations in terms of spatial resolution do not allow the conversion of land- cover classes into accurate, physical exposure maps. To complement LU/LC maps, detailed inventories of infrastructures are essential for assessing risks to infrastructures as well as for managing emergency situations. In 2015, a geographical

FIGURE 2.7

European Settlement Map– 10 m resolution – Genova
Source: European Commission (JRC)



database of infrastructure in Europe was developed including transport networks, power plants and industry locations. (Marin Herrera et al., 2015). The database was successfully used in a comprehensive multihazard and multisector risk assessment for Europe under climate change (Forzieri et al., 2015).

The Urban Atlas is another pan-European LU/LC product describing, in a consistent way, all major European cities' agglomerations with more than 100 000 inhabitants. The current specifications of the Urban Atlas fulfil the condition of a minimum mapping unit of 0.25 ha, allowing the capture of urban, built-up areas in sufficient thematic and geographic detail (Montero et al., 2014). The Urban Atlas cities are mapped in 20 classes, of which 17 are urban classes. It is a major initiative dealing with the monitoring of urban sprawl in Europe, designed to capture urban land use, including low- density urban fabric, and in this way it offers a far more accurate picture of exposure in urban landscapes than the Corine Land Cover does. Despite its accuracy and relevance for risk modelling, the main limitation of this product is its spatial coverage, as it is restricted to large urban zones and their surroundings (more than 100 000 inhabitants).

Currently, the continental map of built-up areas with the highest resolution so far produced is the ESM (Florczyk et al., 2016). The ESM (Figure 2.7) is a 10 metre x 10 metre raster map expressing the proportion of the remote sensing image pixel area covered by buildings; it was produced in 2013-2014. It was developed jointly by two services of European Commission (JRC and REGIO). The ESM is distributed as a building density product at both 10 metre x 10 metre and 100 metre x 100 metre resolutions, each supporting specific types of applications. For a pan-European risk assessment (Haque et al. 2016), the coarser (100 metre) resolution is sufficient, whereas the 10 metre product would be necessary for local to regional risk assessment.

2.2.3.2 Global land-use and land-cover products

A number of global land- cover products covering different time periods and different spatial resolutions have been created from remote sensing, e.g. MODIS (Friedl et al., 2010), Africover, GLC-SHARE of 2014 (Latham et al., 2014), GLC2000 (Fritz et al., 2010), IGBP (Loveland et al., 2000) and GlobCover (Arino et al., 2012). Many of these products are based on coarse resolution sensors, e.g. GLC2000 is at 1 km, MODIS is at 500 metre and GlobCover is at 300 metre resolution, which hampers the potential to provide accurate exposure data that can directly feed into risk assessment models.

The first high- resolution (30 metres) global land -cover product is the GlobeLand30, which comprises 10 types of land cover including artificial surfaces for years 2000 and 2010 (Chen et al., 2015). However, the 'artificial surfaces' class consists of urban areas, roads, rural cottages and mines impeding the straightforward conversion of the data into physical exposure maps.

The Global Urban Footprint describing built-up areas is being developed by the German Aerospace Centre and is based on the analysis of radar and optical satellite data. The project intends to cover the extent of the large urbanised areas of megacities for four -time slices: 1975, 1990, 2000 and 2010 at a spatial resolution of 12 metre x 12 metre (Esch et al., 2012). Once available, this dataset will allow effective comparative analyses of urban risks and their dynamics among different regions of the world.

The global human settlement layer (GHSL) is the first global, fine- scale, multitemporal, open data on the physical characteristics of human settlements. It was produced in the framework of the GHSL project, which is supported by the European Commission. The data have been released on the JRC open data catalogue (Global Human Settlement Layer, 2016). The main product, GHS Built-up, is a multitemporal built-up grid (built-up classes: 1975, 1990, 2000 and 2014), which has been produced at high resolution (approximately 38 metre x 38 metre). The GHS Built-up grid was obtained from the processing of the global Landsat archived data in the last 40 years in order to understand global human settlement evolution. The target information collected by the GHSL project is the built-up structure or building aggregated in built-up areas and then settlements according to explicit spatial composition laws. They are the primary sign and empirical evidences of human presence on the global surface that are observable by current remote sensing platforms. As opposed to standard remote sensing practices based on urban land cover or impervious surface notions, the GHSL semantic

approach is continuously quantitative and centred around the presence of buildings and their spatial patterns (Pesaresi et al., 2015; Pesaresi et al., 2013). This makes the GHSL perfectly suitable for describing the physical exposure and its changes over time at a fine spatial resolution (Pesaresi et al., 2016).

2.2.4 Status of population exposure at the EU and global levels

The static component relates to the number of inhabitants per mapping unit and their characteristics, whereas the dynamic component refers to their demography and their activity patterns that highlight the movement of population through space and time. Population distribution can be expressed as either the absolute number of people per mapping unit or as population density. Census data are commonly used for enumerating population and for making projections concerning population growth. Census data may also contain other relevant characteristics that are used in risk assessment, such as information on age, gender, income, education and migration.

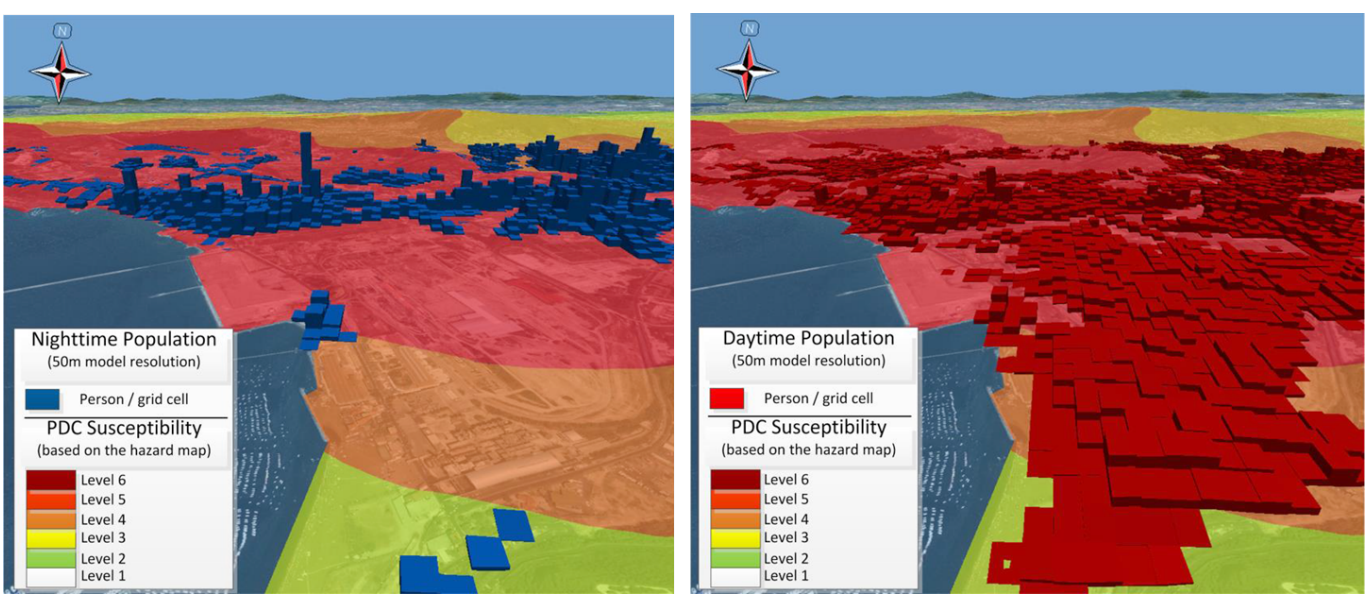
For large- scale analysis, census data are costly and seldom available in large parts of the world or are even outdated or unreliable. Remote sensing, combined with dasymetric mapping, represents an interesting alternative for large- scale mapping of human exposure. Dasymetric mapping consists in disaggregating population figures reported at coarse source zones into a finer set of zones using ancillary geographical data like LU/LC.

2.2.4.1 European-wide population grids

At the EU level, a European population grid with a spatial resolution of 100 metres x 100 metres was produced (Batista e Silva et al., 2013). The method involved dasymetric mapping techniques with a resident population reported at the commune level for the year 2011 and a refined version of the Corine Land Cover as the main input sources. The data are publically distributed on the geographic information system of the Commission following the standardised 1 km x 1 km grid net and the Inspire specifications. A new population grid at 10 me-

FIGURE 2.8

Modeled nighttime and daytime population densities (at 50 m) and volcanic hazard zones in Campi Flegrei – Naples.
Source: Sergio Freire et al. (2015)



tres has recently been produced for the whole European territory, which builds on the ESM at 10 metres as a proxy of the distribution of residential population and 2011 census data (Freire et al., 2015a). The layer has been produced upon request of the European Commission and will soon be made freely available and downloadable online. Figure 2.8. shows an example of potential uses of the 10 -metre- resolution, EU- wide ESM map for modelling day and night population distribution in volcanic risk assessment.

2.2.4.2 Global human exposure

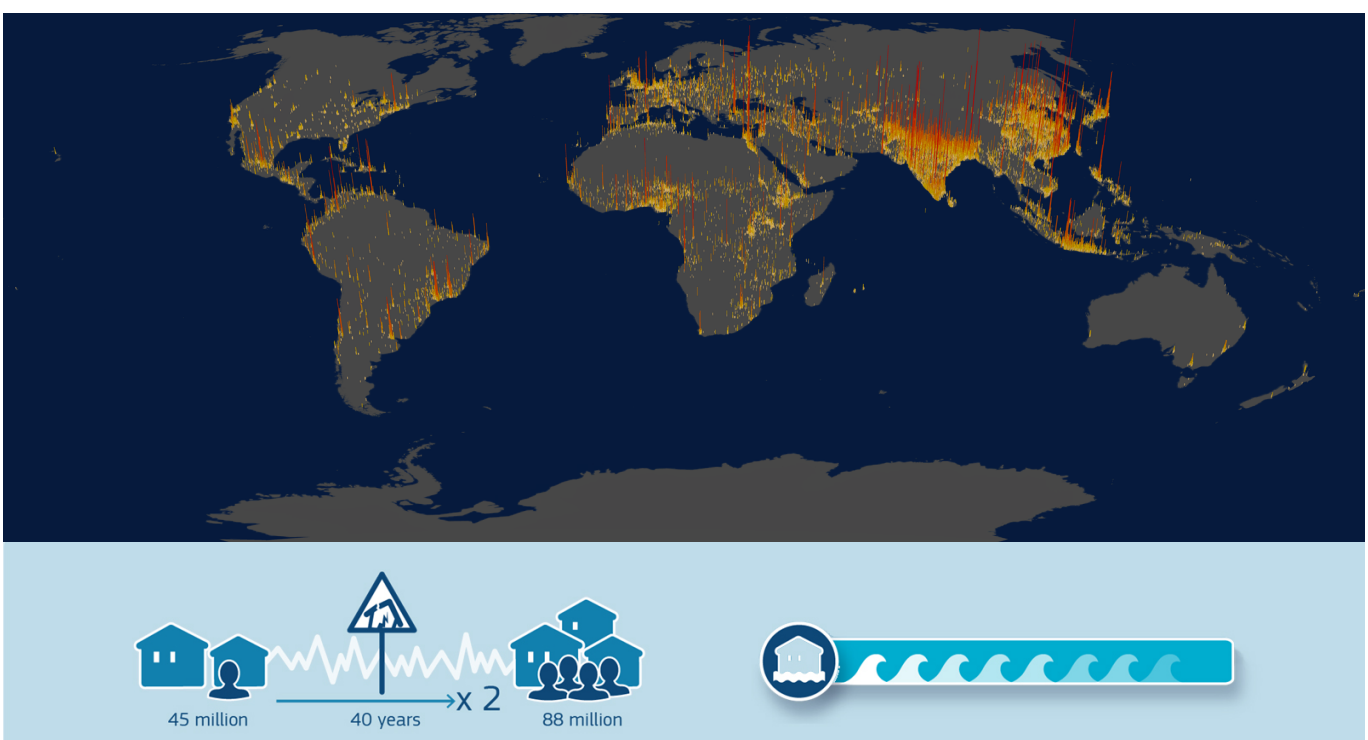
Global distribution of population in terms of counts or density per unit area is considered as the primary source of information for exposure assessment (Pittore et al., 2016). Global population data are available from the LandScan Global Population Database (Dobson et al., 2000), which provides information on the average population over 24 hours and in a 1 km resolution grid.

The LandScan data have annual updates and are widely used despite being a commercial product. Although LandScan is reproduced annually and the methods are constantly revised, the annual improvements made to the model and the underlying spatial variables advise against any comparison of versions.

Other global human exposure datasets include the Gridded Population of the World (GPWv4) available at a resolution of approximately 5 km at the equator. It is developed by SEDAC and provides population data estimates at a spatial resolution of approximately 1 km at the equator. For GPWv4 , population input data are collected at the most detailed spatial resolution available from the results of the 2010 round of censuses, which occurred between 2005 and 2014. The input data are extrapolated

FIGURE 2.9

Global human exposure represented by the GHSL population data in 3D. The box represents an example of application for analysing the evolution of exposure to coastal hazards over the last 40 years.
Source: Pesaresi et al. (2016)



to produce population estimates for the years 2000, 2005, 2010, 2015, and 2020 (Neumann et al., 2015).

The open WorldPop is another initiative providing estimated population counts at a spatial resolution of 100 metres x 100 metres through the integration of census surveys, high- resolution maps and satellite data (Lloyd et al., 2017) . Within the WorldPop project, population counts and densities are being produced for 2000-2020; the available data currently essentially cover America, Asia and Africa.

People present the most important elements-at-risk with a static and dynamic component.

Recently, within the framework of the GHSL, an improved global layer called GHS-POP, which maps the distribution of the population with unprecedented spatio-temporal coverage and detail, has been released. The data have been produced from the best available global built-up layer (GHS-BU) and from census geospatial data derived from GPWv4. The population grids correspond to residential-based population estimates in built-up areas and not 'residential population' or 'population in their place of residence', for which consideration of land use would be required (Freire et al., 2015b).

The multitemporal data are available free of charge at a spatial resolution of 250 metres x 250 metres for 1975, 1990, 2000 and 2015. It has already successfully been used in the context of global risk assessment for the analysis of the increase in population exposure to coastal hazards over the last 40 years (Pesaresi et al., 2016).

2.2.5 Exposure data describing the building stock

Several exposure databases attempt to characterise the assets at risk by including physical exposure information. The latter is often derived from the integration of a large variety of possible exposure information sources using different modelling approaches. We review here the existing initiatives that describe the building stock through a variety of attributes (e.g. height, construction material and replacement value).

2.2.5.1 EU-wide building inventory databases

The European Union's seventh framework programme for research and technological development (FP7) project, the NERA (Network of European Research Infrastructure for Earthquake Risk Assessment and Mitigation) initiated the development of a European building inventory database to feed into the Global Exposure Database (GED) (see Chapter 2.2.5.2). The database builds upon the outcomes of NERIES project (Network of Research Infrastructures for European Seismology) to compile building inventory data for many European countries and Turkey (Erdik et al., 2010). The European building inventory is a database that describes the number and area of different European building typologies within each cell of a grid, with a resolution of at least 30 arc seconds (approximately 1 km2 at the equator) for use in the seismic risk assessment of European buildings (Crowley et al., 2012). The database includes building/dwelling counts and a number of attributes that are compatible with the Global earthquake model's basic building taxonomy (i.e. material, lateral load, number of storeys, date of construction, structural irregularity, occupancy class, etc.). This inventory contains useful information for the assessment of risk assessment and for the estimation of economic loss at the EU level.

2.2.5.2 Global building inventory databases

The prompt assessment of global earthquakes for response (PAGER) (Jaiswal et al., 2010), the GED for GAR 2013 (GEG-2013) and the GED for the Global earthquake model (GED4GEM) are examples of global exposure databases that specifically include physical exposure information.

On a country-by-country level, the PAGER (Jaiswal et al., 2010) contains estimates of the distribution of building types categorised by material, lateral force resisting system and occupancy type (residential or non-residential, urban or rural). The database draws on and harmonises numerous sources: (1) United Nations statistics, (2) the United Nations habitat's demographic and health survey database, (3) national housing censuses,

(4) the world housing encyclopaedia project and (5) other literature. PAGER provides a powerful basis for inferring structural types globally. The database is freely available for public use, subject to peer review, scrutiny and open enhancement.

The GEC-2013 (De Bono and Chatenoux, 2015) is a global exposure dataset at 5 km spatial resolution which integrates population and country-specific building typology, use and value. It has been developed for the global risk assessment 2013 with the primary aim of assessing the risk of economic loss as a consequence of natural hazards at a global scale. The development of GEG-2013 is based on a top-down or 'downscaling' approach, where information including socioeconomic, building type and capital stock at a national scale are transposed onto a regular grid, using geographic population and gross domestic product distribution models as proxies. GEG-2013 is limited in some important ways: i) it was fundamentally constructed using national indicators that were successively disaggregated onto a 5 × 5 km grid; and ii) the capital stock in each cell is distributed on the basis of the number of persons living in that cell and does not take into account the real value of the assets of the cell. The data can be downloaded from the GAR risk data platform.

The GED4GEM is a spatial inventory of exposed assets for the purposes of catastrophe modelling and loss estimation (Dell'Acqua et al., 2013, Gamba et al., 2012). It provides information about two main assets at risk: residential population and residential buildings. Potentially, it can also include information about non-residential population and buildings, although the amount of information for these two additional assets is currently quite limited. In general, the GED is divided into four different levels, which are populated from different data sources and use different techniques. Each level has a different geographical scale as for the statistical consistency of the data it contains as well as a different level of completeness. Each level is thus appropriate for a different use:

- Level 0 — A representation of the population and buildings on a 30-arc seconds grid with information about the buildings coming from statistics available at the country level. The building distribution is thus the same for each element of the grid belonging to a given country, with a binary difference between 'rural' and 'urban' areas.

- Level 1 — A representation of population and buildings on a 30 -arc seconds grid with information about the buildings that is available using the subnational statistics (e.g. for regions, states, provinces or municipalities according to the different countries).

- Level 2 — A representation where each element of the same 30 -arc seconds grid includes enough information to be consistent by itself, and no distribution on a bigger geographical scale is used. This case corresponds to the situation when all building counts are actually obtained, not by means of a disaggregation of a distribution available on a wider area on the elements of the grid but by aggregating building -level data, possibly available for the area of interest.

- Level 3 — A representation at the single building level, including all the possible information about each building, such as structural, occupancy and economic variables.

The first version of the GED contains aggregate information on population and the number/built area/reconstruction cost of residential and non-residential buildings at a 1 km resolution. Detailed datasets on single buildings are available for a selected number of areas and will increase over time.

2.2.6 Future trends in exposure mapping: towards a dynamic exposure modelling

The review of existing initiatives for defining and mapping exposure shows that there is a clear trend towards the use of satellite data in combination with statistical modelling (top-down and bottom-up approaches) for building exposure data: remotely sensed data sourcing for exposure is particularly useful in low-income and emerging economies which lack well-established data collection resources, frameworks and agencies. These economies are often also undergoing rapid urbanisation with dramatically changing exposure concentrations over short periods of time.

In parallel, over the last 5 years, the field of risk assessment has been increasingly driven by open data and open -source modelling, as highlighted in the report Understanding risk in an evolving world (GFDRR, 2014).

Open data initiatives such as the Humanitarian OpenStreetMap Team has contributed significantly to the collection of exposure data in vulnerable countries: in a little over a year, more than 160 000 individual buildings were mapped through crowdsourcing and in situ surveys.

At present, one of the most challenging aspects of exposure modelling is to implement multihazard exposure models through dynamic, scalable frameworks. The dynamic nature of such frameworks in this context reflects the need to explicitly account for both the time variability of the exposed assets and the constant evolution of their representation in the model, which is seldom complete and exhaustive.

Remote sensing, combined with dynamic exposure modelling and bottom-up approaches such as citizen mapping initiatives, can be an effective way to build large exposure databases .

In a dynamic, multiresolution exposure model, two basic types of entities should therefore coexist: atomic data and statistical (aggregated) models. Atomic data refer to physical structures such as buildings or bridges that have been analysed individually and possibly not fully enumerated. Statistical models are aggregated descriptions defined over specific geographic boundaries and possibly influenced by atomic data. Atomic data and statistical models are closely related and mutually interactive, with both having geometric properties and attributes. Compound models accommodating both atomic data and statistical models would be able to optimally exploit direct, in situ information obtained from specialised surveys, even if not complete and exhaustive, by constraining a set of statistical distributions describing the assets' attributes at the atomic level (e.g. material properties for a single building) or at the aggregation boundary level (for instance the expected number of storeys of different building types based on empirical observations in a city district). At atomic level, this can be obtained for instance by modelling the (in)dependence relationships among different assets' attributes and with external covariates (e.g. geographical location, altitude, terrain slope, etc.).

An example for a probabilistic information integration approach is given in Pittore and Wieland (2013), where Bayesian networks are proposed for their sound treatment of uncertainties and for the possibility of seamless merging of different data sources, including legacy data, expert judgement and data mining- based inferences. Due to the increasingly large variety of possible exposure information sources including sparse and incomplete data available at small- scale resolution, the issue of the need for the flexible integration of existing information at different scales and accuracies in order not to discard available information needs to be confronted.

To exploit the full capabilities of the available information in combined spatio-temporal approaches, a database is needed that allows one to model and query complex data types composed of multiple spatial and temporal dimensions. Information extracted from a satellite image or manually sampled in situ show different degrees of quality in terms of reliability and accuracy. Therefore, a probabilistic framework for information integration, updating and refinement is required, as exemplified in Pittore and Wieland (2013). During monitoring activities, the resulting information model continuously evolves and a dynamic exposure database should be able to track an object's evolution over space and time while accounting for its identity which is the lifespan of an object. To this regard, Pittore et al. (2015) propose a novel approach to prioritise exposure data collection based on available information and additional constraints. They utilise the concept of focus maps (Pittore, 2015), which combine different information layers into a single raster representing the probability of the point being selected for surveying, conditional on the sampling probability of each of the other layers. Based on a focus map, a set of sampling points is generated and suitably routed on the existing road network. This allows one to realise a further optimisation of the overall data collection by including additional survey constraints in the routing algorithm and which drives the in situ data collection phase. Iteratively repeating this process allows for an efficient model updating which can be optimised to fit the available time and resources.

2.2.7 Conclusions and key messages

The increasing availability of detailed and harmonised hazard datasets is calling for parallel efforts in the production of standardised multihazard exposure information for disaster risk models. GEDs can be a possible solution for harmonisation and for moving beyond single-hazard databases. Several recommendations can be distilled from this overview and are provided here to develop a roadmap towards the effective implementation of global, dynamic exposure databases. Finally, exposure data collection should be regarded as a continuous process sustaining a continuous re-evaluation of risks to enable an effective DRR.

Partnership

Authoritative and non-authoritative sources should be integrated in order to ensure quality standards and compliance with the disaster risk- reduction purposes. Within this context, it becomes important to harvest data from crowd-sourced information and exploit volunteered geographic information to augment authoritative sources and involve communities and experts, especially in data-poor countries.

Knowledge

The need for quality assessment and an analysis of the uncertainty in the exposure data to avoid error propagation. Quantification of exposure data uncertainty is useful for anatomising the structure of the total uncertainty in the risk assessment into individual uncertainties associated with the risk components (exposure uncertainty compared to that of hazard and vulnerability). In addition, the communication of uncertainty to the users of the exposure databases is also essential to ensure local understanding and trust in the data.

Innovation

Data and (statistical) models have to coexist in a statistically sound framework in order to overcome the impracticality of having a complete and fully enumerated global dynamic exposure database. Flexible integration of existing information at different scales and accuracies in order not to discard available information needs to be confronted. To this regard, rapid, large-scale data collection based on remote sensing should be fully exploited and be complemented whenever possible by information collected in situ using suitable sampling methodologies.

2.3 The most recent view of vulnerability

***Stefan Schneiderbauer**, Elisa Calliari, Unni Eidsvig*
Michael Hagenlocher

2.3.1 The importance of vulnerability for disaster risk assessment

2.3.1.1 Vulnerability: a key component to determine risks

Disaster risk is determined by the combination of physical hazards and the vulnerabilities of exposed elements. Vulnerability relates to the susceptibility of assets such as objects, systems (or part thereof) and populations exposed to disturbances, stressors or shocks as well as to the lack of capacity to cope with and to adapt to these adverse conditions. Vulnerability is dynamic, multifaceted and composed of various dimensions, all of which have to be considered within a holistic vulnerability assessment.

Vulnerability plays a fundamental role for understanding, assessing and reducing risks. When a hazardous event occurs — be it of natural, technological or man-made origin — the vulnerability of exposed people, objects (e.g. critical infrastructure, etc.) and systems (e.g. socioecological systems) at different scales is key to determine the severity of the impact. Though this fact has been widely accepted, the definition of vulnerability and the components it comprises varies between different authors and disciplines.

The United Nations Office for Disaster Risk Reduction (UNISDR Terminology, 2017) defines vulnerability as 'the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. This definition reflects the last decades' shift in the understanding of vulnerability from a focused concept (for example limited to physical resistance of engineering structures) to a more holistic and systemic approach. At the same time, it does not provide reference to the political/institutional situation and does not account for power relations or the heterogeneity within communities, which are aspects considered as important and included in the definitions proposed by other authors (Cardona et al., 2012; Alexander, 2013; Birkmann et al., 2013; Wisner, 2016)

Vulnerability represents a fundamental component of risk. A proper understanding of vulnerability comprising its dimensions as well as its root causes is important for effective risk assessment and risk reduction.

The significance of vulnerability for assessing risk is emphasised by the fact that the consequences of a haz-

ardous event largely depend on human factors. That is, the hazardous event itself may be predominantly an external phenomena out of the control of those affected; any devastating impact caused by this event, however, is mainly influenced by inherent societal conditions and processes.

The L'Aquila earthquake in April 2009 in Italy is an example of a medium-power seismic event that had a disproportionately large human impact. It caused 308 fatalities, most of which were the young and elderly, as well as women. The death toll is partially linked to the high vulnerability of building stock in the mountains of Abruzzo. It is in part explained by the risk perception among female victims, who tend to be more fatalistic than men and who perceived their homes as a refuge, instead of leaving it (Alexander, 2010; Alexander and Magni, 2013).

The degree of vulnerability within a society or a population group is usually not homogenously distributed; social class, ethnic origin, age and gender may determine a lower or higher probability of being affected. Evidence of this fact has been shown by the impact of Hurricane Katrina, which caused a disproportionately high number of victims amongst the poor black and elderly population in New Orleans in 2005 (Cutter et al., 2006).

Addressing vulnerability — together with exposure — represents the gateway for risk reduction measures. Consequently, the importance of vulnerability for DRM is underlined by the Sendai framework for disaster risk reduction, claiming that understanding disaster risk (Priority 1) and developing related policies and practices need to consider the various dimensions of vulnerability (UNISDR, 2015a).

BOX 2.1

Resilience and capacities

Besides the notion of 'vulnerability' there are other terms and concepts addressing the possibility of harm to a system, people or specific objects by certain events and processes. Vulnerability – understood as a holistic and systemic concept – is closely related to and partly overlaps, for example, with the concepts of resilience and of coping and adaptive capacity.

'Resilience' is a term that has been widely used over the last years to describe characteristics related to the ability to absorb stresses, to respond to changes and to recover from shocks. Some authors see resilience as the positive flipside of vulnerability. A broader understanding of resilience incorporates the ability and willingness to learn, to reorganise and to undertake critical self-reflection (Alexander 2013; Kelman et al., 2016). Climate resilience has emerged into a new doctrine under the umbrella of which communities define the activities to combat the impending implications of climate change.

There are numerous related activities within Europe, for example the RESIN project is investigating climate resilience in European cities, the European Commission's FP7 project emBRACE has focused on community resilience and developed a set of key indicators for assessing it, and the Commission's Horizon 2020 project 'resilens' is scrutinising the resilience of European critical infrastructure.

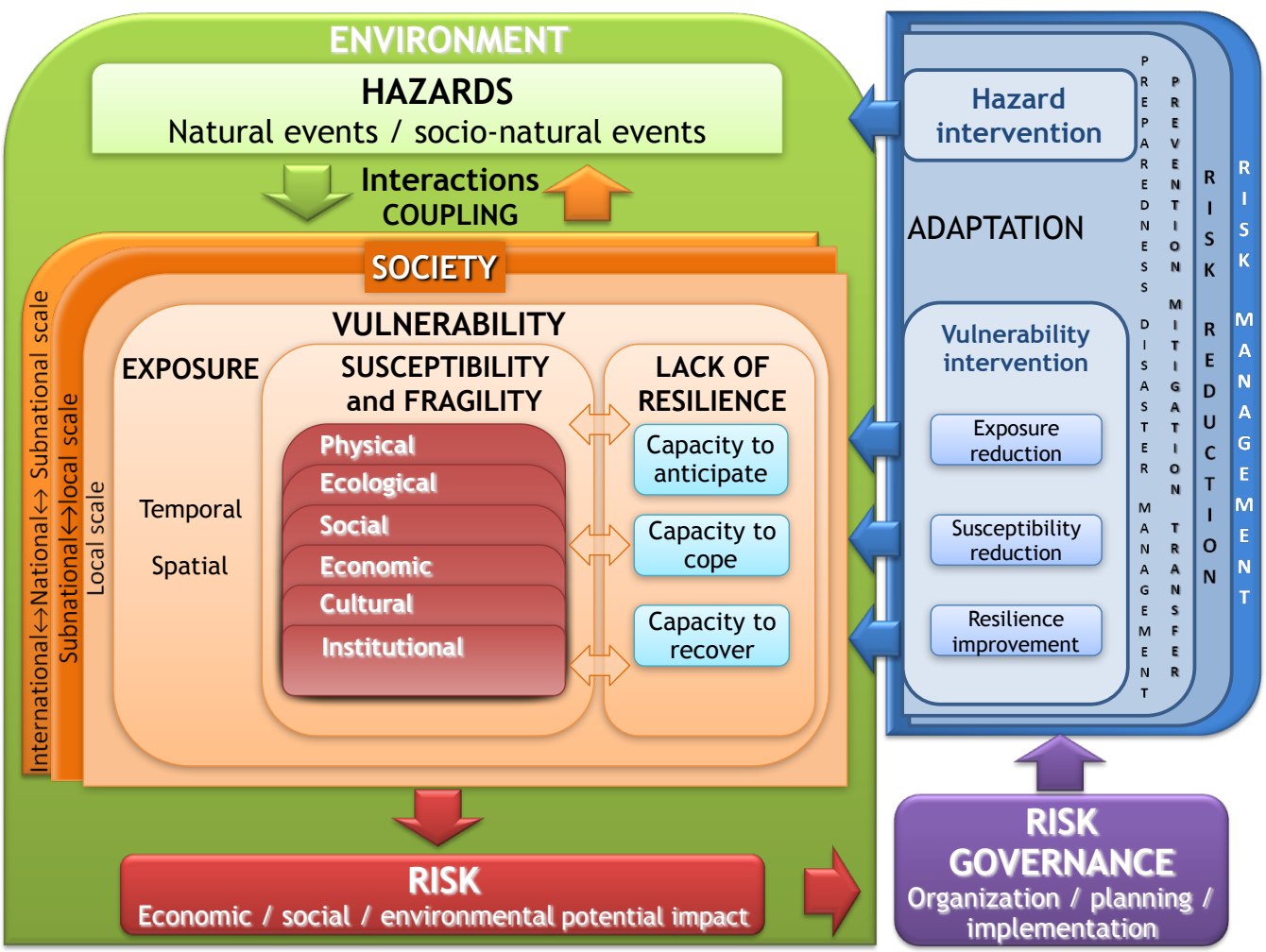
Just as the term 'resilience', the concept of capacities relates to the possibilities and abilities to reduce harm under hazardous conditions. Hereby, 'coping capacity' rather deals with the short-term conservation and protection of the current system and institutional settings, whilst 'adapting capacity' denotes a longer-term and constantly unfolding process of learning (Birkmann et al., 2013).

2.3.1.2 Conceptual issues and dimensions of vulnerability

Just as there are numerous definitions of the term 'vulnerability', there exist many models and concepts that describe vulnerability in its relation to other terms, such as resilience, exposure or capacities, and that elaborate on vulnerability's key dimensions. The European project 'Methods for the improvement of vulnerability assessment in Europe' (MOVE) developed such a concept, which attempts to represent the multifaceted nature of vulnerability (Figure 2.10). In its central part, it identifies six thematic dimensions of vulnerability: the physical, the ecological, the social, the economic, the cultural and the institutional dimension. All of these dimensions have to be considered within a holistic vulnerability study. The majority of assets and systems exposed to hazard will exhibit more than one dimension of vulnerability and hence these dimensions need to be addressed more in detail for any

FIGURE 2.10

The MOVE framework to conceptualise vulnerability
Source: Birkmann et al. (2013)



assessment (Birkmann et al., 2013). This framework is particularly useful within the context of disaster risk since it embeds vulnerability in the wider framework of risk governance/ management and emphasises the various intervention opportunities that may be taken to reduce risk.

A key initial question when scrutinising vulnerability is who or what is vulnerable to what type of threat or hazard. This leads to the question of how the interactions between hazards and vulnerabilities look like. In fact, there are significant differences in the way the various factors that determine vulnerability are linked or connected to different types of hazards. Typically, physical characteristics of elements at risk are directly linked to a particular hazard. For example, the degree to which a building withstands an earthquake is directly linked to the type of building material used. However, a great level of resistance related to earthquakes as a result of building material does not automatically imply that the ability to resist a flood event is similarly high. On the other hand, the predisposition to be adversely affected due to the economic, sociocultural or political-institutional susceptibilities is to a large degree hazard independent. A community, for instance, with a well-working emergency response system and a strong social network is better forearmed against any type of hazardous event than a community with corrupt public authorities and disrupted internal linkages (Brooks, 2003; Schneiderbauer and Ehrlich, 2006; Cardona et al., 2012).

Transferring these rather theoretical concepts into operational vulnerability assessments in practice results in a number of challenges. Most importantly, the majority of non-physical aspects of vulnerability are not measurable in the way in that we are able to determine temperature or people's income. Consequently, alternative methods for assessing vulnerability are applied. They can be quantitative or qualitative or a mix of both (see Chapter 2.3.4). Widely applied and accepted tools comprise vulnerability curves predominantly used for assessing physical vulnerabilities and the use of (proxy-) indicators, particularly to estimate the vulnerability of non-physical dimensions (for example social, economic or institutional vulnerabilities). Here, indicators are used to communicate simplified information about specific circumstances that are not directly measurable or can only be measured with great difficulty (Meyer, 2011). At local level, where spatial data and statistics often do not exist in sufficient resolution, expert opinions as well as participatory, community- based approaches play a major role in vulnerability assessments.

Power relations, cultural beliefs, the attitude towards risk- reduction efforts or the willingness and capacity to learn from previous events are essential for the degree of preparedness of a population. Related information can be found in story lines rather than in statistics. Another challenge lies in providing evidence about the degree of vulnerability and its causes. Vulnerability bears witness only in the aftermath of an event when damage and loss are realised. Loss and damage data, though strongly depending on the magnitude of the hazard itself, are therefore important data sources for vulnerability assessments and/or for the validation of assessment attempts (see Chapter 2.4).

Due to the conceptual complexity and methodological challenges connected with vulnerability, the uncertainties of vulnerability assessments and their results is a topic of ongoing discussion. The uncertainties are an aggregation of uncertainties from several sources. They include limitations in knowledge about the socioecological systems that the vulnerable elements are part of as well as inaccuracies of empirical data and limitations of models applied for vulnerability assessments.

Uncertainty can be classified in many different ways. One possibility is to subdivide it into 'aleatory uncertainty', which represents the variability of the properties of concern, and 'epistemic uncertainty', which stems from limited knowledge. A sophisticated estimation of uncertainties is usually a difficult and costly exercise. Hence, the level of complexity and sophistication and the effort and resources to be spent should be in line with the risk management issue and correspond to the level of detail needed.

2.3.1.3 State of the art and research gaps

The number of existing theoretical frameworks and concepts related to various aspects of vulnerability is striking. Future work should focus on the translation of these concepts into action, namely by developing easy-to-use tools to implement vulnerability studies that yield useful results for the stakeholder and user. At least within Europe, a set of standardised methods for defined purposes at certain scales would help to monitor changes

over time and to compare vulnerability patterns spatially. The respective activities need to consider the developments of other relevant fields of action such as climate change adaptation or sustainable development.

The awareness of the significance of vulnerability for DRM has significantly increased over the last decades. Nevertheless, the importance of underlying triggering factors of vulnerability and not directly tangible aspects such as the cultural and institutional dimension requires further attention.

2.3.2 System and systemic vulnerability

In order to advance the understanding of vulnerability and its dynamics as well as to set appropriate policy agendas, it is crucial to look at how the vulnerability dimensions interact at different spatial, temporal and functional scales (Cardona et al., 2012).

The fact that our modern world is increasingly interconnected calls for systemic approaches when assessing vulnerabilities and risks, which take into account feedback loops and cascading chains of impacts

In particular, analysing vulnerability in the framework of sustainable development or climate change adaptation requires considering the interactions between human and natural systems.

2.3.2.1 System dynamics affecting vulnerability

Vulnerability is a dynamic concept (Cardona et al., 2012) and thus varies in space and time. Trends in exposure and vulnerability are influenced by changes in the demographic, economic, social, institutional, governance, cultural and environmental patterns of a system (Oppenheimer et al., 2014). Taking demography as an example, the current trend of an ageing population that characterises developed countries has considerably influenced people's vulnerability to heat stress, as shown by the high death toll paid by the elderly during the 2003 heatwave event in Europe (Robine et al., 2008).

Another example is the concentration of assets and settlements (and economic activities) in hazard-prone areas due to population growth and the lack of related spatial planning. At a first view this phenomena simply represents increased exposure values. At a closer look, it is strongly linked to vulnerability. Hazard-prone areas are in general characterised by lower land values and are thus occupied by low-income households. The scarcity or non-existence of infrastructure, services, social protection and security in these sites eventually leads to 'socially segregated' urban development, which in turn generates new patterns of vulnerability and risk (UNISDR, 2015b).

For instance, the most damaged areas during the 2010 floods in Bursa (Turkey) were those neighbourhoods characterised by the presence of informal settlements and occupied by low-income families (Tas et al., 2013).

Another aspect of systemic vulnerability is the dependence of human societies on ecosystem services, particularly those regulating climate, diseases and providing buffer zones (Millennium Ecosystem Assessment, 2005). For example, coastal wetlands increase energy dissipation of storm surges, dampen wind-driven surface waves, modify wind fields and reduce the exposure of (and thus protect) people and physical assets in the hinterland. Moreover, provisioning services include food, raw materials, fresh water and medicinal resources, the availability of which determines well-being and thus can strongly influence the socioeconomic vulnerability profile of a community. Consequently, ecosystem-based adaptation approaches have been applied in DRM to address potentially hazardous processes such as flash floods, heat waves, sea level rise, increasing water scarcity, etc.

2.3.2.2 System criticality

Globalisation has made communities and nations interdependent in a number of realms, including politics, economy, culture and technology.
A systemic view postulates to consider those linkages within and without a socioecological system that may affect its vulnerability, thus drawing attention to wider human and environmental processes and phenomena (Turner et al., 2003). In concrete terms, this means that systems and their popula-

tions are not only affected by hazards to which they are physically exposed but also — by means of cascading effects — to those experienced elsewhere. Recent disasters such as the eruption of Eyjafjallajökull in Iceland (2010), the floods in Thailand (2011), the Great East Japan Earthquake (2011) and Hurricane Sandy in the United States (2013) called attention to the severe effects of such cascades of disasters.

Cascading disasters can be exemplified by the vulnerability of critical infrastructure (Pescaroli & Alexander, 2016). When in 2003 a tree fell on a Swiss power line, causing a fault in the transmission system, 56 million people in Italy suffered the effects of the worse blackout in the country's history. 30 000 people were trapped on trains and many commercial and residential users suffered disruption in their power supplies for up to 48 hours (Johnson, 2007). At a larger scale, failures in the global supply chain highlight how the vulnerability of one system may depend on the resilience of another system working in far spatial distance.

The Swedish company Ericsson experienced substantial loss due to the vulnerability of a subsupplier. A 10-minute fire at Philips' plant in New Mexico, caused by a lighting hitting the electric line, translated into a loss in phone sales of about EUR 375 million (Jansson, 2004).

This was mainly because Ericsson took no action after Philips' reassurance about production returning on track in a week — which was not the case. On the contrary, Nokia, another big Philips customer, promptly switched supplier and it even re-engineered some of its phones to accept both American and Japanese chips. By doing so, it raised its profits by 42 % that year and managed to acquire new market shares (Economist Intelligence Unit, 2009). The Ericsson–Nokia example underscores the fundamental role played by coping capacity in reducing the adverse effects of experienced hazards. Moreover, it calls for drawing attention not only to the triggering event when considering cascading disasters, but more importantly to how vulnerabilities of different system's components may align and thus amplify impacts (Pescaroli & Alexander, 2016).

2.3.2.3 State of the art and research gaps

Disaster risk research often remains fragmented in a number of disciplines and focused on single hazards (Cutter et al., 2015), with limited interaction with other relevant communities. Research adopting a coupled human-environmental system approach in framing vulnerability has contributed to the integration of separate domains (Cardona et al., 2012).

Namely, the approach of ecosystem-based adaptation has transferred this holistic view into practice. Yet, the level of trans- and interdisciplinarity that would be required to implement truly systemic approaches in vulnerability assessment is rarely achieved. Hence, future applied research should follow an approach of coproduction of knowledge and need to integrate relevant disciplines. Relevant university education and training programmes should prepare young scientists and practitioners accordingly.

2.3.3 Vulnerability within the context of changing climate conditions

Climate change is one of the most prominent examples of an external biophysical stressor putting coupled human-natural systems at risk and the vulnerabilities to changing climate conditions has been the focus of many assessment studies. Originally, the understanding of 'vulnerability' in the community of climate scientists differed from that of the disaster risk research by encompassing the hazard component itself. That is, the projected change of relevant climate parameters was seen as part of the system's vulnerability to climate change (IPCC, 2007).

Knowledge on climate change is growing fast, but standardised vulnerability assessment approaches are lacking. Vulnerability assessment must consider changing socioeconomic, political and organisational conditions that determine possible vulnerability pathways.

The Intergovernmental Panel on Climate Change (IPCC) special report,

Managing the risks of extreme events and disasters to advance climate change adaptation (IPCC, 2012a), and later on its fifth assessment report (IPCC, 2013) have introduced the concept of 'climate risks' and have hence worked towards converging the concepts of both communities. The currently ongoing integration of climate change adaptation and disaster risk- reduction approaches leads to an increase of knowledge and has the potential to foster network building and to develop more efficient policies. A respective report is under preparation under the lead of the European Environment Agency (EEA).

The IPCC's fifth assessment report identifies several ways in which increasing warming and climate-related extremes can have an impact on a socioecological system and focuses in particular on those complex interactions between climate and such systems that increase vulnerability and risk synergistically (Oppenheimer et al., 2014). One of them is the negative effect of climate change on human health, which results from a number of direct and indirect pathways.

Direct biological consequences to human health can derive from heatwaves, extreme weather events and temperature-related concentrations of pollutants; yet most of the impacts will be indirectly triggered by warming-induced changes in environmental and social conditions (Mc Michael, 2013) and are hence in their extent determined by respective vulnerabilities. Moreover, climate change induced adverse impacts on crop yields' quantity and quality can exacerbate malnutrition (Met Office & WFP, 2014) and thus contribute to new or stronger vulnerabilities to a range of diseases.

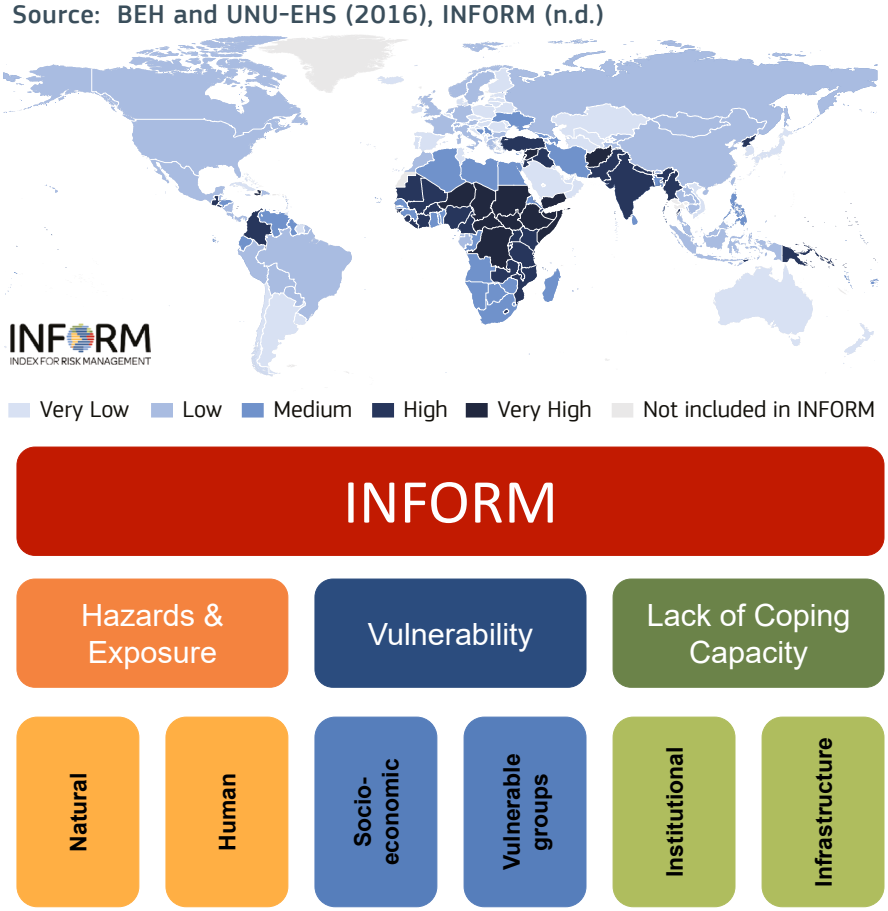
The assessment of climate-related risks and the identification of respective key vulnerabilities needs to consider the variety of these possible direct and indirect impacts. Useful tools to tackle this challenge are so-called impact chains, which represent cascading cause-effect relationships and allow for structuring assessment processes and the prioritisation of fields of action (Schneiderbauer et al., 2013; Fritzsche et al., 2014). Impact chains have, for example, been developed and applied by the ci:grasp adaptation support platform (n.d.) and the latest German climate change vulnerability study (Buth et al., 2015).

2.3.3.1 Vulnerability and climate change in Europe

At European level, climate change is recognised as an important driver of risk due to both climate extremes (for example heavy precipitation events or storms) and slow onset events of long-term duration (for example sea

FIGURE 2.11

Global maps of vulnerability index calculated by INFORM (upper left) approaches and the identified sub-components of risk and vulnerability left and the WorldRiskIndex on the bottom right.
Source: BEH and UNU-EHS (2016), INFORM (n.d.)

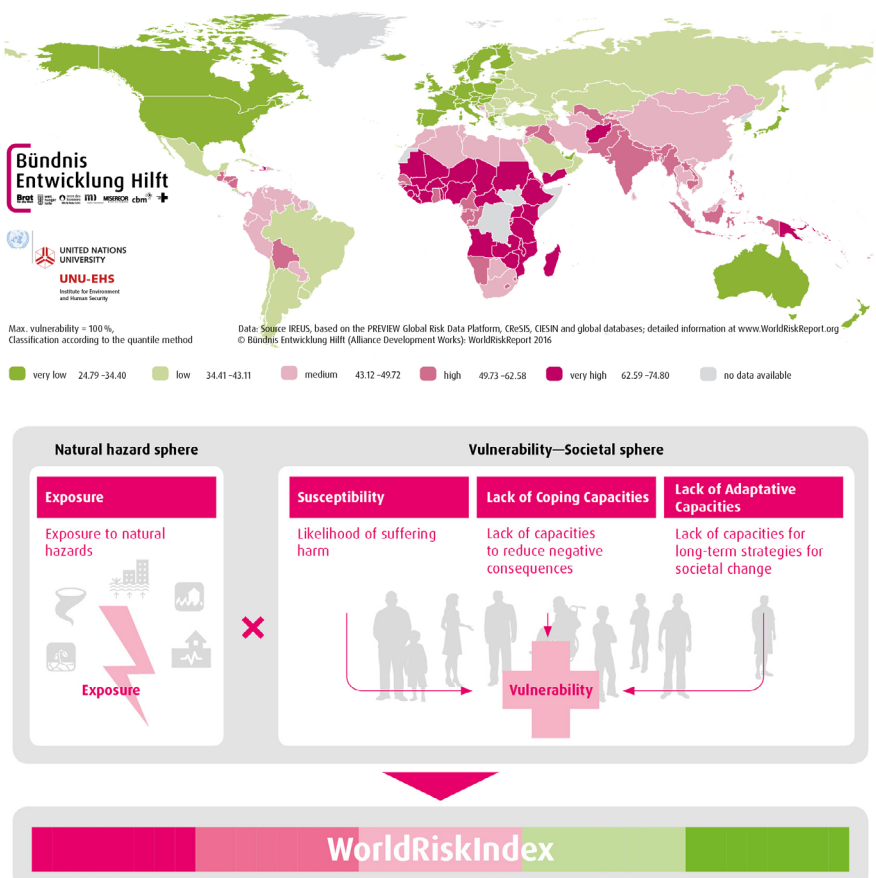


level rise or glacier retreat) Climate change will also have positive impacts in Europe in specific sectors and in certain regions (for example agriculture and tourism in northern Europe). In this chapter we concentrate on potential adverse impacts that require actions to reduce related risks.. Though all the countries in the EU are exposed to climate change, the related impacts vary depending on differences in climate conditions but also in vulnerabilities and degree of exposure (EC, 2013). Many EU Member States have based their national adaptation strategies on studies about risks and vulnerabilities to climate change, for example the United Kingdom in 2016 (UK, 2016), Germany in 2015 (Buth et al., 2015) and the Netherlands (PBL, 2012). At European level, respective studies have been implemented by the European Observation Network, Territorial Development and Cohesion (ESPON) in 2011 (EPSON, 2011) and the EEA in 2012 (EEA, 2012) and 2016 (EEA, 2017), as well as the European Commission in 2014 (Ciscar et al., 2014). The EEA hosts the European climate adaptation platform website that represents the knowledge hub for climate change risks and adaptation in Europe (Climate-ADAPT, n.d.).

Some key vulnerabilities related to climate change identified by these reports are:

- demographic change / aging population;
- population growth in low- lying urban agglomerations;
- vulnerability of (critical) infrastructure to warming and floods;
- increasing dependency on electricity, particularly linked with the increasing internationalisation of power grids.

and WorldRiskIndex (upper right). The respective underlying conceptual are shown in the lower part representing the INFORM index on the bottom



2.3.3.2 State of the art and research gap

The knowledge about future climate conditions is vast and continues to increase. There are numerous studies scrutinising climate change impacts and vulnerabilities. However, most of them have been carried out in a static context and they have not considered future socioeconomic developments resulting in changes of land use, urbanisation or demography. Besides climate scenarios, climate risk studies should aim to integrate vulnerability pathways.

Europe-wide climate risk assessment should further be supported and coordinated with the results from national and subnational studies, where appropriate. A certain level of standardisation is desirable in order to allow for comparison in space and time.

2.3.4 Approaches to assess vulnerability

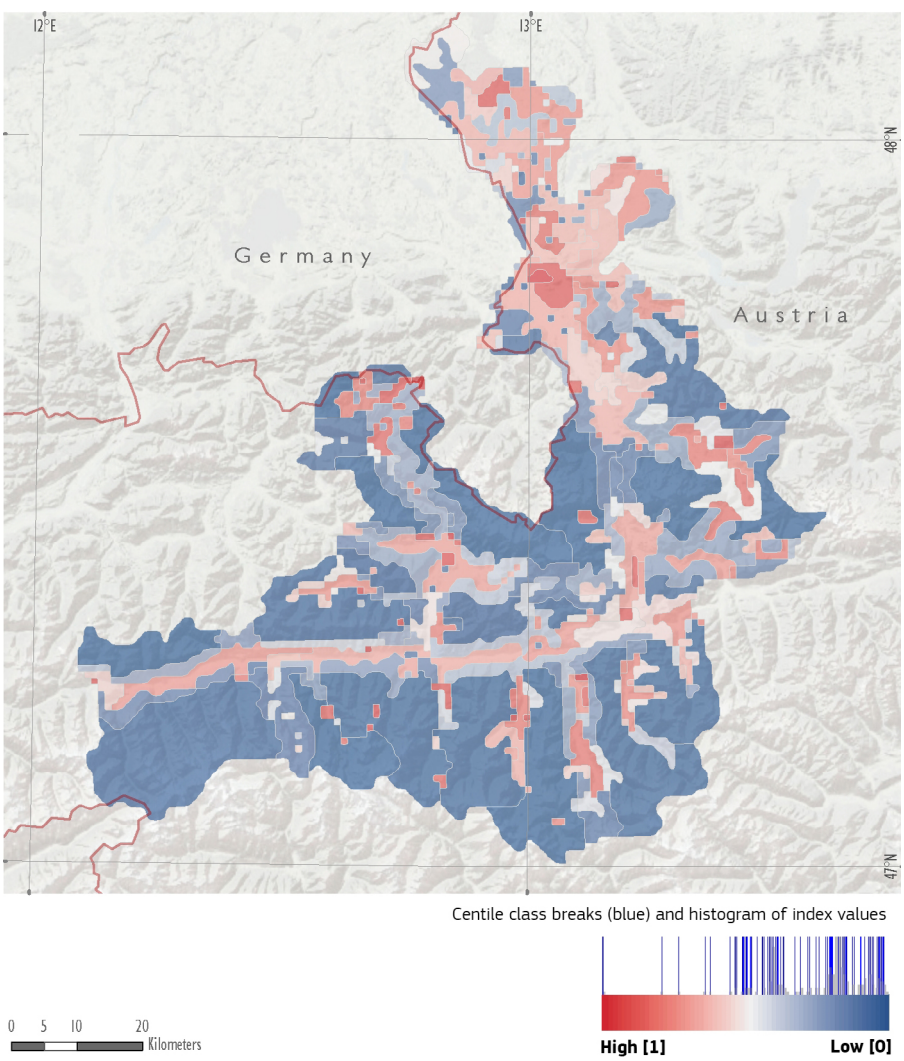
Researchers and practitioners apply quantitative, semi-quantitative, qualitative and increasingly mixed-methods approaches in order to assess vulnerability. Whether an approach is best suitable strongly depends on the objective and the scope of the assessment (e.g. understanding root causes, identification of hotspots, trend analysis or the selection of risk- reduction measures), as well as on the temporal and spatial scale; there is no 'one size fits all' approach.

Qualitative vulnerability analyses are based on experts' estimates. They are particularly useful if time and resources for the study are limited and if accessible data/information is not sufficient for quantitative analysis of complex phenomena. Qualitative assessment carried out with participatory techniques, such as interviews or focus group discussions, is particularly important for work at local/community level and can reveal context-specific root causes for vulnerabilities. Quantitative assessments are often based on statistical analysis exploiting data about loss and damage related to certain hazards (see Chapter 2.3.4.1). The most widely employed alternative to this is the application of indicator-based approaches, which ideally allows assessing patterns and trends of vulnerability across space and time. The multifaceted nature of vulnerability cannot be adequately represented by a single variable (e.g. income per capita). Consequently, the generation of composite indicators has gained importance for grasping such complexities. It allows for combining various indicators into a vulnerability index and helps to translate complex issues into policy-relevant information.

At global level, there are a number of composite indicators to assess disaster risk, which represent vulnerability as one of the risk's dimensions next to hazard and exposure, for example the WorldRiskIndex (Welle and Birkmann, 2015; BEH and UNU-EHS, 2016) and the INFORM Index (De Groeve at al., 2014; INFORM, n.d.). Both are continuously updated multi-hazard risk indices aiming to support disaster risk reduction. The WorldRiskIndex is a means for understanding natural hazard related

FIGURE 2.12

Social vulnerability to floods in the Salzach river catchment, Austria. Source: Kienberger et al. (2014)



risks including the adverse effects of climate changes whilst INFORM is a tool for understanding risks to humanitarian crises and disasters. Conceptually, both indices are very similar. Their methodologies are presented in Figure 2.11. In the WorldRiskIndex, the vulnerability part comprises the components of susceptibility, coping capacity and adaptive capacity, which are represented by 23 indicators. In INFORM, vulnerability and lack of coping capacity are divided into two separate dimensions, which are described by 31 indicators. Figure 2.11 shows the countries' vulnerability scores based on data from 2016 calculated using the INFORM approach (left) and the WorldRiskIndex approach (right). Below these maps, the respective approaches and sub-components are visualised. Both indices started with an approach at nation-state resolution and global scale but strive for more sub-national applications of their methodology (Wannewitz et al., 2016).

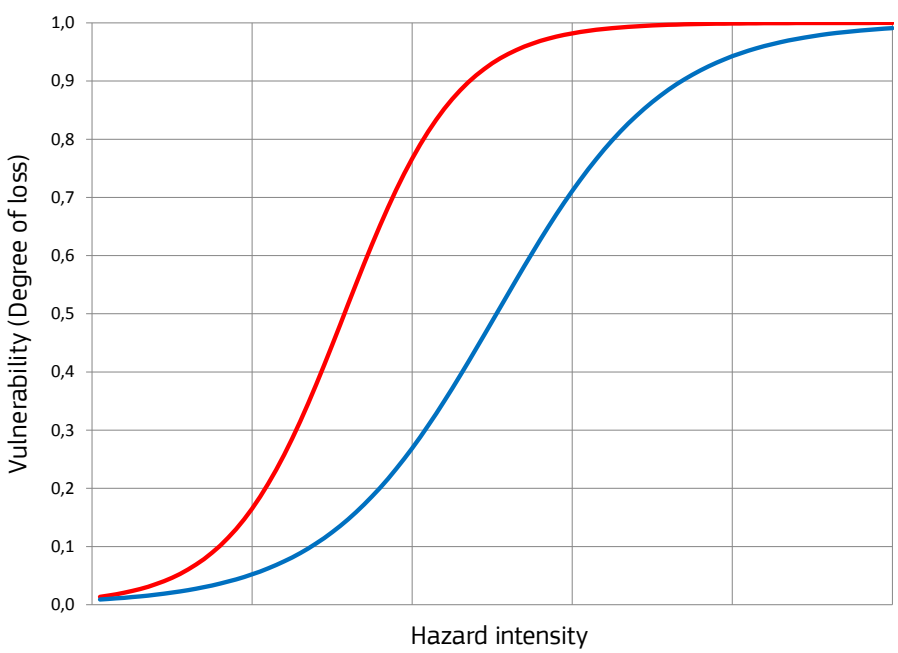
In Europe, a range of assessments have used spatial approaches, such as spatial multicriteria analysis or composite indicators to create maps at subnational level that facilitate the identification of hotspots and offer information for place-based intervention planning. For instance, a number of studies have investigated vulnerability in the context of river floods at different spatial scales. Examples include assessments: (1) in Vila Nova de Gaia, a flood-prone municipality in northern Portugal (Fernandez et al., 2016); (2) along the rivers Rhine, Danube and Elbe in Germany (Fekete, 2009); or (3) in the Salzach catchment in Austria (Kienberger et al., 2014) (Figure 2.12). Using indicator-based approaches, the three case studies identify a set of social (e.g. age, education and gender), economic (e.g. income, employment and dependency), organisational and institutional (e.g. early warning systems (EWS), access to health services, proximity to first responders, etc.) indicators and aggregate them into a composite index of vulnerability.

Composite indicators have the advantage to represent complex phenomena in a single value. If necessary, the underlying indicators or subcomponents of the index can be visualised separately to support the understanding of which factors contribute most to a positive or negative situation in the aggregated result (Hagenlocher et al., 2013). On the other hand, composite indicators are always data driven and might conceal crucial aspects that are not or cannot be expressed in numbers and statistics.

In recent years, there is an increasing number of studies aiming to understand and analyse vulnerability in multihazard settings. For example, Welle et al. (2014) present an approach for the assessment of social vulnerability to heat waves and floods as well as institutional vulnerability to earthquakes in the city of Cologne, Germany. While different sets of vulnerability indicators are used and aggregated to assess vulnerability to heat waves (e.g. age, unemployment, place of origin, etc.) and floods (age and occupan-

FIGURE 2.13

Generic quantitative vulnerability functions showing vulnerability (i.e. degree of loss) as a function of hazard intensity. The red curve represents a more vulnerable element and the blue curve a less vulnerable element. Source: courtesy of authors



cy rates per household), institutional vulnerability was evaluated using qualitative information obtained from a series of stakeholder consultations. Acknowledging the fact that communities are often affected by multiple hazards — combined, sequentially or as a cascading effect —, these studies present an important step towards providing solutions for real-world challenges.

2.3.4.1 Quantitative vulnerability functions

Potential damage to physical assets and loss of human lives are often assessed using quantitative vulnerability functions. These functions take into account the intensity of the hazard and the properties of the exposed elements. The intensity expresses the damaging potential of the hazard. Properties represent the resistance of the exposed elements such as building material and maintenance level. Vulnerability functions are widely applied to illustrate the relationship between hazard characteristics and fatalities and damage. Generic vulnerability functions are shown in Figure 2.13 and refer to physical vulnerability, described as 'the degree of loss to a given element, or set of elements, within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss)' (UNDRO, 1984).

Vulnerability functions may be subdivided into fatality/mortality functions and damage functions (the latter denoted and formulated in different ways, e.g. loss functions, susceptibility functions and fragility functions). Damage functions are mainly based on empirical data collected in the aftermath of an event. Damage functions, in particular functions relating building damage to water depth, have a long tradition in the context of flood damage evaluation (Meyer et al., 2013). Physical vulnerability of buildings can also be assessed by physical models or by use of expert judgement. For some hazard types, fatality or mortality functions are developed to determine the death ratio for a single hazard parameter, e.g. water depth or earthquake magnitude. This allows the estimation of numbers of fatalities occurring at, for example, a certain water level. However, the development of fatality functions goes along with a high degree of uncertainty, which stems from the variety of physical and human parameters influencing the loss of life. For example, water depth may not be the only and most relevant intensity measure. Aspects such as flow rate, flood duration or sediment transport might be equally as important.

The most appropriate methodology to assess vulnerability strongly depends on the purpose and the context, as well as the temporal and spatial scales; there is no 'one size fits all' approach.

For quantitative physical vulnerability assessment, one can apply existing vulnerability curves, which are appropriate for the specific hazard and the exposed elements (e.g. building types) in study. Vulnerability curves have been developed for several types of natural hazards, such as wind storms, landslides, floods, tsunamis and earthquakes. There are curves expressing loss within the built environment as well as loss of human lives. Most of the curves are developed from empirical data and accordingly fit well with previous events in the area where the data was collected. For other locations a calibration or validation of the model is necessary prior to use. Validation is also needed for physical or analytical vulnerability functions.

Application of vulnerability functions is useful in several phases of the risk management, such as risk assessment and risk treatment. Risk analysts, scientists, stakeholders and decision-makers could be users of vulnerability functions with the purpose to provide input to:

- decisions about the question of whether risks need to be treated or about issues such as the prioritisation of risk treatment options of different areas and of different hazard types;
- identification of appropriate and optimal risk- reduction measures;
- financial appraisals during and immediately after a disaster as well as budgeting and coordination of compensation (Merz et al., 2010).

Alternatives to vulnerability curves are fragility curves, which also express the uncertainty in the physical vulnerability. Fragility curves have been widely applied in probabilistic risk and vulnerability assessment, in particular for earthquake risk (Hazus n.d.), but

recently also for landslide risk assessment. These functions describe the probability of exceeding different damage states for various intensities. In a recent study on seismic risks in the city of Barcelona, Spain, a physical vulnerability assessment approach was first carried out based on vulnerability functions for different building types (e.g. unreinforced masonry or reinforced concrete, steel and wood buildings). In a second step this was combined with a probabilistic analysis of the seismic hazard into a seismic risk assessment for buildings across the city (Carreño et al., 2014). The authors also considered conditions related to social fragility and lack of resilience that favour second order effects when a city is hit by an earthquake. Factors such as population density, population with poor health or social disparity were used as proxies for social fragility. In addition, the operating capacity in case of an emergency, the state of development or the access to health services were used as indicators of lack of resilience and combined in an overall urban seismic risk index (Carreño et al., 2007). The results show that the population in the central parts of Barcelona lives at a considerably higher risk than those living on the outskirts of the city.

2.3.4.2 State of the art and research gaps

Indicator-based assessment methods have proved to support the drafting and prioritisation of disaster risk- reduction measures and strategies as well as the allocation of resources. Several challenges exist with respect to the dependency on data availability and quality, the validation of the applied methodology and related uncertainty analysis (Hinkel, 2011).

Vulnerability curves are widely applied for physical vulnerability assessment. Future activities should focus on the development of a repository of vulnerability curves with user guidelines for different hazard types and different types of assets. Research should work on the development and use of multiparameter vulnerability functions that are transferable, i.e. valid for different building types, and applicable for vulnerability changing over time and for multirisk scenarios.

In order to fill these gaps, more data are required for improving and calibrating existing models as well as for proposing new empirical vulnerability models (see Chapter 2.4). Data collection and analysis should be extended and streamlined through the use of remotely sensed data and geographic information system technology. The potential of Copernicus services and particularly of Sentinel data has not been fully exploited by the disaster risk community.

An additional challenge lies in the forward-looking nature of vulnerability. That is, vulnerability assessment needs to take into account those factors and processes that may not yet have become evident in past disaster situations. This is particularly valid in highly dynamic environments where both socio-natural hazards and vulnerability patterns might undergo rapid changes in the near- and mid-term future (Garschagen, 2014).

The importance to integrate uncertainty in vulnerability assessment has often been underlined but remains an issue of concern still today.

2.3.5 How vulnerability information is used in practice

The IPCC acknowledges DRM as a process that goes beyond DRR (IPCC, 2012b). Decisions to reduce disaster risk must be based on a sound understanding of the related vulnerabilities.

A requirement that has clearly been articulated in the SFDRR (UNISDR, 2015b) as one of four main priorities for action in the years to come.

2.3.5.1 Vulnerability in disaster risk management: from knowledge to action

Complementing hazard analysis, vulnerability studies generate information of relevance for various aspects of risk reduction and adaptation strategies, emergency management and sustainable territorial planning. They are of importance for all phases of the DRM cycle covering short-term response as well as long-term preparedness or recovery. Correspondingly large is the field of potential users of vulnerability information, including public administration staff who are responsible for civil protection or spatial planning, actors in the field of insurance, private companies running critical infrastructure, the civil society and, finally, any individual. One way of grouping the various purposes of vulnerability studies and their main users is to classify them according to

TABLE 2.1

Overview of vulnerability assessments, their main objectives and potential users at different spatial scales. Source: courtesy of authors

Scale	Main objective	Examples	Potential users
Global	Identification of spatial hot spots; allocation of resources; awareness raising	The vulnerability components of the following risk indices: INFORM index (De Groeve et al., 2015); World Risk Index (BEH & UNU-EHS, 2016); Disaster Risk Index (Peduzzi et al., 2009); Natural Disaster Hotspots index (Dilley et al., 2005)	International organisations (including donors); international non-governmental organisations (NGO); regional intergovernmental organisations
		Notre Dame Global Adaptation Index (ND-GAIN, n.d.)	
International/ regional	Identification of spatial hot spots; allocation of resources; awareness raising	The vulnerability component of the INFORM Subnational risk index for the Sahel and the Greater Horn of Africa (INFORM subnational models, n.d.)	International organisations (including donors); international NGOs; ROI
		Vulnerability to climate change in Europe (ESPON, 2011); climate change vulnerability mapping for Southeast Asia (Yusuf & Francisco, 2009)	
National / subnational	Identification of hot spots; development of risk reduction / adaptation strategies; allocation of resources; awareness raising; advocacy	The vulnerability component of the INFORM Subnational risk index (INFORM subnational models, n.d.) for Lebanon and Colombia, World Risk Index subnational for the Philippines (Wannewitz et al., 2016); Social Vulnerability Index for the USA (Cutter et al., 2003)	International organisations (incl. donors); international /national / local NGOs; national, subnational and local governments and public administration
		Numerous studies in Europe. For an overview of work related to climate change, see Prutsch et al., 2014	
Local	Identification of root causes; strengthening capacities of local actors; empowering communities	For an overview of vulnerability assessments in Europe with respect to natural hazards, see Birkmann et al., 2014;	International organisations (incl. donors); international / national/ local NGOs; national, subnational and local governments and public administration-affected communities
		A semi-quantitative assessment of regional climate change vulnerability by Kropp. et al., 2006	

spatial scale. Extending the examples presented above, Table 2.1 provides an illustrative overview of selected vulnerability assessments, their main purposes and potential users at different spatial scales.

Vulnerability assessment is used to support stakeholders and policymakers in prioritising various risks, in identifying root causes and spatial hotspots and in developing risk reduction strategies and measures.

The complexity of vulnerability and the wide range of possible applications of assessment studies require considerable effort to define the studies' scope (objective, target groups, spatial and temporal scale, spatial resolution of results, etc.). In practice, vulnerability studies have benefited from pursuing a process of co-production of knowledge. The integration of scientists, practitioners and potential users in the process of a vulnerability assessment right from the beginning usually results in a higher level of acceptance of their results. They are also more likely to be used in decision- and policymaking. An example is the latest vulnerability assessment for Germany within the scope of which a network of national authorities was created and which participated in all important decisions (Greiving et al., 2015).

2.3.5.2 Conclusions and key messages

Over the past decades, vulnerability research has made considerable progress in understanding some of the root causes and dynamic pressures that influence the progression of vulnerability and raised awareness that disasters are not natural but predominantly a product of social, economic and political conditions (Wisner et al., 2004).

Vulnerability assessments are a response to the call for evidence by decision-makers for use in pre-disaster risk assessment, prevention and reduction, as well as the development and implementation of appropriate preparedness and effective disaster response strategies by providing information on people, communities or regions at risk.

The following steps are proposed to further improve vulnerability research and related applications with the final aim to inform policymakers to most appropriately:

- co-produce knowledge in a transdisciplinary environment;
- evaluate and present inherent uncertainties;
- integrate intangible but crucial factors into quantitative assessments;
- develop and apply methods that allow for considering cascading and multirisks;
- combine vulnerability scenarios with (climate-) hazard scenarios when assessing future risks;
- empower communities to better understand and reduce their vulnerability in order to make them more resilient to identified hazards;
- design and facilitate multilevel and cross-sectoral feedback loops between public, practitioners and policymaking bodies (local, regional, national and European) and other stakeholders;
- standardise vulnerability assessment approaches in order to allow for more comparison (in space and time);
- work on improved evidence within vulnerability assessment — this requires continuous effort to improve loss and damage data.

Partnership

The comprehensive analysis and assessment of vulnerability requires an interdisciplinary approach involving both natural and social sciences. In addition, in order to foster sustainable and efficient vulnerability reduction strategies and measures, an approach to produce knowledge co-productively is desirable. This calls for a partnership with affected communities, practitioners and decision-makers. A stronger link and enhanced interaction with other relevant communities is desirable, namely climate change adaptation, natural resource management, public health, spatial planning and development.

Knowledge

The determination of risk often remains hazard centred and hazard specific and does not consider vulnerability appropriately. Vulnerability assessment has tended to be mostly quantitative in nature. Cultural aspects as well as formal (procedures, laws and regulations) and tacit informal (values, norms and traditions) institutions play a fundamental role as both enabling or limiting factors

of resilience and have not gained sufficient attention. A challenge is the need to consider local data and information in order to account for small-scale specificities of vulnerability. Present databases on damage and loss caused by natural hazards should be standardised and extended to support evidence building in vulnerability assessment. Existing barriers in the co-production, exchange and use of knowledge have to be understood and minimised.

Innovation

In recent years, improved approaches to assess vulnerability by statistical analyses or indices have been established. Fostering the integration of Earth observation data and technology to detect changes would improve the possibility to represent some of the dynamic aspects of vulnerability. Further improvement requires enhanced event and damage databases and more sophisticated methods for potential future vulnerability pathways and their integration into risk scenarios. The challenge to integrate qualitative information, which often contains crucial facts, needs to be addressed. Observation data and technology to detect changes would improve the possibility to represent some of the dynamic aspects of vulnerability. Further improvements require enhanced event and damage databases and more sophisticated methods for potential future vulnerability pathways and their integration into risk scenarios. The challenge to integrate qualitative information, which often contains crucial facts, need to be addressed.

2.4 Recording disaster losses for improving risk modelling capacities

***Scira Menoni**, Costanza Bonadonna, Mariano García-Fernández, Reimund Schwarze*

2.4.1 Relationship between pre-event risk modelling and post-disaster loss data

Pre-event risk assessment and post-event damage estimation are more linked than is generally thought. As shown in Figure 2.14, either probabilistic or deterministic damage forecasts are appraised in pre-event risk assessment, whilst in the aftermath of the event, the scenario that occurred is analysed. Both modelled and estimated damage can regard one or few exposed items or multiple sectors ranging from businesses to lifelines (available in fewer cases). Damage can be expressed as physical damage to items and/or monetary costs of repair or as loss to individual economic sectors or to a given economy and society as a whole.

In the case of the pre-event assessment, hazard, exposure and vulnerability are the components that need to be evaluated and combined in order to obtain a risk assessment. In the post-event analysis, the estimated damage must be described on the basis of the observed hazard features, on the configuration of exposed systems and on their vulnerability at the time of the event.

Pre- and post-damage assessment have more in common than generally perceived; in both cases there is a need to understand the relative contribution of hazard, exposure and vulnerability factors on the overall damage.

There is still a debate on the meaning of damage and losses and which types should be considered; here, an interpretation based on previous EU projects and available literature is proposed (Merz et al., 2010; Meyers et al., 2015; Van der Veen and Logtmeijer, 2005). As can be seen in Figure 2.15, damage due to natural hazards is generally divided into damage to tangible objects and assets, meaning those for which a monetary assessment is easily obtained and not controversial, and damage to intangibles, meaning values such as human life, historic heritage or natural assets for which monetisation is either extremely difficult or controversial. Damage to both tangibles and intangibles can be direct, meaning the damage provoked by the hazardous stressor, or indirect, which is consequent upon the direct damage (e.g. production loss due to damaged machinery) or upon ripple effects due to the interdependency of economic systems, both forward and backward linkages. Whilst direct damage generally occurs locally, indirect damage can develop over much greater time and space scales, also far from the event's 'epicentre' and long

after the event has occurred. In some methodologies, damage and losses are distinct: the first term refers to affected infrastructure and buildings, whilst the second refers to economic losses (GFDRR, 2013). In the following sections, the link between pre- and post-event damage and loss assessment is discussed, showing the contribution that enhanced post-disaster analysis can make in terms of knowledge and information to improve the quality and comprehensiveness of pre-event risk models.

Examples will be taken from three distinct hazard domains, such as earthquakes, floods and volcanic eruptions, in order to provide evidence for more theoretical assumptions. These natural disasters were chosen because of their diversity, the difference in terms of types and the extent of damage they produce. However, their use is just paradigmatic. Experts in other fields will be able to find correspondences to the hazard risk they are more familiar with.

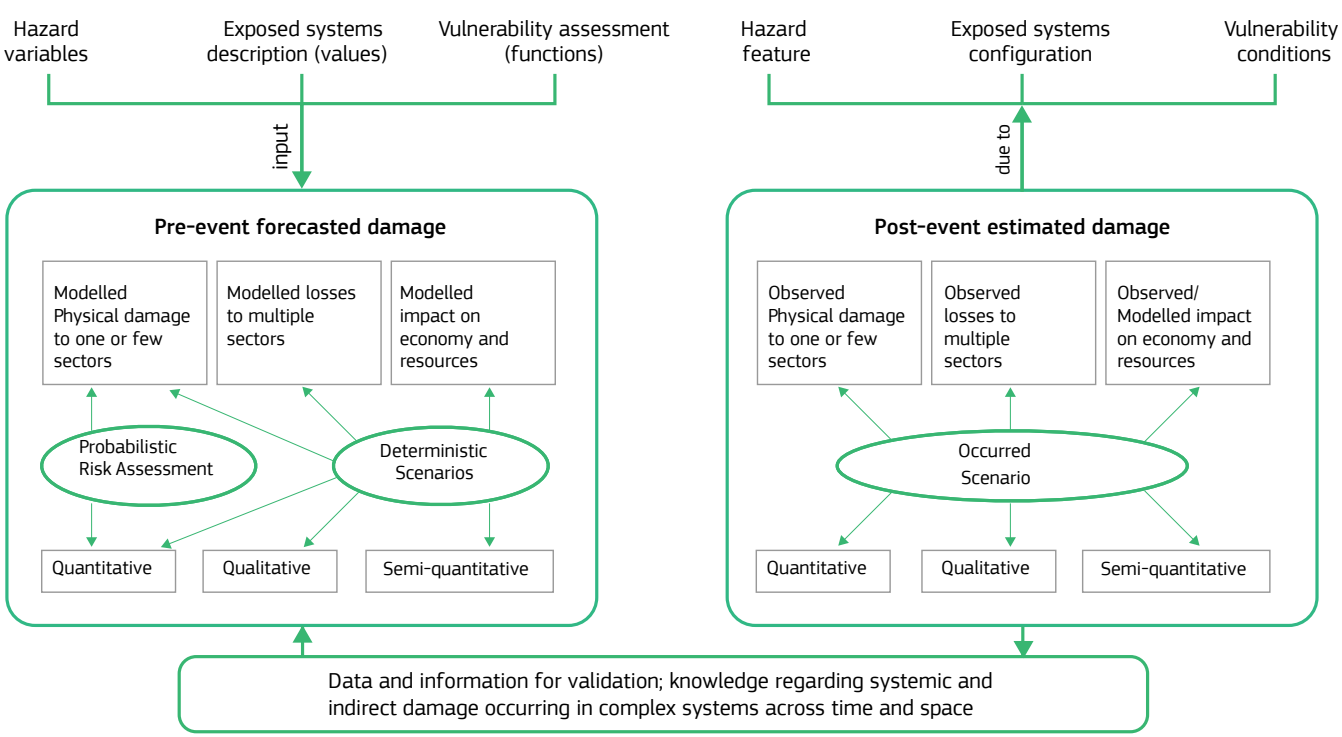
2.4.2 How post-disaster damage has been used to develop risk models: state of the art in a nutshell

2.4.2.1 State of the art of risk models

Expected damage can be assessed using quantitative, qualitative and semi-quantitative risk models (Figure 2.14, see also Chapter 2.1). Quantitative risk assessments dominate in

FIGURE 2.14

Pre - and post - disaster damage assessments
Source: courtesy of authors



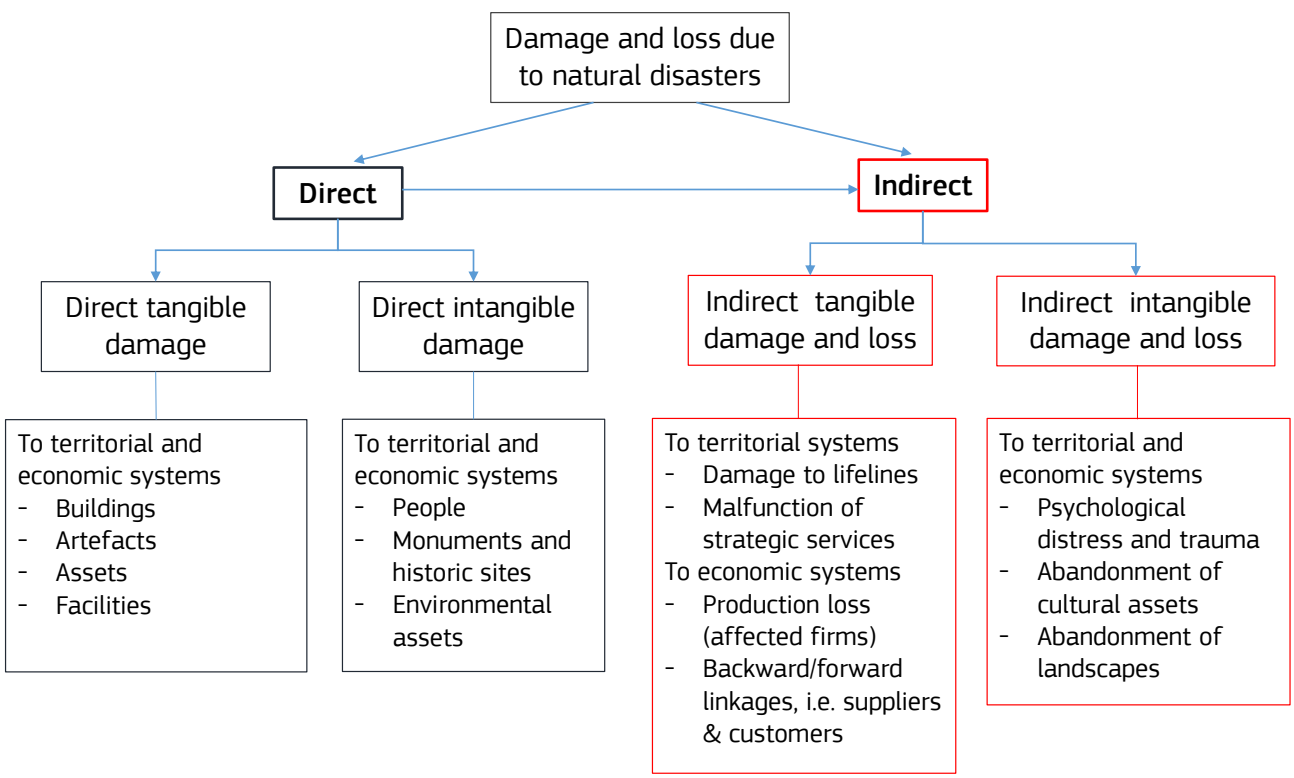
scientific journals; however, they generally consider quite a limited number and type of variables. More complex understandings of risk, which also comprise the consequences on the social, economic and environmental systems as well as on complex built systems such as critical infrastructures, are inevitably covered by a mixture of quantitative and qualitative appraisals (OECD, 2012; Theocharidou and Giannopoulos, 2015; Menoni et al., 2007). In the more widely accepted definition, risk is measured in terms of expected damage (probability of expected damage or deterministic damage scenarios) and is obtained as a function of hazard, exposure (see also Chapter 2.2) and vulnerability (see also Chapter 2.3). Whilst the first two aspects are provided in quantitative terms, the last one is often assessed through more qualitative or semi-qualitative approaches (Turner et al., 2003; Petrini, 1996). In the past, risk assessments were actually mainly hazard analyses, whereas in more recent times, quantitative appraisals of exposure have been increasingly included in risk assessment. Besides exposed people and assets, more realistic evaluations take into consideration their relative vulnerability as well, intended as the susceptibility to damage, which is an intrinsic measure of weakness and fragility (Mc Entire, 2005; Scawthorn, 2008).

Vulnerability and damage functions have been the most widely used tools, especially by engineers, to deal with pre-event damage assessment fed by post-disaster statistical data.

The capacity to assess the latter is more recent and restricted to some exposed elements and systems, with

FIGURE 2.15

Definition of direct and indirect damage
Source: Merz et al. (2010)



the obvious difficulty of constructing a comprehensive and coherent picture of what the total effect of a disaster in a given area may be (Barbat et al., 2010).

In the following section, the state of the art in vulnerability or damage functions in the field of seismic, volcanic and flood hazards are provided, highlighting similarities and differences. Vulnerability or damage functions are used to correlate hazard indicators (such as acceleration or water depth) with damage (such as damage index or monetary cost of repair and recovery).

2.4.2.1.1 How vulnerability/damage curves have been developed for seismic risk

Seismic engineers have started developing vulnerability curves long before colleagues in other natural hazards fields, coherent with the fact that the only possible protection measure against earthquakes is reducing buildings' vulnerability. Early seismic vulnerability methods were proposed in the seventies in Japan and the United States, and were being developed during the eighties in Europe (Corsanego, 1991; Senouci et al., 2013). Main European seismic vulnerability methods include GNDT (Benedetti et al. 1988), Risk-UE (Lagomarsino and Giovinazzi, 2006) and Vulneralp (Guéguen et al., 2007). Thus, the seismic field set the floor for a general methodology that was followed in other fields as well; it can also be considered as having general relevance. First, damage after earthquakes was observed in a very large number of cases and in structures differing in their layout, material, typology, age, resistant systems, etc. Two relevant results were achieved: on the one hand, a very large database with hundreds of failure cases was developed, and on the other hand, the specific factors determining buildings' response to earthquakes were identified. Such factors have been translated into parameters, as in the example provided in Table 2.2 (Zonno et al., 1998). In the practical application of the latter, the vulnerability of buildings is obtained from the weighed sum of the score assigned to each parameter, ranging from A (no vulnerability) to D (very high vulnerability), and multiplied by a weight expressing the relative relevance of the parameter.

TABLE 2.2

Indicators to assess seismic risk
Source: Zonno et al. (1998)

	PARAMETERS	VULNERABILITY CLASS				WEIGHT
		A	B	C	D	
1	Organization of resistant elements	0	5	20	45	1
2	Quality of resistant elements	0	5	25	45	0.25
3	Conventional Strenght	0	5	25	45	1.5
4	Building position and foundations	0	5	25	45	0.75
5	Floors	0	5	15	45	var
6	Plan Shape	0	5	20	45	0.5
7	Elevation Shape	0	5	20	45	var
8	Maximum distance between walls	0	5	20	45	0.25
9	Roof	0	15	20	45	var
10	Non structural elements	0	0	20	45	0.25
11	Maintenance conditions	0	5	20	45	1

Second, vulnerability curves are compiled by plotting seismic severity (on the horizontal x axis), expressed, for example, as acceleration, versus the percentage of damage or a damage index between 0 and 1 (on the vertical y axis). At maximal stress, any building is expected to collapse, whereas at no stress no building is expected to be damaged; anything in between, the intrinsic vulnerability of buildings is likely to produce differential damage. As a third step, a comparison between modelled damage based on vulnerability curves and post-event observed damage should be carried out as discussed in Chapter 2.3.

2.4.2.1.2 How vulnerability/damage curves have been developed for volcanic risk

Vulnerability curves in volcanology have been developed much more recently and are available only for some of the hazards that may be triggered by an explosive eruption. More specifically, vulnerability curves describing the collapse of roofs are available for

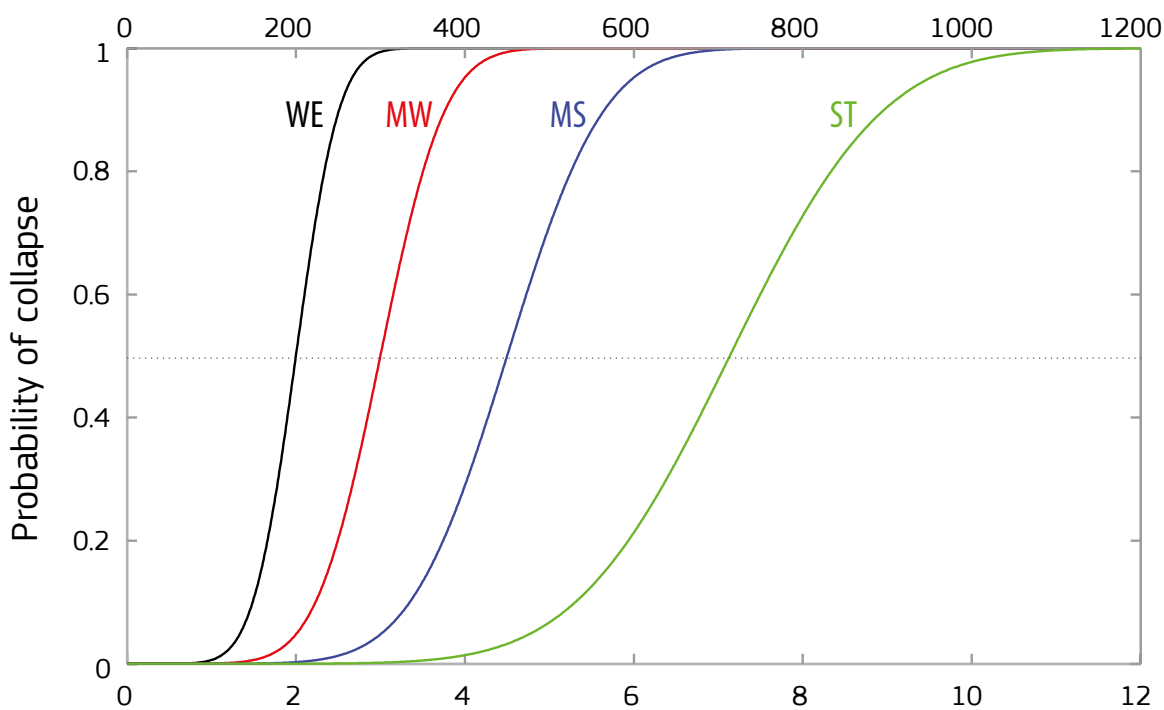
tephra fallout (e.g. Figure 2.16), while initial curves have been proposed for ballistic and pyroclastic flows in EU funded project MIAVITA (n.d.) (see also in Chapter 3.2 for the description and definition of volcanic hazards). The lack of vulnerability data for other hazards includes the unfeasibility of building constructions that are able to stand the stress due to lava or pyroclastic flows. Exposure, i.e. the location of constructions, becomes more important. In addition, given the relative low frequency of large volcanic eruptions affecting largely inhabited places, damage to modern structures could be observed only in a limited number of cases and mostly related to the collapse of roofs under tephra load. This is why vulnerability curves have been developed only for the damage to building roofs due to tephra fallout (Figure 2.16). The effect of tephra on other exposed elements, e.g. agriculture and infrastructures, have also recently been attempted (Wilson et al., 2014; Craig et al., 2016).

2.4.2.1.3 How vulnerability/damage curves have been developed for flood risk

It should be highlighted that in the flood case, scholars refer to damage rather than vulnerability curves, even though the followed method is very similar. Curves are plotted on a plane with an x axis that generally reports water depth and a y axis where damage is reported as costs of repair. Curves represent types of buildings differing for the number of floors, material, presence of basement or not and occupation of the first level. For a comprehensive overview of such curves, one may refer to the work of Jongman et al. (2012) and Thieken et al. (2008). Both recognise the limitations of current methods that neglect hazard severity variables such as velocity or sediment transport, which may be more relevant than water depth as a damage cause, especially in the case of flash floods.

FIGURE 2.16

Damage curves for collapse of roofs associated with tephra fallout
Source: Biass et al. (2016)



2.4.2.2 Key aspects of currently used vulnerability and damage curves

The brief discussion of the three domains permits to highlight some commonalities: first, the philosophy according to which vulnerability is represented by curves that depend on the intrinsic characteristics of different types of structures; second, the need of a statistically meaningful population of observed damaged buildings to develop vulnerability or damage curves; and third, vulnerability or damage curves are available for a limited set of structures and a limited number of sectors. They are largely available for residential buildings, far less for industrial facilities and even less for infrastructures. This restricts the capacity to construct comprehensive quantitative risk assessment for all assets and sectors. Furthermore, whilst vulnerability curves are derived from the observation of individual objects, risk assessment is developed for an area or a region. Therefore, risk assessment is based on the hypothesis that assets in a given region can be averaged in terms of their vulnerability features.

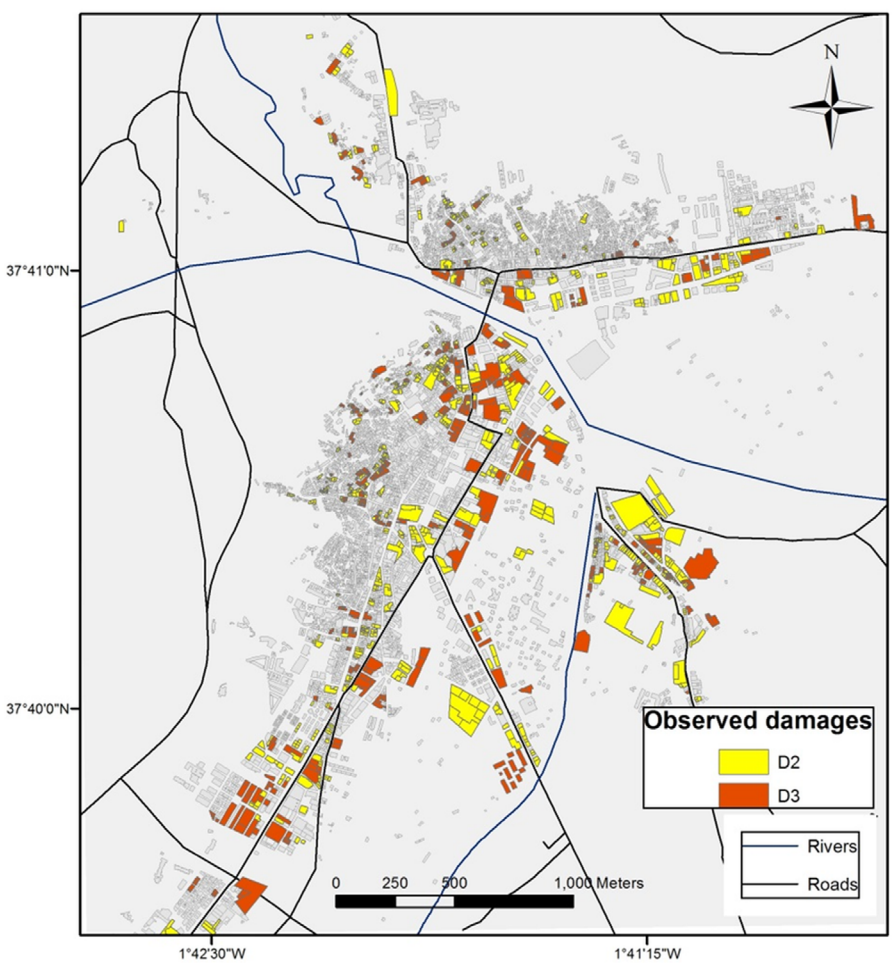
Another factor limiting the possibility to transfer such curves from one geographic area to another derives from the fact that the observed damage and relative vulnerability factors are highly context dependent, as they are linked to the types of buildings and structures that have been surveyed. This is the reason why consulting firms that provide insurance and reinsurance companies with immediate figures of loss due to a recent calamity carry out post-disaster surveys. The rapid evolution of information technology information technology has given an important impulse to the use of risk assessment scenarios by means of very large datasets comprising information on land uses and basic built stock characteristics that can be digested in a rather short time. However, feedback from real events is crucial to increasing the reliability of their modelling capacity (Marsh, 2015).

2.4.2.3 Use of post-event damage data for evaluating the reliability of risk models results

Even though separate events that have occurred cannot provide a com-

FIGURE 2.17

Observed building damage in the city of Lorca in terms of mean damage grade (D1: slight, D2: moderate, D3: heavy and D4: partial collapse) for the Mw5.2 earthquake on 11 May 2011
Source: DG Citizen Security and Emergencies of the Region of Murcia



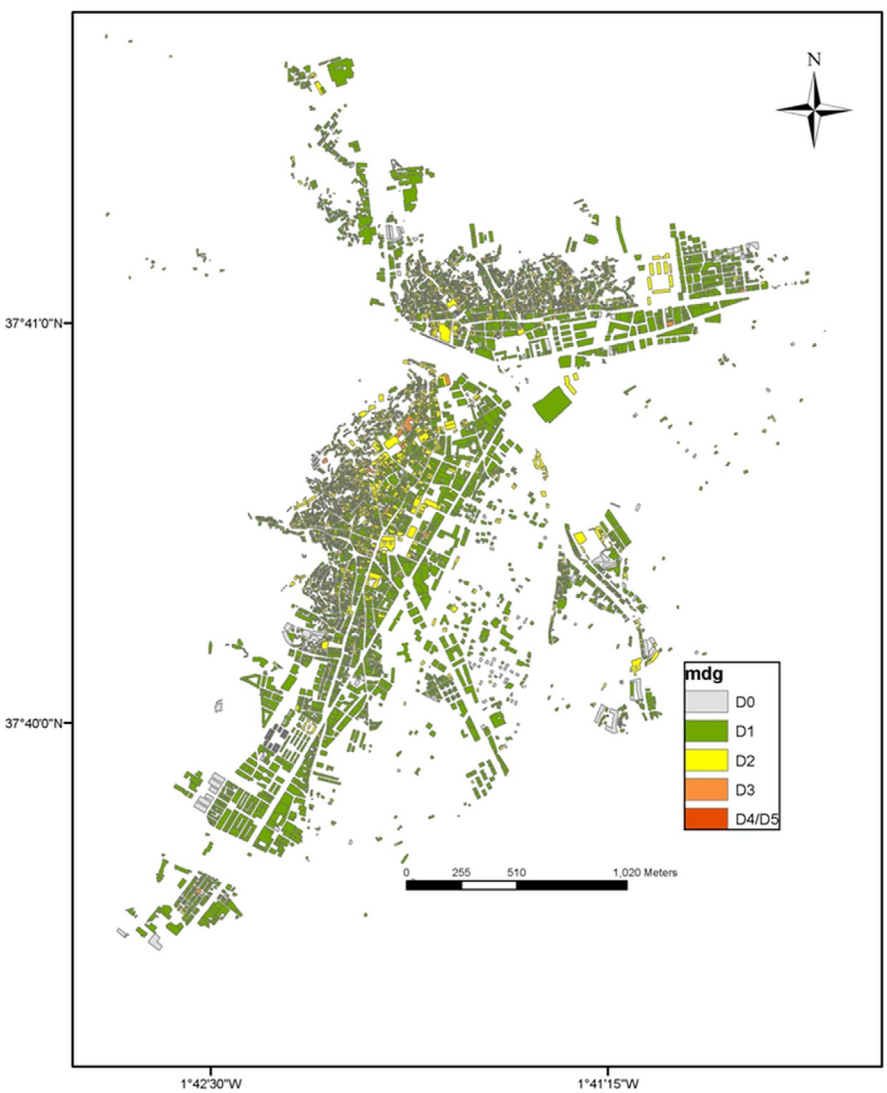
prehensive validation for risk models, they can be used to assess the discrepancies between the model forecasts and observations.

Here the comparison between pre- and post-damage assessments conducted for the city of Lorca in Spain is provided. Figure 4 shows the actual observed damage in the most affected suburbs in Lorca as a consequence of the earthquake that occurred on 11 May 2011. Figure 2.18 represents the modelled damage using Risk-EU approach (Lagomarsino and Giovinazzi, 2006), considering the seismic load by the observed European macroseismic scale (EMS-98) intensity and the vulnerability index by building typology, age and number of floors.

The comparison between Figure 2.17 and Figure 2.18 shows that the modelled scenario underestimates the damage, particularly for the highest damage levels. This suggests the need to consider additional vulnerability factors such as the state of preservation, orientation, discontinuities, soft story buildings, plan/vertical irregularities, openings and quality of construction that were missing in the pre-event vulnerability appraisals. Also, in this specific case, there could be possible previous effects from a M4.5 foreshock.

FIGURE 2.18

Simulation of physical damage to buildings in the city of Lorca using the direct approach.
Source: courtesy of authors



2.4.3 Damage and losses to multiple sectors: relevance for more comprehensive risk assessments

Exercises similar to the one briefly shown in Chapter 2.4.2.3 are very important to evaluate the consistency of risk models; however, they are often limited to a restricted number of assets and to direct physical damage. In the following, the state of the art in risk assessments and damage estimations by sectors will be shortly discussed, distinguishing between tangible and intangible exposed assets. Needs in terms of future damage data provision are also discussed.

2.4.3.1 Damage to tangibles

2.4.3.1.1 Agriculture

As suggested by Brémond et al. (2013), damage to agriculture should comprise different elements: crops, soil, infrastructures and storage facilities, which are differently exposed and vulnerable to various hazards such as earthquakes, volcanic eruptions and floods (FAO, 2015).

Post-event damage assessment can provide a more comprehensive understanding of damage to multiple sectors including agriculture, infrastructure, services and industrial and commercial activities, overcoming the narrow approach taken so far.

Earthquakes have usually been associated with potential damage to storage facilities for animals or machinery; not much thought has been given to infrastructures used in agriculture. Nonetheless, the 2012 earthquake in Italy proved to be devastating for hydraulic infrastructures needed for irrigation that was halted for several days with heavy consequences for production.

Damage due to volcanic hazard, in particular gas and tephra, is associated with animals, crops, irrigation water and soil that can be devastated for a long time (Craig et al., 2016).

Floods may affect all above mentioned components differently, but as mentioned by Brémond et al. (2013), this is not reflected in currently available damage curves.

2.4.3.1.2 Industries and commercial businesses

Industries and commercial businesses are often treated as buildings, even though they differ from the latter in many regards. A first difference is the large space usually necessary for activities that make these facilities more vulnerable to earthquakes. Secondly, potential damage to machinery and raw and finished products may be more relevant than damage to structures, particularly in the case of floods, where damage to structures is generally low.

Thirdly, businesses present a very large combination of buildings, machinery, activities and processes that make it hard to standardise vulnerability assessment. Information on damage suffered by industries and factors that make them vulnerable are available for flood risk and earthquakes (Suzuki, 2008; Krausman, 2010). Damage to business can sometimes turn into a severe secondary hazard (risk cascade), when dangerous plants are affected by natural hazards producing the so called Natech hazards (Cozzani et al., 2010; Ministère chargé de l'environnement, 2005; see also Chapter 3.14).

2.4.3.2 Damage to intangibles

Damage to intangibles is that which affects people and artefacts that are considered of incommensurable value, i.e. it is very difficult or controversial to monetise. Consideration in this paper will be limited to three examples, one for each hazard.

2.4.3.2.1 Loss of cultural heritage due to earthquakes

Earthquakes occurring in historic towns often affect ancient buildings and monuments more permanently and dramatically. Their vulnerability is due to several factors including construction material, type of resistant technology, lack of maintenance and poor or totally lacking seismic retrofitting. Furthermore, historic centres in Mediterranean areas, e.g. Greece, Spain, southern France, Italy and Slovenia, are characterised by complex urban blocks. The vulnerability of these blocks is exacerbated by the presence of shared structural components between adjacent buildings, topographic layout and the recent introduction of infrastructures, without taking seismic risk into sufficient consideration. From a cultural perspective, it is very difficult to assess the value of lost heritage. Methods are available but evaluations are always heavily loaded with societal and emotional concerns that are hard to represent in formalised quantitative terms.

2.4.3.2.2 Loss of natural assets and soil as a consequence of floods

Floods may damage, for example, parks and natural preserves in different ways (Gautak and Van der Hoek, 2003): light structures used for visiting such areas may be destroyed and contamination due to toxic and dangerous substances carried out by inundating waters may occur with different degrees of severity, while fauna and flora may also be affected. When a post-flood damage assessment was conducted it was observed that certain species of birds abandoned the area due to the loss of nutrients in the soil and water (Menoni et al., 2017). Time is required in order to assess whether or not such damage is permanent and whether or not eventual substituting species are as rich in biodiversity as those they have substituted. Similar considerations may regard the soil itself for agricultural purposes. Salinisation resulting from coastal inundations and loss of fertile soil may be more or less permanent. Those observations should lead to enhanced risk models that provide an output to show not only the immediate damage due to the event, but also its evolution and dynamic over time, which may require years to appraise the real, longer-term effects.

2.4.3.3 Historical examples of permanent relocation

Loss of social capital as a result of temporary or long-term relocation is an issue that should be considered whenever such a measure is examined. Sometimes during volcanic crises, such a decision is inevitable to safeguard people's life. Examples of past relocations such as those associated with the 1982 El Chichón eruption in Mexico (Marrero et al., 2013), the 1991 Pinatubo eruption in the Philippines (Newhall and Punongbayan, 1997), the 1991 Hudson volcano eruption in Chile (Wilson et al., 2012) and the 2010 Merapi eruption in Indonesia (Mei et al., 2013) suggest that without careful planning, communities can be largely disrupted. In all these examples, people were detached from their source of income and from the territory that is often a fundamental component of their livelihood and identity.

2.4.4 The relevance of indirect damage and losses to account for the complexity of events

Literature on direct, indirect and secondary damage is rather significant and there is still no perfect consensus on what those terms mean; however, larger convergence by the scientific and practitioner communities has been achieved in more recent years thanks to efforts at the European and international levels.

At the former level, one may consider the results of the Conhaz project (Meyer et al., 2015), the Nedies project (Van der Veen et al., 2003) and, lately, the work carried out by the European Commission on disaster loss data (De Groeve et al., 2013; EU technical working group, 2015). At the international level, the work carried out within ECLAC (Cepal, 2014) and the post-disaster needs assessment (PDNA) (GFDRR, 2013) has provided relevant approaches to pave the way for the SFDRR.

2.4.4.1 Indirect damage due to ripple effects in complex systems

The need to consider other types of damage as well as damage to multiple systems stems from the recognition that real events are much more complex than the representation of physical damage to few assets. Cascading effects, enchained failures, malfunctions of critical lifelines and inaccessibility to facilities and affected areas may be more severe in terms of impact and victims than the physical damage itself (Park et al., 2013). This can be considered as the systemic facet of indirect damage due to the interconnection and interdependency of urban and regional systems as well as among components of complex systems (Pitilakis et al., 2014).

As for systemic aspects, there have so far been few and partial attempts to model them to make them part of a more complete risk assessment (Bruneau et al., 2003). The MATRIX (2013) and the Syner-G (2014) projects can be recalled here, in particular with reference to the work done on modelling lifeline disruption due to natural disasters. By analysing in detail the models provided by both projects, it is evident that even though they are rather formalised, expert decisions must be provided at crucial nodes in order to run them. This is consistent with the fact that there is not enough

statistical evidence for each type of malfunction of complex lifeline systems to allow for a more general formalisation of the evaluation procedure. In fact, until recently, only anecdotic narrative was available, accompanied by a few numerical figures. Few written reports regarding damage suffered by lifelines in case of floods are available (Pitt, 2008; Ministère de l'écologie, 2005). As for earthquakes, only recently the EERI reports providing first reconnaissance analysis of events have introduced a more in-depth section on lifelines. For the volcanic risk a rather interesting work has been conducted upon observations for a few eruptions, e.g. the Puyehue-Cordón Caulle 2011 eruption in Chile (Wilson et al., 2013; Craig et al., 2016; Elissondo et al., 2016) and the Shinmoedake 2011 eruption in Japan (Magill et al., 2013). Such efforts have not produced the number and extensive data available for physical damage, yet they represent an important first step that would require more focus on future efforts of collecting and analysing post- disaster damage data.

2.4.4.2 Indirect economic damage

Even less evidence is available for indirect damage on economic systems induced by direct damage, lifelines failures, and losses due to business interruption. Such damage and losses include induced production losses suffered by suppliers and customers of affected companies, the costs of traffic disruption or the costs of emergency services. Evidence to date suggests that indirect damage is more important in big disasters than in more trivial ones. For example, Hallegatte (2008) demonstrates that significant indirect loss for the state of Louisiana only arises when direct losses exceed EUR 50 billion. In a separate study, he also demonstrates that indirect impacts are greater if a natural disaster affects the economy during the expansion phase of its business cycle than if it touches it during a recession phase (Hallegatte et al., 2007).

Systemic interconnections and complexity of modern societies require new approaches of damage analysis and representation with respect to the ones that have been in use so far. Post-event damage assessment can provide key knowledge regarding multiple types of failures and indirect damage and loss.

Compared to direct physical effects, indirect economic losses are much more difficult to measure. Additionally, there are limited available sources of data for measuring indirect losses. It seems that defined and agreed-upon protocols for identifying and collecting useful data in this domain are still missing or are still in their early stages. Insurance data on business interruption are of limited value for that purpose, as most indirect effects, for example power outage, do not qualify for compensation under business interruption insurance. Moreover, insurance data must be indexed by insurance market characteristics (e.g. market penetration and average deductibles) to allow correct data interpretation and cross-country investigations. Also, until recently, most insurance companies tended to treat this data as private asset.

The limitation of accessible primary data have led to attempts to measure indirect losses using economic models of the type that have long been utilised for economic forecasting, such as:

- simultaneous equation econometric models (Ellison et al., 1984; Guimares et al., 1993; West and Lenze, 1994),
- input-output models (e.g. Rose and Benavides, 1997; Boisevert, 1992; Cochrane, 1997),
- computable general equilibrium models (Brookshire and McKee, 1992; Boisevert, 1995).

Studies evaluating model-based estimates (Kimbell and Bolton, 1994; Bolton and Kimbell, 1995; West, 1996) show that models developed for traditional economic forecasting tend to overstate the indirect effects. Differences to observed impacts from post- event economic surveys are by 70 % to 85 % (West and Lenze, 1994). The reason for this overestimation of both indirect regional economic losses from natural disasters and indirect regional economic gains from reconstruction is that statistically based economic models have been designed primarily to forecast the effects of a lasting impact.

The historical interlinkages embodied in these models are likely to be substantially disturbed and temporarily

changed during a disaster. Dynamic adjustment features such as recovery, resilience, interregional substitution, inventory adjustments, changes in labour supply, number of displaced, etc. are not reflected in these models. In short, these models must be substantially revised in order to produce reliable estimates of indirect effects. Computational algorithms modelling supply shocks, post- event supply constraints and time- phased reconstruction in disaggregated spatial settings (as, for example, applied in van der Veen and Logtmeijer, 2005 and Yamano et al., 2007) seem promising to overcome this methodological gap.

2.4.4.3 Changes needed to improve post-disaster damage and loss data availability and quality

In order to obtain a more comprehensive and satisfactory overview of damage to assets, systems and sectors following a disaster, more consistent and systematically gathered data to address the complexity of real events are needed. Furthermore, as already suggested by the World Meteorological Organisation guidelines (2007), efforts of data collection should be reiterated in the same areas in order to detect trends that cannot be seen a few hours or days after the event and to monitor the rehabilitation and recovery process.

To achieve such a goal of obtaining and maintaining a more robust repository of different types of damage to multiple sectors, a standardised reporting system, similar to the PDNA or to the so- called Retour of Experience in France (Direction territoriale Méditerranée du Cerema, 2014) would provide significant advantages. First, because they will permit comparison between cases across geographic regions and time; it will then be easier to recognise similarities among cases and aspects that are specific to each case. Second, data collected and processed in the same way for key variables will allow us to obtain statistical evidence for some variables that at present are described only in a qualitative way. Third, more comprehensive and comparable reports will permit the building of a body of knowledge on different types of damage to several sectors that can support decision-making for a more resilient recovery and to feed pre-event modelling, as suggested in Figure 2.14.

2.4.4.3.1 Costs versus physical damage

Another field that would require substantial advancement relates to the reconciliation between different ways of representing damage and losses. Engineers generally provide a physical representation of damage in terms of affected buildings, bridges, lifelines and plants (and related components). Costs of asset repair or substitution can then be estimated. It is less easy than generally perceived to find an exact match between the estimated repair and substitution costs and the real expenses that are declared for the reconstruction of the same items (Comerio, 1996). This can be due to the fact that costs of amelioration are included too or that, if not governed, the process may lead to some distortions where someone takes undue advantage of the disaster. Extra costs may be due also to the excessive amount of needed repair material or workers from other areas to be recruited as local capacities are overwhelmed.

Furthermore, there are spatial and temporal scale issues that cannot be neglected; for example, the shift from individual items that are assessed to entire sector categories, like the shift between individual residential buildings to residential land uses. For an attempt of alignment, one may consider the recent work carried out by Amadio et al. (2015).

More comprehensive post-event damage analysis will provide fundamental knowledge to a variety of stakeholders. Innovation is needed to reconcile the 'engineering' representation of the physical damage and the economic assessment of direct and indirect damage and loss

The economic damage, however, is not restricted to the translation of physical damage or services malfunction into monetary terms. Instead, it reflects the economist's perspective, according to which loss goes beyond repair and reconstruction needs and comprises the total effect the damage will have on a given economy (either local or national) in terms of lost resources and assets (Pesaro, 2007).

Such resources can be linked to material damage, to business and service interruption or to the fact that customers will be lost as a consequence of prolonged businesses' interruption, etc. Systemic effects due to the failure or malfunction of lifelines and services can be described in terms of numbers (days/hours of interruption, number of customers without service) or in terms of the economic loss that has been caused by such a failure. The two representations of damage and losses do not fully coincide; instead it would be very important to find correspondences between them.

2.4.5 Conclusions and key messages

Partnership

A stronger partnership among a variety of stakeholders is required to achieve a more comprehensive and realistic picture of complex disasters' impact on society. Despite claims related to the usefulness of risk models for decision-making, researchers devoted attention to models that were already satisfactorily developed and to sectors for which it was relatively easy to get data (Grandjean, 2014). In fact, the focus of many scientific studies is improving the quality and the reliability of models, independently of completeness in terms of covered sectors and types of item. Completeness is important, however, for decision-makers. Local and regional governments are certainly interested in assessing not only the potential physical damage to buildings and a limited number of assets, but also the larger systemic effects, potential disruption of services and businesses and overall impacts on the regional economy. Depending on whether their role is managing prevention or emergencies, they are keen to know which sectors deserve more resources to reduce future risk and how expected damage will be distributed in space and in time.

Insurers are also interested in enhanced damage modelling and in a wider view of impacts that may shape the environment in which the damage they will have to compensate for occurs. In fact, duration of interruption is a crucial factor, particularly for businesses. In recent years, insurance companies have become more active in supporting their customers after an event to reduce such a duration. Knowing in advance what 'external factors' may impact on the capacity to return to normal operations will allow us to better tailor advice for mitigation that is increasingly recognised as part of insurers' work to diminish their own financial exposure.

Ultimately, we conclude that improved risk models supported by larger and more refined evidence derived from the observation of what actually happens after real events is for the benefit of risk mitigation measures, be they structural or non -structural.

Knowledge

The potential benefits for risk modelling that may be provided by enhanced damage data collection and analysis is still an open issue for both academic researchers and practitioners. Following a review of existing methods of damage modelling in Europe and the United States, Hubert and Ledoux (1999) had already suggested that post -event surveys may provide more 'reality' to assessments by subtracting the field of imagined and hypothesised damage and providing more evidence from observed and surveyed damage. They suggest this is necessary, particularly for those sectors such as lifelines and industries, for which risk models are still in their infancy in terms of robustness and completeness. In fact, as shown in this chapter, knowledge is more advanced in the field of direct physical damage to certain assets, in particular buildings, while less so with respect to other sectors and different types of damage.

Innovation

Multiple innovations are needed to enhance our capacity for damage modelling . First, there is the need to substantially improve post- disaster event and damage data collection and analysis (Barredo, 2009) to account for the different types of damage to multiple sectors that are currently missing. Second, there is a need to reconcile different interpretations of damage, not only in terms of definitions, a field where significant advances have been achieved, but also in terms of adopted units of measure and methods to aggregate cost at different scales.

Closer interaction between engineers, volcanologists, geophysicists, geographers and economists has to be sought in order to understand the implications and the links between different ways of accounting for and reporting damage and loss. This would permit an advancement of risk modelling by overcoming the apparent randomness of current assessments, which for some risks and for some assets are provided as damage index, and for others as costs.

Also, a more comprehensive framework considering spatial and temporal scales should be adopted in risk assessment. As for the former, it would be established looking at the chain of potential impacts, physical and systemic, and the quality and quantity of exposed elements and systems (including economic systems). Therefore, damage should not be considered only in the core area, where most physical damage has occurred, but case by case in the area of relevance, which can range from local to global in some extreme instances (Nanto et al., 2011). As for the temporal scale, it is key to reiterate the data collection at time intervals relevant for the type of event that has occurred. This will help to provide risk assessments with a clearer timestamp. A shift from a static representation of damage, defined in a pre-assigned time (often not made explicit), to more dynamic representations is necessary to show how damage changes and what type of damage becomes more prominent at each stage of the disaster event (impact, emergency or recovery).

2.5 Where are we with multihazards, multirisks assessment capacities?

Jochen Zschau

2.5.1 Why do we need a change in the way we assess natural risks?

2.5.1.1 Multirisk assessment versus single-risk assessment for disaster risk management

A given location on Earth may be threatened by more than one hazard. One of the challenges of disaster risk management (DRM) is to prioritise the risks originating from these different hazards to enable decisions on appropriate and cost-effective mitigation or preparedness measures. However, comparability between risks associated with different types of natural hazards is hampered by the different procedures and metrics used for risk assessment in different hazard types (Marzocchi et al., 2012). A common multirisk framework is needed being designed around a homogeneous methodology for all perils. In addition, many of the natural processes involve frequent and complex interactions between hazards. Examples include the massive landslides triggered by an earthquake or floods and debris flows triggered by an extreme storm event.

Risk globalisation and climate change are great challenges that require a shift in the way we assess natural risks from a single-risk to a multirisk perspective.

The chain of events — referred to as cascade or domino effects — can increase the total risk, and the secondary events may be more devastating than the original trigger, as shown in the 2004 Indian Ocean tsunami or the 2011 tsunami in Japan (Zschau and Fleming, 2012). Even independent events, if they occur at the same time and at the same place (e.g. hurricanes and earthquakes), may generate greater loss than the sum of totally separated single events.

The consequences of disastrous events are often propagated through the human-made system, causing interrelated technological, economic and financial disruptions, which may also result in social and political upheavals on all spatial scales. Even worldwide economies could potentially be disrupted by major disasters through their impact upon global supply chains (Zschau and Fleming, 2012). In addition, the impact of one hazard may increase the potential harmful effect of another hazard. For example, by changing vegetation and soil properties, forest fires may increase the probability of debris and flash floods (Cannon and De Graff, 2009). Similarly, a building's vulnerability to ground shaking may increase due to additional structural loads

following volcanic ash fall or heavy snowfall (Lee and Rosowsky, 2006; Zuccaro et al., 2008; Selva, 2013). Vulnerability in these cases would be highly time variant.

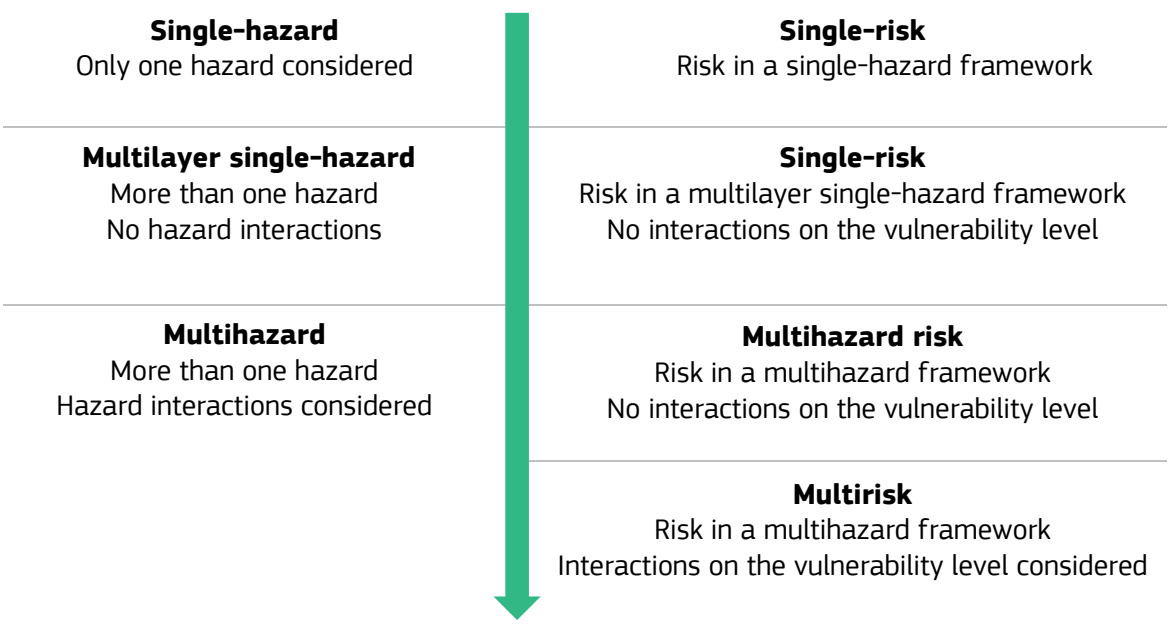
Multihazard risk approaches start from single-hazard risk assessments. Figure 2.19 attempts to capture the transition from single-hazard to multihazard risk as well as the definitions used. Single-hazard risk is the most common method.

2.5.1.2 Emerging challenges: risk globalization and climate change

The risks arising from natural hazards have become globally interdependent and, therefore, not yet fully understood. The ongoing 'urban explosion', particularly in the Third World, an increasingly complex cross-linking of critical infrastructure and lifelines in the industrial nations as well as an increasing vulnerability due to climate change and growing globalisation of the world's economy, communication and transport systems, may play a major part (Zschau and Fleming, 2012, Gencer, 2013). These factors are responsible for high-risk dynamics and also constitute some of the major driving forces for disaster risk globalisation. Communities are affected by extreme events in their own countries and become more vulnerable to those occurring outside their national territories. The effects of a destructive earthquake in Tokyo, for instance, may influence London through shaky global markets and investments; or a disaster in a global city such as Los Angeles may affect developing economies like Mexico and can put the already vulnerable poor into further poverty (Gencer, 2013). In addition, the increased mobility of people can spatially enlarge the scale of natural disasters. This was demonstrated, for example, by the fatal tsunami disaster of 2004 along the coasts of the Indian Ocean, where the victims did not only come from the neighbouring countries, but included nearly 2 000 citizens from Europe, for instance, most of whom had been visiting resorts in the affected region during their Christmas holidays when the tsunami struck. Globalisation is not

FIGURE 2.19

From 'single-hazard' to 'multirisk' assessment and terminology adopted here.
Source: courtesy of author



the only reason for the growing interdependencies and the high dynamics seen in the risks from natural hazards. Climate change may be another important factor. According to IPCC (2014), it is very likely that extreme events will occur with higher frequency, longer duration and different spatial distribution. Climate change is also projected to increase the displacement of people, which will lead to an increase of exposure to extreme events. They will be exposed to different climate change impacts and consequences such as storms, coastal erosion, sea level rise and saltwater intrusion (Nicholls and Cazenave, 2010).

A multirisk modelling approach will be required in order to capture the dynamic nature and various interactions of the hazard and risk-related processes driven by both climate change and globalisation. Moreover, the sought-after solutions for risk assessments are no longer exclusively aiming at the best possible quantification of the present risks, but also at keeping an eye on their changes with time and allowing to project these into the future.

2.5.2 Towards multirisk assessment methodology: where do we stand?

2.5.2.1 Sources of our present knowledge: the role of EU-funded projects

The Agenda 21 for Sustainable Development (UNEP, 1992), the Johannesburg Plan for Implementation (UN 2002), the Hyogo Framework for Action (UNISDR, 2005) and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) promote multihazard risks of natural hazards. Together with the International Decade for Natural Disaster Reduction (IDNDR) from 1990 to 1999 and the following permanently installed International Strategy for Disaster Reduction (ISDR), they constitute a worldwide political framework for the initiation of a multitude of scientific projects in the risk research community (Zentel and Glade, 2013). These projects include global index-based multihazard risk analysis such as Natural Disaster Hotspots (Dilley et al., 2005) or INFORM (De Groeve et al., 2015). They also include regional multihazard initiatives like the cities project for geohazards in Australian urban communities (Middelmann and Granger, 2000), the Risk Scape project in New Zealand (Schmidt et al., 2011) and the platforms HAZUS (FEMA, 2011) and CAPRA (Marulanda et al., 2013) for the automated computation of multihazard risks in the United States and Central America, respectively.

The European Union funded projects on multihazard and multirisk assessment within its framework programmes FP4, FP5, FP6 and FP7. The TIGRA project (Del Monaco et al., 1999) and the TEMRAP project (European Commission, 2000) were among the first attempts to homogenise the existing risk assessment methodologies among individual perils. The European Spatial Planning Observation Network (ESPON) compiled aggregated hazard maps weighting the individual hazards by means of expert opinion and taking into account various natural and technological hazards in Europe (Schmidt-Thomé, 2005).

A multirisk assessment framework should allow for the comparison of risks and account for dynamic vulnerability as well as complex chain reactions on both the hazard and vulnerability levels

Quantitative, fully probabilistic methods for multihazard and multirisk assessment were developed in a series of FP6 and FP7 projects: Na.R.As. 2004-2006 (Marzocchi et al., 2009), ARMONIA 2004-2007 (Del Monaco et al., 2007) and MATRIX 2010-2013 (Liu et al., 2015). Their results allow independent extreme events (coinciding or not coinciding) as well as dependent ones, including cascades, to be treated on both the hazard and the vulnerability levels. Moreover, these projects have time-dependent vulnerability taken into account. Their methods were applied in the CLUVA project 2010-2013 to future projections of the influence of climate change on natural hazards and urban risks in Africa (Bucchignani et al., 2014; Garcia-Aristizabal et al., 2015 a, b, 2016) as well as in the CRISMA project 2012-2015 to crisis scenario

modelling for improved action and preparedness(Garcia-Aristizabal et al., 2014).

In addition, projects in Europe funded on a national or regional basis have contributed significantly to our present knowledge on multirisk assessment. The German Research Network for Natural Disasters (DFNK), which had undertaken comparative multirisk assessments for the city of Cologne (Grünthal et al., 2006), gives an example of this. The Piedmont region project in Italy, with a focus on a methodological approach for the definition of multirisk maps (Carpignano et al., 2009), and the ByMuR project 2011-2014 on the application of the Bayesian probabilistic multirisk assessment approach to natural risks in the city of Naples (Selva, 2013) are two other examples. Furthermore, the Centre for Risk Studies of the University of Cambridge in the United Kingdom is presently one of the first to systematically address the globalisation aspect of risk. The centre is currently setting up a global threat taxonomy and a risk assessment framework aiming at macro-catastrophe threats that have the potential to cause large-scale damage and disruption to social and economic networks in the modern globalised world (Coburn et al., 2014).

2.5.2.2 Multilayer single-risk assessments: harmonisation for risk comparability

In order to assist decision-makers in the field of DRM in their prioritising of mitigation actions, one has to understand the relative importance of different hazards and risks for a given region. This requires the threats arising from different perils to be comparable with each other. However, this is difficult, because different hazards differ in their nature, return period and intensity, as well as the effects they may have on exposed elements. Moreover, the reference units, such as ground acceleration or macroseismic intensity for earthquakes, discharge or inundation depth for floods and wind speed for storms, are different among the hazards. This does not only hamper the comparability between the threats, but it also makes it difficult to aggregate the single perils in a meaningful way in order to assess the total threat coming from all the hazards in a region. These problems exist independently of whether hazard interactions and/or interactions on the vulnerability level are important or not. Thus, to overcome them, and as a first step towards a full multirisk assessment, one may treat them in the context of a multilayer single-hazard/risk assessment approach, ignoring the interactions but harmonising and standardising the assessment procedures among the different perils.

Three major standardisation schemes can be distinguished in this context (Kappes et al., 2012; Papathoma-Köhle, 2016). They make use of:

- matrices — hazard matrix, vulnerability matrix and risk matrix;
- indices — hazard index, vulnerability index and risk index; and
- curves — hazard curves, vulnerability curves and risk curves.

They are applicable on all three assessment levels: hazard, vulnerability and risk, respectively.

Matrices

A hazard matrix applies a colour code to classify certain hazards by the intensity and frequency (occurrence probabilities) determined qualitatively, for instance 'low', 'moderate' and 'high (Figure 2.20). Based on this, one can compare the importance of hazards and one may derive the overall hazard map by overlaying the classification results of all single hazards. An example of this approach is the risk management of natural hazards in Switzerland (Figure 2.20, redrawn from Kunz and Hurni, 2008; see also Loat, 2010). The European Commission-funded Armonia project (Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment) has proposed a similar classification scheme (Del Monaco et al., 2007). Likewise, the French risk prevention plans (Cariam, 2006) follow this kind of approach.

Like in the 'hazard case', overarching matrix schemes also exist on the vulnerability level. So-called damage matrices, for example, are discrete approaches to vulnerability assessment that oppose relative damage or damage grades to classified hazard intensities in a matrix. The resulting vulnerability (fragility) is either qualitatively described (few, many or most), for instance as the proportion of buildings that belong to each damage grade for various levels of intensity (see Grünthal, 1998 in relation to the European macroseismic scale), or quantitatively described as the probability to reach a certain damage grade (Tyagunov et al., 2006).

For the aim of comparing and aggregating risks coming from multiple

hazards, assessment procedures are required that combine both hazard and vulnerability information. Various authors (e.g. Sterlacchini et al., 2007; Sperling et al., 2007; Greiving, 2006) have suggested matrix schemes that fulfil this requirement. The European Commission (2010) proposed a risk matrix that relates the two dimensions, likelihood (probability) and impact (loss), for a graphical representation of multiple risks in a comparative way (Figure 2.21). Distinct matrices were suggested for human impact, economic and environmental impact and political/social impact, as these categories are measured with distinct scales and would otherwise be difficult to compare.

Indices

Apart from the matrix-based approaches described above, index-based approaches are another means to achieve comparability in the multilayer single-hazard and -risk context. The methodology of composite indicators allows to combine various indicators to obtain a meaningful measure.

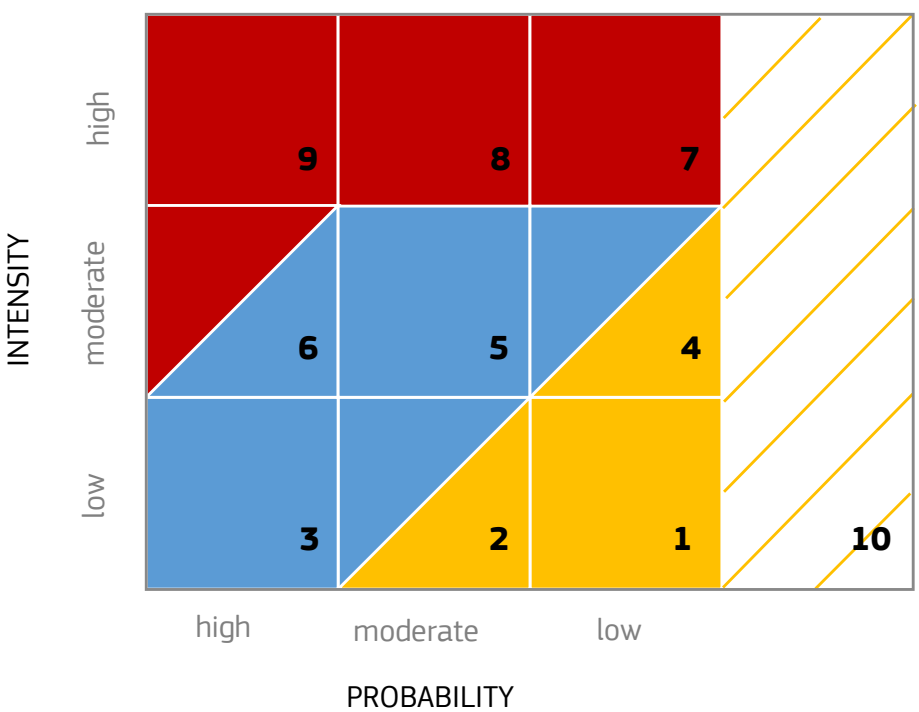
An example of an index-based approach on the hazard level is global Natural Disaster Hotspots (see also Chapter 2.5.2.1), which is an aggregated multihazard index calculated from the exposure of a region to various hazards and is used to identify key 'hotspots', where the exposure to natural disasters is particularly high. A more recent example was put forward by Petitta et al. (2016) who suggested a multihazard index for extreme events capable of tracking changes in the frequency or magnitude of extreme weather events.

Vulnerability indices (see also Chapter 2.3) are already widely used in the socioeconomic field, including multihazard settings, as for example in the studies of Wisner et al. (2004), Collins et al. (2009) and Lazarus (2011), but they are rarely hazard specific (Kappes et al., 2011). In contrary , physical vulnerability is regarded as hazard- specific. An increasing number of studies is now available that applies hazard-specific vulnerability indicators to, for instance, tsunamis (Papathoma et al., 2003), floods (Barroca et al., 2006, Balica et al., 2009; Müller et al., 2011), landslides (Papathoma-Köhle et al., 2007; Silva and Pereira, 2014) and mountain hazards (Kappes et al., 2011). In various cases the indicators are combined with the PTVA (Papathoma Tsunami Vulnerability Assessment) method (Papathoma and Dominey-Howes, 2008).

Going from vulnerability indices to risk indices is another solution to achieving comparability in the multilayer single-risk context. As a risk indicator includes hazard information in addition to vulnerability information, such a step also allows the aggregation of the risks coming from different perils. Dilley et al. (2005), who computed hazard and vulnerability for natural hazards on a global scale and weighted the hazard with the vulnerability index to calculate risk, gave an example. For the derivation of the multihazard risk, all single-hazard

FIGURE 2.20

Swiss hazard matrix
Source: Kunz and Hurni (2008)



risks were added up.

All three levels of an index-based approach, i.e. the hazard, vulnerability and risk levels, are addressed in the ongoing European project INFORM (see also Chapter 2.5.2.1), where separate indices for hazard and exposure, vulnerability, lack of coping capacity and risk are developed in order to identify countries where the humanitarian crisis and disaster risk would overwhelm national response capacity.

Curves

More quantitative methods for assessing natural threats in a multilayer single-hazard approach are based on 'curves' ('functions').

Hazard curves present the exceedance probabilities for a certain hazard's intensities in a given period. Vulnerability curves graphically relate the loss or the conditional probability of loss exceedance to the intensity measure of a hazard (for instance ground motion, wind speed or ash load) in order to quantify the vulnerability of elements at risk. When the probability of exceeding certain damage levels is considered, the curves are referred to as 'fragility curves'.

One may easily combine vulnerability curves with the corresponding hazard curves to arrive at a measure of risk. This could be the average loss per considered period, the so-called average annual loss or expected annual loss, if the period is 1 year. It could also be a risk curve, which graphically relates the probability of loss exceedance within the period under consideration to the loss coming from all possible hazard intensities. As exceedance probabilities and loss are not expressed in hazard-specific units, they are directly comparable among different hazards and can easily be aggregated to an overall multilayer single risk.

Figure 2.22 shows the annual exceedance probability of direct economic loss from earthquakes, floods and storms in the city of Cologne (Grünthal et al., 2006). Storms turn out to be the dominant risk at return periods lower than 8years (largest loss!). Floods take over for higher return periods up to 200 years and earthquakes become the dominant risk for return periods higher than 200 years.

A comparison between the risks from the different perils can be accomplished based on the expected average loss within the considered period represented by the area under the risk curve (Van Westen et al., 2002).

Fleming et al. (2016) demonstrated that one may also easily aggregate the single-hazard-specific risk curves to obtain a 'total risk' curve without considering potential interactions between the hazards. Figure 2.23 shows the wind, storm and earthquake risks for the city of Cologne. The various aggregations of the risk probabilities, for instance for loss in the order of EUR 100 million, indicate enhanced loss probabilities from between 15 % and 35 % for the individual hazards and up to 56 % in 50 years when combined.

FIGURE 2.21

Risk matrix proposed by the European Commission
Source: European Commission (2010)

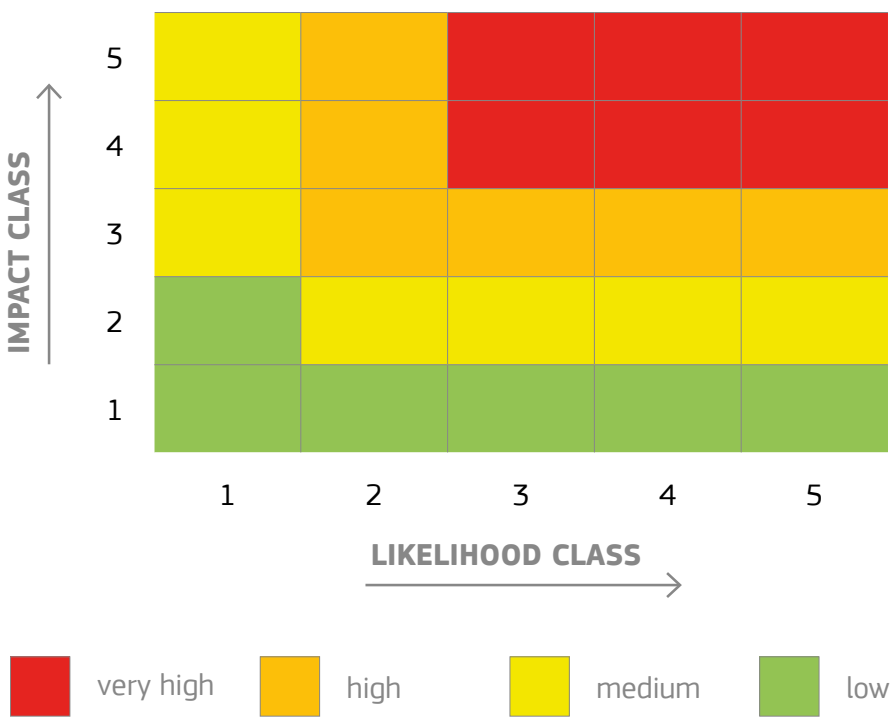


FIGURE 2.22

Risk curves for the city of Cologne
Source: Grünthal et al. (2006)

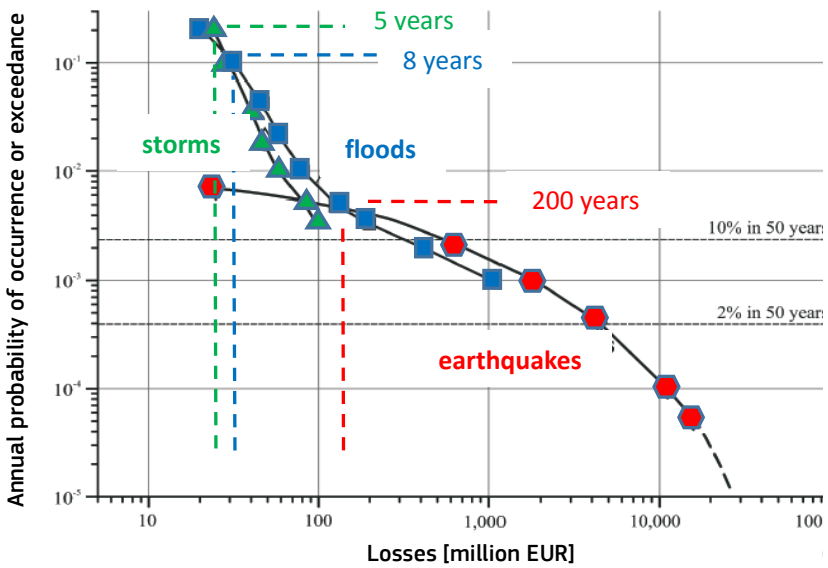
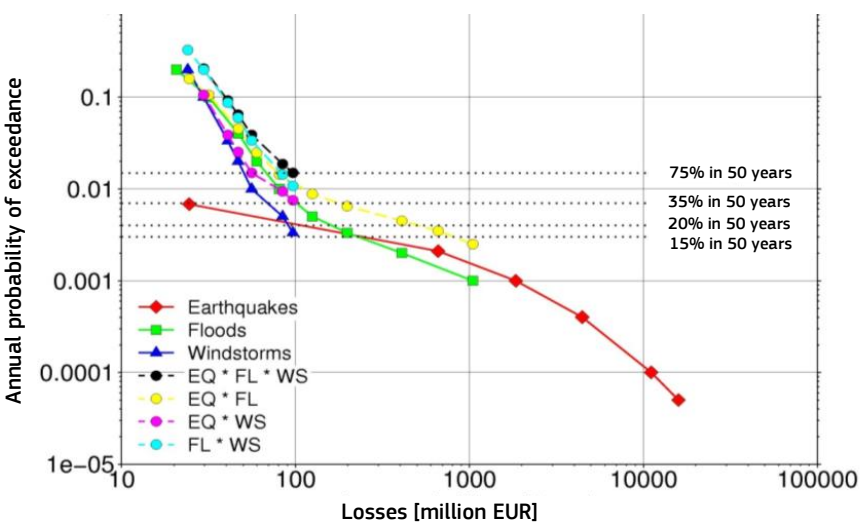


FIGURE 2.23

Risk curves and their aggregations for the city of Cologne
Source: Fleming et al. (2016)



Hazard, vulnerability and risk curves are the quantitative equivalent to the hazard, vulnerability (damage) and risk matrices. On the other hand, there is a distinct difference between them: the curves only make use of two dimensions, frequency and impact, to characterise risk, whereas matrices use three dimensions, by additionally introducing colour codes. The third dimension expresses different levels of risk from 'low' to 'high' with different colours, which gives extra weight to either the impact or the likelihood (see, for instance, Figure 2.21).

This is an added value of risk matrices, since the additional colour code makes it possible to compare high-probability and low-consequences events with low-probability and high-consequences ones, for instance. To extract similar information from risk curves, probabilities and loss can simply be multiplied (P×L). The lines of equal loss–probability products, P×L, in a logarithmic risk curve plot would be straight diagonal lines (Figure 2.24, left). In the case of a single-risk scenario with a given annual probability, the loss-probability-product directly represents the average annual loss (impact). This is not the case for the risk curve, which includes the loss from all possible hazard intensities. However, one may easily show that in this case it represents the contribution to the average annual loss per increment of logarithmic probability. Thus, from additionally displaying the exceedance probability as a function of the loss-probability-product instead of the loss alone, one may learn which part of the risk curve, in terms of return periods, will contribute most to the average annual loss. In the case of Cologne (Figure 2.24,

right), storms and floods contribute the most in the range of small return periods, whereas for earthquakes the return periods of around 1 000 years have the highest contribution to the average annual loss.

The probabilistic concept of risk curves is used for both economic losses of a potential disaster and the indirect, socioeconomic impacts, as long as these are tangible. As examples, Garcia-Aristizabal et al. (2015a) mention losses in work productivity, losses due to missing income, costs of evacuation and the costs of medical assistance as well as effects of the loss of functionality of systems and networks including disruptions of productivity and the means of production. Garcia-Aristizabal et al. (2015a) also describe how the information from the socioeconomic context can be integrated straightforwardly into the quantitative multi-layer risk framework by harmonizing the metrics of the different loss indicators and producing the single loss exceedance curves and their sum, respectively, equivalent to the methodology used for direct losses. However, this needs to introduce quantitative vulnerability/fragility information for each of the different indicators or even their respective vulnerability/fragility curves, which still is the bottleneck of the method.

2.5.2.3 Hazard interactions: cascading events and Co.

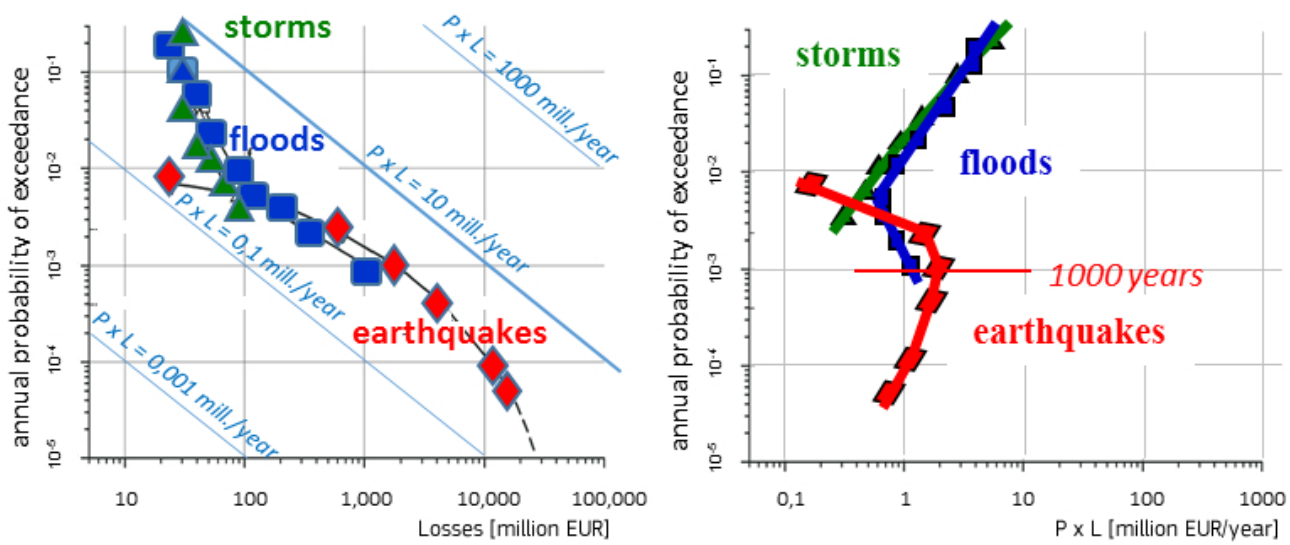
Multilayer single-risk assessments, as described in the previous section, analyse the risks coming from different perils separately. Assuming independence between the hazard-specific risks, they simply add them up to obtain the overall hazard in a region. However, in a complex system like nature, processes are very often dependent on each other, and interact. There are various kinds of interactions between hazards that often lead to significantly more severe negative consequences for the society than when they act separately. A multilayer single-risk perspective does not consider this, but a multihazard approach does.

Classification of hazard interactions

The complexity of interactions between hazards has led to a multitude of terms in use for describing different types of interdependencies. The term 'cascades' has been used, for instance, by Carpignano et al. (2009), Zuccaro and Leone (2011), Choine et al. (2015) and Pescarol and Alexander (2015); 'chains' by Xu et al. (2014), among others; and 'interaction hazard networks' by Gill and Malamud

FIGURE 2.24

Risk curves and P x L - curves for the city of Cologne (Exceedance probability versus loss (left) and versus its product with loss (right)
Source: courtesy of author



(2016). Further terms in use are 'coinciding hazards' (Tarveinen et al., 2006; European Commission, 2010), 'coupled events' (Marzocchi et al. 2009), 'domino effects' (Luino, 2005), 'follow-on events' (European Commission, 2010) and 'triggering effects' (Marzocchi et al., 2009). More of such terms are presented and explained in Kappes et al. (2012).

Gill and Malamud (2014, 2016) suggested classifying the different hazard interaction types into five groups (Box 1). In the first group, the 'triggering relationship', the secondary (triggered) hazard, might be of the same type as the primary (triggering) one or different, for instance an earthquake that triggers another one or a rainfall event that triggers a landslide, respectively. In the second group, the 'increased probability relationship', the primary hazard, does not directly trigger a secondary event but changes some aspects of the natural environment, leading to an increase of the probability of another hazard. For instance, in the event of a wildfire, vegetation is destroyed, which can result in an increased vulnerability of a slope to landslides (Gill and Malamud, 2014). In the third group, 'decreased probability relationship', the probability of a secondary hazard is decreased due to a primary hazard (third group), therefore it does not pose a problem to risk management. Gill and Malamud (2014) gave the example of a heavy rainfall event that increases the surface moisture content, whereby reducing the depth to the water table and consequently decreasing the probability of a wildfire. Similarly, the spatial and temporal coincidence of events, the 'coincidence relationship' (fourth group), may be considered as some kind of interaction, because although independent of each other, together they can increase the impacts beyond the sum of the single components if the hazards had occurred separately in time and space. An example can be seen in the coincidence of the Mount Pinatubo volcano eruption in 1991 with Typhoon Yunya (Gill and Malamud, 2016), where the combination of thick and heavy wet ash deposits with rainfall triggered both lahars (Self, 2006) and structural failures (Chester, 1993). In the fifth group, the 'catalysis/impedance relationship' between hazards, a triggering relation between two hazards may be catalysed or impeded by a third one. A volcanic eruption, for instance, can trigger wildfires, but this triggering interaction may be impeded by a tropical storm.

Furthermore, anthropogenic and technological hazards may interact with natural hazards, not only by the trigger and increased probability relationships, but also by catalysis/impedance relationships. These may include, for example, storms impeding an urban fire-triggered structural collapse or storm-triggered floods, which are catalysed by a blocking of drainage due to technological failures.

Based on geophysical environmental factors in the hazard-forming environment, Liu et al. (2016) proposed a different classification scheme for hazard interactions by distinguishing between stable environmental factors, which form the precondition for the occurrence of natural hazards, and trigger factors, which determine the frequency and magnitude of hazards. Dependent on these environmental factors, one may divide the hazard relationships into four classes: independent, mutex (mutually exclusive), parallel (more than one hazard triggered in parallel) and series relationships (one hazard follows another). Classification schemes for hazard interactions help to ensure that all possible hazard interactions among different hazards are considered in a

BOX 2.1

Classification of hazard interactions

Source: Gill and Malamud (2014, 2016)

(1) Triggering relationship
(2) Increased probability relationship
(3) Decreased probability relationship
(4) Coincidence relationship
(5) Catalysis/ impedance relationship

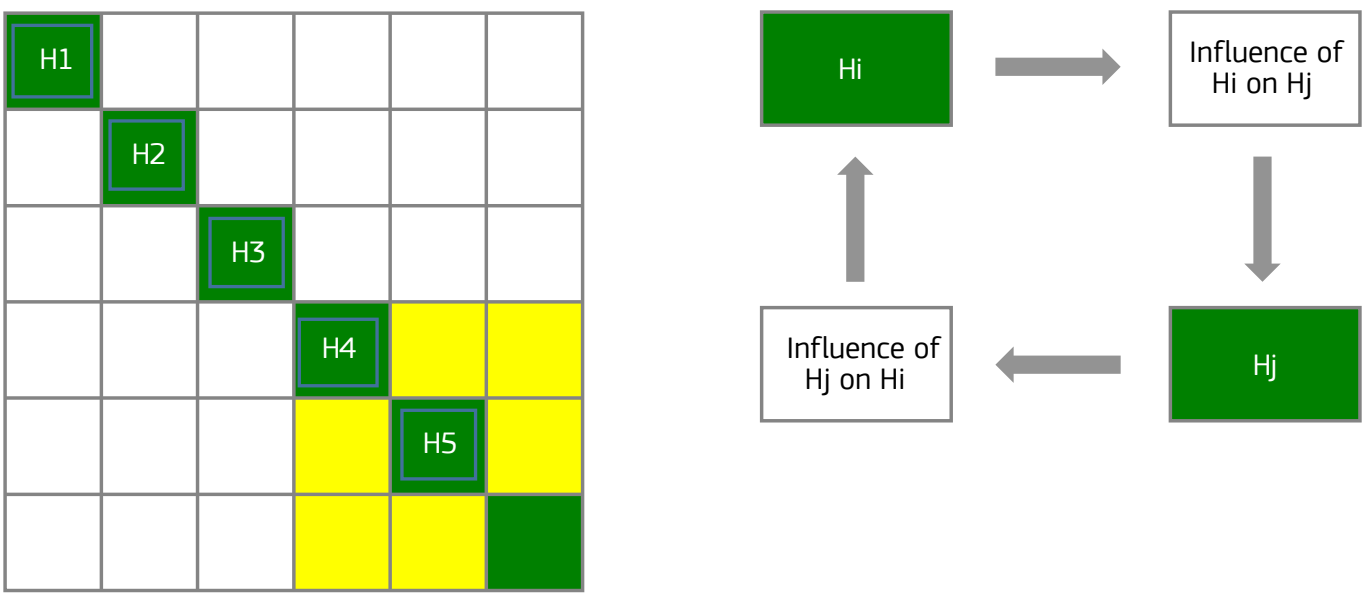
multihazard risk assessment (Liu et al., 2016).

Methods

Among the available methods to integrate hazard interactions into disaster risk assessment, there are qualitative, semi-quantitative and quantitative ones. Qualitative methods settle for qualitative descriptions and classifications of interactions with the aim of identifying the most important hazard relations in a region. Semi-quantitative approaches are mainly based on so-called hazard-interaction matrices (not to be confused with the hazard matrix addressed in Chapter 2.5.2.2). They offer a structured approach to examine and visualise hazard interactions and to see how strong these interactions are, aiming not only at the identification of important hazard relations but also at getting insight into the evolution of the system when different hazards interact. This kind of matrix has been used, for instance, by Tarvainen et al. (2006), De Pippo et

FIGURE 2.25

Matrix approach for the identification of hazard interactions.
Source: Liu et al. (2015)



Slides (H4)	2	2
0	Debris flows (H5)	2
1	1	River floods (H6)

0 – No interaction

1 – Weak interaction

2 – Medium interaction

3 – Strong interaction

Slides (H4)	Deposits only	Cut off a flow in a water course
No interaction	Debris flows (H5)	Change of river bed morphology
Erosion / saturation of deposits	Re-mobilisation of deposits	River floods (H6)

al. (2008), Kappes et al. (2010), Gill and Malamud (2014), Mignan et al (2014) and Liu et al. (2015). Figure 2.25 gives an example of how this matrix approach can be used in multihazard assessment: first, the matrix is set up in a way that all potentially interacting hazards in the region under consideration are occurring in the matrix's diagonal (Figure 2.25a). The possible interactions are described in a clockwise scheme (Figure 2.25b), which results in the influences of a hazard on the system appearing in the related matrix row and the influences of the system on the hazard in the hazard's column (Figure 2.25c). In addition, a coding between 0 and 3 is used (Figure 2.25d) to semi-quantitatively describe how strong the interactions are between the different hazards, respectively, and are entered into the matrix (Figure 2.25e). Liu et al. (2015) propose this scheme to be used as second level in their three-level framework from qualitative to quantitative multirisk assessment in order to decide whether it is justified to go to the third quantitative level of assessment or not.

Gill and Malamud (2014) have used a similar kind of matrix to characterise the interaction relationships between 21 natural hazards, both qualitatively as well as semi-quantitatively. This matrix identifies and describes hazard relations and potential cascades as well as characterises the different relationships between the intensity of the primary hazard and the potential intensity of the secondary hazard in both the triggering and increased probability cases. Moreover, they were able to indicate the spatial overlap and temporal likelihood of each triggering relationship.

Quantitative methods for integrating hazard interactions into disaster risk assessment are mainly based on event tree and fault tree strategies (see the event tree example in Figure 2.26 for volcano eruption forecasting) combined with probabilistic approaches for quantifying each branch of the tree. Among them, the concept of Bayesian event trees, where the weight assigned to a branch of a node in the tree is not a fixed single value but a random variable drawn from a probability distribution function, is of particular interest. It allows the rigorous propagation of uncertainties through the different computation layers when simulating all the hazard relations in a complex chain. The event tree structure (Newhall and Hoblitt, 2002; Marzocchi et al., 2004, 2008, 2010; Selva et al., 2012) is particularly suitable for describing scenarios composed by event chains. Neri et al. (2008), for instance, compiled a probability tree for future scenarios at the volcano Mount Vesuvius, including various eruption styles and secondary hazards associated with them. Marzocchi et al. (2009, 2012) also employed a probabilistic event tree to analyse triggering effects in a risk assessment framework. Moreover, Neri et al. (2013) used a probability/scenario tree for multihazard mapping around the Kanlaon volcano in the Philippines. However, the available quantitative studies in this field that explicitly consider hazard interactions remain rare (Liu et al., 2015).

The probabilistic framework to be combined with an event tree strategy for quantifying hazard interactions has been discussed in Marzocchi et al. (2004, 2008, 2010 and 2012); Selva (2013); Garcia-Aristizabal and Marzocchi (2013); Gasparini and Garcia-Aristizabal (2014); and Garcia-Aristizabal et al. (2015a). It is equivalent to the probabilistic framework for the multilayer hazard assessment introduced in Chapter 2.5.2.2, where the single hazards are quantified by their hazard curves, respectively, and are combined with vulnerability curves to obtain the probability of potential loss. The difference, however, is that in the case of interactions between two perils, the secondary hazard's probabilities for all possible intensity scenarios will form a hazard surface rather than a hazard curve (Figure 2.27).

So far, vulnerability has been considered as static. Like exposure, vulnerability is also highly dynamic regardless of whether it is physical, functional or socioeconomic

This is because the probability of a hazard event that has been affected by another one depends on the intensities of both the primary and secondary events.

Long-term event databases on a certain hazard may already contain the secondary events arising from interactions with other primary hazards (Marzocchi et al., 2012). Hence, for long-term problems, e.g. when the tsunami hazard over the next 50 years

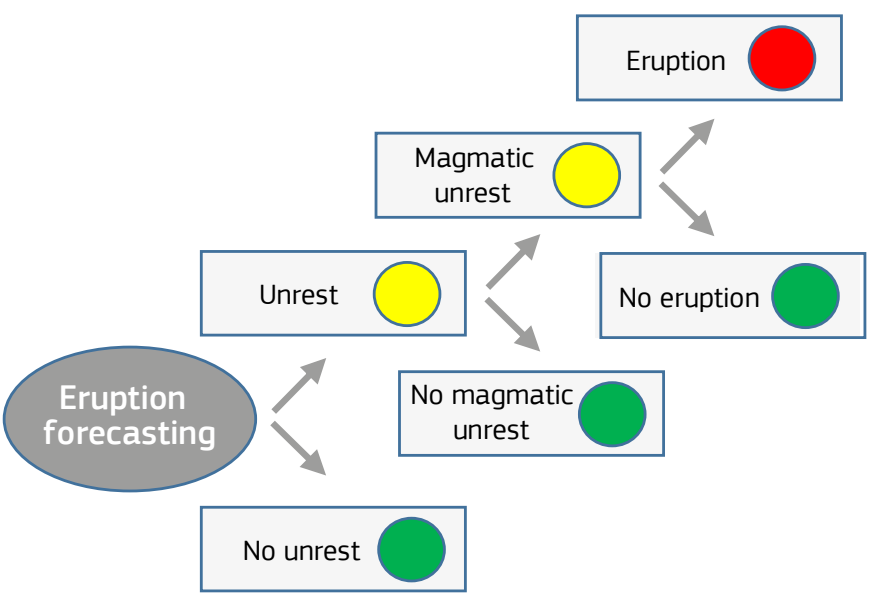
is to be assessed, there is no need to apply a multihazard methodology. A multilayer single hazard one would do, as was demonstrated by Garcia-Aristizabal et al. (2015b) with regard to future projections of the climate-related triggering of floods, drought and desertification in the area of Dar es Salaam (Tanzania) until 2050. However, in the short term (e.g. hours to days), for instance, when heavy rain changes the landslide occurrence probability in a time horizon of a few days, a multihazard approach is necessary to account for this interaction.

Marzocchi et al. (2012) also gave a simple example showing how the adoption of a single-hazard perspective instead of a multihazard one could be misleading in a short-term problem. Their example addresses the possible collapse of a pipe bridge in the Casalnuovo municipality in southern Italy, which has an increased probability, when volcanic activity triggers heavy ash loads. The collapse in an industrial centre could cause an explosion and subsequent air and water contamination. In this example it appeared that one would underestimate the probability of a pipe bridge collapse and, hence, the industrial risks (explosion, contamination) that might follow from it by more than one order of magnitude, if the secondary ash loads from volcanic activity were neglected.

A full hazard curve to quantify hazard interactions is still rare, although Garcia-Aristizabal et al. (2013) have shown that this is possible when they presented hazard curves for volcanic swarms and earthquakes triggered by volcanic unrest in the region of Naples.

FIGURE 2.26

Event tree scheme for eruption forecasting
Source: Selva et al. (2012)



Application to climate change

Based on the concept of risk curves above, it is not immediately visible the extent to which the probabilistic framework is also suitable for treating the interactions of climate change with natural hazards. The reason is that the framework has its origins in stationary processes, whereas an impact of climate change on natural hazards, resulting in more or less gradual changes regarding the hazards' frequencies and their intensity extremes, represents a non-stationary process. The methodology applied to it has to account for this (see, for instance, Solomon et al., 2007; Ouarda and El Adlouni, 2011; Seidou et al., 2011, 2012). The problem is rendered even more difficult by the fact that the probabilities of future extremes could be outside the data range of past and present observations and, hence, we cannot draw on experience, i.e. on existing data catalogues. A solution to the problem comes from extreme value theory, as this theory aims at deriving a probability distribution of events at the far end of the upper and lower ranges of the probability distributions (Coles, 2001), where data do not exist or are very rare.

The generalised extreme value distribution, combined with a non-stationary approach (the so-called non-stationary GEV model), is therefore, widely applied today to predict the effects of climate change on meteorological hazards. Examples are El Adlouni et al. (2007) and Cannon (2010) for precipitation, Siliverstovs et al. (2010) for heat waves, Seidou et al. (2011, 2012) for floods and Garcia-Aristizabal et al. (2015b) for ex-

treme temperature and precipitation. How this approach can be integrated into the above probabilistic framework for multihazard and multihazard risk assessment was demonstrated by Garcia-Aristizabal (2015b), who succeeded in harmonising the outcome of the non-stationary GEV model application to Dar es Salaam in Tanzania in the form of time-dependent, high-resolution probabilistic hazard maps and hazard curves.

2.5.2.4 Dynamic vulnerability: time- and state-dependent

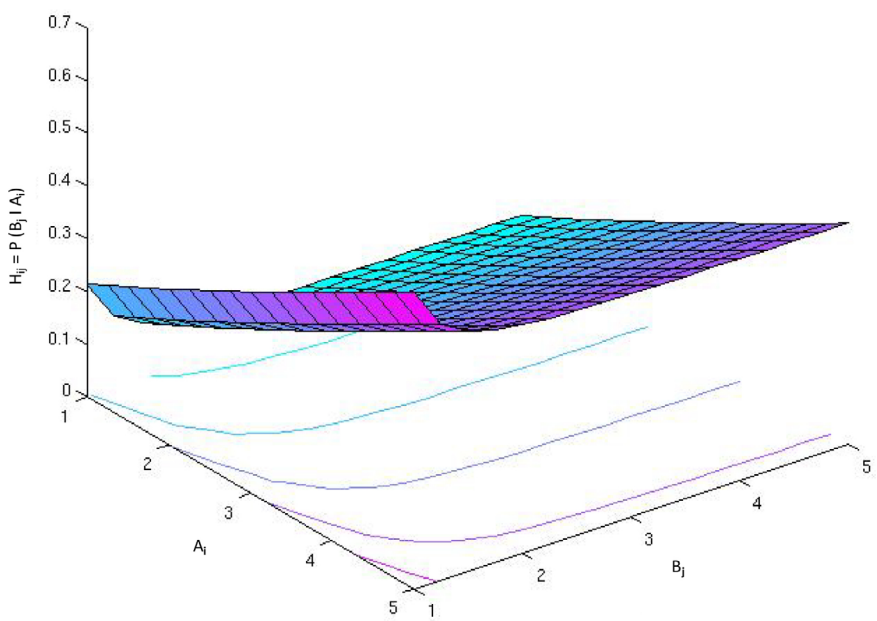
The different types of vulnerability dynamics

One may distinguish between two types of vulnerability dynamics, the time-dependent and the state-dependent one. In the first, we refer to more or less gradual changes of vulnerability with time. In the second, vulnerability depends on a certain state of a system that may change abruptly, due to a natural hazard event, for instance. If a load on a system (e.g. snow on a roof) determines the relevant vulnerability state, the expression would be 'load-dependent vulnerability'; if it is about a pre-damage state (e.g. a building that has been pre-damaged by a seismic main shock and threatened by aftershocks), the term 'pre-damage-dependent vulnerability' is employed.

The term 'time-dependent vulnerability' is used in the engineering community for distinguishing between the gradual deterioration of a building's fragility due to corrosion and the abrupt changes when an earthquake strikes.

FIGURE 2.27

Example of a hazard surface, Hij, describing hazard interaction as a probability surface that depends on all possible intensities, Ai and Bj, of the primary event 'A' and of the secondary event 'B', respectively
Source: Garcia-Aristizabal and Marzocchi (2013)



Time-dependent vulnerability

Time-dependent vulnerability dynamics may have many origins, depending on the problem under consideration and the dimension of vulnerability involved, i.e. social, economic, physical, cultural, environmental or institutional (for the dimensions of vulnerability see Birkmann et al. 2013). Vulnerability changes due to the ageing of structures, for instance, have been addressed by Ghosh and Padgett (2010), Choe et al. (2010), Giorgio et al. (2011), Yalcinev et al. (2012), Karapetrou et al. (2013) and Iervolino et al. (2015 a), among others. Münzberg et al. (2014) pointed to power outages, where the consequences and hence the vulnerability of the public may progressively change within hours or days. Moreover, Aubrecht et al. (2012) made short-term social vulnerability changes in terms of human exposure in the diurnal cycle subject of discussion. In the long term, especially when regarding the possible effects of climate change and globalisation over the next decades, the interacting social, economic and cultural factors will probably be the most important drivers of vulnerability dynamics. These include demographic, institutional and governance factors (IPCC, 2012; Aubrecht et al., 2012; Oppenheimer et al., 2014). Some of them could be related to the rapid and unsustainable urban development, international financial pressures and increases in socioeconomic inequalities, as well as failures in governance and environ-

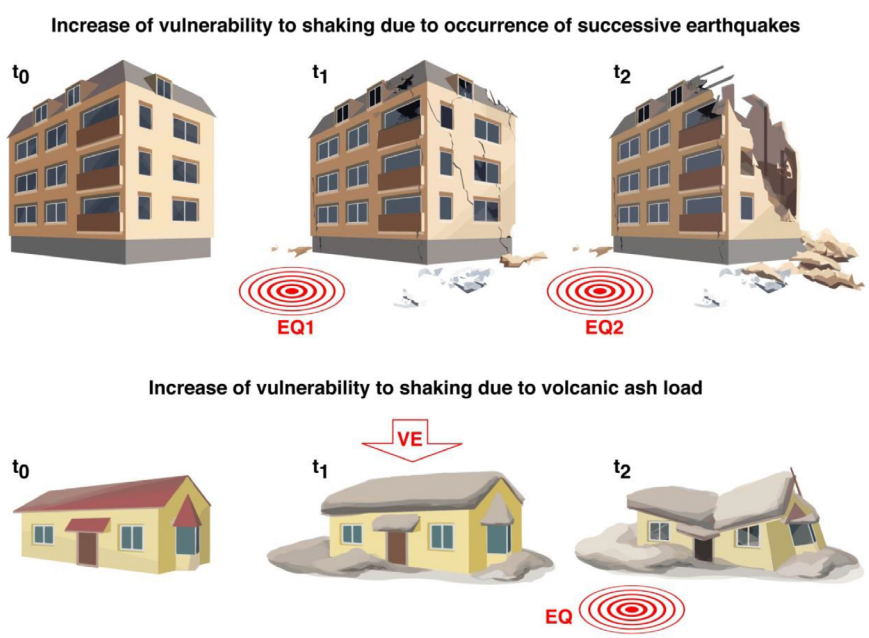
mental degradation (Oppenheimer et al. 2014).

State-dependent vulnerability

The more abrupt state-dependent vulnerability changes occur when two hazards interact on the vulnerability level and the first one alters the exposure or the state of exposed elements in a way that changes the response of the elements to the second one. This second event may or may not be of the same hazard type as the former, and is either independent or dependent on the first one. An example for load-dependent vulnerability can be found in Lee and Rosowsky (2006), who discussed the case of a wood-frame building loaded by snow and exposed to an earthquake. Accordingly, Zuccaro et al. (2008), Marzocchi et al. (2012), Garcia-Aristizabal et al. (2013) and Selva (2013) gave the example of the seismic vulnerability of buildings loaded by ash due to volcanic activity (Figure 2.28, below). In addition, Selva (2013) presented an example for state-dependent exposure. In this case, strong local earthquakes changed the exposure to a tsunami by people escaping from their damaged buildings and concentrating in seaside areas, which is where tsunamis hit. Pre-damage-dependent seismic vulnerability/fragility is important for earthquake aftershock risk assessment (Figure 2.28, above) and so has been addressed by Bazurro et al. (2004), Sanchez-Silva et al. (2011), Polese et al. (2012, 2015) and Iervolino et al. (2015a, 2015b), among others.

FIGURE 2.28

Two examples of state-dependent seismic vulnerability: pre-damage-dependent vulnerability (above) and load-dependent vulnerability (below)
Source: Mignan (2013)



Integration into a probabilistic framework

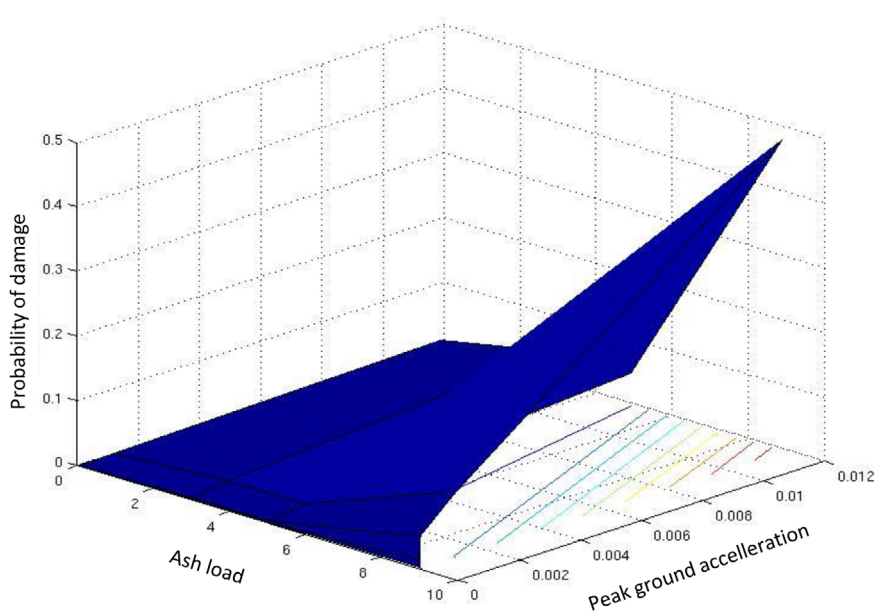
In the case of the ageing of structures, whereas one may easily integrate time-dependent vulnerability into a probabilistic multirisk assessment approach, for instance by means of time-dependent fragility functions (see Ghosh and Padgett, 2010; Karapetrou et al., 2013), this is not the case for the long-term vulnerability changes relevant to climate change and globalisation. Despite the existence of a few studies in the climate change research community that have made an attempt to project probabilistic risk curves into the future (e.g. Jenkins et al., 2014), the use of vulnerability/fragility curves does not seem to be common. According to Jurgilevich et al. (2017), the main bottleneck in assessing vulnerability and exposure dynamics and projecting them into the future is poor availability of data, particularly for socioeconomic data. Another bottleneck relates to the uncertainty and accuracy of the projections. Whilst one might have data about the future population, these data are often useless for assessing the future levels of education, income, health and other important socioeconomic aspects. This may be the reason why vulnerability assessments are still mostly based on present socioeconomic data, whereas current climate change projections go up to the year 2100 (Cardona et al., 2012). In light of the significant uncertainties involved in future projections of vulnerability, climate change-related literature has suggested the production of a range of alternative future pathways instead of one most plausible vulnerability scenario (Dessai et al., 2009; Haasnoot et al., 2012, O'Neill et al., 2014, among oth-

ers). Still, dynamics of vulnerability or exposure are presently only included in half of the future-oriented studies related to climate change. Moreover, the inclusion of dynamics in both is observed in less than one third of the studies oriented to the future (Jurgilevich et al. 2017).

Following Garcia-Aristizabal and Marzocchi (2013), Garcia-Aristizabal et al. (2015 a) and Gasparini and Garcia-Aristizabal (2014), the situation is different for the pre-damage- and load-dependent vulnerabilities. One may easily integrate them into a probabilistic multirisk approach by extending the above framework for multilayer single-risk and multihazard risk assessment to account for hazard interactions on the vulnerability level. The main difference of such an extended multirisk approach compared to the former one is the fact that vulnerability/fragility is introduced into the multirisk framework as a vulnerability/fragility surface instead of a curve (see Figure 2.29). This is because vulnerability, in the case of these interactions, depends on both the variable state of the exposed elements as well as on the intensity of the secondary event. In the case of load-dependent fragility/vulnerability, a load, for instance an ash load due to volcanic activity (see the fragility surface in Figure 2.29), determines the variable state of the exposed elements. For pre-damage-dependent fragility/vulnerability, the load parameter of the fragility/vulnerability surface is substituted by a parameter describing the pre-damage state.

FIGURE 2.29

Ash load-dependent, two-dimensional seismic fragility surface
Source: Garcia-Aristizabal and Marzocchi (2013)



In order to get a feeling of how different the results of the multirisk approach can be from those of the single-risk approach, let us take the example of seismic risk in the Arenella area of Naples, which was modified by ash loads. Garcia-Aristizabal et al. (2013) found that, in this case, the expected loss from earthquakes was remarkably sensitive to the thickness of an ash layer from volcanic activity assumed to load the roofs of the area's buildings. Whereas for a 24-cm ash layer the expected loss from earthquakes increased by less than 20% compared to the case without load, it reached an amplification factor of six for a 41-cm thick layer.

A simple example demonstrating what the effect of pre-damage-dependent vulnerability may quantitatively amount to can be deduced from the damage- and pre-damage-dependent fragility curves provided by Abad (2013) for a hospital in Martinique (French West Indies). For a ground motion of 5 m/s2 at the building's resonance, the probability of reaching a damage state 4 (near to collapse or collapse) is found from their curves to be roughly 7 % if pre-damage is not accounted for. On the other hand, assuming a pre-damage state 3 on a scale up to 4 results in a collapse probability of more than 30 %, an increase of nearly a factor of five.

Iervolino et al. (2015b), among others, have extended the concept of pre-damage-dependent vulnerability to account for the accumulation of damage in a series of aftershocks. Moreover, Sanchez-Silva et al. (2011) and Iervolino et al. (2013, 2015a)

proposed to take into account both age-dependent and state-dependent vulnerabilities in one model of the time-variant failure probability of structures.

Matrix city

The 'Matrix city' framework, proposed by Mignan et al. (2014) for a quantitative multihazard and multirisk assessment that accounts for interactions on both the hazard and the vulnerability levels and considers time-dependent vulnerability, is conceptually quite different from the one introduced so far. It consists of a core simulation algorithm based on the Monte Carlo method. This method simulates a large number of stochastic hazard-intensity scenarios, thereby allowing for a probabilistic assessment of the risk and for the recognition of more or less probable risk paths. As each scenario is represented by a time series, the method is also appropriate for assessing the risks associated with non-stationary processes, such as the hazards and/or vulnerabilities under climate change. Intra- as well as interhazard intensity interactions are introduced by a so-called hazard correlation matrix.

This matrix is of the same type as the hazard interaction matrix used by Gill and Malamud (2014) for qualitatively and semi-quantitatively characterising interaction relationships between natural hazards, but by entering the one-to-one conditional probabilities of the secondary hazards it is applied in a quantitative way. For creating a hazard/risk scenario, the Monte Carlo method draws the probabilities from a Poisson distribution. So far, Matrix city has only been used with generic data to demonstrate the theoretical benefits of multihazard and multirisk assessment and to show how multirisk contributes to the emergence of extremes. It has been successfully tested, but 'identifying their real-world practicality will still require the application of the proposed framework to real test sites' (Mignan et al., 2014).

2.5.3 Implementation of MRA into DRM: Present state, benefits and barriers

2.5.3.1 State of implementation

Multirisk is not systematically addressed among DRM in EU countries (Komendantova et al., 2013a, 2013b, 2014, 2016; Scolobig et al., 2013, 2014a, 2014b). Single-hazard maps are still the decision support tool most often used in DRM, even more often than single-risk maps. Along with the missing link between scientific multirisk assessment and decision-making in DRM comes a general lack of integrated practices for multirisk governance.

2.5.3.2 Expected benefits

The practitioners involved in the Matrix study emphasised the following benefits:

- ranking and comparison of risks.
- Improvement of land-use planning, particularly as the multirisk approach provides a holistic view of all possible risks. It may influence decisions about 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 multirisk approach would allow planning for potential damage to critical infrastructure from secondary events and preparation for response actions.
- Improvements in the efficiency of proposed mitigation actions, cost reductions, encouraging awareness of secondary risks and the development of new partnerships between agencies working on different types of risk.

2.5.3.3 Barriers

Barriers to effectively implementing multirisk assessment into DRM are found in both the science and practice domains as well as between them. In addition, individual perceptual and cognitive barriers may play a role in both domains (Komendantova et al., 2016).

Barriers in the science domain mainly relate to an unavailability of common standards for multirisk assessment across disciplines. Different disciplines use different risk concepts, databases, methodologies, classification of the risk levels and uncertainties in the hazard- and risk-quantification process. There is also an absence of clear definitions of terms commonly agreed across disciplines, including the term 'multirisk' itself, for which there is no consensus as regards its definition. These differences make it hard for various risk communities to share results, and hence represent a barrier to dialogue on multirisk assessment.

A lack of quantitative information on the added value of multirisk assessment is perhaps more worrying for risk managers than for scientists. The risk managers who participated in the Matrix study pointed out that there are not enough quantitative multirisk scenarios or their comparisons with single risk ones available from which they could learn about the added value of multirisk. Furthermore, they miss criteria or guidelines that would help them to select the scenarios to be included in a multirisk assessment. Most worrying for them, however, seem to be the strong limitations quantitative multirisk assessment methods, in their opinion, have when one regards their user friendliness. According to them, a high degree of expertise is often required to use the scientific tools, resulting in a restriction of their application to only a narrow number of experts.

Multirisk is presently not systematically addressed among DRM in EU countries. The barriers to the implementation of MRA include a lack of agreed definitions

Moreover, poor cooperation between institutions and personnel, especially when risks are managed by authorities acting at different governmental levels, was identified as a major reason for a lack of integrated practices for multirisk governance in the practical domain (Scolobig et al., 2014a). Decentralised and centralised governance systems have their own weaknesses and strengths in this regard (Komendantova et al., 2013a; Scolobig et al., 2014b). Furthermore, in some cases a multirisk approach is perceived as competing with rather than complementing single-risk approaches. The Matrix study also argued that in many European countries the responsibility for DRM has steadily been shifted to the local level (often to the municipal level) without providing sufficient financial, technical and personnel resources for implementing necessary programmes (Scolobig et al., 2014a). This is a clear obstacle for implementing multirisk methodologies.

Finally, there are individual cognitive barriers to implementing multirisk assessment approaches into the DRM decision-making processes, i.e. barriers related to how people perceive the problem of multirisk. Komendantova et al. (2016) presented the case of the 1995 Kobe earthquake in Japan, where the hazard was underestimated, simply because large earthquakes had been absent during the previous decades. Similar consequences are observed when building codes for earthquake-resistant structures are not followed, a problem that still exists all over the world, including in Europe. Individual cognitive barriers may only be overcome by raising awareness.

Overcoming these barriers will require a long-term commitment on behalf of risk modellers and officials as well as strong partnerships for a 'step-by-step' approach to progressively implementing multirisk methodology into practice.

2.5.4 Conclusions and key messages

Partnership

A better integration of scientific knowledge of multirisk assessment into developing policies and practices will require a long-term commitment from both sides, science and practice, and building new partnerships between them. Such partnerships should enhance the knowledge transfer between science and practice and, among others, should help involve practitioners as well as their requirements in the scientific development of multirisk methodology at an early stage. Common efforts will be particularly necessary for simplifying existing methods for practical use. Furthermore, scientists are asked to provide practitioners with more scenarios demonstrating the added value of multirisk assessments in various situations, and together they should collaborate in establishing criteria for appropriate scenarios to be included in a multirisk assessment.

More specifically, it might also be worthwhile considering the common development of a multirisk rapid response tool for assessing potential secondary hazards after a primary hazard has occurred. As lack of data is a crucial weakness in multirisk assessments, partnerships should also extend their collaboration to sharing data and building common integrated databases, in particular for demographic, socioeconomic and environmental data.

Such partnerships could be realised with common projects or by creat-

ing so-called multirisk platforms for common methods and data, and/or establishing so-called local multirisk commissions, institutional areas with an interdisciplinary and multisector character for discussing and acting on multirisk issues.

Knowledge

Although a theoretical framework for multirisk assessment and scenario development is in place, there is still a need for further harmonisation of methods and particularly terms across the scientific disciplines. Moreover, more quantitative scenarios on present and future risks in a multirisk environment are needed, particularly with regard to potential indirect effects and chain-shaped propagations of damage into and within the socioeconomic system. Such scenarios are still rare, mainly because of two reasons. First, the comprehensive databases needed for a multirisk assessment either do not exist, are not freely available or are insufficient; there is a need for establishing such databases between the disciplines. Second, quantitative fragility/vulnerability information, in particular fragility/vulnerability curves and surfaces, respectively, have so far been developed only for a few specific cases, mostly related to the direct impact of a disaster, but hardly to its indirect consequences; these, however, in many cases may be more important than the direct ones.

Therefore, the scientific knowledge base needs to be extended to quantitative vulnerability information, vulnerability curves and surfaces for indirect disaster impacts as, for instance, the loss in work productivity, loss of the functionality of systems and networks, costs of evacuation, costs of medial assistances and much more.

Innovation

A multi-risk modelling approach will be required in order to capture the dynamic nature and the various interactions of the hazard and risk related processes driven by both climate change and globalization. Moreover, solutions for risk assessments are needed that are no longer exclusively aiming at the best possible quantification of the present risks but also keep an eye on their changes with time and allow to project these into the future.

The future challenges have two dimensions, one focused on empowering good decisions in practice and another on improving our knowledge base for better understanding present and future risks

Developing an integrative model for future risk that considers not only the potential climate change-induced hazard dynamics, but also the potential dynamics of complex vulnerability components and the involved uncertainties will require the expertise of all these disciplines. A strong partnership will be required between the natural sciences, the social and economic sciences, as well as the climate change research community.

Recommendations

DRM requires a combination of skills knowledge and data that will not be held within one firm, one industry, one institution, one discipline, one country or even necessarily one region. Europe contains a concentration of expertise on DRM, perhaps unique in the world; the opportunities here are greatest and should be seized.

Historically, many in industry and the private and public sectors found it challenging to engage with academia. For example, industry often works within tight timescales, wanting to hear a single right answer with certainty, wanting dissemination of what is known now as opposed to new research and wanting it in a form that can be easily incorporated into existing models and processes not requiring detailed assessment, adjustment and review. But there is an increasing awareness of what science has to offer, which often leads to an even greater demand for collective engagement. This engagement has been encouraged by EU research projects encouraging public/private/academic linkages all involved in DRM, where practitioners, scientists and policymakers need to actively seek engagement with others working in the broad DRM space: within their organisation and within their sector, as well as more broadly. This is easy to say but rather more difficult to do.

Only positive interaction will make the practitioner aware of what is possible: what new data, models and techniques are available and how these may be adapted for practical use within their organisation or department. The practitioner lies in the centre of the process. It is they that understand the gaps of knowledge and data, where true value for additional research lies. But often unconsciously there may be 'group think' — an accepted way of working that is not adequately challenged. It is healthy to develop links with other practitioners in their field, in other sectors or industries and in academia. Increasing knowledge and expertise can be both a push and a pull: both learning from others and also using in-house expertise to drive knowledge for the common good.

Areas where other practitioners or academics may have valuable information include the fields of data, methodologies and models. Knowledge may be siloed: restricted to particular risks, hazard or exposure types. The practitioner is in a position to break down these silos, spotting where data or processes in one area may have value in another. This is particularly true when looking at the interaction of hazards, secondary hazards and non-physical impacts such as business interruption and broader economic loss.

It is important to learn from other sectors facing similar issues and learn from their experience. For example, methods have been developed in the insurance industry to model and manage catastrophe risk that can be applied almost di-

rectly to societal risk including to people, property and the environment. There are quick wins available; early adopters are not starting from a clean sheet but building on a framework that is already well founded. No innovation is risk free, but development of a risk management strategy for a city, for example; is based upon well-developed methodologies and so is very likely to deliver real value and be seen to deliver real value.

Science can respond to identified needs but only if it hears the call, as it were. Very often the need is not for new research but for directed application of what is known within academia, not elsewhere. Information and data need to be offered in forms that are accessible, appropriate and affordable. More work is required to build publicly available datasets and models (for example the global earthquake model initiative). Where governments hold data, it is important to balance the desire to exploit that data for profit against the greater good of making the information available to all those who can use it to develop tools that ultimately benefit and protect the broader European population.

Before embarking on a DRM project, like for any other project it is important to understand what the objectives of the project are: what needs to be done and when it needs to be done. DRM is an area where there is always a need for further understanding and knowledge in each of the three pillars of risk assessment: hazard, exposure and vulnerability. Each element requires different skills, different data and different techniques; the process can seem daunting. There are many real examples of best practice, methodologies, data sources and assessment and analytical techniques to act as a template. The process will not necessarily be smooth, but the process of developing understanding and awareness is arguably where the real value lies. It is important not to let the fear of lack of knowledge or data prevent this vital work from commencing. Innovative thinking is required to meet the challenges of a lack of data and partial information endemic in the process, for example new methods to assess exposure by remote sensing or vulnerability, particularly to economies and ecosystems. The challenge is to focus innovation on where it has the most value, a proper risk assessment process will provide a guide to where the greatest requirement for innovation and further research lies.

Risk assessment and analysis provides an objective basis against which policy decisions can be made and transparently justified and the cost and benefits of different strategies and options can be compared in an objective way, open to scrutiny and challenge. All models are assumption dependent, but it is important that the policymaker has some knowledge of the limitations of the modelling done and the key assumptions upon which it depends. The issue is balance: clearly a policymaker cannot be expected to be a risk management expert, but uncritically relying on one source of information can lead to political as well as practical risk — a culture of challenge and evidence- based analysis is required. It is important that policymakers are able to interpret the risk assessments given to them. European insurance regulators demand that directors of insurance companies are able to understand and defend risk assumptions and decisions

made within the firm; they cannot hide behind the judgement of employees or consultants however well qualified. The same scrutiny is applied to policymakers and practitioners in the public sector who respond to disasters. Whilst not hiding behind experts, it is important that policymakers can demonstrate that appropriate expertise has been engaged and risk management decisions have been made firmly founded.

At its best, DRM not only adds to the information available to policymakers, but it also creates a new way of looking at risk within organisations. Risk management should not be seen as just the responsibility of a risk management department but should be understood by all those involved in decision-making. Embracing risk management and risk modelling has transformed the insurance industry in the last 30 years, making it infinitely more aware of the risks that it and its clients face and much more able to meet their needs (and pay their claims). It is a virtuous circle: greater knowledge feeds an understanding of what is missing and a drive to fill those gaps; it demands an engagement with academia, the adoption of best science and the development of best practice via interaction with other practitioners. The process of improvement becomes self-sustaining, increasing knowledge and understanding to the benefit of all. Europe demands better DRM, so the opportunity must be seized.

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Introduction

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