2.4

Recording disaster losses for improving risk modelling capacities

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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.

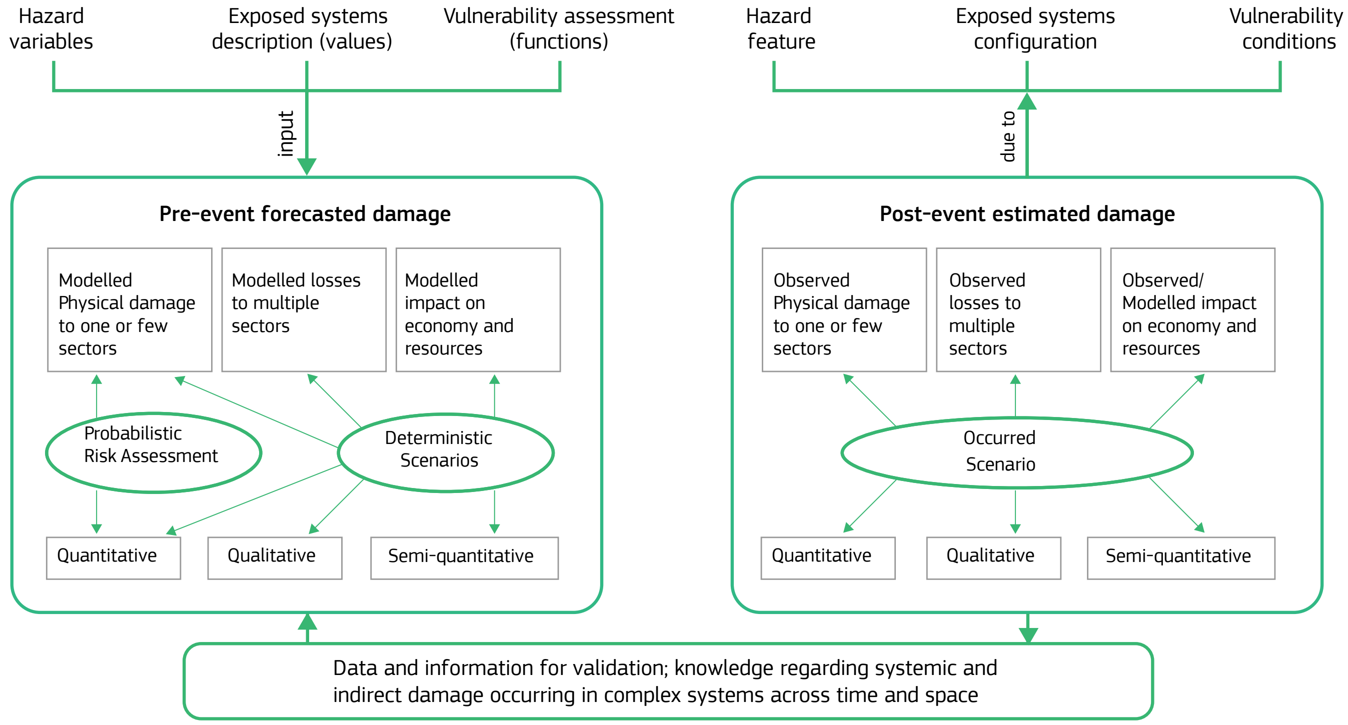
2.4.2
How post-disaster damage has been used to develop risk models: state of the art in a nutshell

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



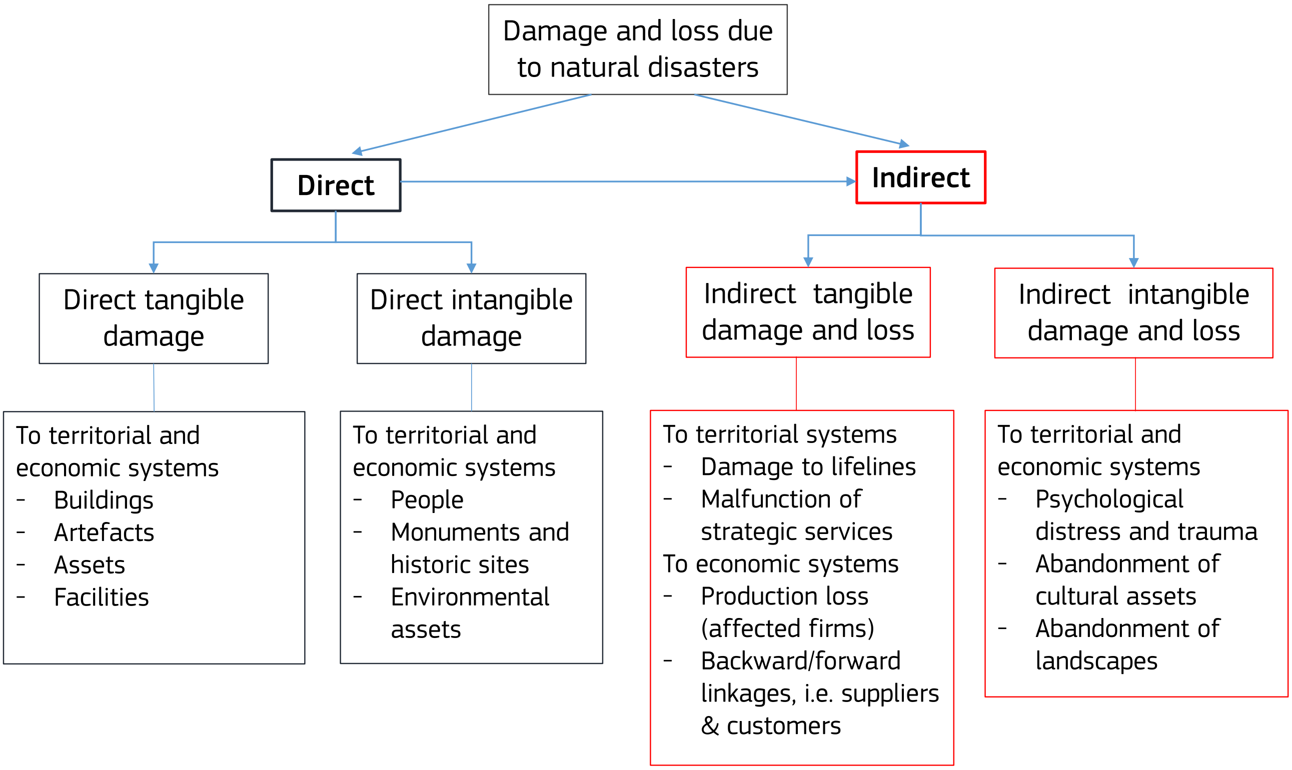
scientific journals; however, they generally consider quite a limited number and type of variables. More complex understandings of risk, which also comprise the consequences on the social, economic and environmental systems as well as on complex built systems such as critical infrastructures, are inevitably 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

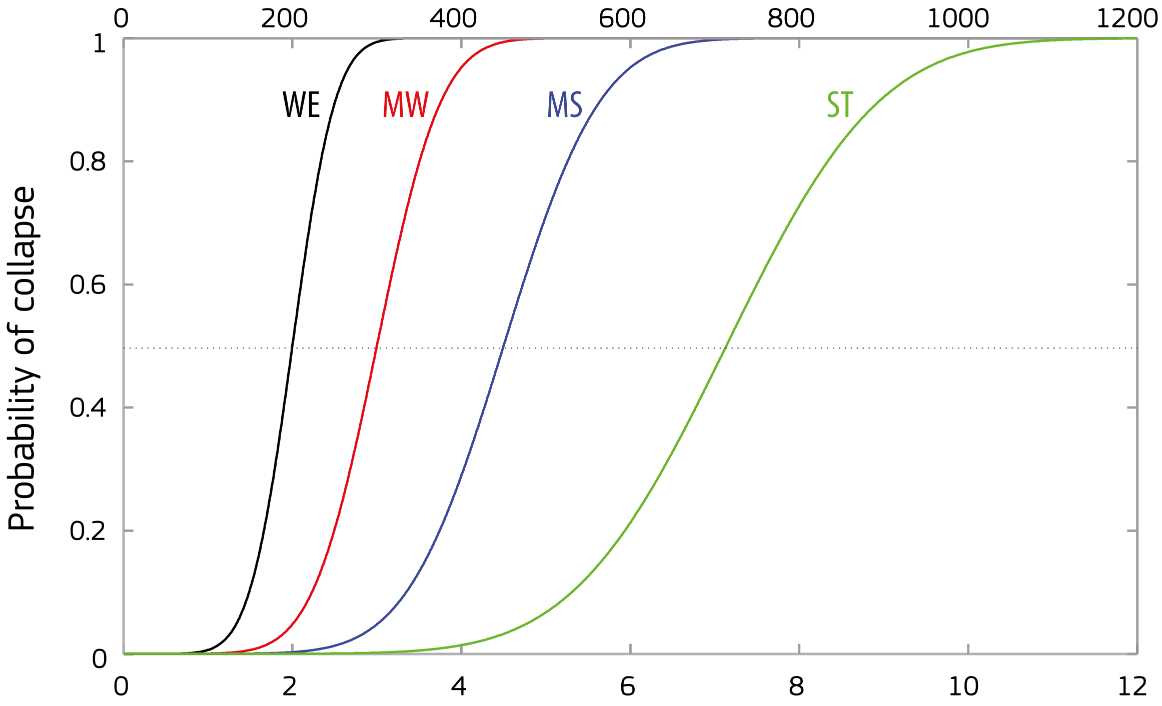
Vulnerability curves in volcanology have been developed much more recently and are available only for some of the hazards that may be triggered by an explosive eruption. More specifically, vulnerability curves describing the collapse of roofs are available for tephra fallout (e.g. Figure 2.16), while 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.

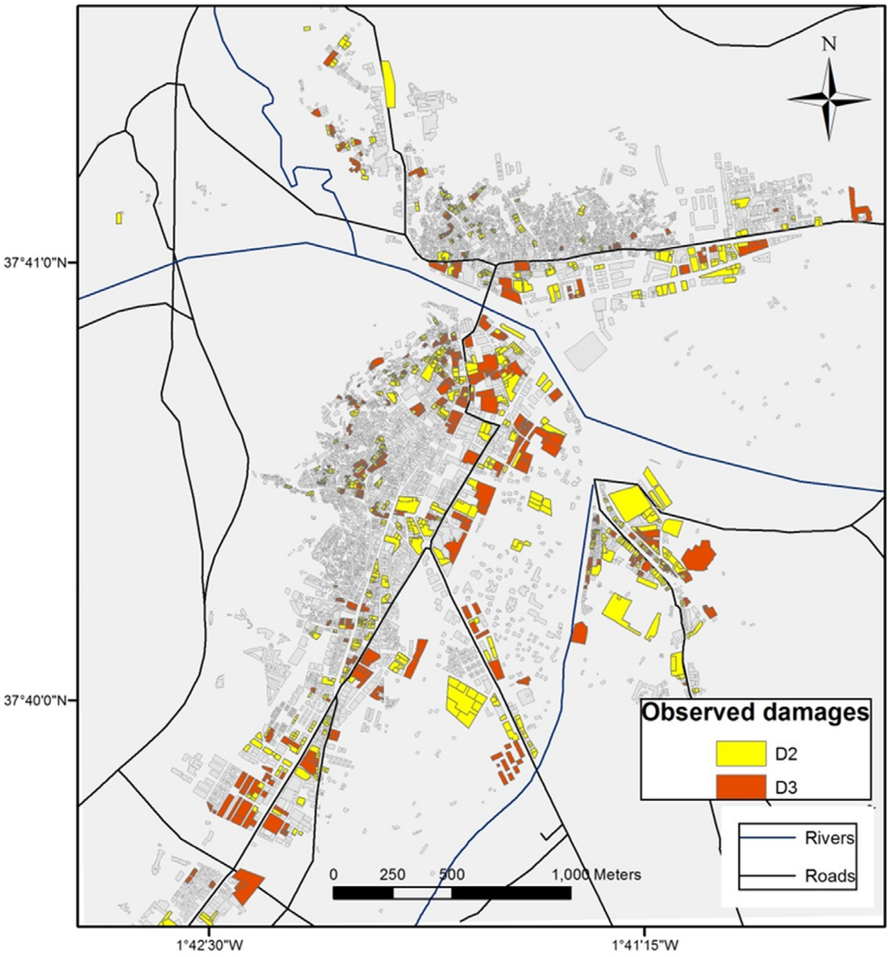
Another factor limiting the possibility to transfer such curves from one geographic area to another derives from the fact that the observed damage and relative vulnerability factors are highly context dependent, as they are linked to the types of buildings and structures that have been surveyed. This 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

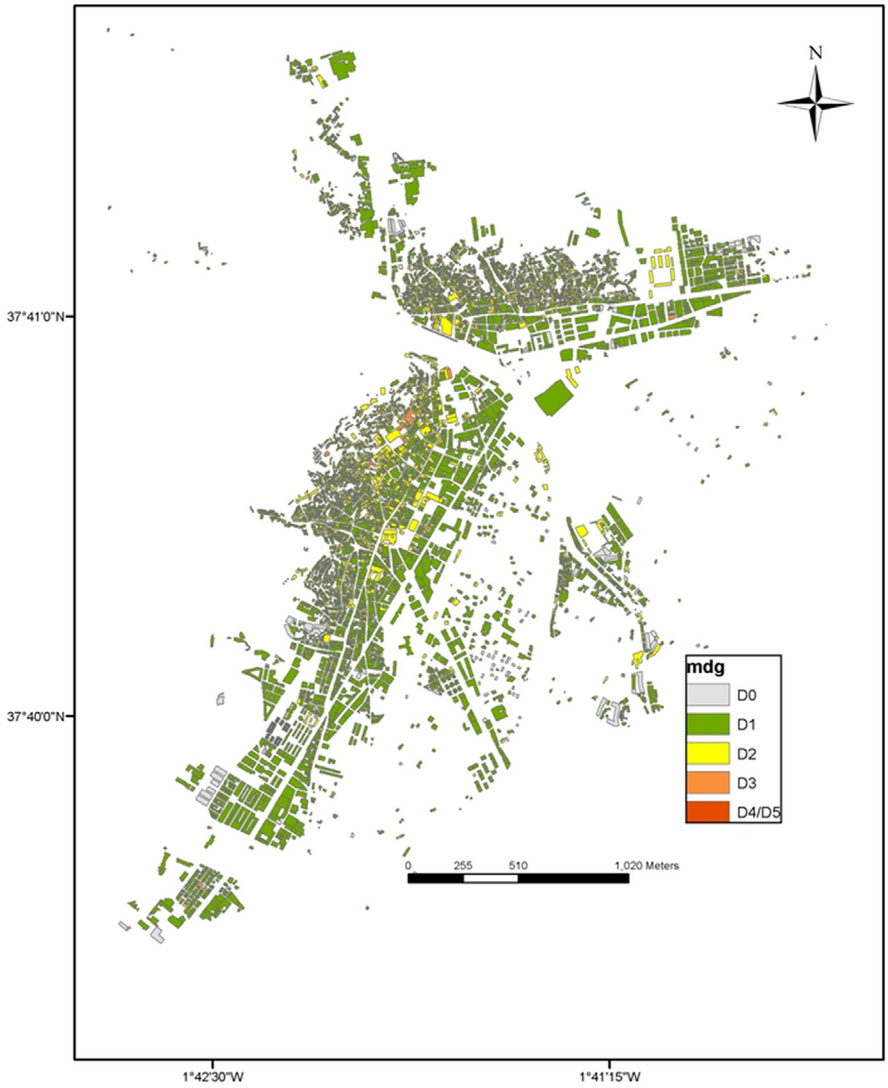


prehensive validation for risk models, they can be used to assess the discrepancies between the model forecasts and observations.

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.

FIGURE 2.18

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



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.

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).

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.

> *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.*

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).

REFERENCES CHAPTER 2

Introduction

Klinke, A., Renn, O., 2002. A new approach to risk evaluation and management: risk-based, precaution-based, and discourse-based strategies. Risk Analysis 22(6), 1071-1094.

The Royal Society, 'Risk analysis, perception and management', 1992.

UNISDR Terminology, 2017.https://www.unisdr.org/we/inform/terminology, [accessed 04 April, 2017].

Vetere Arellano, A. L., Cruz, A. M., Nordvik, P.. Pisano, F. (eds.). 2004. Analysis of Natech (natural hazard triggering technological disasters) disaster management. Nedies workshop proceedings, Italy, 2003. EUR 21054EN, Publications Office of the European Union, Luxembourg.

2.1. Qualitative and quantitative approaches to risk assessment

Apostolakis, G. E., 2004. How useful is quantitative risk assessment? Risk Analysis 24(3),515-520.

Cox, T., 2008. What's wrong with risk matrices. Risk Analysis 28(2), 497-512.

Directive 2009/138/EC of the European Parliament and of the Council of 25 November 2009 on the taking-up and pursuit of the business of Insurance and Reinsurance (Solvency II). Official Journal of the European Union L 335, 17.12.2009, pp 1–155.

Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC. Official Journal of the European Union L 197, 24.7.2012,pp.1-37.

Eurocode website, n.d. The EN Eurocodes. http://eurocodes.jrc.ec.europa.eu/, [accessed 04 April, 2017].

European Commission, 2014. Overview of natural and man-made disaster risks in the EU. Staff working document, SWD(2014) 134 final of 8.4.2014.

European Commission, 2010. Risk assessment and mapping guidelines for disaster management. Staff Working Paper, SEC(2010) 1626 final of 21.12.2010.

Friedman, D. G., 1984. Natural hazard risk assessment for an insurance programme. The Geneva Papers on Risk and Insurance, 9(3), 57-128.

Gowland, R., 2012. The work of the european process safety centre (EPSC) technical Steering committee working group: 'atypical scenarios'. Hazards XXIII, symposium series No 158, Institute of Chemical Engineers.

Grünthal, G., Thieken, A. H., Schwarz, J., Radtke, K. S., Smolka, A., Merz, B., 2006. Comparative risk assessments for the city of Cologne, Germany — storms, floods, earthquakes. Natural Hazards 38(1-2), 21-44.

Health and Safety Executive, 2001. Reducing risks, protecting eople — HSE's decision-making process, Her Majesty's Stationary Office, United Kingdom, www.hse.gov.uk/risk/theory/r2p2.pdf, [accessed 04 April, 2017].

Health and Safety Executive, 2009. Safety and environmental standards for fuel storage sites — Process Safety Leadership Group — Final report, United Kingdom, www.hse.gov.uk/comah/buncefield/fuel-storage-sites.pdf, [accessed 04 April, 2017].

Health and Safety Laboratory, 2005. Review of hazard identification techniques. Sheffield, United Kingdom, 2005, www.hse.gov.uk/research/hsl_pdf/2005/hsl0558.pdf

Hoogheemraadschap van Rijnland, 2009. Flood control in the Netherlands — A strategy for dike reinforcement and climate adaptation.

IAIS International Association of Insurance Supervisors, 2015. Insurance core principles. www.iaisweb.org/file/58067/insurance-core-principles-updated-november-2015, [accessed 04 April, 2017].

Simmons, D. C., 2016. How catastrophe and financial modelling revolutionised the insurance industry. Willis Towers Watson, https://understandrisk.org/wp-content/uploads/Simmons.pdf. [accessed 04 April, 2017].

Skjong, R., Wentworth, B. H., 2001. Expert judgment and risk perception. In Proceedings of the Offshore and Polar Engineering Conference. ISOPE IV, 17-22 June, Stavanger, pp. 537-544.

Stamatis, D. H., 2003. Failure mode and effect analysis: FMEA from theory to execution, ASQ Quality Press.

Tyler, B., Crawley, F., Preston, M., 2015. HAZOP: guide to best practice, 3rd ed., Institute of Chemical Engineers.

United Kingdom Cabinet Office, 2015. National risk register of civil emergencies. www.gov.uk/government/publications/national-risk-register-for-civil-emergencies-2015-edition

White, C. S. and Budde, P. E., 2001. Perfecting the storm: the evolution of hurricane models. www.contingencies.org/marapr01/perfecting.pdf, [accessed 04 April, 2017].

2.2. Current and innovative methods to define exposure

Arino, O., Ramos Perez, J.J., Kalogirou, V., Bontemps, S., Defourny, P., Van Bogaert, E., 2012. Global Land Cover Map for 2009 (GlobCover 2009). © Eur. Space Agency ESA Univ. Cathol. Louvain UCL.

Basher, R., Hayward, B., Lavell, A., Martinelli, A., Perez, O., Pulwarty, R., Sztein, E., Ismail-Zadeh, A.,

Batista e Silva, F., Lavalle, C., Koomen, E., 2013. A procedure to obtain a refined European land use/cover map. Journal of Land Use Science 8(3), 255–283.

Bouziani, M., Goïta, K., He, D.C., 2010. Automatic change detection of buildings in urban environment from very high spatial resolution images using existing geodatabase and prior knowledge. ISPRS Journal of Photogrammetry and Remote Sensing 65(1), 143–153.

Cardona, O.D., Van Aalst, M., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R., Schipper, L., Sinh, B., 2012. Determinants of risk: exposure and vulnerability. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge, pp. 65–108.

Chen, J., Chen, J., Liao, A., Cao, X., Chen, L., Chen, X., He, C., Han, G., Peng, S., Lu, M., Zhang, W., Tong, X., Mills, J., 2015. Global land cover mapping at 30m resolution: A POK-based operational approach. ISPRS Journal of Photogrammetry and Remote Sensing, 103, 7–27.

Crowley, H., Ozcebe, S., Spence, R., Foulset-Piggott, R., Erdik, M., Alten, K., 2012. Development of a European Building Inventory Database. In: Proceedings of 12th World Conference on Earthquake Engineering.

World Bank 2014. Open Data for Resilience Field Guide. Washington, DC: World Bank.

De Bono, A., Chatenoux, B., 2015. A Global Exposure Model for GAR 2015, UNEP-GRID, GAR 2015 Background Papers for Global Risk Assessment, 20 p.

De Bono, A., Mora, M.G., 2014. A global exposure model for disaster risk assessment. International Journal of Disaster Risk Reduction 10, 442–451.

Deichmann, U., Ehlrich, D., Small, C., Zeug, G., 2011. Using high resolution satellite data for the identification of urban natural disaster risk. World Bank and European Union Report.

Dell'Acqua, F., Gamba, P., Jaiswal, K., 2013. Spatial aspects of building and population exposure data and their implications for global earthquake exposure modeling. Natural Hazards 68(3), 1291–1309.

Dobson, J.E., Bright, E.A., Coleman, P.R., Durfee, R.C., Worley, B.A., 2000. LandScan: A global population database for estimating populations at risk. Photogrammetric Engineering & Remote Sensing. 66(7), 849–857.

Ehrlich, D., Tenerelli, P., 2013. Optical satellite imagery for quantifying spatio-temporal dimension of physical exposure in disaster risk assessments. Natural Hazards, 68(3), 1271–1289.

Erdik, M., Sesetyan, K., Demircioglu, M., Hancilar, U., Zulfikar, C., Cakti, E., Kamer, Y., Yenidogan, C., Tuzun, C., Cagnan, Z., Harmandar, E., 2010. Rapid earthquake hazard and loss assessment for Euro-Mediterranean region. Acta Geophysica 58.

Esch, T., Taubenböck, H., Roth, A., Heldens, W., Felbier, A., Thiel, M., Schmidt, M., Müller, A., Dech, S., 2012. TanDEM-X mission—new perspectives for the inventory and monitoring of global settlement patterns. Journal of Applied Remote Sensing 6(1), 061702–1.

Florczyk, A.J., Ferri, S., Syrris, V., Kemper, T., Halkia, M., Soille, P., Pesaresi, M., 2016. A New European Settlement Map From Optical Remotely Sensed Data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 9(5), 1978–1992.

Forzieri, G., Bianchi, A., Marin Herrera, M.A., Batista e Silva, F., Feyen, L., Lavalle, C., 2015. Resilience of large investments and critical infrastructures in Europe to climate change. EUR 27598 EN, Luxembourg: Publications Office of the European Union.

Freire, S., Halkia, M., Ehlrich, D., Pesaresi, M., 2015a. Production of a population grid in Europe. EUR 27482 EN, Luxembourg: Publications Office of the European Union.

Freire, S., Kemper, T., Pesaresi, M., Florczyk, A., Syrris, V., 2015b. Combining GHSL and GPW to improve global population mapping. IEEE International Geoscience & Remote Sensing Symposium, 2541-2543.

Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X., 2010. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. Remote Sens. Environ. 114 (1), 168–182.

Fritz, S., See, L., Rembold, F., 2010. Comparison of global and regional land cover maps with statistical information for the agricultural domain in Africa. International Journal of Remote Sensing 31 (9), 2237–2256.

Gamba, P., Cavalca, D., Jaiswal, K., Huyck, C., Crowley, H., 2012. The GED4GEM project: development of a global exposure database for the global earthquake model initiative. In: 15th World Conference on Earthquake Engineering, Lisbon, Portugal.

Haque, U., Blum, P., da Silva, P.F., Andersen, P., Pilz, J., Chalov, S.R., Malet, J.-P., Auflič, M.J., Andres, N., Poyiadji, E., Lamas, P.C., Zhang, W., Peshevski, I., Pétursson, H.G., Kurt, T., Dobrev, N., García-Davalillo, J.C., Halkia, M., Ferri, S., Gaprindashvili, G., Engström, J., Keellings, D., 2016. Fatal landslides in Europe. Landslides.

Jaiswal, K., Wald, D., Porter, K., 2010. A Global Building Inventory for Earthquake Loss Estimation and Risk Management. Earthquake Spectra 26 (3), 731–748.

Latham, J., Cumani, R., Rosati, I., Bloise, M., 2014. Global Land Cover SHARE (GLC-SHARE) database Beta-Release Version 1.0.

Lloyd, C.T., Sorichetta, A., Tatem, A.J., 2017. High resolution global gridded data for use in population studies. Scientific Data 4, 170001.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, Z., Yang, L., Merchant, J.W., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. International Journal of Remote Sensing 21(6-7), 1303–1330.

Lugeri, N., Kundzewicz, Z.W., Genovese, E., Hochrainer, S., Radziejewski, M., 2010. River flood risk and adaptation in Europe—assessment of the present status. Mitigation and Adaptation Strategies for Global Change 15, 621–639.

Manakos, I., Braun, M. (Eds.), 2014. Land Use and Land Cover Mapping in Europe, Remote Sensing and Digital Image Processing. Springer Netherlands, Dordrecht.

Marin Herrera, M., Bianchi, A., Filipe Batista e Silva, F., Barranco, R., Lavalle, C., 2015. A geographical database of infrastructures in Europe: a contribution to the knowledge base of the LUISA modelling platform. Luxembourg: Publications Office of the European Union.

Michel-Kerjan, E., Hochrainer-Stigler, S., Kunreuther, H., Linnerooth-Bayer, J., Mechler, R., Muir-Wood, R., Ranger, N., Vaziri, P., Young, M., 2013. Catastrophe Risk Models for Evaluating Disaster Risk Reduction Investments in Developing Countries: Evaluating Disaster Risk Reduction Investments. Risk Analysis 33, 984–999.

Montero, E., Van Wolvelaer, J., Garzón, A., 2014. The European Urban Atlas, in: Manakos, I., Braun, M. (Eds.), Land Use and Land Cover Mapping in Europe. Springer Netherlands, Dordrecht, pp. 115–124.

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding — A Global Assessment. PLOS ONE 10, e0118571.

Peduzzi, P., Dao, H., Herold, C., Mouton, F., 2009. Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. Natural Hazards and Earth System Sciences 9, 1149–1159.

Pesaresi, M., Ehrlich, D., Ferri, S., Florczyk, A., Freire, S., Haag, F., Halkia, M., Julea, A.M., Kemper, T., Soille, P., 2015. Global Human Settlement Analysis for Disaster Risk Reduction. In: The International Archives of the Photogrammetry, Remote Sensing and

Spatial Information Sciences, XL-7/W3, 36th International Symposium on Remote Sensing of Environment, 11–15 May 2015, Berlin, German

Academic paper: Global Human Settlement Analysis for Disaster Risk Reduction. Available from: https://www.researchgate.net/publication/277360201_Global_Human_Settlement_Analysis_for_Disaster_Risk_Reduction [accessed Apr 6, 2017]. ISPRS — Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XL-7/W3, 837–843.

Pesaresi, M., Guo Huadong, Blaes, X., Ehrlich, D., Ferri, S., Gueguen, L., Halkia, M., Kauffmann, M., Kemper, T., Linlin Lu, Marin-Herrera, M.A., Ouzounis, G.K., Scavazzon, M., Soille, P., Syrris, V., Zanchetta, L., 2013. A Global Human Settlement Layer From Optical HR/VHR RS Data: Concept and First Results. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 6(5), 2102–2131.

Pesaresi, M., Melchiorri, M., Siragusa, A., Kemper, T., 2016. Atlas of the Human Planet — Mapping Human Presence on Earth with the Global Human Settlement Layer. EUR 28116 EN. Luxembourg: Publications Office of the European Union.

Pittore, M., 2015. Focus maps: a means of prioritizing data collection for efficient geo-risk assessment. Annals of Geophysics 58(1).

Pittore, M., Wieland, M., 2013. Toward a rapid probabilistic seismic vulnerability assessment using satellite and ground-based remote sensing. Natural Hazards 68(1), 115–145.

Pittore, M., Wieland, M., Errize, M., Kariptas, C., Güngör, I., 2015. Improving Post-Earthquake Insurance Claim Management: A Novel Approach to Prioritize Geospatial Data Collection. ISPRS International Journal of Geo-Information 4(4), 2401–2427.

Pittore, M., Wieland, M., Fleming, K., 2016. Perspectives on global dynamic exposure modelling for geo-risk assessment. Natural Hazards 86(1), 7-30.

Rose, A., Huyck, C.K., 2016. Improving Catastrophe Modeling for Business Interruption Insurance Needs: Improving Catastrophe Modeling for Business Interruption. Risk Analysis 36(10), 1896–1915.

UNISDR, 2015a. Making Development Sustainable: The Future of Disaster Risk Management. Global Assessment Report on Disaster Risk Reduction. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland.

UNISDR, 2015b. Sendai framework for disaster risk reduction 2015–2030. United Nations International Strategy for Disaster Reduction. http://www.wcdrr.org/uploads/Sendai_Framework_for_Disaster_Risk_Reduction_2015-2030.pdf, [accessed 04 April 2016].

GFDRR, 2014. Understanding risk in an evolving world, A policy Note. Global facility for disaster reduction and recovery. World Bank, Washington DC, USA, 16pp.

2.3. The most recent view of vulnerability

Alexander, D. and Magni, M., 2013. Mortality in the L ' Aquila (Central Italy) Earthquake of 6 April 2009. PLOS Current Disasters, (April 2009).

Alexander, D., 2010. The L'Aquila Earthquake of 6 April 2009 and Italian Government Policy on Disaster Response. Journal of Natural Resources Policy Research, 2(4), 325–342.

Alexander, D., 2013. Resilience and disaster risk reduction: An etymological journey. Natural Hazards and Earth System Sciences, 13 (11), 2707–2716.

BEH and UNU-EHS, 2016. WorldRiskReport 2016. Berlin and Bonn: Bündnis Entwicklung Hilft and United Nations University – EHS.

Birkmann, J., Cardona, O.D., Carreno, M.L., Barbat, A.H., Pelling, M., Schneiderbauer, S., Kienberger, S., M.Keiler, Alexander, D., Zeil, P., and T., W., 2013. Framing vulnerability, risk and societal responses : the MOVE framework. Nat Hazards, 67, 193–211.

Birkmann, J., Kienberger, S., and Alexander, D., 2014. Assessment of vulnerability to natural hazards : a European perspective. San Diego and Waltham, USA: Elsevier Inc.

Brooks, N., 2003. A conceptual framework Vulnerability , risk and adaptation : A conceptual framework. No. 3.

Buth, M., Kahlenborn, W., Savelsberg, J., Becker, N., Bubeck, P., Kabisch, S., Kind, C., Tempel, A., Tucci, F., Greiving, S., Fleischhauer, M., Lindner, C., Lückenkötter, J., Schonlau, M., Schmitt, H., Hurth, F., Othmer, F., Augustin, R., Becker, D., Abel, M., Bornemann, T., Steiner, H., Zebisch, M., Schneiderbauer, S., and Kofler, C., 2015. Germany's vulnerability to Climate Change. Summary. Dessau-Roßla.

Cardona, O.D., Aalst, M.K. van, Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R.S., Schipper, E.L.F., and Sinh, B.T., 2012. Determinants of Risk : Exposure and Vulnerability. In: C. B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, eds. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, 65–108.

Carreño, M.L., Barbat, A.H., Cardona, O.D., and Marulanda, M.C., 2014. Holistic Evaluation of Seismic Risk in Barcelona. In: Assessment of Vulnerability to Natural Hazards. 21–52.

Carreño, M.-L., Cardona, O.D., and Barbat, A.H., 2007. Urban Seismic Risk Evaluation: A Holistic Approach. Natural Hazards, 40(1), 137–172.

CI:GRASP, n.d. The Climate Impacts: Global and Regional Adaptation Support Platform. http://www.pik-potsdam.de/cigrasp-2/index.html, [accessed 06 April, 2017].

Ciscar, J.C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S., Ibáñez, N., Forzieri, G., Rojas, R., Bianchi, A., Dowling, P., Camia, A., Libertà, G., San Miguel, J., de Rigo, D., Caudullo, G., Barredo, J., Paci, D., Pycroft, J., Saveyn, B., Van Regemorter, D., Revesz, T., Vandyck, T., Vrontisi, Z., Baranzelli, C., Vandecasteele, I., Batista e Silva, F., and Ibarreta, D., 2014. Climate Impacts in Europe: The JRC PESETA II Project. JRC Scientific and Policy Reports. Seville, Spain: Joint Research Centre, Institute for Prospective Technological Studies.

Climate-ADAPT, n.d. European climate adaptation platform. http://climate-adapt.eea.europa.eu, [accessed 06 April, 2017].

Cutter, S., Emrich, C.T., Mitchell, J.T., Boruff, B.J., Gall, M., Schmidtlein, M.C., and Burton, G.C., 2006. The Long Road Home: Race, Class, and Recovery from Hurricane Katrina. Environment, 48(2), 8–20.

Cutter, S.L., Boruff, B.J., and Shirley, W.L., 2003. Social Vulnerability to Environmental Hazards. Social Science Quarterly, 84(2), 242–261.

Cutter, S.L., Ismail-Zadeh, A., Alcántara-Ayala, I., Altan, O., Baker, D.N., Briceño, S., Gupta, H., Holloway, A., Johnston, D., McBean, G.A., Ogawa, Y., Paton, D., Porio, E., Silbereisen, R.K., Takeuchi, K., Valsecchi, G.B., Vogel, C., and Wu, G., 2015. Pool knowledge to stem losses from disasters. Nature, (55), 277–279.

De Groeve, T., Poljansek, K., Vernaccini, L., 2015. Index for Risk Management - INFORM. Concept and Methodology. EUR 26528EN, Luxembourg, Publications Office of the European Union.

Dilley, M., Chen, R.S., Deichmann, U., Lerner-Lam, A.L., Arnold, M., Agwe, J., Buys, P., Kjekstad, O., Lyon, B., and Gregory, Y., 2005. Natural Disaster Hotspots A Global Risk. Disaster Risk Management Series. Washington DC, USA.

EC, 2013. EU Strategy on adaptation to climate change.

Economist Intelligence Unit, 2009. Managing supply-chain risk for reward. London. New York, Hong Kong.

EEA, 2012. Climate change, impacts and vulnerability in Europe: An indicator-based report. Copenhagen, Denmark: European Environment Agency.

EEA, 2017. Climate change, impacts and vulnerability in Europe: An indicator-based report. Luxembourg: Publications Office of the European Union.

ESPON, 2011. ESPON CLIMATE-Climate Change and Territorial Effects on Regions and Local Economies. Luxembourg.

Fekete, A., 2009. Validation of a social vulnerability index in context to river-floods in Germany. Natural Hazards and Earth System Science, 9 (2), 393–403.

Fernandez, P., Mourato, S., and Moreira, M., 2016. Social vulnerability assessment of flood risk using GIS-based multicriteria decision analysis. A case study of Vila Nova de Gaia (Portugal). Geomatics, Natural Hazards and Risk, 7 (4), 1367–1389.

Fritzsche, K., Schneiderbauer, S., Bubeck, P., Kienberger, S., Buth, M., Zebisch, M., and Kahlenborn, W., 2014. The Vulnerability Sourcebook: Concept and guidelines for standardised vulnerability assessments. Bonn and Eschborn.

Garschagen, M., 2014. Risky Change? Vulnerability and adaptation between climate change and transformation dynamics in Can Tho City, Vietnam. Stuttgart, Germany: Franz Steiner Verlag.

Greiving, S., Zebisch, M., Schneiderbauer, S., Fleischhauer, M., Lindner, C., Lückenkötter, J., Buth, M., Kahlenborn, W., and Schauser, I., 2015. A consensus based vulnerability assessment to climate change in Germany. International Journal of Climate Change Strategies and Management, 7(3), 306–326.

Hagenlocher, M., Delmelle, E., Casas, I., Kienberger, S., 2013. Assessing socioeconomic vulnerability to dengue fever in Cali, Colombia: statistical vs expert-based modeling. International Journal of Health Geographics, 12- 36.

Hazus, n.d. Hazus: FEMA's Methodology for Estimating Potential Losses from Disasters. https://www.fema.gov/hazus, [accessed 06 April, 2017].

Hinkel, J., 2011. 'Indicators of vulnerability and adaptive capacity': Towards a clarification of the science–policy interface. Global Environmental Change, 21(1), 198–208.

INFORM subnational models, n.d. INFORM Subnational risk index. http://www.inform-index.org/Subnational, [accessed 06 April, 2017].

INFORM, n.d. Index For Risk Management. http://www.inform-index.org/, [accessed 06 April, 2017].

IPCC, 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.

IPCC, 2012a. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge UK: Cambridge University Press.

IPCC, 2012b. Summary for policymakers - Special report on managing the risk of extreme events and disasters to advance climate change adaptation (SREX). Intergovernmental Panel on Climate Change.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Summary for Policymakers.

Jansson, N.A.U., 2004. Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident. International Journal of Physical Distribution & Logistics Management, 34, 434–456.

Johnson, C.W., 2007. Analysing the Causes of the Italian and Swiss Blackout, 28th September 2003. In: Tony Cant, ed. 12th Australian Conference on Safety Critical Systems and Software Conference. Adelaide, Australia: Australian Computer Society.

Kelman, I., Gaillard, J.C., Lewis, J., and Mercer, J., 2016. Learning from the history of disaster vulnerability and resilience research and practice for climate change. Natural Hazards, 82(1), 129–143.

Kienberger, S., Contreras, D., and Zeil, P., 2014. Spatial and Holisitc Assessment of Social, Economic, and Environmental Vulnerability to Floods – Lessons from the Salzach River Basin, Austria. In: J. Birkmann, S. Kienberger, and D. E. Alexander, eds. Assessment of Vulnerability to Natural Hazards: A European Perspective. Amsterdam, The Netherlands: Elsevier, 53–73.

Kropp, J. p., Block, A., Reusswig, F., Zickfeld, K., and Schellnhuber, H.J., 2006. Semiquantitative Assessment of Regional Climate Vulnerability: The North-Rhine Westphalia Study. Climatic Change, 76 (3-4), 265–290.

Mc Michael, A.J., 2013. Globalization, Climate Change, and Human Health. The New England Journal of Medicine, 368, 1335–1343.

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A., 2010. Assessment of economic flood damage. Natural Hazards And Earth System Sciences, 10(8), 1697–1724.

Met Office and WFP, 2014. Climate impacts on food security and nutrition. A review of existing knowledge. Rome, Italy.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J.C.J.M., Bouwer, L.M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przylusky, V., Thieken, A.H., and Viavattene, C., 2013. Review article : Assessing the costs of natural hazards – state of the art and knowledge gaps, 13, 1351–1373.

Meyer, W., 2011. Measurement: Indicators – Scales – Indices – Interpretations. In: R. Stockmann, ed. A Practitioner Handbook on Evaluation. Cheltenham, UK and Northampton, MA, USA: Edward Elgar Publishing, 189–219.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Washington, DC.

ND-GAIN , n.d. Notre Dame Global Adaptation Initiative (ND-GAIN). http://index.gain.org, [accessed 06 April, 2017].

Oppenheimer, M., Campos, M., R.Warren, Birkmann, J., Luber, G., O'Neill, B., and Takahashi, K., 2014. Emergent Risks and Key Vulnerabilities. In: C. B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White, eds. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA,: Cambridge University Press, 1039–1099.

PBL, 2012. Effect of climate changes on waterborne disease in The Netherlands. The Hague.

Peduzzi, P., Dao, H., Herold, C., and Mouton, F., 2009. Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index. Natural Hazards and Earth System Science, 9 (4), 1149–1159.

Pescaroli, G. and Alexander, D., 2016. Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. Natural Hazards, 82(1), 175–192.

Prutsch, A., Torsten Grothmann, Sabine McCallum, Inke Schauser, and Rob Swart, 2014. Climate change adaptation manual : lessons learned from European and other industrialised countries. Oxford, UK: Routledge.

Robine, J.-M., Cheung, S.L.K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.-P., and Herrmann, F.R., 2008. Death toll exceeded 70,000 in Europe during the summer of 2003. Comptes rendus biologies, 331 (2), 171–8.

Schneiderbauer, S. and Ehrlich, D., 2006. Social Levels and Hazard (in)-Dependence. In: J. Birkmann, ed. Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. Tokyo, Japan: United Nations University Press, 78–102.

Schneiderbauer, S., Zebisch, M., Kass, S., and Pedoth, L., 2013. Assessment of vulnerability to natural hazards and climate change in mountain environments. In: J. Birkmann, ed. Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. Tokyo, Japan: United Nations University Press, 349 – 380.

Tas, M., Tas, N., Durak, S., and Atanur, G., 2013. Flood disaster vulnerability in informal settlements in Bursa, Turkey. Environment and Urbanization, 25(2), 443–463.

Turner, B.L., Kasperson, R.E., Matson, P.A., Mccarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., and Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences, 100(14), 8074–8079.

UK, 2016. UK Climate Change Risk Assessment 2017. Synthesis Report. London, UK.

UNDRO, 1984. Disaster Prevention and Mitigation: a Compendium of Current Knowledge. Volume 11. Geneva: United Nations, Office of the United Nations Disaster Relief Co-ordinator.

UNISDR, 2015a. Sendai framework for disaster risk reduction 2015–2030. United Nations International Strategy for Disaster Reduction. http://www.wcdrr.org/uploads/Sendai_Framework_for_Disaster_Risk_Reduction_2015-2030.pdf, [accessed 04 April 2016].

UNISDR Terminology, 2017.https://www.unisdr.org/we/inform/terminology, [accessed 04 April, 2017].

UNISDR, 2015b. Global Assessment Report on Disaster Risk Reduction.

Wannewitz, S., Hagenlocher, M., Garschagen, M., 2016. Development and validation of a sub-national multi-hazard risk index for the Philippines. GI_Forum – Journal for Geographic Information Science, 1, 133-140.

Welle, T. and Birkmann, J., 2015. The World Risk Index – An Approach to Assess Risk and Vulnerability on a Global Scale. Journal of Extreme Events, 02 (01), 1550003.

Welle, T., Depietri, Y., Angignard, M., Birkmann, J., Renaud, F., and Greiving, S., 2014. Vulnerability Assessment to Heat Waves, Floods, and Earthquakes Using the MOVE Framework: Test Case Cologne, Germany. In: J. Birkmann, S. Kienberger, and D. E. Alexander, eds. Assessment of Vulnerability to Natural Hazards: A European Perspective. Amsterdam, The Netherlands: Elsevier, 91–124.

Wisner, B., 2016. Vulnerability as Concept , Model , Metric , and Tool. In: Oxford Research Encyclopedia of Natural Hazard Science. Oxford University Press, 1–58.

Wisner, B., Blaikie, P., Cannon, T., and Davis, I., 2004. At risk: natural hazards, people's vulnerability, and disasters. 2nd ed. Oxford, UK: Routledge.

Yusuf, A.A. and Francisco, H., 2009. Climate Change Vulnerability Mapping for Southeast Asia. Singapore.

2.4. Recording disaster losses for improving risk modelling

Amadio, M., Mysiak, J., CarreraL., Koks, E., 2015. Improvements in Flood Risk Assessment: Evidence from Northern Italy. Review of Environment, Energy and Economics (Re3).

Barbat, A., Carrenoa, M., Pujadesb, L., Lantadab, N., Cardona, O., Marulanda, M., 2010. Seismic vulnerability and risk evaluation methods for urban areas. A review with application to a pilot area. Structure and Infrastructure Engineering 6(1–2), 17–38.

Barredo, J., 2009. Normalised flood losses in Europe: 1970–2006. Natural Hazards and Earth System Sciences 9, 97–104.

Benedetti, D., Benzoni, G., Parisi, M.A., 1988. Seismic vulnerability and risk evaluation for old urban nuclei, Earthquake Engineering & Structural Dynamics 16(2), 183–201.

Biass, S, Bonadonna, C, Di Traglia, F, Pistolesi, M, Rosi, M, Lestuzzi, P., 2016. Probabilistic evaluation of the physical impact of future tephra fallout events for the Island of Vulcano, Italy. Bulletin of Volcanology 78, 37.

Cochrane, H. 1997. Indirect economic losses. In Development of Standardized Earthquake Loss Estimation Methodology. Vol. II. Washington, D.C.: National Institute for Building Sciences.

Boisevert, R., 1992. Indirect losses from a catastrophic earthquake and the local, regional, and national interest. In Indirect Economic Consequences of a Catastrophic Earthquake. Washington, D.C.: FEMA, National Earthquake Hazard Reduction Program.

Bolton, N. and L. Kimbell. 1995. The Economic and Demographic Impact of the Northridge Earthquake. Paper presented at the annual meeting of the Population Association of America.

Brémond, P., Grelot, F., Agenais, A.L., 2013. Review Article: economic evaluation of flood damage to agriculture — review and analysis of existing methods. Natural Hazards and Earth System Sciences, European Geosciences Union, 13, 2493 — 2512.

Brookshire, D.S. and M. McKee. 1992. Other indirect costs and losses from earthquakes: issues and estimation. In Indirect Economic Consequences of a Catastrophic Earthquake. Washington, D.C.: FEMA, National Earthquake Hazards Reduction Program.

Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., Von Winterfeldt, D., 2003. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra 19(4), 733–752.

Cepal NU, 2014. Handbook for disaster assessment, ECLAC.

Comerio, M., 1996. Disaster Hits Home. New Policy for Urban Housing Recovery. University of California Press.

Conhaz project, 2016. https://www.ufz.de/index.php?en=35939, [accessed 06 April, 2017].

Corsanego, A., 1991. Seismic vulnerability evaluation for risk assessment in Europe. Fourth International Conference on Seismic Zonation, Standford.

Cozzani, V., Campedel, M., Renni, E., Krausmann, E., 2010. Industrial accidents triggered by flood events: Analysis of past accidents. Journal of Hazardous Materials 175(1-3), 501–509.

Craig, H., Wilson, T., Stewart, C., Outes, V., Villarosa, G., Baxter, P., 2016. Impacts to agriculture and critical infrastructure in Argentina after ashfall from the 2011 eruption of the Cordón Caulle volcanic complex: an assessment of published damage and function thresholds, Journal of Applied Volcanology, 5(1), 7.

De Groeve, T., Poljansek, K., Ehrlich, D., 2013. Recording Disasters Losses: Recommendation for a European Approach. EUR 26111 EN, Luxembourg: Publications Office of the European Union. http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/29296/1/lbna26111enn.pdf, [accessed 06, April].

Direction Territoriale Méditerranée du Cerema, 2014. Retour d'expérience sur les inondations du département du Var les 18 et 19 janvier 2014 Volet 2 — Conséquences et examen des dommages. http://observatoire-regional-risques-paca.fr/sites/default/files/rapport_rex83_2014_dommages_sept14_0.pdf, [accessed: 14 May 2015]

Elissondo, M., Baumann, V., Bonadonna, C., Pistolesi, M., Cioni, R., Bertagnini, A., Biass, S., Herrero, JC., Gonzalez, R., 2016. Chronology and impact of the 2011 Cordón Caulle eruption, Chile. Natural Hazards and Earth System Sciences 16, 675–704.

Ellison, R., J.W. Milliman, and R.B. Roberts. 1984. Measuring the regional economic effects of earthquakes and earthquake predictions. Journal of Regional Science 24, 559–579.

EU expert working group on disaster damage and loss data, 2015. Guidance for recording and sharing disaster damage and loss data. Towards the development of operational indicators to translate the Sendai Framework into action, EUR 27192 EN, Luxembourg: Publications Office of the European Union.

FAO, 2015. The impact of disasters on agriculture and food security. Food and Agriculture Organization of the United Nations.

Gautak, K., Van der Hoek, E., 2003. Literature study on environmental impact of floods, GeoDelft internal publication. http://repository.tudelft.nl/islandora/object/uuid%3A4080519e-a46d-4e96-8524-62ee8fd93712?collection=research, [accessed 03 January, 2017].

GFDRR, 2013. Post-disaster needs assessment, Volume A, Guidelines, https://www.gfdrr.org/sites/gfdrr/files/PDNA-Volume-A.pdf, [accessed 12 January, 2017].

Grandjean. P., 2014. Science for precautionary decision-making, In: EEA, Some emerging issues, Late lessons from early warnings: science, precaution, innovation.

Green, C., Viavattene, C., and Thompson, P.: Guidance for assessing flood losses, CONHAZ Report, http://conhaz.org/ CONHAZ %20 REPORT %20WP06 1.pdf, 2011, [accessed 12 January, 2017].

Guéguen P., Michel C., LeCorre L., 2007. A simplified approach for vulnerability assessment in moderate-to-low seismic hazard regions: application to Grenoble (France). Bulletin of Earthquake Engineering 5(3), 467–490.

Guimares, P., Hefner, F.L., Woodward, D.P., 1993. Wealth and income effects of natural disasters: an econometric analysis of Hurricane Hugo. Review of Regional Studies 23, 97–114.

Hallegatte, S. 2008. An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. Risk Analysis 28(3), 779–799.

Hallegatte, S., Hourcade, J.-C., Dumas, P. 2007. Why economic dynamics matter in assessing climate change damages: illustration on extreme events, Ecological Economics 62(2), 330-340.

Hubert, G., Ledoux, B., 1999. Le coût du risque… L'évaluation des impacts socio-économiques des inondations, Presses de l'Ecole nationale Ponts et Chaussées, Paris [in French].

Idea, 2015. www.ideaproject.polimi.it, [accessed 06 April, 2017].

Jongman, B., Kreibich, H., Apel, H., Barredo, J.I., Bates, P.D., Feyen, L., Gericke, A., Neal, J., Aerts, C.J.H., Ward, P.J., 2012. Comparative flood damage model assessment: towards a European approach. Natural Hazards and Earth System Sciences 12, 3733–3752.

Kimbell, L., Bolton, N., 1994. The impact of the Northridge Earthquake on the economies of California and Los Angeles. Paper presented to the Seismic Safety Commission of the State of California, Burbank.

Krausmann, E., Cruz, A.M., Affeltranger, B., 2010. The impact of the 12 May 2008 Wenchuan earthquake on industrial facilities, Loss Prevention in the Process Industry.

Lagomarsino, S. and Giovinazzi, S., 2006. Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bulletin of Earthquake Engineering 4, 415-443.

Magill, C., Wilson, T.M., Okada, T., 2013. Observations of tephra fall impacts from the 2011 Shinmoedake eruption, Japan. The Earth, Planets and Space 65, 677–698.

Marrero, J. M., García, A., Llinares, A., De la Cruz-Reyna, S., Ramos, S., Ortiz, R., 2013. Virtual tools for volcanic crisis management, and evacuation decision support: applications to El Chichón volcano (Chiapas, México). Natural hazards, 68(2), 955-980.

Marsh, A., 2015. Decade of Advances In Catastrophe Modeling and Risk Financing, Insights. http://www.oliverwyman.com/content/dam/marsh/Documents/PDF/US-en/A %20Decade %20of %20Advances %20In %20Catastrophe %20Modeling %20and %20 Risk %20Financing-10-2015.pdf, [accessed 17 February, 2017].

MATRIX project, 2013. http://matrix.gpi.kit.edu/, [accessed 06 April, 2017].

McEntire, D., 2005. Why vulnerability matters: Exploring the merit of an inclusive disaster reduction concept. Disaster Prevention and Management: An International Journal 14(2), 206 — 222.

Mei, E., Lavigne, F., Picquout, A., de Bélizal, E., Brunstein, D., Grancher, D., Sartohadi, J., Cholik, N., Vidal, C., 2013. Lessons learned from the 2010 evacuations at Merapi volcano. Journal of Volcanology and Geothermal Research 261, 348–365.

Menoni, S., Atun, F., Molinari, D., Minucci, G., Berni, N., 2017. Defining complete post flood scenarios to support risk mitigation strategies. In Molinari, D., Ballio, F., Menoni, S. (Eds.). Flood Damage Survey and Assessment: New Insights from Research and Practice. Wiley, AGU (American Geophysical Union) series.

Menoni, S., Pergalani, F., Boni, M. P., Petrini, V., 2007. Lifelines earthquake vulnerability assessment: a systemic approach, In: Linkov, I., Wenning, R., Kiker, G. (Eds). Risk Management Tools For Port Security, Critical Infrastructure, and Sustainability, pp. 111-132.

Merz, B., Kreibich, H., Schwarze, R., Thieken, A., 2010. Assessment of economic flood damage, Natural Hazards and Earth System Sciences 10, 1697–1724.

Meyer, V., Schwarze, R., Becker, N., Markantonis, V., van den Bergh, J.C.J.M., Bouwer, L.M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A., Viavattene, C., 2015. Assessing the Costs of Natural Hazards — State of the Art and the Way Forward. Wiley&Sons.

Miavita project, n.d. http://miavita.brgm.fr/default.aspx, [accessed 06 April, 2017].

Ministère chargé de l'environnement-DPPR / SEI / BARPI, 2005. Inspection des installations classées, L'impact des inondations sur des établissements SEVESO, Séries d'événements de 1993 à 2003 Provence-Alpes-Côte d'Azur, Languedoc-Roussillon, France.

Ministére de l'Ecologie et du Développement Durable, 2005. Réduire la vulnérabilité des reseaux urbains aux inondations, Rapport, Novembre.

Nanto, D., Cooper, W., Donnelly, M., Johnson, R. (2011). Japan's 2011 Earthquake and Tsunami: Economic Effects and Implications for the United States. CRS Report for Congress, Congressional Research Service, 7-5700 -www.crs.gov-R41702.

Newhall, C.G. and Punongbayan R.S. (Eds.), 1997. Fire and Mud. Eruptions and Lahars of Mount Pinatubo, Philippines, University of Washington Press.

OECD, 2012. Global Modelling of Natural Hazard Risks. Enhancing Existing Capabilities to Address New Challenges. Organisation for Economic Co-operation and Development.

Park, J., Seager, T. P., Rao, P.S.C., Convertino, M., Linkov, I., 2013. Integrating Risk and Resilience Approaches to Catastrophe Management in Engineering Systems, Risk Analysis 33(3).

Pesaro, G., 2007. Prevention and mitigation of the territorial impacts of natural hazards: The contribution of economic and public-private cooperation instruments. In: Aven, T., Vinnem, E., (Eds.). Risk, Reliability and Societal Safety, Chapter: Volume 1 — Specialisation Topics. Publisher: Taylor&Francis, pp.603-612.

Petrini, V., 1996. Overview report in vulnerability assessment. In: Proceedings of the Fifth International Conference on Seismic Zonation, Nice, France, October 1995, Edition Ouést, Paris.

Pitilakis, K.P., Franchin,B., Khazai, H., Wenzel, H., (Eds.), 2014. SYNER-G: Systemic Seismic Vulnerability and Risk Assessment of Complex Urban, Utility, Lifeline systems, and critical facilities. Methdologies and Applications. Springer.

Pitt, M., 2008. The Pitt review: learning lessons from the 2007 floods. http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html, [accessed 05 May 2015].

Rose, A. and J. Benavides. 1997. Inter-industry models for analyzing the economic impact of earthquakes and recovery policies: Illustrative examples [7/93; revised 11/93]. In Advances in Social Science Analysis of Earthquakes, B. Jones, ed. Buffalo, N.Y.: National Center for Earthquake Engineering Research.

Scawthorn, C., 2008. A Brief History of Seismic Risk Assessment. In: Bostrom, A., French, S., Gottlieb, S., (Eds.), Risk Assessment, Modeling, and Decision Support, Strategic Directions. Springer.

Senouci, A., Bard, Y., Naboussi Farsi, M., Beck, E., Cartier, S., 2013. Robustness and uncertainties of seismic damage estimates at urban scale: a methodological comparison on the example of the city of Oran (Algeria). Bulletin of Earthquake Engineering 11, 1191–1215.

Spence, R., Kelman, I., Baxter, P., Zuccaro, G., Petrazzuoli, S., 2005. Residential building and occupant vulnerability to tephra fall. Natural Hazards and Earth System Sciences 5:4, 477-494

Spence, R., Pomonis, A., Baxter, P.J., Coburn, A., White, M., Dayrit, M., and Field Epidemiology Training Program Team, 1997. Building Damage Caused by the Mount Pinatubo Eruption of June 15, 1991, In: Newhall, C.G. and Punongbayan R.S. (Eds.), 1997. Fire and Mud. Eruptions and Lahars of Mount Pinatubo, Philippines. University of Washington Press.

Suzuki, K., 2008. Earthquake damage to industrial facilities and development of seismic and vibration control technology. Journal of System design and dynamics 2(1), 2-11.

Syner-G project, 2014. http://www.vce.at/SYNER-G/, [accessed 06 April, 2017].

Theocharidou, M., Giannopoulos, G., 2015. Risk assessment methodologies for critical infrastructure protection. Part II: A new approach. EUR 27332 EN. Luxembourg: Publications Office of the European Union.

Thieken, A. H., Olschewski, A., Kreibich, H., Kobsch, S., Merz, B., 2008. Development and evaluation of FLEMOps — a new Flood Loss Estimation Model for the private sector. In: Proverbs, D., Brebbia, C. A., Penning-Rowsell E., (Eds.) Flood recovery, innovation and response, WIT Press, Southampton, UK.

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N. Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller A., 2003. A framework for vulnerability analysis in sustainable science. PNAS, 100(14), 8074-8079.

Van der Veen, A., Logtmeijer, C. 2005. Economic hotspots: visualizing vulnerability to flooding. Natural hazards 36 (1-2), 65-80.

Van der Veen, A., Vetere Arellano, L., Nordvik, J.P., (Eds.), 2003. In search of a common methodology on damage estimation, EUR 20997 EN, European Communities, Italy

West, C.T., 1996. Indirect economic impacts of natural disasters: policy implications of recent research and experience. In: Proceedings of Analyzing Economic Impacts and Recovery from Urban Earthquakes: Issues for Policy Makers. Conference presented by Earthquake Engineering Research Institute and Federal Emergency Management Agency, Pasadena, Calif.

West, C.T., and D.C. Lenze. 1994. Modeling the regional impact of natural disaster and recovery: a general framework and an application to Hurricane Andrew. International Regional Science Review 17,121–150

Wilson, G., Wilson, T.M., Deligne, N.I., Cole, J.W., 2014. Volcanic hazard impacts to critical infrastructure: A review, Journal of Volcanology and Geothermal Research, 286, 148-182.

Wilson, T., Cole, J., Johnston, D., Cronin, S., Stewart C., Dantas A., 2012. Short- and long-term evacuation of people and livestock during a volcanic crisis: lessons from the 1991 eruption of Volcán Hudson, Chile. Journal of Applied Volcanology Society and Volcanoes 1(2).

Wilson, T., Stewart, C., Bickerton, H., Baxter, P., Outes, V., Villarosa, G., Rovere, E., 2013. Impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption on urban infrastruc-ture, agriculture and public health, GNS Science, New Zealand, GNS Science Report 2012/20, 88 pp.

WMO, 2007. Conducting flood loss assessment. A tool for integrated flood management. APFM Technical Document n.7, Flood Management Tools Series, World Meteorological Organisation.

Yamano, N., Kajitani, Y., Shumuta, Y., 2007. Modeling the Regional Economic Loss of Natural Disasters: The Search for Economic Hotspots, Economic Systems Research 19(2), 163-181.

Zonno, G., Cella, F., Luzi L., Menoni, S., Meroni, F., Ober, G., Pergalani, F., Petrini, V., Tomasoni, R., Carrara, P., Musella, D., García-Fernández, M., Jiménez, M.J., Canas, J.A., Alfaro, A.J., Barbat, A.H., Mena, U., Pujades, L.G., Soeters, R., Terlien, M.T.J., Cherubini, A., Angeletti, P., Di Benedetto, A., Caleffi, M., Wagner, J.J. and Rosset, P., 1998. Assesing seismic risk at different geographical scales: concepts, tools and procedures. In: Bisch, Ph., Labbé, P., Pecker, A. (eds). Proc. of the XI Conference on Earthquake Engineering, CD-ROM, Balkema, Rotterdam.

2.5. Where are we with multihazards and multirisks assessment capacities?

Abad, J.,2013. Fragility of pre-damaged elements: realisation of fragility functions of elements pre-damaged by other past events and demonstration on a scenario. European Commission project MATRIX (New methodologies for multi-hazard and multi-risk assessment methods for Europe), Project No 265138, D4.2.

Aubrecht, C., Freire, S., Neuhold, C., Curtis, A., Steinnocher, K., 2012. Introducing a temporal component in spatial vulnerability analysis. Disaster Advances, 5(2), 48-53.

Balica, S.F., Douben, N., Wright, N.G., 2009. Flood vulnerability indices at varying spatial scales. Water Science and Technology 60(10), 2571-2580.

Barroca, B., Bernardara, P., Mouchel, J.M., Hubert, G., 2006. Indicators for identification of urban flooding vulnerability. Natural Hazards and Earth System Sciences 6, 553-561.

Bazzurro, P., Cornell, C.A., Menun, C.Motahari, M. 2004. Guidelines for seismic assessment of damaged buildings. 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, Paper 1708.

Birkmann, J., Cardona, O. D., Carreno, M. L., Barbat, A. H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P. Welle, T. 2013. Framing vulnerability, risk and societal responses: the MOVE framework. Natural Hazards 67(2), 193-211.

Bucchignani, E., Garcia-Aristizabal, A., Montesarchio, M. 2014. Climate-related extreme events with high-resolution regional simulations: assessing the effects of climate change scenarios in Ouagadougou, Burkina Faso. Vulnerability, Uncertainty, and Risk, 1351-1362.

Cannon, A., 2010. A flexible nonlinear modelling framework for nonstationary generalised extreme value analysis in hydroclimatology. Hydrological Processes 24(6), 673-685.

Cannon, S., De Graff, J., 2009. The increasing wildfire and post-fire debris-flow threat in western USA, and implications for consequences of climate change. In: Sassa, K., Canuti, P.(eds). Landslides — disaster risk reduction, Springer, 177-190.

Cardona, O. D., Van Aalst, M.M., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Puhwarty, R.S., Schipper, E.L.F., Sinh, B.T., 2012. Determinants of risk: exposure and vulnerability. In: Managing the risks of extreme events and disasters to advance climate change adaptation. Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M.,Midgley, P.M. (eds.).A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, 65-108.

Cariam, 2006. Plans de prévention des risques naturels prévisibles (ppr) — Cahier de recommandations sur le contenu des ppr. Tech. rep., Ministère de l'Écologie et du Développement Durable (in French).

Carpignano, A., Golia, E., Di Mauro, C., Bouchon, S., Nordvik, J.-P. 2009. A methodological approach for the definition of multi-risk maps at regional level: first application. Journal of Risk Research 12(3-4), 513.

Chester, D.K. 1993. Volcanoes and society, E. Arnold, London, United Kingdom.

Choe, D.E., Gardoni, P., Rosowski, D., 2010. Fragility increment functions for deteriorating reinforced concrete bridge columns. Journal of Engineering Mechanics 136(8), 969.

Choine, M.N., O'Connor, A., Gehl, P., D'Ayala, D., Garcia-Fernández, M., Jiménez, M., Gavin, K., Van Gelder, P., Salceda, T., Power, R., 2015. A multihazard risk assessment methodology accounting for cascading hazard events. 12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP12, Vancouver, Canada.

Coburn, A.W., Bowman, G., Ruffle, S.J., Foulser-Piggott, R., Ralph, D., Tuveson, M., 2014. A taxonomy of threats for complex risk management. Cambridge Risk Framework series, Centre for Risk Studies, University of Cambridge, United Kingdom.

Coles, S., 2001. An introduction to statistical modelling of extreme values. Springer Series in Statistics, Springer, London, United Kingdom, limited.

Collins, T., Grinseki, S., Romo Aguilar, M. 2009. Vulnerability to environmental hazards in the Ciudad Juárez (Mexico) — El Paso (USA) metropolis: a model for spatial risk assessment in transnational context. Applied Geography 29, 448.

De Groeve, T., Poljansek, K., Vernaccini, L., 2015. Index for risk management — INFORM: concept and methodology, Version 2016. EUR 27521 EN. Luxembourg: Publications Office of the European Union.

Del Monaco, G., Margottini, C., Serafini, S., 1999. Multi-hazard risk assessment and zoning: an integrated approach for incorporating natural disaster reduction into sustainable development. TIGRA project (ENV4-CT96-0262) summary report.

Del Monaco, G., Margottini, C., Spizzichino, D., 2007. Armonia methodology for multi-risk assessment and the harmonisation of different natural risk maps. In: Armonia: applied multi-risk mapping of natural hazards for impact assessment, European Commission project, Contract 511208.

De Pippo, T., Donadio, C., Pennetta, M., Petrosino, C., Terizzi, F., Valente, A., 2008. Coastal hazard assessment and mapping in northern Campania, Italy. Geomorphology 97(3-4), 451-466.

Dessai, S., Hulme, M., Lempert, R. Pielke, R., 2009. Climate prediction: a limit to adaptation. In: Adger, N., Lorenzoni, I. and O'Brien, K.(Eds.). Adapting to climate change: thresholds, values, governance. Cambridge University Press, Cambridge, United Kingdom.

Dilley, M., Chen, U., Deichmann, R.S., Lerner-Lam, A. Arnold, M., 2005. Natural disaster hotspots: global risk analysis. Disaster Risk Management Series 5, The World Bank.

El Adlouni, S., Ouarda, T., Zhang, X., Roy, R., Bobée, B. 2007. Generalised maximum likelihood estimators for the nonstationary generalized extreme value model. Water Resources Research 43(3), 410.

European Commission, 2000. Temrap: the European multi-hazard risk assessment project. DG XII, Environment and Climate Programme, contract ENV4-CT97-0589.

European Commission, 2010. Risk assessment and mapping guidelines for disaster management. Staff Working Paper, SEC(2010) 1626 final.

FEMA, 2011. Getting started with HAZUS-MH 2.1. Tech. rep. United States Department of Homeland Security, Federal Emergency Management Agency.

Fleming, K., Parolai, S., Garcia-Aristizabal, A., Tyagunov S., Vorogushyn, S., Kreibich, H., Mahlke, H., 2016. Harmonising and comparing single-type natural hazard risk estimations. Annals of Geophysics 59(2), So216.

Garcia-Aristizabal, A., Almeida, M., Aubrecht, C., Polese, M., Ribeiro, L.M., Viegas D. Zuccaro, G. 2014. Assessment and management of cascading effects triggering forest fires. In: Viegas, D. Advances in forest fire research, 1073.

Garcia-Aristizabal, A., Bucchignani, E., Manzi, M. 2016. Patterns in climate-related parameters as proxy for rain-fall deficiency and aridity: application to Burkina Faso. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering 3(1).

Garcia-Aristizabal, A., Bucchignani, E., Palazzi, E., D'Onofrio, D., Gasparini, P., Marzocchi, W., 2015b. Analysis of non-stationary climate-related extreme events considering climate change scenarios: an application for multi-hazard assessment in the Dar Es Salaam region, Tanzania. Natural Hazards 75(1), 289-320.

Garcia-Aristizabal, A., Di Ruocco, A., Marzocchi, W., 2013. Naples test case. European Commission project MATRIX, Project No. 265138, D7.3.

Garcia-Aristizabal, A., Gasparini, P., Uhinga, G. 2015a. Multi-risk assessment as a tool for decision-making. In: Pauleit et al. (Eds). Urban vulnerability and climate change in Africa: a multidisciplinary approach. Future City 4(7), Springer, 229-258.

Garcia-Aristizabal, A., Marzocchi, W., 2013. Software for multi-hazard assessment. European Commission project MATRIX, Project No. 265138, D 3.5.

Gasparini, P., Garcia-Aristizabal, A., 2014. Seismic risk assessment, cascading effects. In: Beer, M., Patelli, E., Kougioumtzoglou, I., Au, I. (Eds.).Encyclopedia of earthquake engineering, Springer, Berlin/Heidelberg, 1-20.

Gencer, E. A. 2013. The impact of globalisation on disaster risk trends: macro- and urban-scale analysis. Background paper prepared for the Global Assessment Report on Disaster Risk Reduction 2013, UNISDR, Geneva.

Ghosh, J., Padgett, J.E., 2010. Aging considerations in the development of time-dependent seismic fragility curves. Journal of Structural Engineering 136(12), 1497.

Gill, J.C., Malamud, B.D., 2014. Reviewing and visualising the interactions of natural hazards. Reviews of Geophysics 52, 680.

Gill, J.C., Malamud, B.D., 2016. Hazard Interactions and interaction networks (cascades) within multi-hazard methodologies, Earth System Dynamics 7, 659.

Giorgio, M., Guida, M. Pulcini, G., 2011. An age- and state-dependent Markov model for degradation processes. IIE Transaction 43(9), 621.

Greiving, S., 2006. Integrated risk assessment of multi-hazards: a new methodology. In: Schmidt-Thomé, P. (Ed.). Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions. Geological Survey of Finland 42, 75.

Grünthal, G., 1998. European macroseismic scale. Cahiers du Centre Europeén de Géodynamique et de Séismologie 15, Luxembourg.

Grünthal, G., Thieken, A., Schwarz, J., Radtke, K., Smolka, A. Merz, B. 2006. Comparative risk assessment for the city of Cologne — Storms, floods, earthquakes. Natural Hazards 38(1-2), 21-44.

Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E., Van Deursen, W.P.A., 2012. Exploring pathways for sustainable water management in river deltas in a changing environment. Climate Change 115(3), 795-819.

Iervolino, I., Giorgio, M., Chioccarelli, E., 2013. Gamma degradation models for earthquake-resistant structures. Structural . Safety 45, 48-58.

Iervolino, I., Giorgio, M., Chioccarelli, E., 2015a. Age- and state-dependent seismic reliability of structures. 12th International Conference on Applications of Statistics and Probability in Civil Engineering. ICASP12, Vancouver, Canada.

Iervolino, I., Giorgio, M., Polidoro, B., 2015b. Reliability of structures to earthquake clusters. Bulletin of Earthquake Engineering 13, 983-1002.

IPCC, 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.).Cambridge University Press.

IPCC, 2014. Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

Jenkins, K., Hall, J., Glenis, V., Kilsby, C., McCarthy, M., Goodess, C., Smith, D., Malleson, N., Birkin, M., 2014. Probabilistic spatial risk assessment of heat impacts and adaptations for London. Climate Change 124(1), 105-117.

Jurgilevich, A., Räsänen, A., Groundstroem F., Juhola, S., 2017. A systematic review of dynamics in climate risk and vulnerability assessments. Environmental Research Letters 12(1), 013002.

Kappes, S.M., Keiler, M., Von Elverfeldt, K. Glade, T., 2012. Challenges of analysing multi-hazard risk: a review. Natural Hazards 64(2), 1925-1958.

Kappes, S.M., Keiler, M., Glade, T., 2010. From single- to multi-hazard risk analyses: a concept addressing emerging challenges. In:Malet, J.P., Glade, T., Casagli, N., (Eds.). Mountain risks: bringing science to society. CERG Editions, Strasbourg, France, p.351.

Kappes, S.M., Papathoma-Köhle, M., Keiler, M., 2011. Assessing physical vulnerability for multi-hazards using an indicator- based methodology. Applied Geography 32(2), 577-590.

Karapetrou, S.T., Filippa, A.M., Fotopoulou, S.D., Pitilakis, 2013. Time-dependent vulnerability assessment of rc-buildings considering ssi and aging effects. In Papadrakis, M., Papadopoulos, V. and Plevris V., (Eds.). 4th Eccomas Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering.

Komendantova, N., Mrzyglocki, R., Mignan, A., Khazai, B., Wenzel, F., Patt, A., Fleming, K., 2014. Multi-hazard and multi-risk decision-support tools as a part of participatory risk governance: feedback from civil protection stakeholders. International Journal of Disaster Risk Reduction 8, 50-67.

Komendantova, N., Scolobig, A., Vinchon, C., 2013a. Multi-risk approach in centralized and decentralized risk governance systems: case studies of Naples, Italy and Guadeloupe, France. International Relations and Diplomacy 1(3), 224-239.

Komendantova, N., Scolobig, A., Monfort, D., Fleming, K., 2016. Multi-risk approach and urban resilience Multi-risk approach and urban resilience. International Journal of Disaster Resilience in the Built Environment 7(2), 114-132.

Komendantova, N., van Erp, N., van Gelder, P., Patt, A., 2013 b. Individual and cognitive barriers to effective multi-hazard and multi-risk decision-making governance. European Commission project MATRIX, Project N 265138, D 6.2.

Kunz, M., Hurni, L., 2008. Hazard maps in Switzerland: state-of-the-art and potential improvements. In: Proceedings of the 6th ICA Mountain Cartography Workshop. Lenk, Switzerland.

Lazarus, N., 2011. Coping capacities and rural livelihoods: challenges to community risk management in southern Sri Lanka. Applied Geography 31(1), 20-34.

Lee, K., Rosowsky, D., 2006. Fragility analysis of woodframe buildings considering combined snow and earthquake loading. Structural Safety 28(3), 289-303.

Liu, B., Siu, Y.L., Mitchell, G., 2016. Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment. Natural Hazards and Earth System Sciences 16, 629-642.

Liu, Z., Nadim, F., Garcia-Aristizabal, A., Mignan, A., Fleming, K., Luna, B., 2015. A three-level framework for multi-risk assessment. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards 9(2), 59-74.

Loat, R., 2010. Risk management of natural hazards in Switzerland. Tech. rep. Federal Office for the Environment FOEN.

Luino, F., 2005. Sequence of instability processes triggered by heavy rainfall in the northern Italy. Geomorphology 66(1-4), 13-39.

Marulanda, M.C., Tibaduiza, M.L.C., Cardona, O.D., Barbat, A.H., 2013. Probabilistic earthquake risk assessment using CAPRA: application to the city of Barcelona, Spain. Natural Hazards, 69(1), 59-84.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M. L., Di Ruocco, A., 2012. Basic principles of multi-risk assessment: a case study in Italy. Natural Hazards 62(2), 551-573.

Marzocchi, W., Mastellone, M., Di Ruocco, A., Novelli, P., Romeo, E., Gasparini, P., 2009. Principles of multi-risk assessment: interactions amongst natural and man-induced risks. Tech. rep. European Commission, Directorate-General for Research, Environment Directorate.

Marzocchi, W., Sandri, L, Gasparini, P., Newhall, C., Boschi, E., 2004. Quantifying probabilities of volcanic events: the example of volcanic hazard at Mount Vesuvius. Journal of Geophysical Research 109, B11201.

Marzocchi, W., Sandri, L., Selva, J., 2008. BET_EF: a probabilistic tool for long- and short-term eruption forecasting. Bulletin of Volcanology Bulletin of Volcanology 70, 623.

Marzocchi, W., Sandri, L., Selva, J., 2010. BET_VH: a probabilistic tool for long-term volcanic hazard assessment. Bulletin of Volcanology 72, 717.

Middelmann, M., Granger, K., 2000. Community Risk in Mackay: a multi-hazard risk assessment. Tech. rep., Australian Geological Survey Organisation (AGSO).

Mignan, A., 2013. MATRIX -CITY user manual. European Commission project MATRIX, Project No 265138, D 7.2.

Mignan, A., Wiemer, S., Giardini, D., 2014. The quantification of low-probability-high-consequences events: Part 1, a generic multi-risk approach. Natural Hazards 73(3), 1999-2022.

Müller, A., Reiter, J., Weiland, U., 2011. Assessment of urban vulnerability towards floods using an indicator-based approach - a case study for Santiago de Chile. Natural Hazards and Earth System Sciences, 11, 2107.

Münzberg, T., Wiens, M., Schultmann, F., 2014. Dynamic-spatial vulnerability assessments: a methodical review for decision support in emergency planning for power outages. Procedia Engineering 78, 78-87.

Neri, M., Aspinall, W., Bertagnini, A., Baxter, P.J., Zuccaro, G., Andronico, D., Barsotti, S., D Cole, P., Ongaro, T.E., Hincks, T., Macedonio, G., Papale, P. Rosi, M., Santacroce, R., Woo, G., 2008. Developing an event tree for probabilistic hazard and risk assessment at Vesuvius. Journal of Volcanology and Geothermal Research 178(3), 397-415.

Neri, M., Le Cozannet, G., Thierry, P., Bignami, C., Ruch, J., 2013. A method for multi-hazard mapping in poorly known volcanic areas: an example from Kanlaon (Philippines). Natural Hazards and Earth System Sciences 13,1929-2013.

Newhall, C., Hoblitt, R., 2002. Constructing event trees for volcanic crises. A method for multi-hazard mapping in poorly known volcanic areas: an example from Kanlaon (Philippines). Bulletin of Volcanology 64, 3.

Nicholls, R. J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328 (5985), 1517-1520.

O ´Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climate Change, 122(3), 387-400.

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O ´Neill, B., Takahashi, K., 2014. Emergent risks and key vulnerabilities. In Climate change 2014: impacts, adaptation, and vulnerability. Part A. global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.H., MacCracken, S., Mastrandrea, P.R., White, L.L., (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, New York, United States, pp1039.

Ouarda, T., El Adlouni, S., 2011. Bayesian nonstationary frequency analysis of hydrological variables. Journal of the American Water Resources Association 47(3), 496-505.

Papathoma, M., Dominey-Howes, D., 2003. Tsunami vulnerability assessment and its implications for coastal hazard analysis and disaster management planning, Gulf of Corinth, Greece. Natural Hazards and Earth System Sciences 3, 733-747.

Papathoma, M., Dominey-Howes, D., Zong, Y., Smith, D., 2003. Assessing tsunami vulnerability, an example from Herakleio, Crete. Natural Hazards and Earth System Sciences 3, 377-389.

Papathoma-Köhle, M., 2016. Vulnerability curves vs. vulnerability indicators: application of an indicator-based methodology for debris-flow hazards. Natural Hazards and Earth System Sciences 16, 1771-1790.

Papathoma-Köhle, M., Neuhäuser, B., Ratzinger, K., Wenzel, H., Dominey-Howes, D., 2007. Elements at risk as a framework for assessing the vulnerability of communities to landslides. Natural Hazards and Earth System Sciences 7, 765-779.

Pescaroli, G., Alexander, D., 2015. A definition of cascading disasters and cascading effects: going beyond the ‘ toppling dominos’ metaphor. Planet@Risk 3(1), 58.

Petitta, M., Calmanti, S., Cucchi, M., 2016. The extreme climate index: a novel and multi-hazard index for extreme wheather events. Geophysical Research Abstracts 18, EGU2016 — 13861, EGU General Assembly 2016.

Polese, M., Di Ludovico, M., Prota, A., Manfredi, G., 2012. Damage-dependent vulnerability curves for existing buildings. Earthquake Engineering & Structural Dynamics 42(6), 853–870.

Polese, M., Marcolini, M., Zuccaro, G., Cacace F., 2015. Mechanism based assessment of damage-dependent fragility curves for rc building classes. Bulletin of Earthquake Engineering 13(5), 1323–1345.

Sanchez-Silva, M., Klutke, G.A., Rosowsky, D.V., 2011. Life-Cycle Performance of Structures Subject to Multiple Deterioration Mechanisms. Structural Safety 33(3), 206–217.

Schmidt, J., Matcham, I., Reese, S., King, A., Bell, R., Smart, G., Cousins, J., Smith, W., Heron, D., 2011. Quantitative Multi-Risk Analysis for Natural Hazards: A Framework for Multi-Risk Modelling. Natural Hazards 58, 1169.

Schmidt-Thomé, P., (Ed.), 2005. The Spatial Effects of Management of Natural and Technological Hazards in Europe — Final Report of the European Spatial Planning and Observation Network (ESPON) Project 1.3.1. Geological Survey of Finland.

Scolobig, A., Garcia-Aristizabal, A., Komendantova, N., Patt, A., Di Ruocco, A., Gasparini, P., Monfort, D., Vinchon, C., Bengoubou-Valerius, M., Mrzyglocki, R., Fleming, K., 2013. From Multi-Risk Assessment to Multi-Risk Governance: Recommendations for Future Directions. Chapter prepared for the Global Assessment Report on Disaster Risk Reduction 2015, UNISDR.

Scolobig, A., Garcia-Aristizabal, A., Komendantova, N., Patt, A., Di Ruocco, A., Gasparini, P., Monfort, D., Vinchon, C., Bengoubou-Valerius, M., Mrzyglocki, R., Fleming, K., 2014a. From Multi-Risk Assessment to Multi-Risk Governance: Recommendations for Future Directions. In: Understanding Risk: The Evolution of Disaster Risk Assessment. International Bank for Reconstruction and Development, Washington DC, Chapter 3-20, pp163.

Scolobig, A., Komendantova, N., Patt, A., Vinchon, C., Monfort-Climent, D., Begoubou-Valerius, M., Gasparini, P., Di Ruocco, A., 2014b. Multi-Risk Governance for Natural Hazards in Naples and Guadeloupe. Natural Hazards 73(3), 1523-1545.

Seidou, O., Ramsay, A., Nistor, I., 2011. Climate Change Impacts on Extreme Floods II: Improving Flood Future Peaks Simulation Using Non-Stationary Frequency Analysis. Natural Hazards 60(2), 715–726.

Seidou, O., Ramsay, A., Nistor, I., 2012. Climate Change Impacts on Extreme Floods I: Combining Imperfect Deterministic Simulations and Non-Stationary Frequency Analysis. Natural Hazards, 61(2), 647-659.

Self, S., 2006. The Effects and Consequences of Very Large Explosive Volcanic Eruptions. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 364(1845), 2073.

Selva, J., 2013. Long-Term Multi-Risk Assessment: Statistical Treatment of Interaction among Risks. Natural Hazards 67(2), 701-722.

Selva, J., Marzocchi, W., Papale, P., Sandri, L., 2012. Operational Eruption Forecasting at High-Risk Volcanoes: The Case of Campi Flegrei, Naples. Journal of Applied Volcanology, Society and Volcanoes, 1, 5.

Siliverstovs, B., Ötsch, R., Kemfert, C., Jaeger, C.C., Haas, A., Kremers, H., 2010. Climate Change and Modelling of Extreme Temperatures in Switzerland. Stochastic Environmental Research and Risk Assessment 24(2), 311-326.

Silva, M., Pareira, S., 2014. Assessment of Physical Vulnerability and Potential Losses of Buildings due to Shallow Slides. Natural Hazards 72(2), 1029-1050.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., (Eds.), 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, MA.

Sperling, M., Berger, E., Mair, V., Bussadori, V., Weber, F., 2007. Richtlinien zur Erstellung der Gefahrenzonenpläne (GZP) und zur Klassifizierung des spezifischen Risikos (KSR). Tech. rep., Autonome Provinz Bozen, (in German).

Sterlacchini, S., Frigerio, S., Giacomelli, P., Brambilla, M., 2007. Landslide Risk Analysis: A Multi-Disciplinary Methodological Approach. Natural Hazards and Earth System Sciences 7, 657-675.

Tarvainen, T., Jarva, J., Greiving, S., 2006. Spatial Pattern of Hazards and Hazard Interactions in Europe. In: Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions. Schmidt-Thomé, P. (Ed.), Geological Survey of Finland, Special Paper 42, 83.

Tyagunov, S., Grünthal, G., Wahlström, R., Stempniewski, L., Zschau, J., 2006. Seismic Risk Mapping for Germany. Natural Hazards and Earth System Sciences 6, 573-586.

UN, 2002, Johannesburg Plan of Implementation of the World Summit on Sustainable Development. Tech. rep. United Nations.

UNEP, 1992. Agenda 21. Tech. rep. United Nations Environment Programme.

UNISDR, 2005. Hyogo Framework for Action 2005-2015: Building the resilience of nations and communities to disasters. http://www.unisdr.org/files/1037_hyogoframeworkforactionenglish.pdf, [accessed 04 April 2016].

UNISDR, 2015. Sendai framework for disaster risk reduction 2015–2030. United Nations International Strategy for Disaster Reduction. http://www.wcdrr.org/uploads/Sendai_Framework_for_Disaster_Risk_Reduction_2015-2030.pdf, [accessed 04 April 2016].

Van Westen, C., Montoya, A., Boerboom, L., Badilla Coto, E., 2002. Multi-Hazard Risk Assessment Using GIS in Urban Areas: A Case Study for the City of Turrialba, Costa Rica. In:Regional Workshop on Best Practices in Disaster Mitigation: Lessons Learned from the Asian Urban Disaster Mitigation Program and other Initiatives. Proceedings, Bali, Indonesia, pp120.

Wisner, B., Blaikie, P., Cannon, T., Davis, I., 2004. At Risk: Natural Hazards, People`s Vulnerability and Disasters. New York, Routledge.

Xu, L., Meng, X., Xu, X., 2014. Natural Hazard Chain Research in China: A Review. Natural Hazards 70(2), 1631-1659.

Yalciner, H., Sensoy, S., Eren, O., 2012. Time-Dependent Seismic Performance Assessment of a Single-Degree-of-Freedom Frame Subject to Corrosion. Engineering Failure Analysis, 19, 109.

Zentel, K.-O., Glade, T., 2013. International Strategies for Disaster Reduction (IDNDR and ISDR). In:Encyclopedia of Natural Hazards. Bobrowsky, P.T., (Ed.), pp552.

Zschau, J., Fleming, K., (2012). Natural Hazards: Meeting the Challenges of Risk Dynamics and Globalisation, in ‘ Improving the Assessment of Disaster Risks to Strengthen Financial Resilience’, World Bank and Government of Mexico, Editors, Chapter 9, Germany, ‘Experiences in Disaster Risk Management within the German Development Cooperation’, Neutze F., Lutz, W., (Eds.), pp163.

Zuccaro, G., Gacace, F., Spence, R., Baxter, P., 2008. Impact of Explosive Eruption Scenarios at Vesuvius. Journal of Volcanology and Geothermal Research 178(3), 416-453.

Zuccaro, G., Leone, M., 2011. Volcanic Crisis Management and Mitigation Strategies: A Multi-Risk Framework Case Study. Earthzine 4.