Recording Disaster Losses for improving risk modelling (forthcoming)

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Abstract

This sub-chapter will show why and how better loss and damage assessment can be of use to improve current risk modelling capacities, starting from the modelling of direct physical damage to the representation of systemic and ripple effects throughout complex systems. Direct physical damage and losses have been so far been studied mainly through the use of vulnerability and damage curves. The latter allows us to account not only for the hazard parameters but also for the vulnerability of exposed assets. Examples of how such curves have been developed and applied will be provided in the field of seismic, volcanic and flood hazards; also, the use of post-disaster damage observation to evaluate models' consistency will be discussed. However, limiting the analysis to direct physical damage and losses precludes the possibility to embrace the full complexity of disasters that are a combination of multiple impacts: direct, indirect, and systemic. Post-disaster data can help understand and assess the complexity of scenarios, especially in areas where critical infrastructures, key production assets and diverse communities are exposed and vulnerable to threats to different extents. In order to make the best use of post-disaster data there is a need to improve the current way such data are collected and analysed, extending the knowledge of damage and losses to multiple sectors and to a variety of items that characterize contemporary cities and territories (De Groeve et al., 2013). Improving the overall capacity to include complexity in modelled scenarios used in risk assessments, will allow us to support better mitigation and prevention strategies, tailored to contexts displaying different combinations and levels of hazards, exposure and vulnerability (Park et al., 2013). This more comprehensive and realistic understanding of disasters' impacts should be of great interest to a variety of stakeholders, including academic researchers and representatives of private organisations and public agencies and authorities.

Keywords

Damage and loss data; vulnerability and damage curves; direct and indirect damage; systemic impacts; multi-sectors damage scenarios.

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 generally thought. As shown in Figure 1, in pre-event risk assessment either probabilistic or deterministic damage forecasts are appraised, whilst in the event aftermath the occurred scenario 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, 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 occurrence.

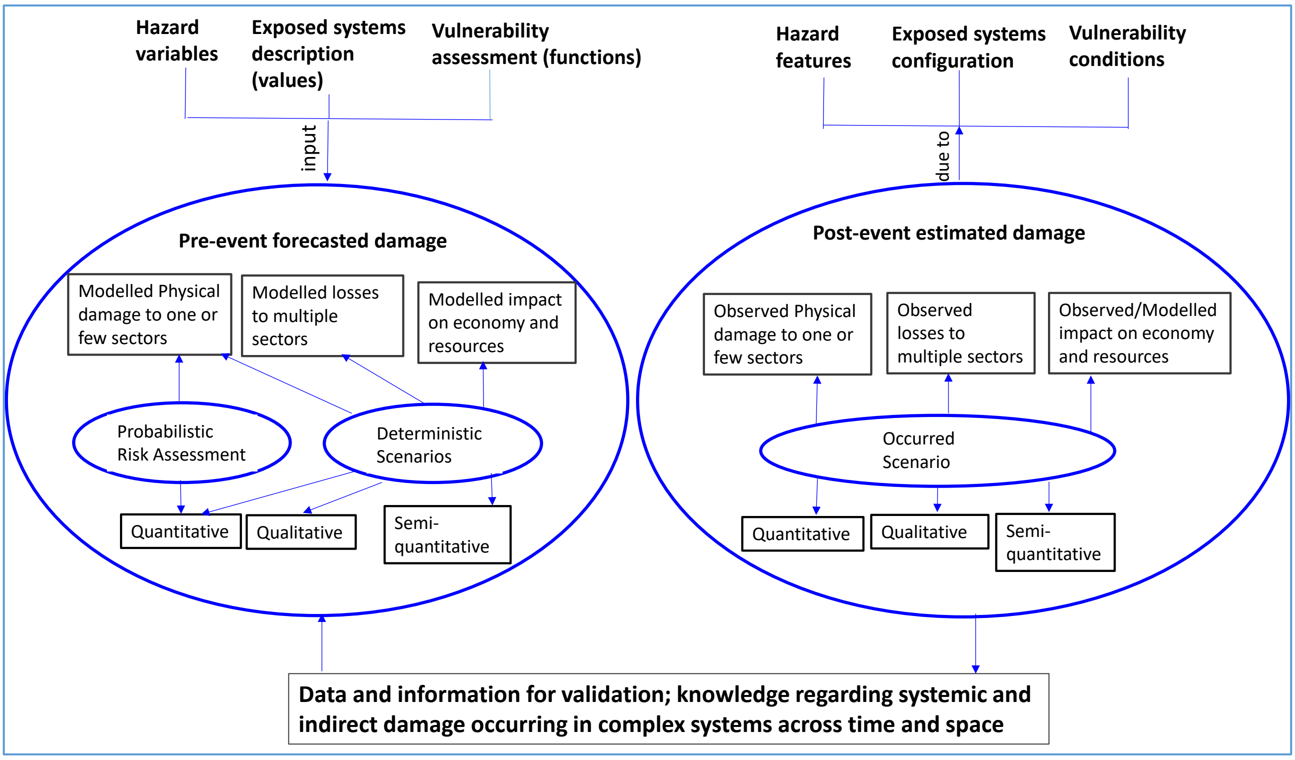

Figure 1. Pre- and post-disaster damage assessments

There is still a debate on the meaning of damage and on which types of damage and losses 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, 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 monetization is either extremely difficult or controversial. Damage to both tangibles and intangibles can be direct, meaning the damages provoked directly by the hazardous stressor, or indirect, consequential 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 larger time and space scales, also far from the event "epicentre" and long after the event has occurred. In some methodologies damages and losses are distinct: the first term refers to affected infrastructure, buildings, whilst the second refers to economic losses (GFDRR, 2013).

In the following sections, the link between pre- and post-event damage and loss assessments is discussed, showing the contribution 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: 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 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.

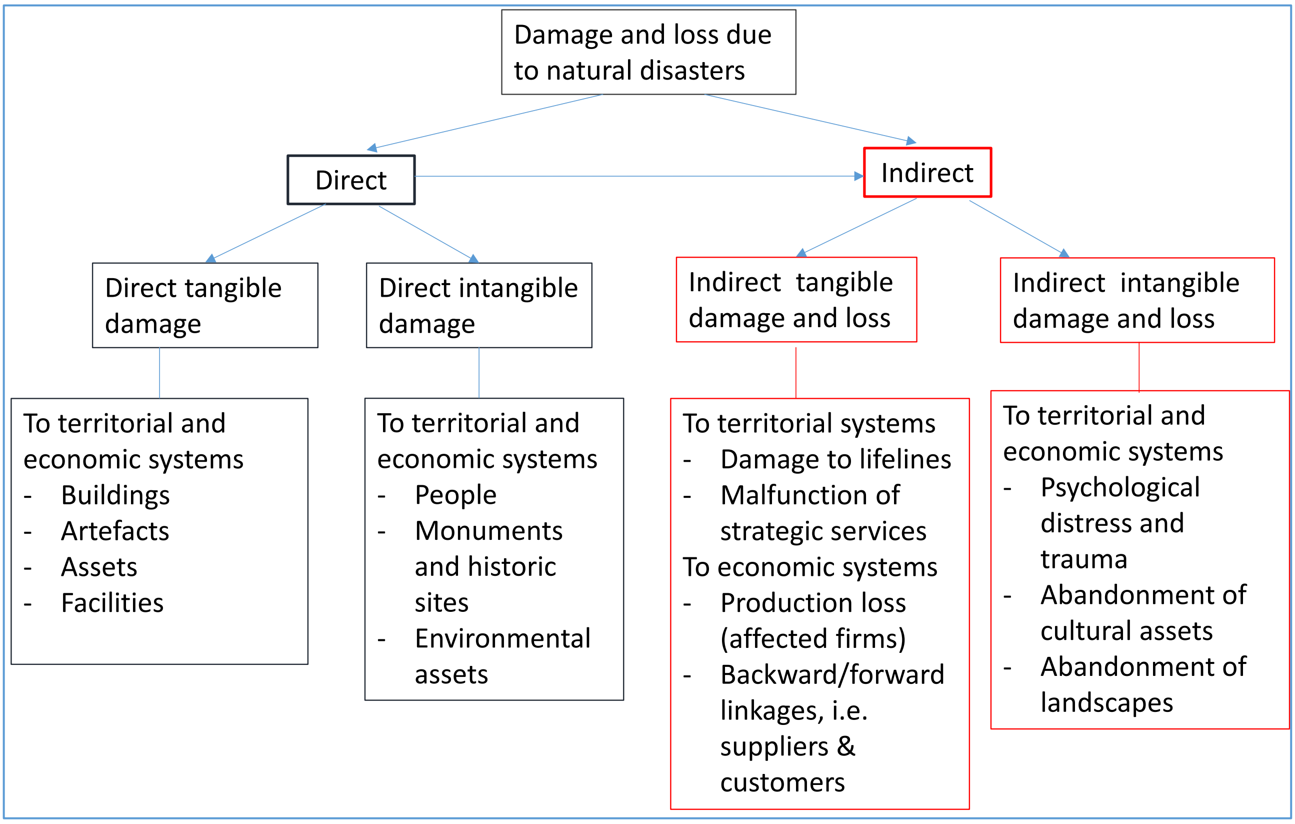

Figure 2. Definition of direct and indirect damage (after Merz et al. 2010).

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

2.1. State of the art of risk models

Expected damage can be assessed using quantitative, qualitative and semi-quantitative risk models (Figure 1, see also Chapter 2.1). Quantitative risk assessments dominate in scientific journals; however they generally consider quite limited number and type of variables. More complex understandings of risk that 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 (Chapter 2.2), and vulnerability (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 assessments. 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). The capacity to assess the latter is more recent and restricted to some exposed elements and systems, with the obvious difficulty of constructing a comprehensive and coherent picture of what may be the total effect of a disaster in a given area (Barbat et al., 2010).

In the following the state of the art of 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).

2.1.1. How vulnerability/damage curves have been developed for seismic risk

Seismic engineers have started developing vulnerability curves and functions 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 USA, while being developed in Europe during the Eighties (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 and can 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; 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 1 (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.

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, at no stress no building is expected to be damaged, 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 section 2.3.

	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

Table 1. Indicators to assess seismic risk
(Source:Zonno et al., 1998)

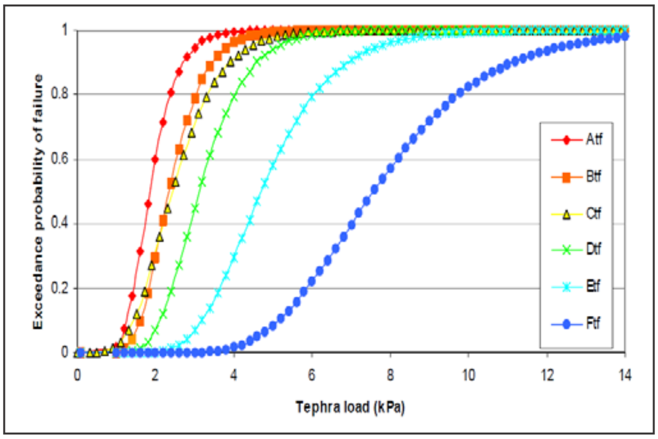

Figure 3. Damage curves for collapse of roofs associated with tephra fallout
(Adjusted from Spence et al. 2005)

2.1.2. How vulnerability/damage curves have been developed for volcanic risk

Vulnerability curves in volcanology have been developed much more recently and they 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. Fig. 3; Spence et al., 2005), while for ballistic and pyroclastic flows initial curves have been proposed in EU funded projects (see for example Miavita) (see Chapter 3.2, this volume for the description and definition of volcanic hazards). The lack of vulnerability data for other hazards includes the unfeasibility of building constructions 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 (Fig. 3). 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).

2.1.3. 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, 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 recognize the limitations of current methods that neglect hazard severity variables such as velocity or sediment transport that may be more relevant than water depth as a damage cause, especially in the case of flash floods.

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. 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 are developed for an area, a region. Therefore, risk assessments are 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 providing insurance and reinsurance companies with immediate figures of losses from a calamity that has just occurred do carry out post disaster surveys. The rapid evolution of IT has given an important impulse to the use of risk assessment scenarios using very large datasets comprising information on land uses and basic built stock characteristics that can be digested in a rather short time. However feedbacks from real events are crucial to increase the reliability of their modelling capacity (Marsh, 2015).

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

Even though occurred individual events cannot provide a comprehensive 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 one of the most affected quartiers in the city of Lorca as a consequence of the earthquake that occurred on the 11th of May 2011. Figure 5 represents the modelled damage using Risk-EU approach (Lagomarsino and Giovinazzi, 2006), considering the seismic load by the observed EMS98 intensity and the vulnerability index by building typology, age and number of floors.

The comparison between Figures 4 and 5 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, 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 Mw4.5 foreshock.

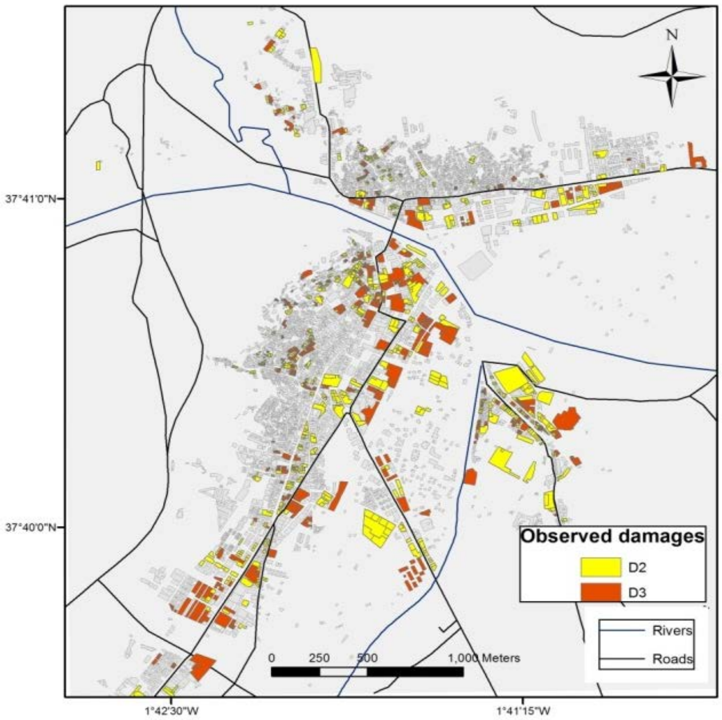

Figure 4. Observed building damage the city of Lorca in terms of mean damage grade, D (D1: slight, D2: moderate, D3: heavy, and D4: partial collapse) for the 11 May, 2011, 5.2Mw earthquake (Source: DG Citizen Security and Emergencies of the Region of Murcia).

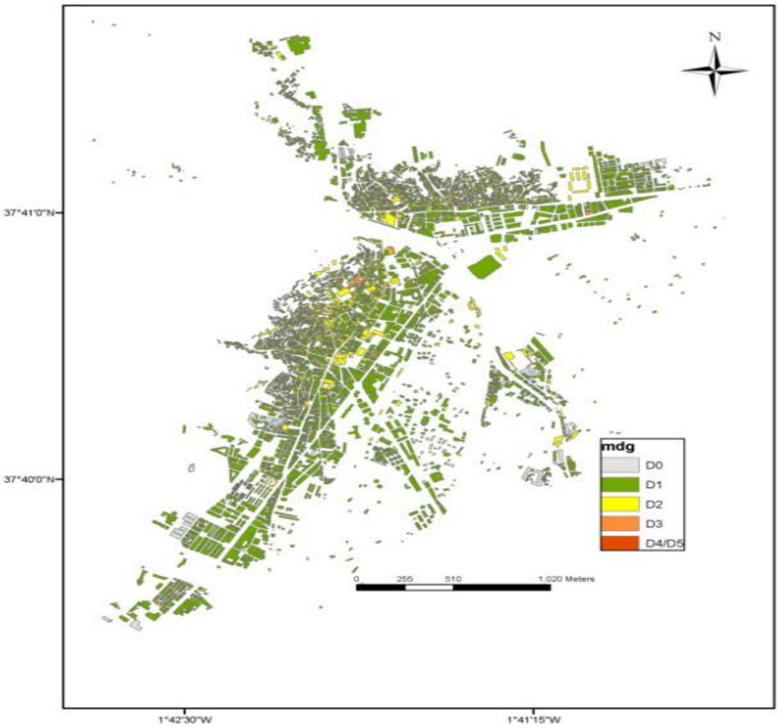

Figure 5. Simulation of physical damage to buildings in the city of Lorca using the direct approach.

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

Exercises similar to the one briefly shown in paragraph 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 of 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 discussed.

3.1. Damage to tangibles

3.1.1. Agriculture

As suggested by Brémond et al. (2013), damage to agriculture should comprise different elements: crops, soil, infrastructures and storage facilities. Those 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; few thoughts have 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 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.

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, 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 variety of combination of buildings, machinery, activities and processes that make it hard to standardize vulnerability assessments. Information on damage suffered by industries and factors that make them vulnerable are available for flood risk and for 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 na-tech hazards (Cozzani et al., 2010; Ministère chargé de l'environnement, 2005, see also Chapter 3.14).

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 monetize. It has been decided here to limit consideration to three examples, one for each hazard considered in this paper.

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. Spain, Southern France, Slovenia, Greece and Italy, are characterized 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 into sufficient consideration seismic risk. 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 formalized quantitative terms.

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, 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 in the water (Menoni et al., forthcoming). 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, requires time. Similar considerations may regard the soil itself for agricultural purposes. Salinization 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.

3.2.3. 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 measure is considered. 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 Chichon eruption (Mexico) (Marrero et al. 2013), the 1991 Pinatubo eruption (Philippines) (Newhall and Punongbayan 1997), the 1991 eruption of Hudson volcano (Chile) (Wilson et al. 2012) and the 2010 eruption of Merapi (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.

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

Literature on direct, indirect, secondary damage is rather large 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 JRC on Disaster Losses Data (De Groeve et al., 2013; EU Technical Working Group, 2015). At the international level, the work carried out within the ECLAC (Cepal, 2014) and the PDNA (GFDRR, 2013) has provided relevant approaches paving the way for the Sendai Framework for Disaster Risk Reduction.

4.1. Indirect damage due to ripple effects in complex systems

The need to consider other types of damages and damage to multiple systems stems from the recognition that real events are much more complex than the representation of physical damage to few assets lets presume. Cascading effects, enchained failures, malfunctions of critical lifelines, 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 been few and partial attempts so far to model them to make them part of a more complete risk assessment (Bruneau et al., 2003). The Matrix and the Syner-G projects can be recalled here, in particular with reference to the work done on modelling lifeline disruption due to natural disasters. Analysing in detail the models provided by both projects, it is evident that even though they are rather formalized, at crucial nodes expert decisions must be provided 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 more general formalization 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; Ministére de l'Ecologie, 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. Cordón Caulle 2011 eruption (Chile; Wilson et al. 2013; Craig et al. 2016; Elissondo et al. 2016) and Shinmoedake 2011 (Japan; Magill et al. 2013). Such efforts have not produced the number and extensive data that is available for physical damage, yet they represent an important first step that would require more focus on future efforts of collecting and analyzing post disaster damage data.

4.2. Indirect economic damage

Even less evidence is available for indirect damages on economic systems, induced by direct damages, lifelines failures, and losses due to business interruption. Such damage and losses include production losses suffered by suppliers and customers of affected companies, costs of traffic disruption or of emergency services. Evidence to date suggests that indirect damages are more important in large than in smaller disasters. For example, Hallegatte (2008) demonstrates that significant indirect losses for the state of Louisiana only arise when direct losses exceed 50 Billion USD. In a separate study, he also demonstrates that indirect impacts are larger 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).

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 in their infancy. 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. Moreover, insurance data must be indexed by insurance market characteristics (e.g. market penetration, 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 utilized 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 percent (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 labor 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.

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, systematically gathered data to address the complexity of real events is needed. Furthermore, as already suggested by the WMO 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 standardized 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 it will permit comparison between cases across geographic regions and time; it will then be easier to recognize 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 qualitative way. Third, more comprehensive and comparable reports will permit to build 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 1.

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, plants (and related components). Costs of asset repair or substitution can then be estimated. It is less easy than generally thought of to find a full 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).

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 (that can be local or national) in terms of lost resources (Pesaro, 2007). Such resources can be linked to material damage, to business and service interruption, 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 days/hours of interruption, number of outages or in terms of the economic loss that has been caused by such failure. The two representations of damage and losses do not fully coincide; it would be very important instead to find correspondences between them.

5. Looking ahead: open questions for researchers and practitioners

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 USA, Hubert and Ledoux (1999) had already suggested that post event surveys may provide more "reality" to assessments, by subtracting the field of imagined and hypothesized 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 to different types of damages.

Innovation. Multiple innovations are needed to enhance our damage modelling capacity. 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 damages to multiple sectors. Second, there is a need to reconcile different interpretation 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 losses. 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 in others as costs.

Also, a more comprehensive framework considering spatial and temporal scales should be adopted in risk assessments. As for the former, the spatial scale of relevance 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, recovery).

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 type of items. 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 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, particularly for businesses, duration of interruption is a crucial factor. In recent years, insurance companies have become more active in supporting their customers after an event to reduce such 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 recognized 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 them structural or non structural.

Key sentences

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

2. 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.

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

4. 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 insofar. Post-event damage assessment can provide key knowledge regarding multiple types of failures and indirect damage and losses.

5. 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 losses.

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References

Amadio, M., Mysiak, J., CarreraL., Koks, E., 2015. Improvements in Flood Risk Assessment: Evidence from Northern Italy. Review of Environment, Energy and Economics (Re3), http://dx.doi.org/10.7711/feemre3.2015.05.005.

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, Vol. 6, Nos. 1–2, February–April, p. 17–38.

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

Benedetti, D., Benzoni, G., Parisi, M.A., 1988. Seismic vulnerability and risk evaluation for old urban nuclei, Earthq Eng Struct Dyn, 16(2), p. 183–201.

Birkmann, J., 2013. Risk, in P.T. Bobrowsky (ed.), Encyclopedia of Natural Hazards, DOI 10.1007/978-1-4020-4399-4,# Springer Science+Business Media Dordrecht.

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.

Boisevert, R. 1995. Computable General Equilibrium Modeling for Earthquake Impact Analysis. Report to the Federal Emergency Management Agency. Ithaca, N.Y.: Cornell University. Cochrane, H. 1997. Indirect economic losses. In Development of Standardized Earthquake Loss Estimation Methodology. Vol. II. Washington, D.C.: National Institute for Building Sciences.

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, p. 2493 - p. 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., and von Winterfeldt, D., 2003. A framework to quantitatively assess and enhance the seismic resilience of communities, in "Earthquake Spectra", vol. 19 :4, pp.733–752.

Cardona, O., 2004. The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective risk management, In: Bankoff G., G. Frerks, D. Hilhorst, (2004) Mapping Vulnerability: Disasters, development & people, London, UK, Earthscan.

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

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

Cochrane, H. C., 2004. Economic loss: myth and measurement. Disaster Prevention and Management: An International Journal 13(4), pp. 290-296.

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, pp. 501–509

Craig, H., Wilson, T., Stewart, C., Outes, V., Villarosa, G., et al., 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, JRC Scientific and Policy Report, available at: http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/29296/1/lbna26111enn.pdf

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 ». [Accessed: 14 May 2015, available at: http://observatoire-regional-risques-paca.fr/sites/default/files/rapport_rex83_2014_dommages_sept14_0.pdf]

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.

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, Nat. Hazards Earth Syst. Sci., 16, 675–704,www.nat-hazards-earth-syst-sci.net/16/675/2016/

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, JRC Scientific and Policy Report.

Fao, 2015. The impact of disasters on agriculture and food security, Report.

Gautak, K., Van der Hoek, E., 2003. Literature study on environmental impact of floods, GeoDelft internal publication, June, available at repository.tudelft.nl, accessed on the 3rd January 2017.

GFDRR, 2013. Post-disaster needs assessment, Volume A, Guidelines, https://www.gfdrr.org/sites/gfdrr/files/PDNA-Volume-A.pdf accessed 12/1/2017.

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%20REPORT%20WP06 1.pdf, 2011.

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

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

Jenkins S., Spence, R.J.S., Fonseca, J.F.B.D., Solidum, R.U., Wilson, T.M. , 2014. Volcanic risk assessment: quantifying physical vulnerability in the built environment, J. Volcanol. Geotherm. Res., 276, pp. 105–120

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.: Comparative flood damage model assessment: towards a European approach, Nat. Hazards Earth Syst. Sci., 2012, 3733–3752, 2012

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), DOI: 10.1111/j.1539-6924.2008.01046.

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.

Kimbell, L., and N. Bolton. 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. Bull. Earthquake Eng., 4, pp. 415-443.

Magill, C., Wilson, T.M., Okada, T., 2013. Observations of tephra fall impacts from the 2011 Shinmoedake eruption, Japan, Earth, Planets, Sp 65:677–698. doi: 10.5047/eps.2013.05.010

Markantonis V., Meyer V. and Schwarze R. , Valuating the intangible effects of natural hazards, Review and analysis of the costing methods, Natural Hazards and Earth System Sciences, 12, 2012, pp. 1633–1640.

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. (October 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%20Risk%20Financing-10-2015.pdf, Accessed on 17th February 2017.

McEntire, D., 2005. Why vulnerability matters: Exploring the merit of an inclusive disaster reduction Concept, Disaster Prevention and Management: An International Journal, Vol. 14 Iss 2, pp. 206 – 222, 2005.

Merz, B., Kreibich, H., Schwarze, R., Thieken, A., 2010. Assessment of economic flood damage, Nat. Hazards Earth Syst. Sci., 10, pp. 1697–1724.

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, Volume 261, pp. 348–365.

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.

Menoni, S., Atun, F., Molinari, D., Minucci, G., Berni, N. (forthcoming May 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.

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.

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

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.

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.

Njome, M.S., Suh, C.E., Chuyong, G., Wit, M.J., 2010. Volcanic risk perception in rural communities along the slopes of Mount Cameroon, West-Central Africa. Journal of African Earth Sciences, 58, pp. 608-622.

OECD, 2012. Global Modelling of Natural Hazard Risks. Enhancing Existing Capabilities to Address New Challenges, September.

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, Vol. 33, No. 3.

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.

Pfurtscheller, P., Lochner, B., and Thieken, A. H.: Costs of Alpine Hazards, CONHAZ Report, http://conhaz.org/, CONHAZ%20REPORT%20WP08 1 FINAL.pdf, 2011.

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.

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 [online]. Accessed: 05 May 2015, available at: http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html

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), Bull Earthquake Eng., 11, pp. 1191–1215.

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.

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, pp. 477-494

Suzuki, K., 2008. Earthquake damage to industrial facilities and development of seismic and vibration control technology, Journal of System design and dynamics, vol 2:1.

Theocharidou, M., Giannopoulos, G., 2015. Risk assessment methodologies for critical infrastructure protection. Part II: A new approach, JRC Science and Policy Reports, Report EUR 27332 EN.

Thieken, A. H., Olschewski, A., Kreibich, H., Kobsch, S., Merz, B., 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, 2008.

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, pp. 8074-8079.

Van der Veen, A., Vetere Arellano, L., Nordvik, J.P., 2003. In search of a common methodology on damage estimation, JRC Report.

Van der Veen, A., Logtmeijer, C. 2005. Economic hotspots : visualizing vulnerability to flooding. In: Natural hazards : journal of the international society for the prevention and mitigation of natural hazards, 36 (2005)1-2: 65-80.

Wergerdt, J. and S.S. Mark. 2010., Post-Nargis Needs assessment and monitoring. ASEAN's Pioneering Response, Final report, Asean Secretariat.

West, C.T., 1996. Indirect economic impacts of natural disasters: policy implications of recent research and experience. 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, 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.

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, pp. 148-182.

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

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: Ph. Bisch, P. Labbé & A. Pecker (eds), Proc. of the XI Conference on Earthquake Engineering, CD-ROM, Balkema, Rotterdam, ISBN 90 5410 982 3.

Websites

Conhaz project, https://www.ufz.de/index.php?en=35939

Idea, www.ideaproject.polimi.it

Matrix project: http://matrix.gpi.kit.edu/

Miavita project: http://miavita.brgm.fr/default.aspx

Perpetuate project, http://www.perpetuate.eu/

Syner-G project: http://www.vce.at/SYNER-G/