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Review Article: A Comparison of Flood and Earthquake Vulnerability Assessment Indicators

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Abstract. In a cross-discipline study, we carried out an extensive literature review to increase understanding of vulnerability indicators used in both earthquake- and flood vulnerability assessments. We provide insights into potential improvements in both fields by identifying and comparing quantitative vulnerability indicators. Indicators have been categorized into physical- and social categories, and then, where possible, further subdivided into measurable and comparable indicators. Next, a selection of index- and curve based vulnerability models that use these indicators have been described, comparing several characteristics such as temporal- and spatial aspects. It appears that earthquake vulnerability methods traditionally have a strong focus on object-based physical attributes used in vulnerability curve-based models, while flood vulnerability studies focus more on indicators applied to aggregated land-use classes in curve-based models. Flood risk studies could be improved using approaches from earthquake studies, such as incorporating more detailed physical indicators, developing object-based physical vulnerability curve assessments and incorporating time-of-the-day based building occupation patterns. Likewise, earthquake assessments could learn from flood studies by refining their selection of social vulnerability indicators. Based on the lessons obtained in this study, we recommend future studies for exploring risk assessment methodologies cross-different hazard types.

1 Introduction

Recent decades have seen a sharp global increase in the economic risk associated with floods and earthquakes, although it should be noted that both earthquake and flood related fatalities might be decreasing. UNISDR (2009) defines this risk as: “the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions”. Based on previous work by Crichton (1999) and Kron (2005), this risk has been formalised in many studies and frameworks (e.g. UNISDR, 2009; Mechler and Bouwer, 2014) using the following Eq. (1):

$$Risk = f(Hazard, Exposure, Vulnerability) , \quad (1)$$

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where *hazard* is defined as 'A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation'; *Exposure* is defined as 'People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses'; and *Vulnerability* as the set of conditions and processes resulting from physical, social, economic, and environmental factors, which increase the susceptibility of a community '(people and assets) to the impact of hazards' (UNISDR 2009).

Many studies suggest that the observed increase in risk in recent decades is mainly due to the increase in exposure of assets and people in hazard prone areas, and an increase in wealth (Kron, 2005; UNISDR, 2011; IPCC, 2012; Doocy et al., 2013b; Blaikie et al., 2014; MunichRe, 2014; Visser et al., 2014; GFDRR, 2016). Most studies on flood risk to date have found little signal for increasing hazard in the last decades (e.g. Kundzewicz et al., 2014; Jongman et al., 2015). However, recent research suggests that this could be due to the fact these studies have not accounted for changes in vulnerability over time (e.g. Jongman et al., 2015; Mechler and Bouwer, 2014). Indeed, the quantification of vulnerability in risk assessments is known to be extremely difficult, which is why most studies assume constant vulnerability over time. Improving methods to assess vulnerability is seen as the 'missing link' for improving our understanding of risk (Douglas, 2007; Jongman et al., 2015).

When focusing on the quantification of vulnerability to (fluvial) flooding, often as part of a flood risk model, there are two main approaches: (a) vulnerability indices; and (b) vulnerability curves (Messner et al., 2007; Kannami, 2008; Merz et al., 2010; Nasiri et al., 2013). Both approaches use one or more indicators that influence vulnerability and are used as measures of vulnerability (Cutter et al., 2003). Well-known contributions to index based vulnerability assessments (broader than only flood-related vulnerability) have been made by Cutter (2003), Davidson (1997), Coburn and Spence (1994 and 2002), and many others. Vulnerability indices are sometimes combined with statistical multi-variate methods to find correlations between empirical losses from natural hazards (e.g. Carreno et al., 2007). In flood risk modeling, there are numerous studies that have studied the influence of temporal and spatial changes in hazard and exposure on risk, using risk models or risk-based indicators (e.g. Apel et al., 2004; Bouwer et al., 2007; Bouwer, 2011; IPCC, 2012; De Moel et al., 2015; Jongman et al., 2015). Most of the risk models, however, make simple assumptions on quantifying vulnerability, and have largely refrained from considering (changing) vulnerability as a potential cause of the growing impacts of floods (Koks et al., 2015b; Mechler and Bouwer, 2014). Several key challenges with the quantification of vulnerability to flooding include: (1) it is difficult to develop meaningful and quantifiable indicators of vulnerability; (2) there is a lack of available and accurate data to measure those indicators, and the required data are often only available at highly aggregated levels; and (3) there is a lack of empirical data on flood losses to relate losses (damage) to vulnerability.

In the domain of earthquake risk modeling, quantifying vulnerability also remains a challenge. Historically, the assessment of physical vulnerability is well-developed and recently it has been attempted to improve the quantification of social vulnerability as well (Sauter and Shah, 1987; Tiedemann, 1991; Yücemen et al., 2004;

Carreno et al., 2005; Douglas, 2007). As with flood risk assessment, most of the methods to assess vulnerability are either based on indices or vulnerability curves. Earthquake vulnerability assessments traditionally have a very strong focus on the physical vulnerability of individual buildings, their construction, and specific structural characteristics. Examples include the number of stories, their ability to resist seismic lateral forces as a primary cause of damage, and casualties caused by building collapse (Coburn and Spence, 2002). Damage to buildings is generally the sole indicator used to predict economic and social losses (Kircher et al., 2006).

The main goal of this study is to conduct a literature review comparing methods for quantitatively assessing vulnerability in flood and earthquake risk assessments. Because the field of vulnerability research is wide, we here focus on the two main types of vulnerability assessment methods: vulnerability indices and vulnerability curves. More specifically, we analyze which vulnerability indicators have been addressed in both methods, and systematically assess the differences in using those indicators in both flood vulnerability and earthquake vulnerability. The paper specifically does not aim to produce another definition of vulnerability and we gratefully acknowledge the broad literature on vulnerability and previous discussions of definitions of vulnerability (e.g. Cutter et al., 2003; Adger, 2006; Barroca et al., 2006; Birkmann et al., 2007; Hinkel, 2011). In this paper, we therefore use the widely applied definition of vulnerability as provided by UNISDR (2009). In comparing the fields of flood vulnerability with earthquake vulnerability, we hope that both fields can learn from each other's respective approaches, further developing vulnerability as an important component in risk modeling.

The remainder of this paper is organized as follows: Sect. 2 describes the methods followed to compare the different vulnerability assessment methods, including a discussion of several well-known earthquake and flood risk or vulnerability assessment methods. In Sect. 3, we discuss main differences and similarities between earthquake and flood vulnerability indicators. Finally, a brief conclusion and recommendations section follows.

2 Identifying different vulnerability indicators and models for comparison

In this section, we describe the methods that we have used to structure an extensive literature review to compare vulnerability assessment models in both flood risk- and earthquake assessments. In Sect. 2.1, we provide an overview of the main vulnerability indicators (physical and social) that have been used to quantify flood and earthquake vulnerability. Next, in Sect. 2.2, we describe the two modeling types that use these indicators to quantify vulnerability: vulnerability curve models and index based vulnerability models. Finally, in Sect. 2.3, we describe additional methods for comparing different vulnerability assessment models, relating to spatial and temporal scale.

2.1 Vulnerability Indicators

Following the existing literature on vulnerability, we classify vulnerability indicators in two main classes: (a) physical indicators that pertain directly to characteristics of the exposed assets, namely infrastructure and lifelines (including transportation infrastructure, utility lifelines, and essential lifelines) and buildings (including structural elements, occupancy, and environment related factors); and (b) social indicators, which include demographics,

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awareness, economics, and institutional factors (e.g. Mileti, 1999; Cutter et al., 2003; Adger, 2006; Balica et al., 2012).

2.1.1 Physical Vulnerability

The physical factor of vulnerability is the most researched part of vulnerability science, and relates to the physical vulnerability of the assets exposed to natural hazards – in our case floods and earthquakes. We here make a distinction in three main exposed assets: (a) infrastructure and lifelines; (b) buildings and their structural and occupancy components; and (c) environment (e.g. Davidson and Shah, 1997; Mileti, 1999; Douglas, 2007).

We distinguish between the following physical vulnerability indicator groups:

Infrastructure and lifelines indicators

In terms of infrastructure assets, we further specify *Transportation infrastructure* (e.g. highways, railways, ports), *Utility lifelines* (e.g. potable water, waste water, electric power, oil systems), and *Essential facilities* (e.g. hospitals, police and fire stations, and schools) (FEMA 2013a and 2013b). Measurable physical vulnerability indicators for infrastructure for both earthquakes and floods include: (a) structural indicators, such as the length of railways and public roads in operation and the length of public roads in operation; and and location indicators, such as accessibility of facilities or the closeness of utilities to another utility (e.g. Rashed and Weeks, 2003; Peng, 2012).

Building structural and occupancy indicators

The vulnerability of buildings can be described using two indicator groups: *structural elements* and *occupancy indicators*. Structural elements comprise of, for example, building type, material, age, and number of floors (e.g. Giovinazzi and Lagomarsino, 2004; Kircher et al., 2006; Porter et al., 2008; Duzgun et al., 2011). Building occupancy refers to the type of usage of the building, for example, commercial, industry or residential. These occupancy types determine the potential values of the losses from a hazard (e.g. Kircher et al., 2006; FEMA 2013a and 2013b).

Environmental indicators

The vulnerability of both infrastructure and buildings are influenced by their environmental characteristics. For example, the proximity of a building to a potential contaminating site may affect vulnerability (e.g. Colombi et al., 2008; Damm 2009). During the Elbe floods of 2002, relatively minor damage (i.e. the damage as percentage of the total damage) was caused due to oil tanks that were buried in gardens of houses, but that were floating and leaking due to flood waters (Kreibich et al., 2005; Müller and Thieken, 2005).

2.1.2 Social Vulnerability

The social factor of vulnerability relates to the vulnerability of the exposed population to natural hazards. This aspect is studied to a lesser extent than the physical vulnerability factors due to the lack of empirical data for quantifying social vulnerability, especially at the more detailed household levels (e.g. Cutter et al., 2003). As a result, social vulnerability is often expressed at more aggregated levels, using vulnerability indicators such as age, ethnicity and welfare levels of communities and countries (Cutter et al., 2003; Blaikie et al., 2014). Two research communities have assessed social vulnerability quite extensively: the climate change adaptation (CCA) community and the disaster risk reduction (DRR) research community (Turner et al., 2003; Thomalla et al., 2006; Mercer, 2010; Dewan, 2013). Concepts from both communities have been increasingly intertwined, integrating concepts of resilience and adaptive- or coping-capacity (e.g. Turner et al., 2003; Deressa, Hassan and Ringler, 2008; Kienberger et al., 2009; Merz et al., 2010; Scheuer et al., 2011; Brink and Davidson, 2015).

We here distinguish four main social vulnerability indicator groups:

Demographic indicators

Demographic indicators refer to the size, structure, and distribution of populations, and related spatial or temporal changes in them in response to natural hazards. For example, for determining social vulnerability to earthquakes, the 'vulnerable age' indicator is often used (e.g. Davidson and Shah, 1997; Schmidtlein et al., 2011).

Awareness indicators

Research has shown that risk perception is an important factor for households to determine their level of preparation for natural hazard events (e.g. Balica et al., 2012; Bubeck et al., 2012). For example, the experience with previous events has a positive effect on the awareness level (Balica et al., 2009). In addition, access to information sources, such as TV, determines the knowledge and awareness of the hazard (e.g. Balica et al., 2009; Brink and Davidson, 2015).

Economic indicators

Wealth is an important indicator for showing the potential capacity of people to prepare for natural hazards. For example, research shows that relatively high-income households have a higher demand for hazard insurance, or more often implement damage mitigation measures (Botzen and Van den Bergh, 2012; Bubeck et al., 2012). Vulnerability in the aftermath of an event can be lower for high-income households as they have more resources to compensate for their losses. Examples of economic vulnerability indicators are GDP, income, or percentage of unemployed people (e.g. Davidson and Shah, 1997; Peduzzi, 2009; Peng, 2012).

Institutional and political indicators

Indicators that refer to institutional and political factors are related to a certain level of planning and preparing for natural hazards. For example, strong (spatial-) planning regulations may be an indicator that building codes and zoning protocols have been developed and enforced (e.g. Cutter et al., 2003; Blaikie et al., 2014).

2.2 Vulnerability models

This section discusses a selection of earthquake and flood vulnerability assessment models. Vulnerability models use indicators from Sect. 2.1, combining information on the hazard, exposure and vulnerability indicators (e.g. Carreno et al., 2007). We use the categorization of vulnerability methods as recognized in the literature (Messner et al., 2007; Merz et al., 2010; Nasiri et al., 2013), which distinguishes two main vulnerability modeling types: index based models and models that use vulnerability curves. We here provide the main characteristics of such models, and describe a few in more detail.

2.2.1 Index based vulnerability models

This category includes models that assess vulnerability based on statistical data for the indicators listed in Sect. 2.1. These models sum different vulnerability indicators into one composite index, which then shows the vulnerability of a household, community, or country to natural hazards (Birkmann, 2007). These indicators are often used in statistical analyses to find relations between the vulnerability index and empirical losses. Simple examples are statistical analyses between damages (or fatalities) and a second variable such as *the number of buildings in need of large repair* in an area as used in the Global Earthquake Model (GEM) (e.g. Burton and Silva, 2014; Silva et al., 2014a and 2014b).

- The Flood Vulnerability Index (FVI) was developed by Connor and Hiroki (2005) and adapted in subsequent studies (Balica et al., 2009; 2010 and 2012). The FVI combines different cause and effect factors and consists of four components (i.e. meteorological, hydrogeological, socio-economic and a countermeasure component) (Connor and Hiroki, 2005; Balica et al., 2009). A similar index is the country level physical and community risk index for earthquakes and floods in the Asia-Pacific region by Daniell et al. (2010). Kannami (2008) developed a country-based flood risk index (FRIc), based on the Pressure and Release (PAR) model.
- UNDP's 2004 Disaster Risk Index (DRI) is an index that aims to explain the role of vulnerability for different risk levels or different numbers of post-disaster fatalities between countries with a given level of physical exposure to three types of natural disasters (i.e. earthquakes, tropical cyclones, floods and, in more recent versions, droughts) (UNDP, 2004; Birkmann, 2007; Peduzzi et al., 2009). Indicator selection focuses on allowing comparison between countries and hazard types (DRI indicators are hazard specific) (UNDP, 2004; Birkmann, 2007).
- Yücemen et al. (2004) developed a multivariate-statistics analysis to assess "the seismic vulnerability of low- to mid-rise reinforced concrete buildings". The six selected indicators are all engineering-based using expert judgment and observations. The model uses five discrete damage states ranging from *none* to *collapse*. It calibrates this based on empirical damage seen in historical events in Turkey.

2.2.2 Vulnerability curve models

The vast majority of flood- and earthquake vulnerability assessment models are based on damage functions or fragility curves that relate the (mostly-) physical indicators described in Sect. 2.1 with hazard parameters (Douglas, 2007). In flood damage models, vulnerability is commonly calculated by relating flood depth to building or land-use type using vulnerability curves per exposed building- or land-use type. These curves provide estimates of potential damage. Occasionally, other hazard parameters such as velocity and duration are added (Merz et al., 2010; Jongman et al., 2012). Earthquake risk assessments traditionally use fragility curves as a measure for vulnerability, in which building characteristics are related to hazard parameters such as ground shaking intensity (Douglas, 2007).

- The HAZUS-Multi Hazard (HAZUS-MH) is a risk model developed by the National Institute of Building Sciences for the Federal Emergency Management Agency (FEMA) in 1997. It addresses four types of natural hazards (i.e. coastal storm surge, earthquakes, river flooding and windstorm damage) and estimates both direct and indirect economic losses (Kircher et al., 2006; Remo and Pinter, 2012). HAZUS-MH' earthquake component uses analytically derived damage curves (Spence et al., 2008). These curves are designed for US buildings, which complicates application to different parts of the world. The flood hazard component addresses riverine and coastal flooding (Scawthorn et al., 2006a; Nastev and Todorov, 2013) and uses more than 900 damage curves mostly derived from FEMA (Scawthorn et al., 2006a). The flood vulnerability component addresses susceptibility to damage, loss and injuries. The HAZUS model, encompassing the capacity spectrum method, has been applied to various locations globally in various software packages including an Australian calibrated methodology – EQRM (Robinson et al., 2005), SELENA (Norway, India and other locations) (Molina et al., 2010), HAZTaiwan (Loh etal., 2000). For a detailed review of Earthquake Loss Estimation software packages, we refer to Daniell (2011).
- The European Macroseismic Method (EMM) is based on the European Macroseismic Scale (EMS-98) and is used as an empirical (meaning: observation-based) and mechanical vulnerability assessment method for buildings (Grünthal, 1998; Giovinazzi and Lagomarsino, 2004 and 2005; Lagomarsino and Giovinazzi, 2006). EMS-98 vulnerability curves assume a probable damage distribution to forecast building damage for different building typologies and for a given intensity (Giovinazzi and Lagomarsino, 2004).
- Contrary to the EMM, the Earthquake Loss Estimation Routine (ELER) is based on analytically derived vulnerability functions, where analytical implies that the "expected performance of buildings [is] based on calculation and building characteristics" (Hancilar et al. 2010, p. 2679). ELER is used as an urban-level tool for earthquake losses and vulnerability assessment method for buildings and casualties as related to building damage (Hancilar et al., 2010). This requires highly detailed building stock inventory and demographic data, including construction year, material type, and number of floors. (Hancilar et al., 2010).
- The Prompt Assessment of Global Earthquakes for Response (PAGER) was developed by the U.S. Geology Survey (USGS) (Wald et al., 2008; Jaiswal et al., 2011). PAGER incorporates three different approaches for assessing vulnerability, i.e. empirical, semi-empirical and analytical. In predicting future vulnerability, the empirical approach uses historic country-level earthquake data and calibrates casualty rates to develop regression parameters (Jaiswal et al., 2011). In the semi-empirical and analytical models, the building inventories together with data on each structure's occupancy type, intensity-based vulnerability (building collapse rate) and the fatality rate are used to derive fatality functions (Jaiswal et al., 2011). In the analytical approach, the same

building inventories and the occupancy types as in the semi-empirical approach are used. However, vulnerability (collapse rates) are based on engineering considerations (such as the HAZUS capacity spectrum based approach) (Wald et al., 2008).

2.2.3 Comparing models: Scale and temporal factors

Apart from the indicators used in the different models, we will compare the different vulnerability models on two main factors: scale and temporal aspects. The importance of incorporating both temporal and spatial scales in vulnerability models has been addressed by many studies (e.g. Cutter et al., 2003; Barroca et al., 2006; Zevenbergen et al., 2008; Fekete et al., 2010; Jongman et al., 2015). We here briefly discuss both factors:

Scale

Dependent on data availability, models can be applied on building scale data (e.g. HAZUS-MH, insurance models). However, some index based vulnerability models use information at the country scale, since a lot of social vulnerability data for measuring those indicators are not available at local scales.

Temporal aspects

Understanding flood vulnerability over time is crucial in examining past, current and future fatalities and losses (Jongman et al., 2015), and can significantly improve a risk managers' ability to more efficiently implement mitigation measures (Birkmann, 2007; Schmidtlein et al., 2011). Therefore, the focus has shifted to assessing vulnerability over time (Jongman et al., 2015), but knowledge gaps continue to exist (Connor and Hiroki, 2005; McEntire, 2005; Birkmann, 2007; Cutter et al., 2008; Balica et al., 2012; Mechler and Bouwer, 2014; Jongman et al., 2015; Koks et al., 2015b). We will subsequently assess how flood and earthquake vulnerability assessments have implemented this 'time' factor.

3 Results and discussion

In this section, we show and discuss the results of the literature review. In Sect. 3.1, a comparison between physical and social vulnerability indicators is presented. Next, in Sect. 3.2, we compare earthquake and flood vulnerability models.

3.1 Physical versus Social Vulnerability Indicators

Tables 1 and 2 present an overview of the different physical and social vulnerability indicators. Each indicator is further sub-divided into the indicator classes provided in Sect. 2.1. Indicators have been briefly described with their unit and scale of the exposed elements they refer to (Ob: object; Agg: aggregated; Com: combination of both). We also show the geographical scale of the application of the indicators and their models (L: Local; R: Regional; N: National; G: Global). The numbers behind each indicator provide examples of papers using that particular indicator.

Physical Indicators

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Table 1 supports the claims as made in Sect. 2 that earthquake vulnerability assessments make use of highly detailed indicators at a building level, as they distinguish the number of stories, occupancy class, and building material. These are indicators also used for flood vulnerability assessments. However, earthquake vulnerability assessments also use indicators that are not, or to a much lesser extent, used in flood vulnerability studies, such as: building design and codes (e.g. Daniell (2015) provides a global review of country-level seismic-building codes from 1900 to 2013, while for floods Nikolowski (2014) provides an overview of different ranges of building age and their flood vulnerability); structural (load carrying) and non-structural (mechanical) components; roof types; and building maintenance factors (e.g. Douglas, 2007). For earthquakes, the strength of a building is often related to ground shaking of a given intensity (Birkmann and Wisner, 2006; Calvi et al., 2006). Detailed vulnerability indicators for buildings are described by Daniell et al. (2012a) and for infrastructure in Daniell (2014). Davidson and Shah (1997) argue that some of these indicators (e.g. maintenance, previous damage, and retrofitting) affect the physical earthquake vulnerability but that it is difficult to find data to measure them which is not analytically based. These indicators could be measured using cadastre or census data (where available) or by sampling the buildings of a neighbourhood or city (e.g. Steimen et al., 2004) which are very time-consuming processes. Steimen et al. (2004) assessed 10% of the building stock in the city of Basel (Switzerland). Rashed and Weeks (2003) include lifeline and infrastructure as well as building related indicators (i.e. transportation and utility lifelines, building square footage, inventories of building value, cost of building repair). Menoni and Pergalani (1996) include a building usage classification and account for the nearby existence of hazardous plants. Flood vulnerability assessments have also mainly focused on physical vulnerability. For flood, vulnerability of building- or land-use types are often related to flood hazard indicators such as flood depth or flood velocity to estimate potential losses (e.g. Roos, 2003; Barroca et al., 2006).

Infrastructure and lifelines indicators

An important difference between the physical factors used in earthquake and flood vulnerability assessments is the traditionally strong focus within earthquake vulnerability studies on indicators of *utility and essential facilities lifelines* (i.e. utility systems such as electricity, telecommunication, potable and waste water, and infrastructure) (Menoni et al., 2002; Menoni et al., 2007). Often used lifeline vulnerability indicators measure the length and accessibility of lifelines, such as a road (e.g. Penning-Rowsell et al., 2010; Peng, 2012). An extensive and highly detailed overview of lifeline indicators used in earthquake vulnerability assessments, and in fragility curves in particular, has been provided by Pitilakis et al. (2014), while Menoni et al. (2002) provide an overview of possible lifeline-indicators. Flood vulnerability assessments use similar lifeline indicators such as the physical aspects of road networks (e.g. Barroca et al., 2008). However, as shown in Table 1, they appear to be less commonly used in flood vulnerability assessments compared to earthquake vulnerability assessments. This is in line with earlier studies, which argued that flood vulnerability research traditionally focus on the vulnerability of the built environment (Miletti, 1999). Therefore, earthquake vulnerability assessment models are sometimes adopted in flood vulnerability models to address infrastructure risk (Merz et al., 2010). Some models, such as HAZUS-MH do include detailed lifeline attributes in both their Earthquake and Flood modules.

Building structural and occupancy indicators

The need for detailed earthquake loss estimations for the insurance and re-insurance industry has advanced the development of detailed object (i.e. building-) based vulnerability assessment models (Spence et al., 2008). An extensive overview of earthquake loss estimation models (ELE) and their respective definition of vulnerability classes has been provided by Daniell (2012a and 2014). As part of earthquake vulnerability assessments' emphasis on individual building characteristics, the building age is an important indicator. Generally, the influence of building age on earthquake vulnerability levels is twofold: (a) with aging comes deterioration of building materials; and (b) more recently built buildings have more often been subjected to improved building codes (Cochrane and Schaad, 1992; Bommer et al., 2002). However, building age does not appear to be an important vulnerability indicator used in flood vulnerability assessments. A reason could be that wall stability is only an issue at those locations where flood velocities are high, which is near the coastline and near rivers, or that the link simply has not been made yet with respect to empirical evidence.

An example of earthquake vulnerability's focus on buildings and the inclusion of more detailed building related indicators compared to those used in flood vulnerability assessments, is the very frequently used building type indicator (e.g. wood, steel, concrete, masonry or mobile homes). Building type is a crucial factor in determining a building's ability to resist ground shaking and is used in many models such as HAZUS-MH (Kircher et al., 1997 and 2006; Bommer et al., 2002; Nastev and Todorov, 2013). It should be noted that a specific building type can have opposing impacts on earthquake versus flood vulnerability. For example, wooden houses tend to be more vulnerable to flooding than stone houses, but for earthquakes generally the opposite holds (Doğangün et al., 2006; Messner and Meyer, 2006). For flooding, multi-story buildings are generally susceptible to a lower damage fraction than single-story buildings (Merz et al., 2010). Moreover, people can evacuate to higher floors in case of a flood, reducing the number of fatalities. For earthquakes, however, multiple floor buildings can have a higher vulnerability depending on the frequency content of the earthquake. Moreover, for earthquakes there are more complicating factors, for example *enforced seismic design codes* and the *type of energy-wave as a result of an earthquake* influence the correlation between building height and vulnerability (Rossetto and Elnashai, 2003).

Environmental indicators

As shown in Table 1, environmental indicators consist of two aspects: the proximity to contaminating sites (e.g. Menoni et al., 2002; Damm 2009) and the susceptibility and vulnerability of the environment captured in indicators such as *types of vegetation*, *soil erosion potential* and *soil quality* (e.g. Barroca et al., 2008; Balica et al., 2009; Damm 2009). The latter are only taken into account as part of flood vulnerability assessments.

3.1.1 Social Indicators

There appear to be fewer differences between the types of social vulnerability indicators used in flood and earthquake vulnerability assessments, compared to the differences found for physical vulnerability indicators. However, from the literature review it appears that social indicators are more often used in flood vulnerability

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studies than earthquake vulnerability studies. Examples of earthquake social vulnerability indicators are: population density (Menoni and Pergalani, 1996; Peng, 2012); household education level (Duzgun et al., 2011; Schmidtlein et al., 2011); shelter demand (e.g. measured using 'perception of population to leave their homes' indicator); health impact related vulnerability as part of SYNERG-G's socio-economic vulnerability component (Pitilakis et al., 2014); and household and population structure as used in GEM's socio-economic vulnerability index (Khazai et al., 2014). For flooding, similar indicators are used, such as population density (Balica et al., 2012), education level (Cutter et al., 2006) and GDP (Balica et al., 2009; Ferreira et al., 2011) but also indicators such as long-term sickness (Tapsall, 2002).

Demography

Flood and earthquake studies both use very similar demographic indicators, such as the identification of weaker groups in society based on age (e.g. those younger than 5 and older than 65 years) and other indicators such as wealth, ethnicity, family structure, and disabled people (Cutter et al., 2003; Schmidtlein et al., 2008; Fekete, 2009; Blaikie et al., 2014). The high importance of *age* as an indicator of social vulnerability is also supported by Rufat et al. (2015). A household's socio-demographic status plays a crucial role in their social vulnerability and their ability to prepare for future disasters. It is often measured using indicators such as education level and percentage of population living in poverty (Cutter et al., 2003; Koks et al., 2015b; Rufat et al. 2015). In a study of the Rijnmond region in the Netherlands, Koks et al. (2015b) simulate the spatial distribution of social vulnerability, using indicators such as ethnicity, age group (elderly) and fiscal income.

Within earthquake research, population-related indicators are used to establish the number of (vulnerable) people present in offices, residences or schools, which is often influenced by the time of the day. This particular focus of the influence on timing and building occupancy is common in earthquake vulnerability assessments (e.g. Lomnitz, 1970; Coburn and Spence., 1992; Ara, 2013). Whilst prominent in earthquake research, these aspects are not taken into account in flood vulnerability assessments. As shown in Table 2, within flood vulnerability assessments there are fewer social indicators used than for earthquake vulnerability assessments but with many studies using similar indicators, social indicator usage appears to be more perfected (e.g. Rufas et al., 2015). For earthquake vulnerability assessments, this appears to be less the case, and more different types of indicators are used.

Awareness

Furthermore, some flood vulnerability assessments use preparedness indicators, such as flood risk awareness, past experiences, and the effect of media exposure on peoples' risk perception (Rufat et al., 2015). Research has shown that previous experience with a disaster (e.g. property damage or loss and personal distress) has a strong correlation with how people prepare for a next disaster (Lindell and Perry, 1992). In a study of flood preparedness in Dresden, Kreibich and Thieken (2009) show that there is a strong correlation between flood risk awareness and improvements in flood levels of individual households. On the other hand, more recent studies with regards to earthquake awareness found a lower correlation between past earthquake experience and awareness, but noted a relationship between education and awareness and preparedness (Rüstemli and Karanci, 1999; Shaw et al., 2004). Also with regards to the impact of social development and welfare levels on vulnerability, flood assessments more often than earthquake vulnerability assessments use comprehensive indicators such as: education level and literacy rate; technological development (e.g. ownership of tv, radio, phone, etc.); and other means of connectivity (e.g. Akukwe and Ogbodo, 2015). Another difference is the usage of a warning-time indicator. Although there is still debate about the inclusion of such an indicator (e.g. Merz et al., 2010), flood vulnerability assessments occasionally include a warning-time indicator (e.g. Penning-Rowsell et al., 2010; Scawthorn et al., 2006b). For flooding, it has been shown that when the warning time is increased by more than two hours, damage can be reduced by more than 10% (Penning-Rowsell et al., 2010; Messner and Meyer, 2006). However, warning-time does not appear to be an indicator used with regard to earthquakes, where the warning time can be a matter of a few seconds (Nakamura and Saita, 2007).

Economic Indicators

Within the sub-category of economic indicators, flood and earthquake vulnerability assessments both use similar income-related indicators such as GDP. Earthquake vulnerability assessments also tend to take sector dependency of a community into account, generally measured through the percentage of people employed in one sector. It has been shown that single-sector dependency increases a community's vulnerability (Cutter, 2003). From Table 2 it also appears that floor vulnerability assessments tend to make more indicators of welfare and social security levels into account than earthquake vulnerability assessments. For economic indicators, it holds again that they are mostly used in index based vulnerability assessments rather than in curve based vulnerability assessments.

Institutional and Political Indicators

From Table 2 it appears that it is more common for flood vulnerability assessments to include indicators related to zoning and land-use planning. For earthquakes, only GEM appears to make use of governance-related indicators such as *political stability* (GEM, 2016).

3.2 Vulnerability models

3.2.1 Curves versus Index based vulnerability assessments

Our study supports the claims that for both earthquake and flood vulnerability models, a large suite of well-developed vulnerability damage curves exists (Douglas, 2007). For assessing social vulnerability, aggregated data as well as index based vulnerability assessments appear to be much more commonly used for both floods and earthquakes than is the case for physical vulnerability. For both floods and earthquakes, these index based vulnerability assessments tend to incorporate demographic indicators much more frequently than assessments based on vulnerability curves. Examples of indicators used in index based vulnerability assessments are to find relationships between: *inventories of building square footage* and *inventories of building value* and *reported earthquake losses as a percentage of modeled exposed GDP* (Rashed and Weeks, 2003). Or in flood modeling:

reported fatalities as a percentage of modeled exposed population (Jongman et al., 2015). Rufat et al. (2015) argue that in recent years indices have become the main tool used to assess social vulnerability to flooding.

Developing meaningful vulnerability indices is difficult, and complex interrelations between vulnerability and hazard or damage are often represented in simple indices (Cutter et al., 2003; Birkmann, 2007; Chang et al., 2015). On a positive side, empirical data on losses, required to relate vulnerability indices to those losses, have been improved over the last 10 years. However, more data is needed and loss data on (extreme-) hazard events are scarce. New global databases of empirical natural disaster loss data include CATDAT (Daniell, 2009), the International Disaster Database (EM-DAT), and UNISDR's Disaster Information Management System (DESinventar). These databases provide useful quantitative input to risk- and vulnerability assessment studies such as PAGER and GEM (Jaiswal et al., 2011; Dell'Acqua et al., 2013; Silva et al., 2014a and 2014b).

For physical vulnerability, earthquake vulnerability assessments show a much more important concentration on buildings and object-level vulnerability curves. Table 1 shows that, for earthquake vulnerability assessments, indicators for utility lifeline vulnerability appear to be commonly employed as part of index based vulnerability assessments. Only few studies on flood vulnerability have similarly addressed utility lifeline indicators. For example, Barroca et al. (2006) incorporate flood lifeline indicators such as: physical aspects of utility lifelines including *energy networks*, *physical aspects of urban lighting*, *heating*, and *water supply networks*. A few main differences relating to scales exist:

3.2.2 Spatial aspects

An important aspect of vulnerability assessments is their spatial scale (Cutter et al., 1996). For different hazards, Birkmann (2007) reviewed indicator usage across three global risk models and a local approach. It appears from this study that downscaling vulnerability indices is very difficult due to data scarcity. Due to this challenge, flood vulnerability assessments generally have a high level of spatial aggregation, often using land-use data to represent exposure. This is also recognised in the literature (e.g. Comfort et al., 1999; Barroca et al., 2006, Zevenbergen et al., 2008), where it has been acknowledged that future flood vulnerability studies should receive more attention and be more available to stakeholders at a local or city level. Some flood assessment tools, however, such as the Flood Vulnerability Analysis Tool (FVAT) (Barroca et al., 2006 and 2008), provide indicators that are available at a local level. Balica et al. (2009) developed their Flood Vulnerability Index (FVI), which is applicable at different spatial scales such as river basin, sub-catchment and urban areas.

Indicators used in vulnerability curve methods for earthquakes seem to have more detail (e.g. *building maintenance level*, *roof type* and *height*) as compared to the flood models. For both vulnerability curve based as well as index based vulnerability assessments, earthquake vulnerability assessments have a very strong focus on individual buildings, their construction and structural characteristics, as well as their ability to resist seismic tension as a primary cause of damage and casualties. HAZUS-MH and the Multi-Coloured Manual by Penning-Rowsell et al.

(2010) are among the few flood vulnerability models that are curve based and developed at an object level (Jongman et al., 2012). On the other hand, the general approach in earthquake modeling is to categorize the general building stock into small groups whose characteristics (e.g. strength, weight, construction material, height, construction quality, and age) create similar seismic responses (Ventura et al., 2005). Building classification systems are used to group buildings based on these characteristics. Next, damage functions are created based on the estimated damage due to ground motion for each building class (Ventura et al., 2005).

Some of the indicators used in earthquake studies are also used in flood studies (e.g. number of stories, building height and age). However, in flood vulnerability assessments there is generally less detail as they often operate at an aggregated land-use class level. As a result, flood vulnerability curves are often designed at an aggregated land-use class level whereas earthquake fragility curves mainly exist for objects (often buildings).

The indirect economic impacts of a local flood on the regional and national economy can be substantial, which underscores the necessity of understanding indirect flood vulnerability (Zevenbergen et al., 2008; Balica et al., 2009). This indirect factor is currently being modeled in for example HAZUS-MH in a rather simplistic way, namely as a fraction of the direct losses. However, new flood research using economic methods shows indirect losses can be substantial and widespread (Koks et al., 2015a).

In terms of upscaling social vulnerability indicators, Fekete et al. (2010) recognize the importance and lack of flood vulnerability studies that account for cross-scale interactions. Some demographic indicators collected at a household or individual level can easily be scaled up. However, social indicators such as *power structures* cannot, because they are not “significantly linked to the structure of a household or person” (Fekete et al., 2010). Koks et al. (2015b) focus on social vulnerability and found that in future flood risk scenarios there is a clear spatial clustering of socially vulnerable groups measured through social-vulnerability indicators such as: age, fiscal income, and ethnicity. Other studies have used spatial analysis techniques to identify clusters of vulnerability (Rashed and Weeks, 2003; Rashed et al., 2007).

In flood assessment studies, it is more common to use aggregated exposure data, such as land-use data from satellite observations as a basis for estimating vulnerability at the river basin, country of continental scales (Jongman et al., 2012; de Moel et al., 2015). Land-use data often replaces building scale data, because: (a) building data are not available at larger scales; and (b) computational efforts are too challenging using detailed exposure data at these scales. Examples of such land-use based flood damage modes are: the DamageScanner (e.g. Klijn et al., 2007), FLEMO (e.g. Apel et al., 2009), and the JRC Model (Huizinga, 2007). We refer to Jongman et al. (2012) for a comparison among different flood damage model assessments.

3.2.3 Temporal Aspects

An interesting aspect of earthquake and flood vulnerability assessments is the extent to which they consider temporal scales in vulnerability, for example through the implementation of building codes or other mitigation policies, land-use change, demographic changes such as population growth, and social- and economic changes (e.g. Zevenbergen et al., 2008).

Chang et al. (2012) studied temporal changes in the seismic risk of Vancouver (Canada). Using a M7.3 earthquake scenario, this study concludes that despite increasing exposure (the population of Vancouver doubled over the course of the 35-year study period from 1971 to 2006), the estimated 2006 casualties remained equal to the estimated number of casualties in 1971. They conclude that the decrease in the per capita casualty ratio is mainly due to improvements in improving building codes and construction changes. Daniell (2015) provides a global overview of seismic-building codes implemented from 1900 until 2013, which shows that the number of countries with a seismic code or zonation has increased (although it should be noted that currently less than 50% of the building stock is covered by a building code). There are several challenges in incorporating temporal scales in earthquake vulnerability assessments. Earthquake vulnerability research mainly focuses on predicting the ability of the (current) building stock to withstand ground shaking. It has been shown that the selection of a building inventory very strongly influences earthquake vulnerability. Faccioli et al. (1999) explain that there are some significant difficulties involved in creating a reliable building inventory for earthquake scenario studies. Steimen et al. (2004) therefore underscore the necessity of uncertainty analysis in earthquake scenarios and building vulnerability estimates. A country-level method for the development of an earthquake risk exposure model for buildings is introduces by Gunasekera et al. (2015).

Another problem in using earthquake scenarios to address temporal changes in vulnerability is the lack of confidence in estimating the location and strength of an earthquake (Faccioli et al., 1999). Menoni et al. (2002) developed a tool to study earthquake event scenarios for lifelines to estimate both the physical and organizational failures originating from lifeline systems. Summarizing, it appears that temporal changes regarding earthquake risk mainly focus on temporal changes in exposure rather than vulnerability. Duzgun et al. (2011) developed an earthquake vulnerability assessment framework for urban areas, which “enables decision-makers to monitor temporal and spatial changes in the urban environment due to implementation of risk reduction strategies”.

There are several papers that include the impacts of non-hazard specific temporally changing factors on flood vulnerability such as population growth (e.g. Hall et al., 2005; Ferreira et al., 2011; Rojas et al., 2013). Hall et al. (2005) look at changing flood risk in England and Wales using a scenario-based approach for 45 and 75 years into the future with changing climate and socio-economic conditions and conclude that economic vulnerability (e.g. increasing infrastructure vulnerability) combined with climate change effects will increase by 2080 causing an increase in flood risk. Hall et al. (2005) use the social flood vulnerability indices as introduced by Tapsell et al. (2002), which constitute an aggregated measure of population vulnerability. Rojas et al. (2013) also acknowledge the lack of studies that have considered the quantification of adaptation measures. In a comparative study, Rojas et al. (2013) look at a *no-adaptation* versus an *adaptation* scenario of future flood risk mitigation (accounting for socio-economic developments and changing population density). Ferreira et al. (2011) focus too on social- and economic indicators (e.g. GDP, GINI coefficient, domestic credit to the private sector, expressed as a percentage of GDP, indicators for corruption, bureaucratic quality, law and order, democratic accountability, government stability, ethnic tensions, and religious tensions) in their study of flood adaptation.

Although vulnerability is usually assumed to be constant, often due to difficulties in accounting for changing vulnerability, several studies have shown the impact of vulnerability reducing measures on risk reduction (Mechler and Bouwer, 2014; Jongman et al., 2015). In a case study of the Meuse, Poussin et al. (2012) use the Damagescanner to show that annual flood risk may increase with 185% over the period 2000 to 2030 due to both land-use and climate changes. However, the study shows that implementing adaptation strategies such as spatial zoning and other vulnerability mitigating measures, including dry- and wet-proofing of buildings, do decrease future risk levels with the relative risk reduction ranging from 10% to 40% depending on the specific measure (Kreibich et al., 2015; Kreibich and Thieken, 2009; Poussin et al., 2012). In a study of the impacts of land-use and climate changes on flood risk of unembanked areas of Rotterdam, De Moel et al. (2014) also find that building-level mitigation measures (e.g. elevating buildings) reduce future flood risk.

4 Conclusions and Recommendations

This cross-discipline study allowed us to obtain lessons from earthquake and flood vulnerability assessments that could be used for advancing risk assessments in both fields. In general, it appears that indicators used in earthquake and flood vulnerability assessment have substantial differences.

- Flood vulnerability assessments have generally used a higher scale of geographical aggregation compared to earthquake vulnerability assessments. The literature suggests that flood vulnerability research could benefit from developing assessments at the more local and object scale.
- This difference between object- versus aggregate scale vulnerability assessments strongly relates to the focus of earthquake vulnerability assessments on physical vulnerability. Despite the differences in application, the physical (i.e. building) aspects of flood vulnerability assessments could be improved by incorporating earthquake vulnerability assessment methods and indicators, specifically for an object (building) based approach. For example, the development of building material based approaches for flood vulnerability assessments lacks behind that of earthquakes. Combined with an object-based approach this could enable the development of building material based depth-damage curves at an object-level.
- Another poignant difference appears to be that flood vulnerability assessments more often take into account indicators related to risk awareness and precautionary measures at a governmental as well as individual level, compared to earthquake vulnerability assessments. This is something where earthquake vulnerability assessments could learn from flood vulnerability assessments.

- Flood vulnerability assessments tend to use more precise indicators of social and economic vulnerability than earthquake vulnerability assessments, and flood vulnerability assessments more often include indicators related to welfare and social security levels. However, earthquake studies do tend to incorporate aspects of local economic-sector dependent vulnerability more often than is the case for floods.
- Another difference is the use of a timing indicator used in earthquake modeling, which shows where people are located throughout the day. Timing and an estimate of where people are during the day could be a useful factor for improving flood risk assessments. At the same time, earthquake modelling could benefit from modelling evacuation patterns as done in flood assessments.
- It appears that flood assessment models examine the impacts of changing exposure over time on vulnerability much more often than earthquake assessments, for example due to the implementation of adaptation measures. One way of improving this aspect of earthquake vulnerability assessments, would be to better incorporate indirect economic loss assessments from natural disasters such as recently published for flood risk. This would benefit and enable more analytical (rather than judgment based) future mitigation and adaptation studies.

One of the issues encountered was that not all studies mention specifically which indicators they use for their vulnerability assessment. Some studies mention the categories or theoretical indicators they look at but do not list the 'measurable indicators' used explicitly. Furthermore, studies that take into account vulnerability in their risk or loss assessment but do not explicitly model the vulnerability component itself, have been excluded from this study, and we have only assessed a selection of the wealth of models that is available.

In general, we advocate cross-disciplinary learning between the earthquake and flood risk modelling communities. An ideal flood vulnerability method encompasses a balanced mix of the two different components: physical and socioeconomic related indicators and attempts to move towards an object scale approach. Furthermore, it is very important to increase understanding of the interaction between flood and earthquake vulnerability and how these can be assessed simultaneously in a risk assessment. Some factors can have positive effects on reducing vulnerability of, for example, floods while simultaneously having negative impacts on earthquake vulnerability. For example, building houses on stilts can be very beneficial in decreasing flood vulnerability while increasing earthquake vulnerability. This calls for more collaboration between the two research communities. Further comparative research is therefore recommended, involving more models and methods.

Competing interests

The authors declare that they have no conflict of interest.

References

Adger, W. N. (1999). Social vulnerability to climate change and extremes in coastal Vietnam. *World development*, *27*(2), 249-269.

Adger, W. N. (2006). Vulnerability. *Global environmental change*, *16*(3), 268-281.

Alesch, D. J., Dargush, G. F., Grigoriu, M., Petak, W. J., & von Winterfeldt, D. (2003). Decision models: approaches for achieving seismic resilience. *Research progress and accomplishments 2001–2003*, 97-114.

Apel, H., Thieken, A. H., Merz, B., & Blöschl, G. (2004). Flood risk assessment and associated uncertainty. Natural Hazards and Earth System Science, 4(2), 295-308.

Apel, H., Merz, B., & Thieken, A. H. (2008). Quantification of uncertainties in flood risk assessments. *International Journal of River Basin Management*, *6*(2), 149-162.

Apel, H., Aronica, G. T., Kreibich, H., & Thieken, A. H. (2009). Flood risk analyses—how detailed do we need to be?. *Natural Hazards*, *49*(1), 79-98.

Ara, S. H. A. R. M. I. N. (2013). Analyzing population distribution and its effect on earthquake loss estimation in Sylhet, Bangladesh. Applied Earth Science Faculty of Geoinformation Science and Earth Observation, University of Twente, Enschede, the Netherlands.

Balica, S. F., Douben, N., & Wright, N. G. (2009). Flood vulnerability indices at varying spatial scales. Water science and technology, 60(10), 2571.

Balica, S., & Wright, N. G. (2010). Reducing the complexity of the flood vulnerability index. Environmental Hazards, 9(4), 321-339.

Balica, S. F., Wright, N. G., & van der Meulen, F. (2012). A flood vulnerability index for coastal cities and its use in assessing climate change impacts. Natural Hazards, 64(1), 73-105.

Bankoff, G., Frerks, G., & Hilhorst, D. (2004). *Mapping vulnerability: disasters, development, and people*. Routledge.

Barroca, B., Bernardara, P., Mouchel, J. M., & Hubert, G. (2006). Indicators for identification of urban flooding vulnerability. Natural hazards and earth system science, 6(4), 553-561.

Barroca, B., Mouchel, J. M., Bonierbale, T., & Hubert, G. (2008). Flood Vulnerability Assessment Tool (FVAT). *Daywater: An Adaptive Decision Support System for Urban Stormwater Management*, 123.

Bilham, R. (2004). Urban earthquake fatalities: a safer world, or worse to come?. *Seismological Research Letters*, *75*(6), 706-712.

Birkmann, J., & Wisner, B. (2006). Measuring the unmeasurable: the challenge of vulnerability. UNU-EHS.

Birkmann, J. (2007). Risk and vulnerability indicators at different scales: applicability, usefulness and policy implications. *Environmental Hazards*, *7*(1), 20-31.

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

Blaikie, P., Cannon, T., Davis, I., & Wisner, B. (2014). *At risk: natural hazards, people's vulnerability and disasters*. Routledge.

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Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 31 January 2017

Bommer, J., Spence, R., Erdik, M., Tabuchi, S., Aydinoglu, N., Booth, E., ... & Peterken, O. (2002). Development of an earthquake loss model for Turkish catastrophe insurance. *Journal of Seismology*, *6*(3), 431-446.

Botzen, W. J., & Van Den Bergh, J. C. (2012). Monetary valuation of insurance against flood risk under climate change. *International Economic Review*, *53*(3), 1005-1026.

Bouwer, L. M., Crompton, R. P., Faust, E., Höppe, P., & Pielke Jr, R. A. (2007). Confronting disaster losses. Science-New York then Washington-, 318(5851), 753.

Bouwer, L. M. (2011). Have disaster losses increased due to anthropogenic climate change?. Bulletin of the American Meteorological Society, 92(1), 39-46.

Brzev, S., Scawthorn, C., Charleson, A. W., Allen, L., Greene, M., Jaiswal, K., & Silva, V. (2013). *GEM Building Taxonomy (Version 2.0)* (No. 2013-02). GEM Foundation.

Brink, S. A., & Davidson, R. A. (2015). Framework for Comprehensive Assessment of a City's Natural Disaster Risk. Earthquake Spectra, 31(4), 1931-1947.

Bubeck, P., Botzen, W. J., & Aerts, J. C. (2012). A review of risk perceptions and other factors that influence flood mitigation behavior. *Risk Analysis*, *32*(9), 1481-1495.

Burton, C. G., & Silva, V. (2014). Integrated risk modelling within the Global Earthquake Model (GEM): test case application for Portugal. In *Proceedings of the second European conference on earthquake engineering and seismology, Istanbul, Turkey*.

Calvi, G. M., Pinho, R., Magenes, G., Bommer, J. J., Restrepo-Vélez, L. F., & Crowley, H. (2006). Development of seismic vulnerability assessment methodologies over the past 30 years. ISET journal of Earthquake Technology, 43(3), 75-104.

Carreño, M. L., Cardona, O. D., & Barbat, A. H. (2007). Urban seismic risk evaluation: a holistic approach. Natural Hazards, 40(1), 137-172.

Carreño, M. L., Cardona, O. D., & Barbat, A. H. (2012). New methodology for urban seismic risk assessment from a holistic perspective. Bulletin of earthquake engineering, 10(2), 547-565.

Chang, S. E., Gregorian, M., Pathman, K., Yumagulova, L., & Tse, W. (2012). Urban growth and long-term changes in natural hazard risk.*Environment and Planning A*, *44*(4), 989-1008.

Chang, S. E., Yip, J. Z., de Jong, S. L. V. Z., Chaster, R., & Lowcock, A. (2015). Using vulnerability indicators to develop resilience networks: a similarity approach. *Natural Hazards*, *78*(3), 1827-1841.

Coburn, A. W., Spence, R. J. S., and Pomonis, A.: Vulnerability and risk assessment, Disaster Management Training Programme, UNDP, 2nd edition edn., 1994.

Coburn A, Spence R (2002) Earthquake protection, 2nd edn. Wiley, Chichester, England.

Cochrane, S. W., & Schaad, W. H. (1992, July). Assessment of earthquake vulnerability of buildings. In *Tenth World Conference on Earthquake Engineering* (Vol. 1, pp. 497-502).

Colombi, M., Borzi, B., Crowley, H., Onida, M., Meroni, F., & Pinho, R. (2008). Deriving vulnerability curves using Italian earthquake damage data. Bulletin of Earthquake Engineering, 6(3), 485-504.

Comfort, L., B. Wisner, S. Cutter, R. Pulwarty, K. Hewitt, A. Oliver-Smith, J. Wiener, M. Fordham, W. Peacock, and F. Krimgold. 1999. "Reframing Disaster Policy: The Global Evolution of Vulnerable Communities. *Environmental Hazards* **1** (1): 39–44.

Connor, R., & Hiroki, K. (2005). Development of a method for assessing flood vulnerability. Water Science & Technology, 51(5), 61-67.

Crichton, D. (1999). The risk triangle. Natural disaster management, 102-103.

Cutter, S. L., Holm, D., & Clark, L. (1996). The role of geographic scale in monitoring environmental justice. *Risk Analysis*, *16*(4), 517-526.

Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social vulnerability to environmental hazards. Social science quarterly, 84(2), 242-261.

Cutter, S. L., & Emrich, C. (2005). Are natural hazards and disaster losses in the US increasing?. EOS, Transactions American Geophysical Union, 86(41), 381-389.

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. Global environmental change, 18(4), 598-606.

Damm, M., 2009. "Mapping Social-Ecological Vulnerability to Flooding-a sub-national approach for Germany." PhD diss., Universitäts-und Landesbibliothek Bonn, 2009.

Daniell, J. E. (2009). Open source Procedure for Assessment of Loss using Global Earthquake Modelling–OPAL-GEM Project. CEDIM Research Report 09-01, Karlsruhe, Germany.

Daniell, J. E., Daniell, K. A., Daniell, T. M., & Khazai, B. (2010). A country level physical and community risk index in the Asia-Pacific region for earthquakes and floods. In 5th Civil Engineering Conference in the Asian Region and Australasian Structural Engineering Conference 2010, The (p. 610). Engineers Australia.

Daniell, J. E., Khazai, B., Wenzel, F., & Vervaeck, A. (2011). The CATDAT damaging earthquakes database. Natural Hazards and Earth System Science, 11(8), 2235-2251.

Daniell, J. E. (2011). Open source procedure for assessment of loss using global earthquake modelling software (OPAL). Natural Hazards and Earth System Sciences, 11(7), 1885-1899.

Daniell, J. E., & Vervaeck, A. (2012a). CEDIM earthquake loss estimation series research report 2012-01. Karlsruhe: CEDIM.

Daniell, J. E., Wenzel, F., & Khazai, B. (2012b). The Normalisation of socio-economic losses from historic worldwide earthquakes from 1900 to 2012. In 15th World Congress on Earthquake Engineering, Lisbon.

Daniell, J. E., 2014. Development of socio-economic fragility functions for use in worldwide rapid earthquake loss estimation procedures. PhD Thesis, Karlsruhe University.

Daniell, J. E. (2015). Global View of Seismic Code and Building Practice Factors. In Encyclopedia of Earthquake Engineering (pp. 1109-1119). Springer Berlin Heidelberg.

Davidson, R. A., & Shah, H. C. (1997). An urban earthquake disaster risk index. Standford University: John A. Blume Earthquake Engineering Center.

De León, V., & Carlos, J. (2006). Vulnerability: a conceptional and methodological review. UNU-EHS.

Deressa, T. T., Hassan, R. M., Ringler, C., Alemu, T., & Yesuf, M. (2008). Analysis of the determinants of farmers' choice of adaptation methods and perceptions of climate change in the Nile Basin of Ethiopia [in Amharic] (No. 15 (9) AMH). International Food Policy Research Institute (IFPRI).

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.

Dewan, A. M. (2013). Floods in a megacity: geospatial techniques in assessing hazards, risk and vulnerability. Dordrecht: Springer.

Doğangün, A., Tuluk, Ö. İ., Livaoğlu, R., & Acar, R. (2006). Traditional wooden buildings and their damages during earthquakes in Turkey. *Engineering Failure Analysis*, *13*(6), 981-996.

Doocy, S., Cherewick, M., & Kirsch, T. (2013a). Mortality following the Haitian earthquake of 2010: a stratified cluster survey. Population health metrics, 11(5).

Doocy, S., Daniels, A., Packer, C., Dick, A., & Kirsch, T. D. (2013b). The human impact of earthquakes: a historical review of events 1980-2009 and systematic literature review. PLoS currents, 5.

Douglas, J. (2007). Physical vulnerability modelling in natural hazard risk assessment. *Natural Hazards and Earth System Science*, *7*(2), 283-288.

EEA: CORINE land cover 2006 (CLC2006) 100 m, [112/2009], Copenhagen, Denmark, European Environment Agency, 2009.

Egorova, R., van Noortwijk, J. M., & Holterman, S. R. (2008). Uncertainty in flood damage estimation. *International Journal of River Basin Management*, *6*(2), 139-148.

Faccioli, E., Pessina, V., Calvi, G. M., & Borzi, B. (1999). A study on damage scenarios for residential buildings in Catania city. *Journal of seismology*, *3*(3), 327-343.

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.

Fekete, A., Damm, M., & Birkmann, J. (2010). Scales as a challenge for vulnerability assessment. *Natural Hazards*, *55*(3), 729-747.

FEMA (2013a). Multi-Hazard Loss Estimation Methodology: Earthquake Model Technical Manual. *Department of Homeland Security, FEMA, Washington, DC*.

FEMA (2013b). Multi-Hazard Loss Estimation Methodology: Flood Model Technical Manual. *Department of Homeland Security, FEMA, Washington, DC*.

Ferreira, S., Hamilton, K., & Vincent, J. R. (2011). Nature, socioeconomics and adaptation to natural disasters: new evidence from floods. World Bank Policy Research Working Paper Series, Vol.

GEM. https://www.globalquakemodel.org. (last access: October 25, 2016).

GFDRR (2016). The making of a riskier future: How our decisions are shaping future disaster risk. *Global Facility for Disaster Reduction and Recovery*, *The World Bank, Washington, DC*.

Giovinazzi, S., and Lagomarsino, S. (2004, August). A macroseismic method for the vulnerability assessment of buildings. In 13th world conference on earthquake engineering, Vancouver, BC, Canada (pp. 1-6).

Giovinazzi, S., & Lagomarsino, S. (2005). Fuzzy-random approach for a seismic vulnerability model. Proc. of ICOSSAR 2005.

GNDT. 1986. Instruzioni per la Compilazione della Scheda di relivamento Esposizione e Vulnerabilita´ Sismica Degli Edifici [Instructions for completing the survey form to display the seismic vulnerability of buildings]. Gruppo Nazionale per la Difesa dai Terremoti, Regione Emilia Romana, Italie, 1986.

Grünthal, G. (1998). European Macroseismic Scale 1998 (EMS-98). European Seismological Commission, Subcommission on Engineering Seismology, Working Group Macroseismic Scales. Conseil de l'Europe. Cahiers du Centre Européen de Géodynamique et de Séismologie, 15.

Gunasekera, R., Ishizawa, O., Aubrecht, C., Blankespoor, B., Murray, S., Pomonis, A., & Daniell, J. (2015). Developing an adaptive global exposure model to support the generation of country disaster risk profiles. Earth-Science Reviews, 150, 594-608.

Hahn, H. (2003). Indicators and other instruments for local risk management for communities and local governments. Document prepared as part of the documents related to the project: local risk management for communities and local governments. The German Technical Cooperation Agency, GTZ, for IADB.

Hall, J. W., Sayers, P. B., & Dawson, R. J. (2005). National-scale assessment of current and future flood risk in England and Wales. *Natural Hazards*, *36*(1-2), 147-164.

Hancilar, U., Tuzun, C., Yenidogan, C., & Erdik, M. (2010). ELER software- a new tool for urban earthquake loss assessment. Natural Hazards and Earth System Sciences, 10(12), 2677-2696.

Hiete, M., & Merz, M. (2009, May). An indicator framework to assess the vulnerability of industrial sectors against indirect disaster losses. In *International ISCRAM Conference, Gothenburg (Sweden)*.

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

Hoozemans, F. M. J., Marchand, M., & Pennekamp, H. A. (1993). A global vulnerability analysis: vulnerability assessment for population, coastal wetlands and rice production on a global scale.

Huizinga, H. J. (2007). Flood damage functions for EU member states. *HKV Lijn in water, Lelystad, the Netherlands*.

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 (Cambridge: Cambridge University Press).

ISDR, UN. (2005, March). Hyogo framework for action 2005-2015: building the resilience of nations and communities to disasters. In *Extract from the final report of the World Conference on Disaster Reduction (A/CONF. 206/6)*.

Jaiswal, K. S., & Wald, D. J. (2008). Developing a global building inventory for earthquake loss assessment and risk management. In *Proc. 14th World Conf. Earthq. Eng., Beijing, China* (Vol. 8).

Jaiswal, K. S., & Wald, D. J. (2010). An empirical model for global earthquake fatality estimation. Earthquake Spectra, 26(4), 1017-1037.

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2017-45, 2017
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 31 January 2017

Jaiswal, K. S., Wald, D. J., Earle, P. S., Porter, K. A., & Hearne, M. (2011). Earthquake casualty models within the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) system. In Human Casualties in Earthquakes (pp. 83-94). Springer Netherlands.

Jongman, B., Kreibich, H., Apel, H., Barredo, J. I., Bates, P. D., Feyen, L., ... & Ward, P. J. (2012). Comparative flood damage model assessment: towards a European approach. *Natural Hazards and Earth System Science*, *12*(12), 3733-3752.

Jongman, B., Winsemius, H. C., Aerts, J. C., de Perez, E. C., van Aalst, M. K., Kron, W., & Ward, P. J. (2015). Declining vulnerability to river floods and the global benefits of adaptation. Proceedings of the National Academy of Sciences, 112(18), E2271-E2280.

Jonkman, S. N., Van Gelder, P. H. A. J. M., & Vrijling, J. K. (2002). Loss of life models for sea and river floods. *Flood defence*, *1*, 196-206.

Jonkman, S. N., Brinkhuis-Jak, M., & Kok, M. (2004). Cost benefit analysis and flood damage mitigation in the Netherlands. *Heron*, *49*.

Jonkman, S. N., & Vrijling, J. K. (2008). Loss of life due to floods. *Journal of flood risk management*, *1*(1), 43-56.

Kannami, Y. (2008). Establishment of a country-based flood risk index, MSc thesis, National Graduate Institute for Policy Studies.

Kappos, A., Pitilakis, K., Stylianidis, K., Morfidis, K., & Asimakopoulos, D. (1995, October). Cost-benefit analysis for the seismic rehabilitation of buildings in Thessaloniki, based on a hybrid method of vulnerability assessment. In *Proceedings of the 5th international conference on seismic zonation, Nice* (Vol. 1, pp. 406-413).

Kappos, A. J., & Dimitrakopoulos, E. G. (2008). Feasibility of pre-earthquake strengthening of buildings based on cost-benefit and life-cycle cost analysis, with the aid of fragility curves. *Natural Hazards*, *45*(1), 33-54.

Keefer, P., Neumayer, E., & Plumper, T. (2010). Earthquake propensity and the politics of mortality prevention. *World Bank Policy Research Working Paper Series, Vol*.

Khazai, B., Merz, M., Schulz, C., & Borst, D. (2013). An integrated indicator framework for spatial assessment of industrial and social vulnerability to indirect disaster losses. *Natural hazards*, *67*(2), 145-167.

Khazai, B., Burton, C. G., Tormene, P., Power, C., Bernasoocchi, M., Daniell, J. E., ... & Henshaw, P. (2014, August). Integrated risk modelling toolkit and database for earthquake risk assessment. In Proceedings of the second European conference on earthquake engineering and seismology, Istanbul, Turkey.

Kienberger, S., Lang, S., & Zeil, P. (2009b). Spatial vulnerability units-Expert-based spatial modelling of socio-economic vulnerability in the Salzach catchment, Austria. Natural Hazards and Earth System Sciences, 9(3), 767.

Kircher, C.A., Nassar, A.A., Kustu, O. and Holmes, W.T. (1997) Development of building damage functions for earthquake loss estimation. *Earthquake Spectra* 13(4), 663–682.

Kircher, C. A., Whitman, R. V., & Holmes, W. T. (2006). HAZUS earthquake loss estimation methods. Natural Hazards Review, 7(2), 45-59.

Klijn, F., Baan, P.J.A., De Bruijn, K.M., Kwadijk, J., 2007. Overstromingsrisico's in Nederland in een veranderend klimaat, WL | delft hydraulics, Delft, Netherlands, Q4290.

Koks, E. E., Bočkarjova, M., Moel, H., & Aerts, J. C. J. H. (2015a). Integrated direct and indirect flood risk modeling: development and sensitivity analysis. *Risk analysis*, *35*(5), 882-900.

Koks, E. E., Jongman, B., Husby, T. G., & Botzen, W. J. W. (2015b). Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. Environmental Science & Policy, 47, 42-52.

Kreibich, H., Thieken, A. H., Petrow, T., Müller, M., & Merz, B. (2005). Flood loss reduction of private households due to building precautionary measures--lessons learned from the Elbe flood in August 2002. *Natural Hazards and Earth System Science*, *5*(1), 117-126.

Kreibich, H., and Thieken, A. H. (2009). Coping with floods in the city of Dresden, Germany. Natural Hazards, 51(3), 423-436.

Kron, W. (2005). Flood risk= hazard• values• vulnerability. Water International, 30(1), 58-68.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., ... & Muir-Wood, R. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, *59*(1), 1-28.

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

Lindell, M. K., & Perry, R. W. (1992). *Behavioral foundations of community emergency planning*. Hemisphere Publishing Corp.

Loh, C. H., Lawson, R. S., & Dong, W. M. (2000). Development of a national earthquake risk assessment model for Taiwan. In The 12th world conference on earthquake engineering, paper (No. 0380).

Lomnitz, C. (1970). Casualties and behavior of populations during earthquakes. Bulletin of the Seismological Society of America, 60(4), 1309-1313.

MCEER, 2003. *Research Progress and Accomplishments: 2001 – 2003*. Red Jacket Quadrangle, Buffalo, New York.

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

Mechler, R., & Bouwer, L. M. (2014). Understanding trends and projections of disaster losses and climate change: is vulnerability the missing link?. Climatic Change, 1-13.

Menoni, S., Pergalani, F., Boni, M. P., & Petrini, V. (2002). Lifelines earthquake vulnerability assessment: a systemic approach. *Soil Dynamics and Earthquake Engineering*, *22*(9), 1199–1208.

Menoni, S., Pergalani, F., Boni, M. P., & Petrini, V. (2007). Lifeline earthquake vulnerability assessment. In *Managing Critical Infrastructure Risks* (pp. 111-132). Springer Netherlands.

Mercer, J. (2010). Disaster risk reduction or climate change adaptation: are we reinventing the wheel?. Journal of International Development, 22(2), 247-264.

Merz, B., Kreibich, H., Thieken, A., & Schmidtke, R. (2004). Estimation uncertainty of direct monetary flood damage to buildings. *Natural Hazards and Earth System Science*, *4*(1), 153-163.

Merz, B., Kreibich, H., Schwarze, R., & Thieken, A. (2010). Review article "Assessment of economic flood damage". Natural Hazards and Earth System Science, 10(8), 1697-1724.

Merz, B., Kreibich, H., & Lall, U. (2013). Multi-variate flood damage assessment: a tree-based data-mining approach. *Natural Hazards and Earth System Sciences*, *13*(1), 53-64.

Messner, F. and Meyer, V. (2006). Flood damage, vulnerability and risk perception–challenges for flood damage research (pp. 149-167). Springer Netherlands.

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S., and van der Veen, A.: Evaluating flood damages: guidance and recommendations on princi- ples and methods, FLOODsite Project Deliverable D9.1, Contract No: GOCE-CT-2004-505420, available at: http://www.floodsite.net/html/partner area/project docs/ T09 06 01 Flood damage guidelines D9 1 v2 2 p44.pdf (last access: October 25, 2016), 2007.

Mileti, D. 1999. *Disasters by Design: A Reassessment of Natural Hazards in the United States*. Washington, D.C.: Joseph Henry Press

Moel, de H. D., Asselman, N. E. M., & Aerts, J. C. J. H. (2012). Uncertainty and sensitivity analysis of coastal flood damage estimates in the west of the Netherlands. *Natural Hazards and Earth System Science*, *12*(4), 1045-1058.

Moel, de H. D., van Vliet, M., & Aerts, J. C. (2014). Evaluating the effect of flood damage-reducing measures: a case study of the unembanked area of Rotterdam, the Netherlands. Regional environmental change, 14(3), 895-908.

Moel, de H.D., Jongman, B., Kreibich, H., Merz, B., Penning-Rowsell, E., & Ward, P. J. (2015). Flood risk assessments at different spatial scales. Mitigation and Adaptation Strategies for Global Change, 1-26.

Moel, de H.D., Jongman, B., Kreibich, H., Merz, B., Penning-Rowsell, E., & Ward, P. J. (2015). Flood risk assessments at different spatial scales. *Mitigation and Adaptation Strategies for Global Change*, *20*(6), 865-890.Munich Re 2014 NatCat SERVICE Database Munich: Munich Reinsurance Company.

Molina, S., Lang, D. H., Lindholm, C. D., & Lingvall, F. (2010). User manual for the earthquake loss estimation tool: SELENA. NORSAR and Universidad de Alicante.

Müller, M., & Thieken, A. (2005). Elementartarife könnten weiter differenziert werden. Keller und Öltanks erhöhen das Schadenspotenzial–Untersuchung des Sommerhochwassers 2002. *Versicherungswirtschaft*, *2*, 145-148.

Nakamura, Y., & Saita, J. (2007). UrEDAS, the earthquake warning system: Today and tomorrow. In *Earthquake Early Warning Systems* (pp. 249-281). Springer Berlin Heidelberg.

Nasiri, H., & Shahmohammadi-Kalalagh, S. (2013). Flood vulnerability index as a knowledge base for flood risk assessment in urban area. *Journal of Novel Applied Science*, *2*(8), 269-272.

Nastev, M., & Todorov, N. (2013). Hazus: A standardized methodology for flood risk assessment in Canada. Canadian Water Resources Journal, 38(3), 223-231.

Nikolowski, J. (2014). Wohngebäude im Klimawandel–Verletzbarkeit und Anpassung am Beispiel von Überflutung und Starkregen. Dresden: Technische Universität, Fakultät Bauingenieurwesen, Institut für Baukonstruktion (Doctoral dissertation, Dissertation).

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 Science, 9(4), 1149-1159.

Peng, Y. (2015). Regional earthquake vulnerability assessment using a combination of MCDM methods. *Annals of Operations Research*, *234*(1), 95-110.

Penning-Rowsell, E., Viavattene, C., Parode, J., Chatterton, J., Parker, D., & Morris, J. (2010). The Benefits of Flood and Coastal Risk Management: a Handbook of Assessment Techniques-2010 (Multi-Coloured Manual). *FHRC, London (book+ CD-ROM with damage data)*.

Pinho, R. (2012). GEM: a Participatory Framework for Open, State-of-the-Art Models and Tools for Earthquake Risk Assessment. In Proceedings of the 15th World Conference on Earthquake Engineering.

Pitilakis, K., Franchin, P., Khazai, B., & Wenzel, H. (Eds.). (2014). SYNER-G: Systemic Seismic Vulnerability and Risk Assessment of Complex Urban, Utility, Lifeline Systems and Critical Facilities: Methodology and Applications (Vol. 31). Springer.

Porter, K. A., Jaiswal, K. S., Wald, D. J., Greene, M., & Comartin, C. (2008). WHE-PAGER Project: a new initiative in estimating global building inventory and its seismic vulnerability. In *Proceedings of the 14th World Conference on Earthquake Engineering*.

Poussin, J. K., Bubeck, P., Aerts, J. C. J. H., & Ward, P. J. (2012). Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse. Natural Hazards and Earth System Science, 12(11), 3455-3471.

Pregnolato, M., Galasso, C., & Parisi, F. (2015). A Compendium of Existing Vulnerability and Fragility Relationships for Flood: Preliminary Results.

Rashed, T., & Weeks, J. (2003). Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas. International Journal of Geographical Information Science, 17(6), 547-576.

Rashed, T., Weeks, J., Couclelis, H., & Herold, M. (2007). An integrative GIS and remote sensing model for place-based urban vulnerability analysis. Integration of GIS and remote sensing. Wiley, Chichester, 199-224.

Remo, J. W., & Pinter, N. (2012). Hazus-MH earthquake modeling in the central USA. Natural hazards, 63(2), 1055-1081.

Rojas, R., Feyen, L., & Watkiss, P. (2013). Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. Global Environmental Change, 23(6), 1737-1751.

Roos, W. (2003). *Damage to buildings*. Delft Cluster.

Rose, A., Benavides, J., Chang, S. E., Szczesniak, P., & Lim, D. (1997). The regional economic impact of an earthquake: Direct and indirect effects of electricity lifeline disruptions. *Journal of Regional Science*, *37*(3), 437-458.

Rose, A., & Lim, D. (2002). Business interruption losses from natural hazards: conceptual and methodological issues in the case of the Northridge earthquake. *Global Environmental Change Part B: Environmental Hazards*,*4*(1), 1-14.

Rossetto, T., & Elnashai, A. (2003). Derivation of vulnerability functions for European-type RC structures based on observational data. *Engineering structures*, *25*(10), 1241-1263.

Rufat, S., Tate, E., Burton, C. G., & Maroof, A. S. (2015). Social vulnerability to floods: Review of case studies and implications for measurement. *International Journal of Disaster Risk Reduction*, *14*, 470-486.

Rüstemli, A., & Karanci, A. N. (1999). Correlates of earthquake cognitions and preparedness behavior in a victimized population. *The Journal of Social Psychology*, *139*(1), 91-101.

Sandi, H., & Vasilescu, D. (1982). National report of Romania on observed vulnerability of buildings.'. Final report of working group B (Vulnerability and Seismic hazard), UNOP Project RER1791014.

Sauter, F., & Shah, H. C. (1978). Studies on earthquake insurance. In Proceedings of the Central American Conference on Earthquake Engineering (Vol. 2, pp. 265-271).

Scawthorn, C., N. Blais, H. Seligson, E. Tate, E. Mifflin, W. Thomas, J. Murphy, and C. Jones. (2006a). HAZUS-MH Flood Loss Estimation Methodology - I: Overview and Flood Hazard Characterization. Natural Hazards Review 7 (2): 60–71.

Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., ... & Lawrence, M. (2006b). HAZUS-MH flood loss estimation methodology. II. Damage and loss assessment. *Natural Hazards Review*, *7*(2), 72-81.

Scheuer, S., Haase, D., & Meyer, V. (2011). Exploring multicriteria flood vulnerability by integrating economic, social and ecological dimensions of flood risk and coping capacity: from a starting point view towards an end point view of vulnerability. Natural Hazards, 58(2), 731-751.

Schmidtlein, M. C., Deutsch, R. C., Piegorsch, W. W., & Cutter, S. L. (2008). A sensitivity analysis of the social vulnerability index. Risk Analysis, 28(4), 1099-1114.

Schmidtlein, M. C., Shafer, J. M., Berry, M., & Cutter, S. L. (2011). Modeled earthquake losses and social vulnerability in Charleston, South Carolina. Applied Geography, 31(1), 269-281.

Shaw, R., Shiwaku Hirohide Kobayashi, K., & Kobayashi, M. (2004). Linking experience, education, perception and earthquake preparedness. *Disaster Prevention and Management: An International Journal*, *13*(1), 39-49.

Silva, V., Crowley, H., Pagani, M., Monelli, D., & Pinho, R. (2014a). Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. Natural Hazards, 72(3), 1409-1427.

Silva, V., Crowley, H., Yepes, C., & Pinho, R. (2014b). Presentation of the OpenQuake-engine, an open source software for seismic hazard and risk assessment. In Proceedings of the 10th US National conference on earthquake engineering, Anchorage, Alaska.

Spence, R., So, E., Jenny, S., Castella, H., Ewald, M., & Booth, E. (2008). The Global Earthquake Vulnerability Estimation System (GEVES): an approach for earthquake risk assessment for insurance applications. Bulletin of Earthquake Engineering, 6(3), 463-483.

Spence, R., So, E., Jenkins, S., Coburn, A., & Ruffle, S. (2011). A global earthquake building damage and casualty database. In *Human Casualties in Earthquakes* (pp. 65-79). Springer Netherlands.

Steimen, S., Fäh, D., Giardini, D., Bertogg, M., & Tschudi, S. (2004). Reliability of building inventories in seismic prone regions. *Bulletin of Earthquake Engineering*, *2*(3), 361-388.

Tapsell, S. M., Tunstall, S. M., Penning-Rowsell, E. C., & Handmer, J. W. (1999). The health effects of the 1998 Easter flooding in Banbury and Kidlington. Report to the Environment Agency, Thames Region. Flood Hazard Research Centre, Middlesex University, Enfield.

Tapsell, S. M., Penning-Rowsell, E. C., Tunstall, S. M., & Wilson, T. L. (2002). Vulnerability to flooding: health and social dimensions. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, *360*(1796), 1511-1525.

Thomalla, F., Downing, T., Spanger-Siegfried, E., Han, G., & Rockström, J. (2006). Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation. Disasters, 30(1), 39-48.

Tiedemann, H. (1991). Earthquakes and volcanic eruptions: a handbook on risk assessment. Catalogue of Earthquakes and volcanic eruptions: this catalogue pertains to the world map of historical and instrumental earthquakes and of volcanoes and volcanic eruptions. Swiss Reinsurance Company.

Tierney, K. J., & Nigg, J. M. (1995). Business vulnerability to disaster-related lifeline disruption.

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., ... & Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. Proceedings of the national academy of sciences, 100(14), 8074-8079.

Ulmi, M., Wagner, C.L., Wojtarowicz, M., Bancroft, J.L., Hastings, N.L., Chow, W., Rivard, J.R., Prieto, J., Journeay, J.M., Struik L.C., and Nastev, M., (2014). Hazus-MH 2.1 Canada User and Technical Manual: Earthquake Module; Geological Survey of Canada, Open File 7474, 245 p.

UNDP (2004). A Challenge for Development. *United Nations Development Programme, Bureau for Crisis Prevention and Recovery, New York*.United Nations Development Programme. Bureau for Crisis Prevention, & Recovery. (2004). *Reducing Disaster Risk: A Challenge for Development-a Global Report*. United Nations.

UNESCO-IHE. (2016) http://unescoihefvi.free.fr/vulnerability.php.

UNISDR 2009 Global Assessment Report on Disaster Risk Reduction. Risk and Poverty in a Changing Climate (Geneva: United Nations International Strategy for Disaster Reduction Secretariat).

UNISDR 2011 Global Assessment Report on Disaster Risk Reduction. Revealing Risk, Redefining Development (Geneva: United Nations International Strategy for Disaster Reduction Secretariat).

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

Ventura, C. E., Finn, W. L., Onur, T., Blanquera, A., & Rezai, M. (2005). Regional seismic risk in British Columbia-classification of buildings and development of damage probability functions. *Canadian Journal of Civil Engineering*, *32*(2), 372-387.

Visser, H., Petersen, A. C., & Ligtvoet, W. (2014). On the relation between weather-related disaster impacts, vulnerability and climate change. Climatic change, 125(3-4), 461-477.

Wald, D. J., Earle, P. S., Allen, T. I., Jaiswal, K., Porter, K., & Hearne, M. (2008, October). Development of the US Geological Survey's PAGER system (prompt assessment of global earthquakes for response). In Proceedings of the 14th world conference on earthquake engineering.

Ward, P. J., Jongman, B., Weiland, F. S., Bouwman, A., van Beek, R., Bierkens, M. F., ... & Winsemius, H. C. (2013). Assessing flood risk at the global scale: model setup, results, and sensitivity. Environmental research letters, 8(4), 044019.

Ward, P. J., Jongman, B., Salamon, P., Simpson, A., Bates, P., De Groeve, T., ... & Winsemius, H. C. (2015). Usefulness and limitations of global flood risk models. *Nature Climate Change*, *5*(8), 712-715.

Winsemius, H. C., Van Beek, L. P. H., Jongman, B., Ward, P. J., & Bouwman, A. (2013). A framework for global river flood risk assessments. Hydrol. Earth Syst. Sci. Discuss, 9, 9611-9659.

Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2004). At Risk: Natural Hazards. *People's Vulnerability and*.

Yücemen, M. S., Özcebe, G., & Pay, A. C. (2004). Prediction of potential damage due to severe earthquakes. *Structural Safety*, *26*(3), 349-366.

Zahran, S., Brody, S. D., Peacock, W. G., Vedlitz, A., & Grover, H. (2008). Social vulnerability and the natural and built environment: a model of flood casualties in Texas. *Disasters*, *32*(4), 537-560.

Zevenbergen, C., Veerbeek, W., Gersonius, B., & Van Herk, S. (2008). Challenges in urban flood management: travelling across spatial and temporal scales. *Journal of Flood Risk Management*, *1*(2), 81-88.

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	FLOOD VULNERABILITY		EARTHQUAKE VULNERABILITY	
Vulnerability indicators	**Vulnerability curves**	**Index**	**Vulnerability curves**	**Index**
Transportation infrastructure	• Material and segment length (Ob, L) [12,27] • Traffic volumes, extra travel times (Ob, L) [23]	• Location, availability and length of roads (Com, L) [4]	• Material and segment length (Ob, L) [11, 16] • Material of supporting system of tunnels (Ob, L) [24] • Shape and depth of tunnels (Ob, L) [24] • Bridge design type (e.g. single versus multiple span) (Ob, L) [24]	• Location and availability of transportation facilities (Com, R) [22, 26]
Utility lifelines	• Material, anchored (Y/N) and segment length (Ob, L) [12, 27, 28]	• Location and length of utility lifelines (Com, L) [4]	• Material, anchored (Y/N) and segment length (Ob, L) [11, 16] • Natural gas pipeline material and construction types (Ob, L) [24]	• Accessibility of utility lifeline (Ob, L) [19] • Maintenance of utility lifeline (Ob, L) [19] • Age of utility lifeline (Ob, L) [19] • Closeness one utility to another (Ob, L) [19] • # Lifelines on bridges and viaducts (Ob, L) [19]
Essential facilities	• Structure, occupancy, quality (Ob, L) [12, 27,28]		• Structure, design level, occupancy class, construction quality factor (Ob, L) [11, 16]	• Accessibility of essential facilities (Ob, L) [19]
Buildings - Structural elements	• Building structural types (Ob, L) [12, 22, 23, 26, 27, 31] • # of stories (Ob, L) [12, 23, 27, 28, 31] • Building height (Ob, L) [12, 23, 27, 28, 31] • Building age (Ob, L) [23] • Foundation type (Ob, L) [12, 27, 28]	• Quality of building structure (Agg, L) [1, 20] • # of stories (Agg, L) [20] • Floor space of building (Agg, L) [20]	• Building structural types (i.e. material) (Ob, L-G) [6, 8, 11, 13, 15, 16, 18, 21, 25] • # of stories (Ob, L-G) [11, 13, 16, 18, 21] • Building height (Ob, L-G) [6, 11, 13, 16, 18, 21] • Building age (Ob, L) [10, 14] • Roof type (Agg, G) [13] (Com, L-G) [10, 18] • Building maintenance (Ob, L-R) [13, 17] • Building configuration (Ob, L) [16, 21] • Wall structural type (Com, L-G) [10, 18]	• # Stories (Agg, L-R) [30] • # Stories above ground level (Agg, L-R) [30] • Building height (Agg, L-R) [30] • Roof type (Agg, L-R) [30] • % of buildings in need of large repairs (Agg, N) [7] • Soft story index (ratio of the ground story height to the first story height) (Agg, L-R) [30] • Normalized redundancy score (Agg, L-R) [30]

			• Date of construction retrofit (Com, N) [6] • Lateral load-resisting system (Com, N) [6]	• Min. norm. lateral stiffness index (Agg, L-R) [30] • Overhang ratio (the floor area beyond outer frame / area ground fl (Agg, L-R) [30] • Completed buildings in new constructions per 800 population (Agg, N) [7]
Buildings - Occupancy	• Building occupancy (Ob, L) [12, 22, 23, 26, 27]	• Building occupancy class (Ob, L) [3, 4, 20]	• Building occupancy (Ob, L-G) [5, 6, 11, 16, 18, 29]	
Environmental		• Proximity to contaminating sites (Agg, R) [9] • Types of vegetation (Agg, R) [2] • Soil erosion potential (Agg, R) [9] • Soil quality (Agg, R) [2, 4]		• Proximity to contaminating sites (Ob, L) [19]

Table 1: Overview of physical earthquake and flood vulnerability assessment indicators.

Selected references:

[1] Akukwe and Ogbodo, 2015
[2] Balica et al., 2009
[3] Barroca et al., 2006 (FVAT)
[4] Barroca et al., 2008
[5] Bommer et al., 2002
[6] Brzev et al., 2013 (GEM)
[7] Burton and Silva, 2014 (GEM)
[8] Colombi et al., 2008
[9] Damm, 2009
[10] De Leon and Carlos, 2006 (used by CAPRA)
[11] FEMA Earthquake model, 2013
[12] FEMA Flood model, 2013
[13] GEM, 2016
[14] Hahn, 2003 (used by CAPRA)
[15] Kircher et al., 1997
[16] Kircher et al., 2006 (HAZUS-MH)
[17] Lagomarsino et al., 2006
[18] Marulanda et al., 2013 (CAPRA)
[19] Menoni et al., 2002
[20] Merz et al., 2013
[21] Nastev and Todorov, 2013 (HAZUS-MH)
[22] Peng, 2012
[23] Penning-Rowsell et al., 2010
[24] Pitilakis et al., 2014
[25] Porter et al., 2008 (PAGER)
[26] Rashed and Weeks, 2003
[27] Scawthorn et al., 2006a (HAZUS-MH)
[28] Scawthorn et al., 2006b (HAZUS-MH)
[29] Spence et al., 2008 (GEVES)
[30] Yücemen et al., 2004
[31] See also Merz et al., 2010 for other selected reference

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Discussions

	FLOOD VULNERABILITY		EARTHQUAKE VULNERABILITY	
Vulnerability indicators	**Vulnerability curves**	**Index**	**Vulnerability curves**	**Index**
Demographics	• Age (Agg, L) [12,25,26] • # Vulnerable age (e.g. HAZUS: <16, >65) (Agg, L) [12, 25, 26] • # Households (Agg, L) [12, 25, 26] • Ethnicity (Agg, L) [12, 25, 26]	• Pre-existing health problems (Agg, L) [22] • # Vulnerable age (e.g. MCM: > 75) (Agg, L-R) [9, 18,22, 29] • # Children (<14yr) (Agg, R) [18] • # Elderly (>65yr) (Agg, R) [18] • # Disabled (Agg, L) [3, 4, 29] • Single parents (Agg, L) [22, 29] • Household size (Agg, R) [18] • % Pop. access sanitation (Agg, L) [2] • Illiteracy rate (Agg, R) [1] • Population density (Agg, R-G) [2, 38] • Size of urbanized area (Agg, R) [2] • % People in urban areas (Agg, R) [12]	• Age (Agg, L) [11, 16, 19] • # People in vulnerable age range (e.g. HAZUS: <16, >65) (Agg, L) [11, 16, 19] • # Households (Agg, L) [11, 16] • Ethnicity (e.g. HAZUS) (Agg, L) [11, 16] • Female population (Agg, L) [11, 16, 19]	• % Vulnerable age (e.g. Schmidtlein et al. (2011): < 5, >65) (Agg, L-N) [6, 9, 14, 17, 27] • % Households vulnerable age (Ob, L) [5] • % Institutionalized elderly (Agg, L-R) [27] • % Disabled (Agg, N) [6] • # People per household/house (Agg, L-N) [6, 14, 17, 27] (Ob,L) [5] • Ethnicity (e.g. Schmidtlein et al., 2011): (Agg, L-N) [6, 27] • % Immigrants (Agg, L-N) [6, 27] (Ob, L) [10] • % Female (Agg, L-N) [6, 27] • % Female headed household (Agg, L-N) [6, 27] • % Population in poverty (Agg, L-R) [27] • Access to education (Agg, L-N) [14] • Education level (Agg, L-N) [6, 14, 27] and (Ob, L) [5] • Population density (Agg, L-N) [6, 7, 17, 21, 23] • % Rural farm population (Agg, L-R) [27] • % of Urban growth (Agg, N) [20] • % Urban population (Agg, L-R) [27] • Agricultural acreage (Agg, R) [20, 21, 24] • % rural farm population (Agg, R) [30]
Awareness		• Awareness and preparedness (Agg, L-R) [1, 3, 4, 19, 22]		• Emergency preparedness (Agg, L-R) [17]

		• Access to information (phone/tv/radio) (Agg, L) [1, 2] • Past experience (Agg, L) [2, 19, 22] • Pre-disaster coping strategies (Agg, L) [22] • Existence of early warning systems (Agg, L-R) [4, 18, 32]		• Access to information (last month's internet usage (Ob, L) [5] • Household disaster-related attitudes, behaviours, customs and believes (Ob, L) [10] • Ratio of expected financial loss to the total insured value (Agg, N) [28]
Economics	• # Households per income classes (Agg, L) [12, 25, 26] • # people working in commercial and industry (Agg, L) [12, 25, 26] • % Rental / home owners (Agg, L) [12, 25, 26] • Non-car ownership (Agg, L) [25, 26]	• Monthly net income in classes (Agg, L-R) [2, 18] • % Unemployment (Agg, L) [22, 29] • Housing ownership structure (Agg, L-R) [18, 29] • Non-car ownership. (Agg, L) [29] • Socioecon. status (defined by Schnell et al.1699 or Plapp 2003) (Agg, R) [18] • GDP (Agg, L-G) [2, 15] and (Agg, N) [13, 20] • GINI coefficient (Agg, N) [13] • Welfare level (Agg, R) [1] • Centrality of an economic activity in a network (Agg, R) [31]	• # Households per income classes (Agg, L) [11, 16] • # House rental / owners (Agg, L) [11,16] • # grad. students (Agg, L) [11, 16] • # students College (Agg, L) [11, 16] • Sector-specific capital dependency (Agg, L-N) [14] • Sector-specific labour dependency (Agg, L-N) [14] • Sector-specific supply chain dependency (Agg, L-N) [14] • Sector-specific infrastructure dependency (Agg, L-N) [14] • # People in commercial and industry (Agg, L) [11, 16]	• Household wealth (e.g. private toilet) (Ob, L) [5] • Income distribution (Agg, L-N) [9, 14, 27] and (Ob, L) [5, 10] • % Unemployment (Agg, L-R) [6, 27] and (Ob, L) [10] • % Household social security (Agg, L-N) [6, 27] • % Rental housing units (Agg, L-R) [6, 27] and (Ob, L) [10] • Median gross rent (US$) (Agg, L-R) [27] • % Employed industry (farming, fishing, mining) (Agg, L-R) [27] • % Employed secondary industry (Agg, N) [6] • % Female labour fore participation / unemployed (Agg, L-N) [6, 27] • % People employed in transportation, communications, public utilities (Agg, L-R) [27]
Institutional and political		• Urban planning institutions Y/N? (Agg, L) [2, 22] • Investments in precautionary measures (Agg, L) [8]		• Political stability (Agg, L-N) [14] • Crime rate (Agg, N) [6]

Table 2: Overview of social earthquake and flood vulnerability assessment indicators.

Selected references:

[1] Akukwe and Ogbodo, 2015
[2] Balica et al., 2009
[3] Balica et al., 2012

[4] Barroca et al., 2008
[5] Brink and Davidson, 2015
[6] Burton and Silva, 2014 (GEM)
[7] Carreno, 2012
[8] Connor and Hiroki, 2005
[9] Davidson and Shah, 1997
[10] Duzgun et al., 2011
[11] FEMA Earthquake model, 2013
[12] FEMA Flood model, 2013
[13] Ferreira et al., 2011
[14]GEM, 2016
[15] Jongman et al., 2015
[16] Kircher et al., 2006 (HAZUS-MH)
[17] Menoni and Pergalani, 1996
[18] Merz et al., 2013
[19] Nastev and Todorov, 2013 (HAZUS-MH)
[20] Peduzzi, 2009 (GEM)
[21] Peng, 2012
[22] Penning-Rowsell et al., 2010
[23] Pergalani, 1996
[24] Rose et al., 1997
[25] Scawthorn et al., 2006a (HAZUS-MH)
[26] Scawthorn et al., 2006b (HAZUS-MH)
[27] Schmidtlein et al., 2011
[28] Spence et al., 2008 (GEVES)
[29] Tapsall, 2002
[30] Tierney and Nigg (1995)
[31] Van der Veen and Logtmeijer, 2005
[32] See also Merz et al., 2010 for other selected references