Nat Hazards (2012) 64:1925–1958
DOI 10.1007/s11069-012-0294-2

REVIEW ARTICLE

Challenges of analyzing multi-hazard risk: a review

Melanie S. Kappes · Margreth Keiler · Kirsten von Elverfeldt · Thomas Glade

Received: 14 September 2010 / Accepted: 9 July 2012 / Published online: 31 July 2012

Abstract Many areas of the world are prone to several natural hazards, and effective risk reduction is only possible if all relevant threats are considered and analyzed. However, in contrast to single-hazard analyses, the examination of multiple hazards poses a range of additional challenges due to the differing characteristics of processes. This refers to the assessment of the hazard level, as well as to the vulnerability toward distinct processes, and to the arising risk level. As comparability of the single-hazard results is strongly needed, an equivalent approach has to be chosen that allows to estimate the overall hazard and consequent risk level as well as to rank threats. In addition, the visualization of a range of natural hazards or risks is a challenging task since the high quantity of information has to be depicted in a way that allows for easy and clear interpretation. The aim of this contribution is to give an outline of the challenges each step of a multi-hazard (risk) analysis poses and to present current studies and approaches that face these difficulties.

Keywords Multi-hazard risk · Hazard · Vulnerability · Risk · Hazard cascades · Hazard chains

1 Introduction

The use of the term *multi-hazard* is in most cases closely related to the objective of risk reduction. For example, within international politics, one of the first references to this term

M. S. Kappes · M. Keiler · K. von Elverfeldt · T. Glade
Department of Geography and Regional Research, University of Vienna, Vienna, Austria

M. S. Kappes (✉)
The World Bank, 1818 H St. NW, Washington, DC 20433, USA
e-mail: kappes.melanie@googlemail.com

M. Keiler
Institute of Geography, University of Bern, Bern, Switzerland

K. von Elverfeldt
Department of Geography and Regional Science, Klagenfurt University, Klagenfurt, Austria

has been made in the Agenda 21 for sustainable development (UNEP 1992). This document calls for "complete multi-hazard research" as a part of human settlement planning and management in disaster-prone areas (UNEP 1992, paragraph 7.61). The term reappears in the Johannesburg Plan in the context of "protecting and managing the natural resource base of economic and social development" (UN 2002, p. 14). It refers to "[a]n integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery" as "an essential element of a safer world in the twenty-first century" (UN 2002, p. 20). In the following, the Hyogo Framework of Action (UN-ISDR 2005, p. 4) adopted this aspect and suggests an "integrated, multi-hazard approach for disaster risk reduction […] into policies, planning and programming related to sustainable development, relief, rehabilitation, and recovery activities in post-disaster and post-conflict situations in disaster-prone countries." Furthermore, also FEMA (1995) uses this term in the U.S. national mitigation strategy with the goal to lower risks and reduce the effects of disasters due to natural hazards by focusing on the application of multi-hazard building approaches in the design and construction of buildings.

The awareness of the necessity to investigate and manage the whole range of natural hazards that pose a risk to humans, assets, and societies continued to grow in the last. Thereby, the identification of the risks to be taken into account is mostly based on a spatial approach, that is, a certain area is considered and all threats within this zone are taken into account (c.f. Greiving et al. 2006, p. 1). Hewitt and Burton (1971, p. 5) refer to this concept as the "all-hazards-at-a-place" approach. According to DHS (2011, 1–7), *all-hazards* "encompasses all conditions, environmental or manmade, that have the potential to cause injury, illness, or death; damage to or loss of equipment, infrastructure services, or property; or social, economic, or environmental functional degradation". Consequently, "a first definition of the term *multi-hazard* in a risk reduction context could read as follows: *the totality of relevant hazards in a defined area"* (Kappes 2011, pp. 6 & 7). However, whether a hazardous process is *relevant* has to be defined according to the specific setting of the respective area and to the objective of the study. For instance, Hewitt and Burton (1971) propose a *cut-off point* for the hazard-related damages: Depending on the respective scale, a process is considered irrelevant if it causes damages below a certain point. The larger the observed area, the higher is this cut-off point. Another example is given by the European Commission (2011, p. 24) in their guidelines for risk assessment and mapping. These guidelines propose a set of criteria for the determination of all significant hazards at a national level. For example, those threats with an annual probability of at least 1 % "and for which the consequences represent significant potential impacts, i.e.: number of affected people greater than 50, economic and environmental costs about € 100 million, and political/social impact considered significant or very serious [need to be taken into account]. Where the likely impacts exceed a threshold of 0.6 % of gross national income (GNI) also less likely hazards or risk scenarios should be considered (e.g., volcanic eruptions, tsunamis)". In the context of spatial planning, Greiving et al. (2006) and Greiving et al. (2006, p. 4) define *relevant* according to differing criteria and restrict the set of considered processes to "hazards that are closely tied to certain areas that are especially prone to a particular hazard," whereby ubiquitous threats such as meteorite impacts are excluded.

However, not all studies on multiple hazards share the aim of involving *all relevant processes of a defined area,* but can rather be described as *more-than-one-hazard* approaches. This is especially true for scientific studies and supposedly is, among multiple reasons, due to the strict separation of disciplines (with all the consequences for differing terminology, partly conflicting definitions, and approaches, etc.) that hamper multi-hazard studies (c.f. WMO 1999).

Nevertheless, in certain contexts, the joint investigation of two or more processes is indispensable, that is, whenever one hazard triggers a second process, for example, earthquakes leading to landslides (e.g., Bommer and Rodríguez 2002; Keefer 2002; Lin et al. 2006; Chang et al. 2007; Chang et al. 2007; Lee et al. 2008; Miles and Keefer 2009). Moreover, an event may cause multiple threats such as a volcanic eruption resulting in lava flows, lahars, and ash and lapilli fallout (e.g., Zuccaro et al. 2008; Thierry et al. 2008). Another reason for considering several hazards jointly are common characteristics, as, for example, within the system RAMMS (RApid Mass MovementS) that spans snow avalanches, debris flows, and rock fall (Christen et al. 2007). In the SEDAG project (SEDiment cascades in Alpine Geosystems), Wichmann and Becht (2003) focus on the sediment cascade, thereby considering soil erosion, rock falls, full-depth avalanches, shallow landslides, and debris flows.

In summary, two approaches to multi-hazard can be distinguished. The first one is primarily spatially oriented and aims at including all relevant hazards. The second, in contrast, is primarily thematically defined.

One challenge related to multi-hazard risk[1] analyses is related to the fact that while for many, if not most, single processes a multitude of well-established approaches is available (please refer to review articles provided by Ancey et al. (2004) and Bründl et al. (2010) for snow avalanches; Hunter et al. (2007) for river floods; Dai et al. (2002), Glade and Crozier (2004), and Fell et al. (2005) for landslides; WMO (1999) for meteorological, volcanic, and seismic hazards), much fewer studies analyze multiple hazards. In consequence, experience with associated problems is rare, and also, standard approaches are not available. This is problematic, because multi-hazard risk analyses are not just the sum of single-hazard risk examinations:

1. hazard characteristics differ, and thus also the methods to analyze them (c.f. Carpignano et al. 2009),
2. hazards are related and influence each other. This results in phenomena often described as hazard chains, cascades, etc. (c.f. Tarvainen et al. 2006; Marzocchi et al. 2009; Kappes et al. 2010),
3. natural processes exert diverging impacts on elements at risk, and methods to describe vulnerability vary between hazards (c.f. Hufschmidt and Glade 2010; Papathoma-Köhle et al. 2011; Kappes et al. 2011), and
4. a variety of risk description and quantification measures exists and has to be adapted to enable the comparison of multiple risks (c.f. Marzocchi et al. 2009; Marzocchi et al. 2012).

These issues are major challenges for the analysis of multi-hazard risks. Therefore, the aim of this contribution is threefold: Firstly, it aims at detailing the difficulties and challenges associated with multi-hazard risk analysis. Secondly, the objective is to give an overview of existing approaches that meet these challenges. Thereby, not only multi-hazard strategies with a focus on risk reduction are considered, but also those studies that deal with *more-than-one-hazard*. These studies were incorporated since they provide profound insight into specific aspects that are mostly neglected by studies focusing on a very large number of processes. And thirdly, the paper seeks to give a coherent overview of all steps in multi-hazard analysis. Thus, this paper is structured accordingly: (1) the joint hazard analysis of multiple natural threats, (2) the assessment of the physical vulnerability of elements at risk toward

[1] The term *multi-hazard risk* refers to the risk arising from multiple hazards. By contrast, the term *multi-risk* would relate to multiple risks such as economic, ecological, social, etc.

multiple hazards,[2] (3) the analysis of risk arising from multiple natural hazards, combining the aspects *hazard* and *vulnerability* of exposed elements at risk, and (4) the joint visualization of multiple hazards. For each step, the multi-hazard-specific challenges are described, discussed, and current studies and approaches are presented. Thereby, this paper rather provides a comprehensive introduction into the field of multi-hazard risk analyses and its specificities, and the authors do not claim completeness. Furthermore, the main focus is on the multi-hazard aspect rather than on the vulnerability and risk issue. Finally, exclusively physical vulnerability is considered, while social vulnerability and other types of vulnerability are not included in this article. The analysis of social or community vulnerability is a topic in its own right and thus cannot be covered in this review. Hereby, it is by no means intended to foster the rather outdated perception that nature is the 'problem' while engineering measures are the *solution*. Accordingly, linking respective social and nature-scientific approaches is yet another challenge that needs to be covered elsewhere.

The terms hazard, vulnerability, and risk exhibit multiple definitions and are described by various authors and institutions that often refer to Varnes (1984) and UNDHA (1992). To avoid confusion, definitions of the main terms are highlighted at the beginning of each section. Furthermore, the described concepts are classified in qualitative, semiquantitative, and quantitative approaches (c.f. Altenbach 1995; Borter 1999; DIN 2009):

Qualitative: Description in words (e.g., high, medium, and low) which relate to, or involve quality or kind. Qualitative judgments rank in higher and lower without the information on how much higher or lower and are commonly based on expert appraisals.

Semiquantitative: Description by means of a scale that consists of words or numbers. This scale allows a relative ranking and provides a measure for how much more one scenario contributes over the next.

Quantitative: Relates to or can be expressed in terms of quantities or totals. It allows the determination of absolute values on a determined scale.

2 Challenges and current approaches in the field of multi-hazard risk analyses

According to Varnes (1984, p. 10), hazard is defined as the "probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon." In addition to the hazard aspect, risk involves the vulnerability of the elements at risk and is established as the "expected degree of loss due to a particular natural phenomenon," thus suggesting that the product of hazard and vulnerability of exposed elements at risks (Varnes 1984, p. 10). This section focuses on the three steps of a multi-hazard risk analysis, namely the analysis of multi-hazard (2.1), vulnerability of elements at risk for multiple processes (2.2) and multi-hazard risk (2.3). Furthermore, examples of existing methods for the joint investigation of multiple hazards are presented (2.4).

2.1 Multi-hazard analyses

Delmonaco et al. (2006b, p. 15) define multi-hazard analyses as the "[i]mplementation of methodologies and approaches aimed at assessing and mapping the potential occurrence of different types of natural hazards in a given area." The employed methods "have to take

[2] The exposure of elements at risk is not considered separately since this article focuses on the issues and challenges that arise in multi-hazard context in contrast to single hazard analysis, and exposure does not change.

into account the characteristics of the single hazardous events […] as well as their mutual interactions and interrelations (e.g., landslide induced earthquake, floods and landslides triggered by extreme rainfall, natural disasters as secondary effect from main disaster types)" (Delmonaco et al. 2006b, p. 15). This description indicates two major challenges: (1) differing process characteristics so that it becomes difficult to compare multiple hazards, and (2) the existence of relations and interactions between hazards. In the following, both aspects are presented and current approaches are exemplified.

2.1.1 Comparability of hazards due to differing process characteristics

Within multi-hazard analyses, it is essential to assess the respective level of each threat of the investigated multiple hazards. However, hazards "differ by their nature, intensity, return period and by the effects they may have on exposed elements. […] Their magnitudes are also measured in different ways, using different units of reference, for example, discharge or inundation depth for floods, ground motion or macro-seismic intensity for seism" (Carpignano et al. 2009, p. 515). Thus, the principal difficulty in the comparison of multiple hazards is the distinct *reference units*. An approach to overcome this problem is the standardization to a common measure. Reviewing numerous studies (e.g., Heinimann et al. 1998; Odeh Engineers, Inc 2001; Delmonaco et al. 2006b; El Morjani et al. 2007; Bartel and Muller 2007; Thierry et al. 2008), two major standardization approaches can be distinguished: (1) the classification of hazards (qualitative approach) and (2) the development of indices (continuous, semiquantitative approach).

(1) The standardization by means of classification is the most frequently used approach to enable the comparison of different hazards. Intensity and frequency thresholds are defined in order to classify the respective hazards into a predefined number of hazard classes. In order to determine thresholds, a framework of shared objectives or criteria describing the classes has to be established. This assures the equivalence and comparability of, for example, *high* earthquake and *high* flood hazard (Delmonaco et al. 2006a). At the same time, however, it becomes very difficult or even impossible to compare information from different sources since, most probably, different criteria were applied (Marzocchi et al. 2009). In the following, an overview of a number of studies employing diverse classification schemes is presented.

With their study, Moran et al. (2004, p. 185; based on Heinimann et al. 1998; Fuchs et al. 2001) aim at a "conceptual approach to natural hazard investigations in regions lacking hazard zoning or where only rudimentary hazard assessments exist" to "identify the risk potential at a regional scale" as "foundation for further detailed studies." In order to reach this aim, Moran et al. (2004) used a worst-case scenario for the regional scale modeling of avalanches and rock falls. Due to the common basis (worst-case scenario), the resulting areas of potential impact can be compared and jointly visualized. Additionally, by overlay with elements at risk, the number of endangered buildings or affected road kilometers by each process can be determined and compared.

One objective of the ARMONIA project (Applied Multi Risk Mapping of Natural Hazards for Impact Assessment) was to define a "new harmonised methodology for integrated management of data from different risk analysis approaches and set-up basic principles for a EU directive on harmonized risk maps aimed at spatial planning" (Delmonaco et al. 2006b, p. 5). In this context, a classification scheme was proposed for hazard intensities at a regional scale. The hazard is classified in low, medium, and high intensity with regard to spatial planning purposes (Table 1). Subsequently, the importance of hazards can be compared and consequences for the spatial planning process can be defined (Delmonaco et al. 2006b).

Table 1 ARMONIA hazard intensity classification matrix for a regional scale (Menoni 2006)

Natural Hazard	Intensity Scales			
	Low	Medium	High	Parameters
Flood	<0.25	0.2–1.25	>1.25	Flood depth (m)
Forest Fire	<350	350–1,750	>1,750–3,500	Predicted fire line intensity (*)(kW/m)
Forest Fire	<1.2	1.2–2.5	>2.5–3.5	Approximate flame length (m)
Volcanoes	<5	5–10	>10	Intensity = volcanic explosive index $\log_{10}$(mass eruption rate, kg/s) + 3
Landslide (fast and slow movements)	<5	5–15	>15	Percentage of landslide surface (m^2, km^2, …) vs. stable surface (%)
Seismic	<10	10–30	>30	Peak Ground Horizontal Acceleration (%g)

Another example for the utilization of a classification approach is the Swiss guidelines for the analysis and evaluation of natural hazards. These guidelines focus on spatial planning as instrument for risk reduction (Heinimann et al. 1998). Similar to the ARMONIA classification scheme, high, medium, and low hazards are distinguished. Furthermore, the Swiss concept includes frequency classes, and by means of a combination of the intensity and the frequency class, the hazard level is determined. The respective thresholds relate to the possible effects on buildings and humans. Each hazard class and its implication in the context of spatial planning is defined as follows:

- High hazard (red zone): People in- and outside of buildings are at risk and the destruction of buildings is possible, or events with a lower intensity occur but with higher frequency, and persons outside of buildings are at risk. Further construction of buildings is prohibited.
- Medium hazard (blue zone): People inside of buildings are slightly endangered, damages of buildings are possible, but destruction is rare. Further construction of buildings is allowed under constraints, for example, related to building codes.
- Low hazard (yellow zone): People are slightly endangered, and small damages and interferences are possible. Further construction of buildings is allowed without constraints.
- Residual hazard (yellow white striped): Hazards of very low frequency and high intensity are possible.

Methodologically, the hazard classes are defined by their constellation of intensity and probability (Fig. 1).

The *translation* of the potential effects on humans and buildings thus results in the intensity thresholds presented in Table 2. Thereby, one set of return period thresholds applies to all processes with 1–30 years for the high, 30–100 years for the medium, 100–300 years for the low, and <300 years for the very low probability class, respectively (Loat and Petraschek 1997).

The overall hazard map is derived by overlaying the classification result of all single hazards. In those areas where multiple scenarios of the same process or different processes are overlapping, the highest hazard class is adopted. Hazards of an equal or lower hazard class can be indicated by an additional index letter (Heinimann et al. 1998).

Fig. 1 Swiss intensity-probability matrix after Kunz and Hurni (2008)

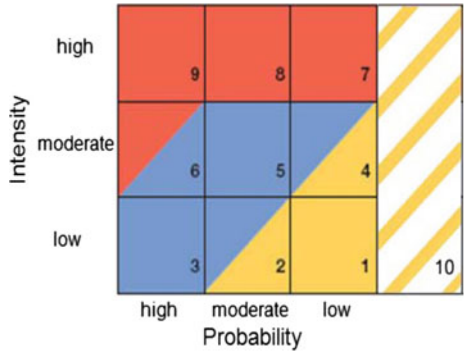

Table 2 Swiss hazard intensity classification matrix as summarized in Loat (2010). For details on the single processes, refer to SLF 1984 for avalanches, Lateltin 1997 for landslides, and Loat and Petrascheck 1997 for floods

Process	Low intensity	Average intensity	High intensity
Rock fall	$E < 30$ kJ	20 kJ $< E <$ 300 kJ	$E > 300$ kJ
Landslide	Vs < 2 cm/year	Vs: dm/year	Vs > dm/day; displacement > 1 m per event
Debris flow	–	$D < 1$ m and $V < 1$ m/s	$D > 1$ m and $v > 1$ m/s
Static flooding	$h < 0.5$ m	$0.5 < h < 2$ m	$h > 2$ m
Dynamic flooding	$q < 0.5$ m^2/s	$0.5 < q < 2$ m^2/s	$q > 2$ m^2/s
Bank erosion	$t < 0.5$ m	$0.5 < t < 2$ m	$t > 2$ m
Snow avalanche	$P < 3$ kN/m^2	3 kN/m^2 $< P <$ 30 kN/m^2	$P > 30$ kN/m^2

E kinetic energy, *Vs* mean annual velocity of landslide, *D* thickness of debris front, *v* flow velocity (flood or debris flow), *h* flow depth, *q* specific discharge (m^3/s/m) = h × v, *t* extent of lateral erosion, *P* avalanche pressure exerted on an obstacle

A very similar approach used Thierry et al. (2008) for the multi-hazard analysis of the active volcano Mount Cameroon in order to improve the safety of the local population. Six volcanic hazards, two slope instability processes, and one tectonic phenomenon were included. Thresholds for five intensity classes were determined for each process according to the expected damage level ($\leq$5 % very low, 5–10 % low, 10–50 % moderate, 50–80 % high, and $\geq$80 % very high) by means of expert knowledge following the proposal of Stiltje (1997, cited in Thierry et al. 2008). Additionally, seven frequency classes were established from 1 to 10 years (quasi-permanent), 10 to 50 years (very frequent), 50 to 100 years (high), 100 to 500 years (moderate), 500 to 1,000 years (low), 1,000 to 5,000 years (very low), and 5,000 to 10,000 years (very low to negligible). The combination of frequencies and intensities was classified into five hazard classes ranging from negligible to very high hazard. The nine classified hazard maps were superimposed to the overall geological hazard zoning of Mount Cameroon, and in zones of overlap, the maximum hazard class was adopted.

Chiesa et al. (2003) present a different classification scheme. It focusses on earthquakes and tropical storms in the Asia Pacific region and is applied in the framework of the Asia Pacific Natural Hazards and Vulnerabilities Atlas. Although Chiesa et al. (2003) also used a classification scheme, the hazard level in zones of overlap is not determined by the

Table 3 Matrix for the determination of the multi-hazard (Chiesa et al. 2003)

	Tropical storm hazard			
	Low/none	Mod.	High	Ext. high
Eq. hazard				
Low/none	Low/none	Mod.	Mod.	High
Mod.	Mod.	Mod.	High	High
High	Mod.	High	High	Ext. high
Ext. high	High	High	Ext. high	Ext. high

maximum of overlapping classes, but by means of a matrix (Table 3). In comparison with the previous two studies where the maximum class is adopted, this approach leads to differing results for very distinct classes of earthquake and storm threat. For instance, the combination of high and low/none hazard results in moderate, and the overlap of extremely high and low/no hazard results in high overall hazard.

As in the case of Swiss guidelines, also the French risk prevention plans (Plan de Prévention des Risques naturels prévisibles, PPR) focus on risk reduction by spatial planning measures (Delattre et al. 2002). A range of guides is available to support a harmonized preparation of PPRs such as Garry et al. (1997), MEDD (2003), Thierry (2003), or Cariam (2006). These documents offer instructions for the hazard modeling as well as guidance on how to establish thresholds for the hazard classification. In contrast to the Swiss approach, however, the thresholds are not generalized to all regions, but each municipality is allowed to determine the classification scheme according to their specific needs. Subsequently, the criteria for the classification have to be presented in a document accompanying the PPR (Besson et al. 1999; MEDD 1999, MEDD 2002; Liévois 2003).

Despite the fact that all of the presented approaches utilize classification schemes, they differ significantly. This is mainly due to the constellation of considered hazards or the differing objectives of the studies. For instance, the frequency classification of the Swiss approach ranges between 1 and >300 years and considers mountain hazards, while the scheme used in the study of Thierry et al. (2008) comprises the time span of 1 to 5,000–10,000 years for hazards occurring in volcano vicinities. Moreover, distinct methods to determine the overall hazard in zones of overlapping hazards are applied such as the adoption of the maximum hazard class (e.g., Heinimann et al. 1998) or the intermediate rating (e.g., Chiesa et al. 2003). Though classification schemes offer a simple way to compare hazards, they are specifically developed for a certain situation, application, or study and are thus restricted to this respective use. In addition to difficulties to use classified information for other objectives than the one it was produced for, it becomes obvious that classified information of different sources can only (if at all) be compared after a careful examination of the study objectives, the applied methods, classification scheme, and the research foci.

(2) In contrast to classification approaches, indices offer a continuous standardization of differing and, therefore, not directly comparable parameters. Additionally, they allow for quantifying the difference between two hazard levels (semiquantitative) instead of only ranking them (qualitative). In the following, several studies applying index schemes for standardization purposes are presented.

Based on classified single-hazard magnitudes, frequencies, and proportions of the potentially affected area, Odeh Engineers Inc. (2001) compute continuous *Hazard Scores*

(HS). The HS are calculated on a subregional level, that is, for communities as a whole (instead of modeling hazards in a distributed way, pixel by pixel) according to the following equation:

$$HS = FS \cdot AIS \cdot IS$$

with:

- *FS* Frequency Scores: measuring how often a given hazard occurs [events per year, classified in five levels],
- *AIS* Area Impact Score: measuring the extent of the geographical area that potentially will be affected by a hazard event [gross or relative area, classified in five levels], and
- *IS* Intensity Score: measuring the intensity level of a hazard [hazard-specific units, classified in five levels]

Due to the multiplication of the classified input scores (*FS*, *AIS,* and *IS*), the resulting *HS* is a continuous measure. By conducting the analysis at community level, indices of different hazards can be compared for one community. This thus indicates the importance of each hazard and in addition allows for the comparison between communities. The disadvantage of this approach is that no information is given on the spatial distribution of hazard and risk within the community.

The World Bank initiated *A Global Risk Analysis* to globally identify "key 'hotspots' where the risks of natural disasters are particularly high." The aim is to provide "information and methods to inform priorities for reducing disaster risk and making decision on development investment" (Dilley et al. 2005, p. vii). In this study, a *Simple Multihazard Index* is proposed. It is composed by single-hazard analyses, investigated by combining data on past events (inventories) and modeling. Thereby, the choice of approach strongly depends on the availability of the respective process information. For the definition of classification thresholds, the total number of pixels affected by a certain hazard is divided into ten approximately equally sized groups, the so-called deciles. The first to fourth deciles indicate low, the fifth to seventh medium, and the eighth to tenth deciles high hazard. Subsequently, for the calculation of the *Simple Multihazard Index,* only the high hazard class is taken into account, adding up the values of all overlapping hazards within a pixel. The result is given as number of hazards affecting each pixel.

El Morjani et al. (2007, p. 20) perform a study in the Eastern Mediterranean Region including the West Bank and the Gaza Strip territory in order to "identify potential hotspots where the population might be exposed to several hazards at the same time." Here, the hazards are modeled separately and classified into five classes according to separately defined thresholds. Subsequently, the processes are weighted with the impact on humans and economics (numbers of people killed, injured, homeless or affected, and total damage expressed in USD) caused in the past by these hazards and as recorded in EM-DAT[3] (Table 4). These weights are based on regional averages of the area under consideration. They are used as a measure for the importance of each process.

After summing these weighted indices, they are presented in the "multi hazard index distribution map" and finally classified in five "intensity level[s] of multihazard" (El Morjani et al. 2007, pp. 20 & 23).

[3] EM-DAT is the Emergency Disaster Data Base maintained by CRED, the Centre for Research on the Epidemiology of Disasters. It contains essential core data on the occurrence and effects of over 18,000 mass disasters in the world from 1,900 to present (CRED 2009).

Table 4 "Normalised weights applied to the different hazards when calculating multihazard" (El Morjani et al. 2007, p. 22)

Hazard	Normalized weight
Seismic	0.41
Flood	0.36
Wind speed	0.09
Heat	0.08
Landslide	0.06
Sum	1

The U.S. Department of Homeland Security (DHS 2011, pp. 2–2) developed the *Integrated Rapid Visual Screening* (IRVS). It is a methodology to "quantify the risk and resilience of [mass transit stations, tunnels, or buildings] to manmade and selected natural hazards that are capable of causing catastrophic losses in fatalities, injuries, damage, or business interruption." This approach is understood as first step in a tiered assessment that is followed by more refined and detailed analyses. Thereby, the hazard level is determined by means of a qualitative assessment of the *screener* performing the IRVS. It is based on available hazard maps, information on past events, the site observation, etc. The assessment includes several standardized questions, exemplified here for floods: (1) floodplain (yes/no), (2) maximum flood depth (no previous flooding, low, medium, high), (3) flood duration (no previous flooding, short, medium, long, very long), (4) floodwater velocity (no previous flooding, low, medium, high, extreme), and (5) distance from a flooding source (far, medium, close, adjacent). The value for each question ranges between 0.1 and 100 %. In a subsequent step, the overall threat is calculated by combining the result of the hazard rating, the consequences rating, and the vulnerability rating to the risk score (for more detail refer to DHS 2011).

Bartel and Muller (2007) elaborated a slightly different semiquantitative approach, which is not based on an index scheme. They assess the probability that "a given natural disaster will develop in a given area of the HOA in within a given year" (HOA—Horn of Africa, Bartel and Muller 2007, p. 1). The study considers moderate to severe droughts as well as floods above a certain threshold, and locust infestations defined as "outbreaks of gregarious swarms of hoppers and adults" (Bartel and Muller 2007, p. 4). Firstly, the analyses result in an estimation of the annual probability of each process. Secondly, the probability of occurrence of any of these hazards is given, the so-called *joint probability*. Thirdly, the distribution of the most probable hazard is identified. As large damaging earthquakes are occurring rather infrequently in the study area, the study does not include earthquake hazards. They are "not an annual concern like the other hazard types" (Bartel and Muller 2007, p. 1 et seq.).

In the studies presented so far, the multiple hazards are analyzed according to an overall analysis scheme. Thus, single-hazard analysis results can be compared and combined to a multi-hazard assessment. They are, however, analyzed separately assuming independence from each other, and single hazards are simply summed up to the overall hazard. Nevertheless, "[n]atural processes are components of systems (ecosystems, geosystems, etc.) and [a]s components of complex systems these processes are not independent and separated from each other but are linked and connected" (Kappes et al. 2010, p. 351 et seq.). They are, therefore, interacting (possibly nonlinearly), eventually leading to the occurrence of hazard changes, changes of the system state, etc. Within another system state, new and different hazard patterns may emerge that differ from the simple sum of all single hazards. The negligence of these relations between processes might thus lead to misestimation of the actual hazard level. Due to growing awareness of this fact, the importance of the relations between hazards is increasingly acknowledged within multi-hazard research.

2.1.2 *Dealing with relations between hazard types*

Despite growing awareness of relations between hazards still neither a uniform conceptual approach nor a generally used terminology is applied. Rather, a multitude of terms is in use to describe several types of relations between processes (Kappes 2011):

Cascades, cascading effects, cascading failures, or cascade events	Delmonaco et al. (2006b), Carpignano et al. (2009), Zuccaro and Leone (2011), European Commission (2011)
Chains	Shi (2002), Erlingsson (2005)
Coincidence of hazards in space and time	Tarvainen et al. (2006)
Coinciding hazards	European Commission (2011)
Compound hazards	Hewitt and Burton (1971), Alexander (2001)
Coupled events	Marzocchi et al. (2009)
Cross-hazards effects	Greiving (2006)
Domino effects	Luino (2005), Delmonaco et al. (2006b), Perles Roselló and Cantarero Prados (2010), European Commission (2011)
Follow-on events	European Commission (2011)
Interactions	Tarvainen et al. (2006), dePippo et al. (2008), Marzocchi et al. (2009), Zuccaro and Leone (2011)
Interconnections	Perles Roselló and Cantarero Prados (2010)
Interrelations	Delmonaco et al. (2006b), Greiving (2006)
Knock-on effects	European Commission (2011)
Multiple hazard	Hewitt and Burton (1971)
Synergic effects	Tarvainen et al. (2006)
Triggering effects	Marzocchi et al. (2009)

Precise definitions of the terms are rare. Nevertheless, one type of phenomena can clearly be distinguished: the triggering of one hazard by another, eventually leading to subsequent hazard events. This is referred to as *cascade, domino effect, follow-on event, knock-on effect,* or *triggering effect*. Delmonaco et al. (2006a, p. 10) describe a "domino effect or cascading failure" as "failure in a system of interconnected parts, where the service provided depends on the operation of a preceding part, and the failure of a preceding part can trigger the failure of successive parts." By contrast, terms such as *compound hazards, interactions, interrelations,* or *synergic effects* are far less explicit and obvious. The term *interaction* is used by many authors. However, while *interaction* indicates a mutual influence between two processes, many studies do not refer to impacts in both directions. For example, Tarvainen et al. (2006) distinguish between vice versa *interactions* and interactions during which only one process exhibits a significant influence on the other. Hewitt and Burton (1971) present a concept that differentiates between *compound* and *multiple hazards*: While they characterize *compound hazard* as "several elements acting together above their respective damage threshold-for instance wind, hail, and lightning damage in a severe storm," they refer to *multiple hazard* as "elements of quite different kinds coinciding accidentally, or more often, following one another with damaging force-for instance floods in the midst of drought, or hurricane followed by landslides and floods" (Hewitt and Burton 1971, p. 30). Kappes et al. (2010), on the other hand, propose a different approach as they explicitly distinguish between two types of hazard relations: (1) those in which one process triggers the next (cascades, domino effects, etc.) and (2) those in which the disposition of one hazard is altered by another. This applies whenever a process modifies the disposition of another process, thus resulting in frequency and/or magnitude alterations. An example is the removal of protective forest by avalanches in winter that leads to a higher frequency and magnitude of rock falls in this area in the following spring.[4]

In summary, hazard relations and interactions may have unexpected effects and pose threats that are not captured by means of separate single-hazard analyses. Thus, their negligence is problematic. But as our understanding of process relations and cascades still is very limited, this hampers multi-hazard risk research that explicitly addresses process interactions. Still, the number of respective research studies and methodological approaches is very limited.

According to Delmonaco et al. (2006a, p. 10), "basically two ways of how to assess the coupled hazards" exist as follows: "[w]e can investigate the individual possible chains of hazardous events—one triggering another—and try to assess probability values in order to transfer these phenomena into risk maps [or we] assess the risk for coincidences of different hazards, even without supposing any direct linkage among them." While the first is extremely data-demanding and the complexity of the hazard chains can be overwhelming, the second method is more robust and less data intensive.

The studies of Tarvainen et al. (2006) and dePippo et al. (2008) provide interesting examples for the "second way" to investigate the hazard coincidences. In both studies, a matrix is used for the identification of possible hazard cascades and influences by opposing the respective processes taken into account (Fig. 2). The possibility of an impact of one hazard on another is identified, and the relation is either simply marked as in the study of Tarvainen et al. (2006), or shortly described as done by dePippo et al. (2008, see Fig. 2).

DHS (2011) integrate in their IRVS approach multi-hazard interaction scores in a matrix. These scores indicate the level of interaction, though without signaling if it is a positive or negative impact. They are created on the basis of built-in weights and building characteristics. High values suggest a potentially high impact and thus indicate that further detailed studies are needed (DHS 2011, pp. 3–10).

The general identification of possible relations between the respective hazards is followed by the determination of the spatial location of these interactions. Tarvainen et al. (2006) locate possible interactions by identifying those areas (NUTS 3 units) in Europe where the potentially interacting hazards overlay and show a significant magnitude. By contrast, DePippo et al. (2008) work with geomorphic units of a coastal area. Based on the matrix, they detect units with certain hazard combinations that might lead to interactions.

Thus, interaction matrixes provide the possibility to identify general relations and cascades within a set of processes and subsequently the location of potential occurrences can be determined by overlay of the spatial hazard information. If, however, potential consequences are to be examined (this refers to the first type of approaches according to

[4] Multi-hazard settings arising from one phenomenon, such as hurricanes that entail storms and heavy rainfall which again may lead to storm surges, flooding and landslides, or volcano eruptions that may imply lapilli and ash ejection, lahars and lava flows, are not considered separately. The reason is that they are covered under the presented concepts.

Fig. 2 "Descriptive matrix of the interaction of each hazard with one another" modified after dePippo et al. (2008, p. 459). In the dialog are the four leading processes located and in the cells between them their possible interaction. The process situated in the same line as the cell describing the relation indicates the causing, the process in the same column the affected process. Example: Surges (cell 3.3) may influence the occurrence of landslides (cell 4.4) as surges "affect a high cliff, both eroding the base (wave-cut notch) and scattering the marine spray along the slope" (cell 3.4—the intersecting cell between 3.3 and 4.4)

Delmonaco et al. 2006a), this approach is insufficient while event trees are a currently used methodology (e.g., Egli 1996 and Marzocchi et al. 2009). With event trees, possible scenarios following an initial event are identified and their probabilities quantified (Marzocchi et al. 2009). According to Egli (1996), event trees are constructed in four steps: (1) the triggering event is determined, (2) the possible following effects are identified, (3) probabilities are assigned to each step, and (4) the probabilities of the possible final states of the whole system are computed. Additionally, inverting this procedure, Egli (1996) proposes the use of fault trees to assess the probability of certain unwanted *top-events*. Thereby, possible partial scenarios are related to the previously defined top-event and their probability of occurrence is estimated (Fig. 3).

These general methods can be applied to a variety of processes, but apart from these, particular approaches for hazard-pair-specific relations exist. For instance, Carrasco et al. (2003) developed a GIS-based methodology to identify cascade areas including floods and landslides. Within this approach, the consequences of the undercutting of slopes or of the damming of torrents are considered. In a first step, the general landslide susceptibility is calculated and displayed. In a second step, gorges (narrow streams and torrents) are identified, and by overlying with the susceptibility map, slopes connected to narrow streams and torrents are determined. Consequently, the delineated areas do not only display "intrinsic" susceptibility, but rather "the possibility of external contribution by undercutting has been added" (Carrasco et al. 2003, p. 377). Finally, it is also considered that displaced material possibly converts into a debris flow or torrential flood.

Huggel et al. (2004) investigated in how far ice avalanches and mobilized periglacial debris might trigger lake outbursts. For this purpose, only those ice avalanches and debris flows are considered that are large enough to cause an overtopping or even a complete emptying of the lake. The principal target is to determine those areas potentially prone to critical situations during such an event.

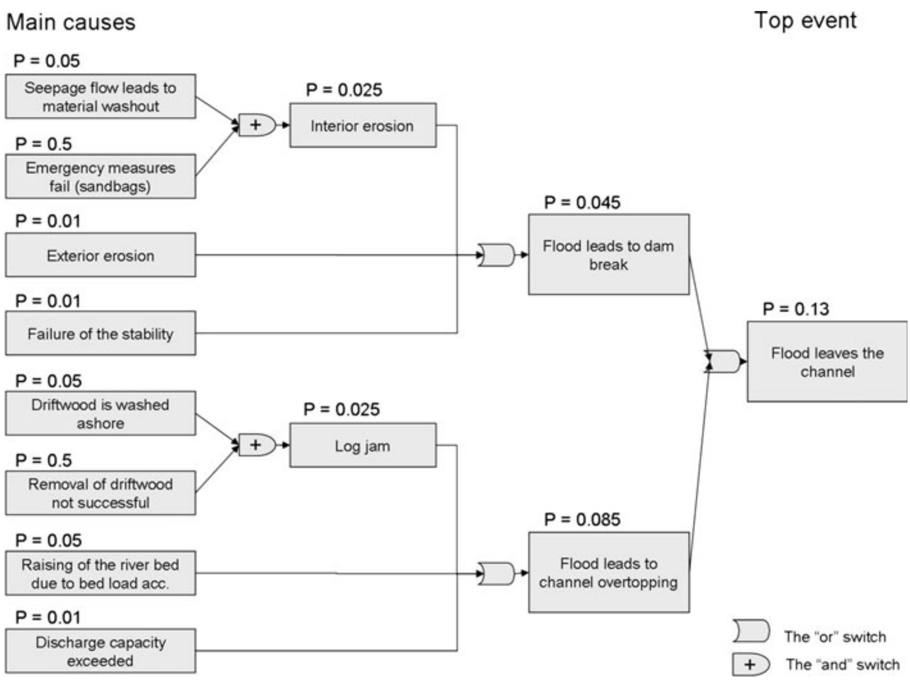

Fig. 3 The example of a fault tree after Egli (1996)

One of the most prominent cascades is the triggering of landslides by earthquakes. In studies such as Harp and Wilson (1995), Keefer (2002), or Meyenfeld (2008), the objective is to determine minimum earthquake magnitudes for landslide initiation as well as the general stability of slopes under earthquake influence. ARMAGEDOM, a French tool developed for earthquake modeling, includes a module to identify slope instabilities potentially triggered by earthquakes (Sedan and Mirgon 2003).

With their research on increased flood and debris flow frequency due to forest fires, Cannon and deGraff (2009) exemplify that the disposition of one hazard can be altered by another hazard. They investigate recurrence intervals and rainfall threshold intensities for the initiation of debris flows and floods shortly after fires and in time steps during the recovery phase. In a second step, they compare their findings with thresholds of unburned settings. The results indicate that the thresholds for burned settings are significantly lower, thus suggesting the need for fast post-fire identification of the most critical locations in order to prevent damages and losses from debris flows and floods. Bovolo et al. (2009) investigate a similar case, firstly modeling possible forest fire scenarios resulting from four different ignition points, and secondly estimating the effect on hydrology, sediment yield, and erosion with the SHETRAN approach (Ewen et al. 2000).

Garcin et al. (2008) considered a raised sea level due to climate change and developed a forecast of future (around the year 2100) marine submersion of coastal areas due to storm surges and tsunamis.

Within the SEDAG project (SEDiment cascades in Alpine Geosystems), Wichmann et al. (2009) examine the sediment pathways in high mountain areas. Investigated phenomena include hill slope processes, channel fluvial processes, debris flows, full-depth snow avalanches, rock fall, landslides, and slow mass movements (Wichmann and Becht

2003; Wichmann et al. 2009). The processes are modeled independently, and respective geomorphic process units (erosion, transport, and deposition) are subsequently delineated. Linkages between two and more processes, for example, rock fall deposits accumulating in debris flow erosion area units and thereby providing material, are identified by overlaying.

An integrated approach is applied within the CAPRA software (Central American Probabilistic Risk Assessment, CEPREDENAC et al. 2011), which offers modules for the analysis of earthquakes, hurricanes, rainfall, volcanic hazards, landslides, and floods. Thereby, the modules are related according to triggering effects between hazards; for instance, the earthquake and the rainfall modules are related to the landslide module (Fig. 4). Thus, the result from one module directly feeds into the subsequent module.

Evidently, the consideration of relations between hazardous processes is a challenging task. So far, two main approaches were identified: the investigation of hazard coincidence and thus possibility of relations, and the development of detailed hazard chains. However, their rigorous implementation is still rare and challenging.

In summary, the comparison of hazards is difficult due to different process characteristics. Classification and index schemes help to overcome this problem; however, they are specifically elaborated for one purpose and/or type of stakeholder and can thus only be applied in the respective specific context. Menoni (2006, p. 10) concludes that “[i]t is hard to find common units of measures” that are useful for emergency managers as well as urban and regional planners since they “face specific problems provoked by hazards in a given context.” A possible solution to this problem is to analyze multi-hazard risk instead of multi-hazard. Risks, although emerging from different hazards, are directly comparable since they describe and/or quantify the possible consequences in numbers or probabilities of loss of life, injury, damages, etc. For the calculation of risks, the possible impact of hazards has to be related to the vulnerability of, for example, people, buildings, and infrastructure. Risk is, as highlighted in the definition by Varnes (1984), a function of

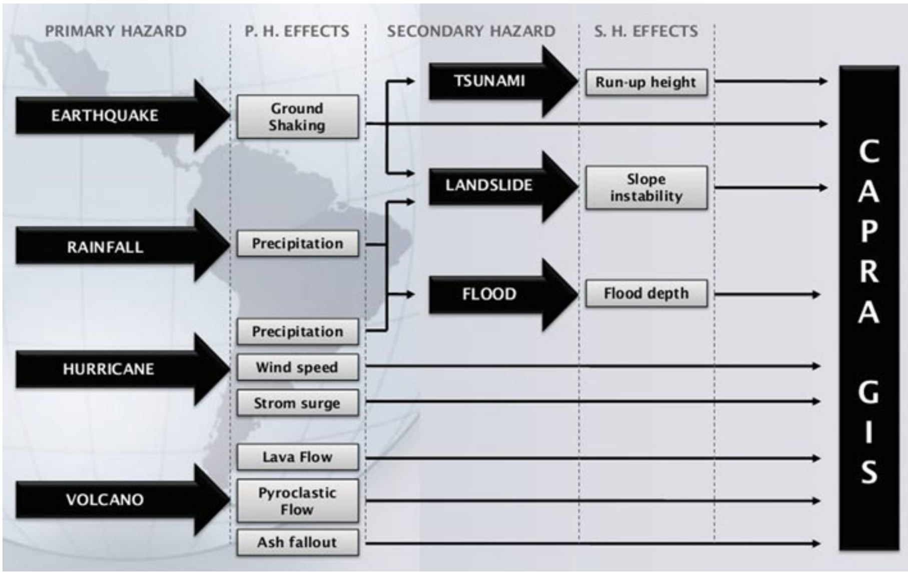

Fig. 4 Modules of the CAPRA software and their relations (Bernal 2010)

hazard and vulnerability of the elements at risk. Therefore, vulnerability is a one key element in risk analysis, and in the following, physical vulnerability approaches proposed in a multi-hazard context will be reviewed.

2.2 Analyses of the physical vulnerability for multiple hazards

As indicated by a recent review of Papathoma-Köhle et al. (2011), a wide variety of approaches and methods exist for the vulnerability assessment of different hazards. However, the primary objective in the multi-hazard context is the comparability of single-hazard risks, and to achieve this goal, a joint analysis approach with equivalent single-hazard vulnerability assessment methods is required. An additional challenge vulnerability assessments face in a multi-hazard setting is spatiotemporal relations of hazards since they alter the vulnerability.

In this section, current vulnerability approaches in a multi-hazard context are presented, followed by a discussion of the effects of related hazards.

2.2.1 Availability and applicability of physical vulnerability analysis methods in a multi-hazard context

Individual process characteristics require not only adjusted methods for hazard analysis, but they also strongly influence the vulnerability approach. While vulnerability and damage assessments for earthquakes are already widely applied (c.f. Calvi et al. 2006), assessments of landslides, coastal erosion, and volcanic vulnerability developed much later are still less frequent and not well-established so far (Glade 2003; vanWesten 2004; Douglas 2007; Foerster et al. 2009). Moreover, the respective study objectives differ fundamentally: For example, in the case of earthquakes, the potential impact of an event is estimated since these incidences can neither be predicted nor prevented, while vulnerability analyses for volcanic or landslide activity are primarily aiming at evacuation and prevention (Foerster et al. 2009). Thus, the development and performance of vulnerability analyses in a multi-hazard context is a challenging task and still only few integrated approaches exist.

The most important approaches to assess physical vulnerability[5] are curves (functions), matrices (coefficients), and indicator-/index-based methods (Foerster et al. 2009). While they are utilized for the multi-hazard context, none of the approaches is equally well applicable to all hazard types. Thus, the method choice is related to the hazard constellation.

Vulnerability curves (frequently also referred to as damage, fragility, or risk curves or functions) need extensive information on damaged buildings. The assessments relate event intensity and resulting damages to a certain building type. Finally, a curve is adjusted to the plotted observations (Menoni 2006). Due to the high data requirement, curves are best applicable for processes with widespread consequences such as earthquakes, storms, or floods, while they are less suitable for local hazards (e.g., rock falls). Thus, they are especially usable for multi-hazard analyses that include extensive and widespread processes. For instance, Grünthal et al. (2006) consider storms, floods, and earthquakes, and the software tool Hazus (HAZards U.S.) provides modules for hurricane, earthquake, and flood risk calculation (FEMA 2011b, c, d).

While curves offer continuous vulnerability information, matrices are discrete approaches (Foerster et al. 2009). They "express [...] the combination of [classified]

[5] Numerical approaches from engineering sciences, which consider individual structural features, are not included.

hazard levels and [stepwise] vulnerability" and are either based on observed damages or based on rough appraisals as in the case of qualitative matrices (Menoni 2006, p. 40). Consequently, the development of matrices is simpler, requires less data, and expert appraisal can be integrated to a higher degree (Menoni 2006; Calvi et al. 2006). In a multi-hazard context, matrices obviously show a wider applicability since they can be developed rather easily or are already available for a wide range of hazard types (Menoni 2006).

Although curves and matrices are commonly used, they share an important constraint: In most cases, only one or two building characteristics are considered (Papathoma-Köhle et al. 2011). The most common characteristic is the building type (wooden, masonry, concrete, or reinforced; e.g., Keylock and Barbolini 2001; Büchele et al. 2006). The integration of building type and condition in Zezere et al. (2008) presents one of few exceptions. Nevertheless, a multitude of further properties such as shape, design, or foundation contributes to the vulnerability of a structure. Indicator approaches overcome this problem by considering several building properties and by combining them to a vulnerability description or quantification of an element at risk (c.f. Kappes et al. 2011). The respective indicators are chosen according to the objective of the study. For instance, Puissant et al. (2006) include building type, height, and function to evaluate the relative damage potential, while Schneiderbauer and Ehrlich (2006) propose indicators such as building age and material, height and size, location of dwelling, etc. In contrast to vulnerability curves and matrices, indicator approaches are used rather qualitatively than quantitatively.

To ensure comparability in a multi-hazard context, a common method has to be chosen for the vulnerability assessment of all different processes. Furthermore, with regard to the comparability of the vulnerabilities for multiple hazards, it is desirable to use the same or at least equivalent criteria for the development of curves, matrices, and especially indicator systems. This implies that a common vulnerability analysis scheme to establish these criteria is needed. Thus, one major challenge is the choice of vulnerability assessment approach and the performance of the analyses in a common scheme. Another significant challenge is the effects that emerge from the relation between hazards. This issue will be presented in the following section.

2.2.2 *Effects of related hazards*

Hazards may overlap spatially and temporally, and arising hazard relations may not only influence the overall hazard level, but also the vulnerability of elements at risk. According to Kappes et al. (2011), three types of settings are distinguished that lead to an alteration of vulnerability levels:[6] (1) the exposure of buildings to multiple hazards, (2) the simultaneous impact of two or more hazards, and (3) the sequential impact on a building of multiple hazards in a short time period.

[6] As in the multi-hazard section, phenomena that entail multiple hazards are not considered separately. The reason is that although during a hurricane event, there will be some community elements that will be exposed to storm tide, some that are exposed to destructive winds, some that are exposed to inundation from either flash flooding or riverine flooding, and some that are potentially exposed to landslide; however, in most cases, no single property will be exposed to all of those hazards. On the contrary, even phenomena that entail only a singular hazard such as earthquake lead to consequential harm-producing effects such as fires or the decontainment of hazardous materials. Thus, it is crucial to analyze potential exposure separately from the consideration of vulnerability; still, the methodology to assess exposure for multiple hazards is not specific to the multi-hazard context and is not posing additional challenges and difficulties in comparison with single-hazard analyses, and therefore, exposure is not considered separately in this article. However, the exposure of one building to multiple hazards affects its vulnerability.

(1) Exposure of buildings to multiple hazards: Building characteristics contribute in different ways and to different degrees to the hazard-specific vulnerabilities of a structure. For example, large unprotected windows increment the vulnerability for storms, but conduce to a far less degree to the earthquake vulnerability of this building (Table 5).

Another example is the height of the building, that is, the number of floors: This characteristic is of much higher importance for the earthquake and flood vulnerability than for wind or hail. For buildings within a multi-hazard area, the hazard-specific vulnerabilities for each of the processes have to be taken into account.

(2) The alteration of the vulnerability of a building in case of the simultaneous impact of several hazards: For example, the impact of an earthquake on a building depends on whether it is covered by snow or volcanic ash (e.g., Lee and Rosowsky 2006; Zuccaro et al. 2008), since the load on the roof leads to alterations of the structural properties of the building. These changed properties have to be considered, as separate analyses or the summing up of vulnerabilities cannot capture these modifications. Lee and Rosowsky (2006)

Table 5 Relative contribution of building characteristics to vulnerability (Granger et al. 1999)

Characteristic	Flood	Wind	Hail	Fire	Quake
Building age	***	*****	**	*****	*****
Floor height or vertical regularity	*****	*		****	*****
Wall material	***	***	*****	****	****
Roof material		****	*****	****	***
Roof pitch		****	***	*	
Large unprotected windows	**	*****	****	*****	**
Unlined eaves		***		*****	
Number of stories	****	**		*	*****
Plan regularity	**	**		***	*****
Topography	*****	****		****	***

The number of stars reflects the significance of the contribution

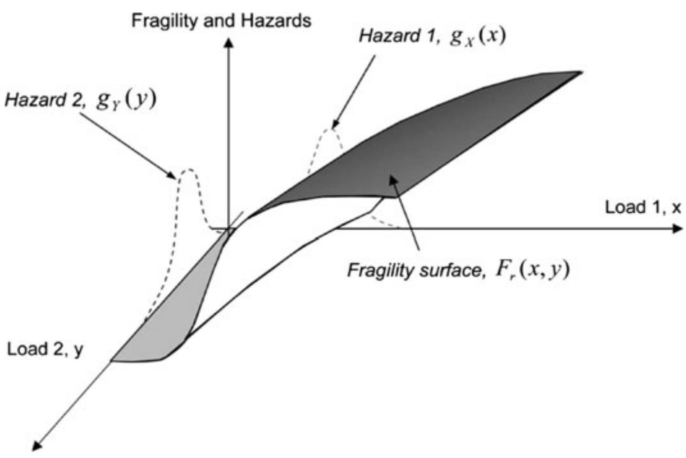

Fig. 5 Fragility surface as function of the combined load of hazard 1 with load 1 and hazard 2 with load 2 after Lee and Rosowsky (2006)

face this challenge by integrating both factors in a *fragility surface*, adding one dimension to the conventional vulnerability or fragility curves (see Fig. 5).

For the hurricane component of Hazus, FEMA developed a combined wind and flood loss assessment methodology in order to avoid "double counting" of damage FEMA (2011c, p. 13–1). This approach is based on the following assumptions: "At a minimum, the combined wind and flood loss must be at least the larger of the wind-only or the flood-only loss" FEMA (2011c, p. 13–43). On the other hand, the loss cannot be higher than the sum of both types of losses or 100 % of the building/content replacement value. These conditions lead to the following formula:

$$\max(W, F) \leq C \leq \min(W + F, 1.00)$$

with the modeled hurricane-only building/contents loss ratio W (as fraction of the building/contents replacement value), the modeled flood-only building/content loss ration F, and the combined wind and flood loss ration C. If the damages are spread randomly and uniformly over the building and the two types of losses can be treated as independent, the combined loss ratio is:

$$C = W + F - W * F$$

For instance in the case of $W = 30$ % and $F = 40$ %, the combined loss ratio $C = 58$ %.

(3) Sequential impacts refer to the cumulative effect of multiple hazard impacts on a building, taking place in a relatively short time period (also referred to as hazard sequence, Zuccaro et al. 2008). One possible impact sequence on a building is the occurrence of an earthquake that leads to first damages, followed by a landslide that has been triggered by the ground movements. As the structure is already affected, the effect of the landslide impact will most probably be higher than in the case of an intact building (Zuccaro et al. 2008). Hence, summing the vulnerabilities or potential damages cannot account for such phenomena.

In summary, the effects of overlapping and related hazards on the vulnerability of elements at risk are still rarely considered and only few approaches and studies on this topic are available. Currently, the topic receives most attention in the engineering field dealing with multi-hazard designs, but also in this context, the number of studies remains low. The topic of hazard sequences is particularly scarcely present in the literature—studies dealing with sequential damages and/or with the separation of the respective impact of each one of the processes (e.g., earthquake followed by tsunami or earthquake followed by landslide) have not been found.

2.3 Multi-hazard risk analyses

Since risk results from the combination of hazard and vulnerability of exposed elements at risk, multi-hazard risk analyses are facing all the previously identified challenges plus those difficulties that arise from combining both components.

In natural and engineering science, risk is a qualitative or quantitative description of expected damages or losses. Thus, in a multi-hazard context, risk has one major advantage: It is not expressed in hazard-specific units but in damage- or loss-specific units such as "expected number of lives lost, persons injured, damage to property or disruption of economic activity" (Varnes 1984, p. 10). As a consequence, risks posed by several hazards are directly comparable and do not need standardization as it is the case for hazard levels. Nevertheless, the type of risk to be computed (e.g., annual probability of loss of life, or potential monetary losses from a certain scenario event) has to be defined from the beginning. This assures the comparability of the single result and allows for combination to

Table 6 Total risk (TR) classes concerning a specific hazard type resulting from contribution of vulnerability (CtV) and exposure (E)

	Low exposure	High exposure
Low contribution of vulnerability	Low total risk	Significant total risk
High contribution of vulnerability	Moderate total risk	High total risk

the overall multi-hazard risk. According to Marzocchi et al. (2012) and the concord during the workshop "Multi-Hazard Risks—status quo and future challenges,"[7] the minimum condition to achieve comparability is the determination of common output metrics and scale of modeling. Marzocchi et al. (2012) use the term *scale,* referring to the space–time window that has to be defined before analyzing a multi-hazard risk. Thereby, *spatial scale* relates to two aspects, the size of the area under investigation and the required level of detail. *Temporal resolution* refers to the time window under consideration, for example, several days with respect to the planning and performance of emergency activities, or several weeks, years, decades, or even centuries for land-use planning activities (Marzocchi et al. 2012). The term *risk metric* describes the type of risk to be studied, that is, direct or indirect, economic, ecological, or social risks. In this context, Marzocchi et al. (2012) primarily refer to quantitative metrics. Nevertheless, qualitative and semiquantitative methods are also in use. Subsequently, (1) qualitative, (2) semiquantitative, and (3) quantitative approaches are presented briefly and several examples given.

(1) Qualitative multi-hazard risk analyses classify hazards and vulnerabilities, which are eventually combined to risk according to a predefined scheme. Two basic requirements for the comparability of the final risk classes are (a) the equivalence of all single-hazard classes and vulnerability classes, and (b) the compatibility of the hazard with the vulnerability classes. In consequence, an overarching analysis scheme is needed (Kappes 2011). A possible application of qualitative approaches for multi-hazard risk is that of the Province of Bolzano (Sperling et al. 2007): Hazard zone plans are derived according to the Swiss method (Heinimann et al. 1998), and vulnerabilities are assigned depending on the land-use type (e.g., built-up area, roads, recreation area). The classified hazard (three classes) and the classified vulnerability (four classes) are combined in a matrix leading to four levels of classified specific risk.

(2) Within the Cities Project (National Geohazards Vulnerability of Urban Communities Project), Geoscience Australia developed a semiquantitative method: Suburbs of one city environment are ranked according to their contribution to the city's risk (e.g., Granger et al. 1999, Middelmann and Granger 2000). Firstly, the hazard exposure is calculated separately for multiple hazards, and the suburbs are ranked according to their contribution to the city's exposure. Secondly, the vulnerability is assessed based on the 'five esses' (shelter, sustenance, security, society, and setting), and the suburbs are ranked again according to their contribution to the city's vulnerability. Finally, both lists of ranks are classified in either high (top 50 % of ranks) or low (bottom 50 % of ranks). Using the predefined matrix (cf. Table 6), the total risk posed by each single-hazard risk for each suburb is calculated.

The final results can be applied for several evaluations: For each suburb the hazard with the highest risk can be identified, the level of risk can be compared between suburbs, and the process with the highest risk for the whole community can be identified.

In the case of semiquantitative index-based approaches, the final risk is not the result of a classification step as in the case of the combination of hazards and vulnerabilities for

[7] December 20–21 2010, University of Vienna, Vienna, Austria.

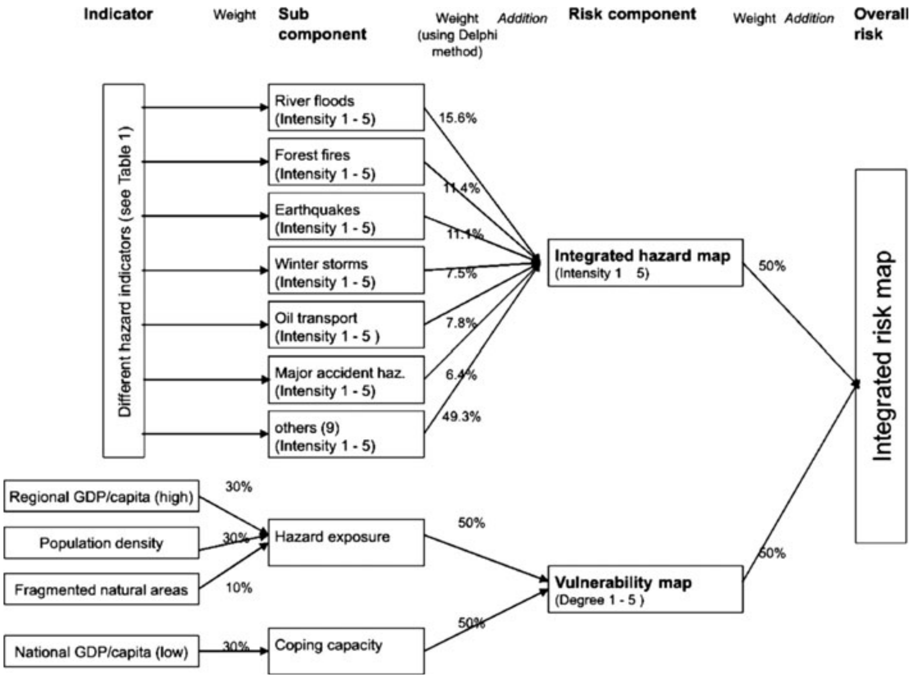

Fig. 6 Calculation scheme of the Integrated Risk Index (Greiving 2006)

qualitative analyses, but of a computation process. Examples of index-based multi-hazard risk analysis schemes are provided by Dilley et al. (2005), Greiving (2006), and Greiving et al. (2006). Dilley et al. (2005) compute hazard and vulnerability as described above and weight the hazard with the vulnerability index to calculate risk. For the derivation of the multi-hazard risk, the single-hazard risks are summed. Greiving (2006) presents the qualitative Integrated Risk Index (IRI) as basis for spatial planning decisions, which also results in the overall risk posed by several processes: All hazards relevant for spatial planning are analyzed, classified in five intensity classes, and the resulting maps are added up equally weighted to the integrated hazard map (Fig. 6).

In contrast to the previously characterized method, weights can be assigned to the single processes according to their importance in the particular area. Greiving (2006) proposes the collaborative elaboration of the weights with the main stakeholders in a Delphi process (Helmer 1966). The vulnerability map originates from two indicators, hazard exposure and coping capacity, which are weighted, added, and subdivided in five classes. The integrated risk matrix then opposes the overall hazard intensity (1–5) to the degree of vulnerability (1–5). Finally, the values are added, leading to the resulting integrated risk (2–10).

In comparison with the qualitative and semiquantitative multi-hazard approaches, multi-hazard risk analyses already take the vulnerability component of elements at risk into consideration. However, the classification and index schemes still exhibit two disadvantages: They are subjective (e.g., the definition of the class thresholds), and they cannot be transferred to other applications. Quantitative methods present a less subjective alternative and thus a broader applicability of the results for decision-making since class thresholds and index ranges do not have to be defined in advance.

(3) Quantitative multi-hazard risk approaches provide information on potential damages or losses. As diverse objectives of different stakeholders have to be met, a multitude of different metrics and formula based on differing parameters has developed. These approaches are especially applied in the (re-)insurance sector as well as in regional or local scale scientific case studies and several few modeling platforms that were explicitly developed to support decision-making.

On a global perspective, there exist three major platforms for the automated computation of multi-hazard risks for the governmental risk management on a national level: Hazus, RiskScape, and CAPRA. These software packages offer guided step-by-step analyses. However, they differ fundamentally with respect to methodology, which is due to different main objectives and expectations of stakeholders.

Hazus (HAZards U.S.) is a software tool developed by FEMA (U.S. Federal Emergency Management Agency, FEMA 2009) for the USA. It is GIS-based, running on ArcGIS and since 2011 available in version 2.1 (FEMA 2011a). It allows for the standardized estimation of potential losses resulting from floods, hurricanes, and earthquakes by means of physically based methods (Baker et al. 1997, FEMA 2011b, c, d). Hazus offers multiple analysis options and levels: The principal option is scenario (deterministic) modeling; however, probabilistic investigations as well as the calculation of annualized losses of all three processes are offered in addition (Schneider and Schauer 2006). Moreover, three analysis levels are available. While at level 1, also referred to as an "out-of-the-box" or default loss estimate, calculations are performed by means of expert-based analysis parameters and national (USA) databases (supplied with the software), at level 2, "[m]ore accurate loss estimates are produced by including detailed information on local hazard conditions and/or by replacing the national default inventories with more accurate local inventories of buildings, essential facilities or other infrastructure" (FEMA 2010). Level 3 includes all improvements of level 2 in addition to "expert adjustment of analysis parameters and use of advanced Hazus capabilities" and results in state-of-the-art loss estimates (FEMA 2010).

In New Zealand, the RiskScape tool has been developed for the modeling of potential multi-hazard losses. It utilizes physically based deterministic approaches, but the aim is an extension toward physically based probabilistic methods (Reese et al. 2007a; GNS and NIWA 2010; Schmidt et al. 2011). RiskScape offers direct and indirect loss quantification as well as an impact assessment including river floods, earthquakes, volcanic activity (ash), tsunamis, and wind storms on people's lives (Reese et al. 2007b). It is designed as flexible and extensible software tool and offers the possibility to plug in additional modules. To facilitate this flexibility, clear specifications of the required in- and outputs and their formats are provided for each module (Schmidt et al. 2011).

CAPRA (CEPREDENAC et al. 2011) is a tool for physically based probabilistic analyses for risk management. It considers earthquakes, hurricanes, volcanic activity, floods, tsunamis, and landslides. CAPRA produces reports on the risk situation (annual expected losses, pure risk premium, loss exceedance curves, and probable maximum losses) for spatial planning purposes, cost-benefit evaluations, or studies on insurance premiums. In addition, it is designed as a platform for communication, understanding, and cooperation with a community of practice that is created around the tool and focuses on the interactive aspect between stakeholders. For these purposes, Web 2.0 technologies have been established, which allow mass collaboration on the tool and analyses. Innovations can rather easily be implemented due to its modular, extensible, and open structure. This reflects the aim to enable an ever-evolving and sustainable "living tool" (GFDRR 2010).

Marzocchi et al. (2009) present a method that focuses on the quantification and comparison of risks on a regional and/or local scale. The specific aim of this method is to identify the most dangerous hazard for a certain area. The first step is to establish a common definition of the boundary conditions for the single-hazard risk analyses (the timeframe and the specific kind of damage). In their case study, in the Casalnova municipality (Italy), they investigate the risk of human life loss in the timeframe of one year. Thereupon, the single risks are quantified for each process. In a next step, the results are compared so that the most threatening ones can be identified. By adding up the single risks, the overall risk to die by one of the investigated processes is quantified.

Additionally to the probability of loss of life per year, Bell (2002) calculated the individual risk to life [probability of loss of life per year], object risk to life [probability of loss of life per year] as well as the economic risk [Icelandic Krona/m^2/a, EUR/m^2/a] emerging from multiple hazards. However, in contrast to Marzocchi et al. (2009), he used a distributed raster-based approach. For the calculation of the overall risk emerging from the multiple hazards, the single risks are summed. Technically, this means that the raster of the single individual risks to life is overlaid and added up to the overall individual risk to life. It is thus possible to compare the results of multiple hazards, to identify the most threatening processes (with regard to their spatial and temporal distribution), and to get an overview of the overall risk (Bell and Glade 2004). In other multi-hazard risk analyses, the collective and individual risks (Bründl 2008) or the economic risk to buildings and infrastructure (Bell 2002) are quantified.

Instead of merely calculating the damage or risk of events of one specific return period, frequency, or exceedance probability, vanWesten et al. (2002) and Grünthal et al. (2006) elaborate continuous damage curves. In their case study for the city of Cologne (Germany), Grünthal et al. (2006) clearly show the utility of such curves, as they capture the characteristics of different processes and help to understand their respective significance. While on the one hand high-frequency events such as floods may indeed lead to high losses, on the other hand, low-frequency processes may result in very high losses as it is the case for earthquakes (Fig. 7).

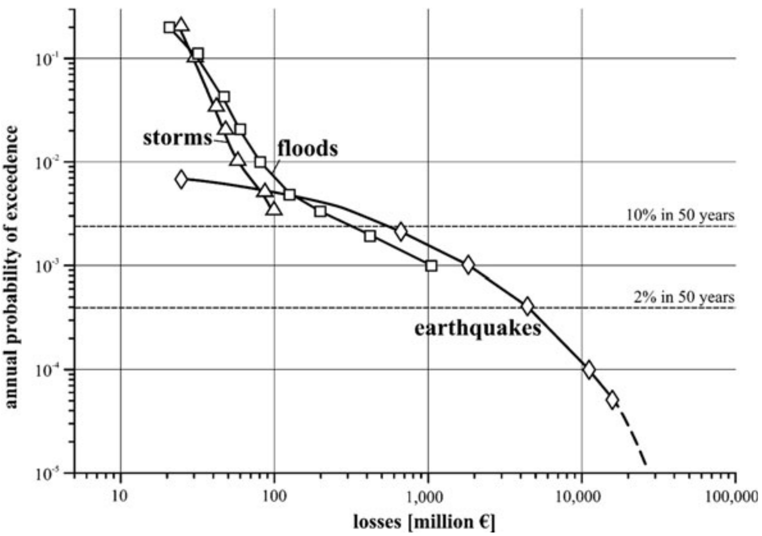

Fig. 7 Risk curves for the total direct monetary losses for buildings and their contents (Grünthal et al. 2006)

In their study, vanWesten et al. (2002) assume that the area under the curve represents the expected annual damage. By comparing the total expected annual losses of different hazards, risks can be ranked. Moreover, by combining the curves of various hazards, a *total risk curve* can be derived. This curve then shows the total expected annual damage from all considered hazards.

Within the (re-)insurance business, various cat-models (catastrophe models) have been developed, so that probably the (re-)insurance sector is most experienced in risk quantification methods. For example, the MRCatPMLService is a tool for accumulating loss potential analyses (of probable maximum losses) based on the models MRQuake, MRStorm, and MRFlood (Munich Re 2000). Additionally, scenarios of historical or hypothetical events can be simulated; the effect on individual portfolios can be derived by deterministic analyses, and the tool offers probabilistic evaluations for calculating loss occurrence probabilities (Munich Re 1998).

Risk Management Solutions (RMS) is a company providing products, services, and expertise for the quantification and management of catastrophe risk to (re-)insurers and catastrophe management professionals (RMS 2009). They offer several products as the Simulation Platform, the RiskLink-ALM (Aggregate Loss Module), and the RiskLink-DLM (Detailed Loss Mode). Furthermore, they provide RiskTools for the smooth integration of RMS products in (re-)insurers' applications.

The Australian Risk Frontiers developed the models FloodAUS (river floods), FireAUS (bushfires), HailAUS (hail), QuakeAUS (earthquakes), and CyclAUS (tropical cyclone winds) for risk analyses (partly probabilistic) and relative risk ratings for (re-)insurers (Risk Frontiers 2008). The risk is rated by the classification of each hazard in a five-point scale, and multi-criteria can be purchased at a range of spatial scales: urban areas, postcodes/CRESTA zones, census collection districts, and company-specific portfolios.

However, it is difficult to access the knowledge and experience of (re-)insurers: Source codes are mostly unavailable as they are intellectual property of the (re-)insurers, and since the development of cat-models is very expensive, model licenses are difficult to achieve (Porter and Scawthorn 2007). This insufficient transparency results in severe limitations of the cat-models such as result dependency to a model, changes of the analyses with new releases, and—most of all—a comparatively minor input and knowledge transfer of (re-)insurance companies to the multi-hazard risk modeling community. This is why the models and tools of the (re-) insurance groups cannot be explained in detail.

In summary, if single hazards have to be compared and summed in a multi-hazard context, this is easier at a risk than at a hazard level: The single risks can be easily compared and combined because of matching units. At the same time, the data requirements are problematic. Firstly, they are especially high for quantitative analyses, secondly, the procedure faces the challenge of interacting hazards, and thirdly, it also depends on a coherent overall vulnerability analysis.

After the calculation of the required hazard or risk product, the final and important step is the communication of the results. In most cases, this means the graphical visualization since descriptions and explanations are more easily communicated when visualized.

2.4 Visualization

One of the principal products of multi-hazard risk studies are maps. They foster the communication of the spatial aspect of this multi-dimensional topic. However, a key question remains: How can all dimensions (namely the multiple hazards) be displayed simultaneously while ensuring that not only the single-hazard patterns are clearly distinguishable, but also their overlapping and coincidences can be illustrated?

Three mapping approaches have been identified within the multi-hazard risk framework (also refer to Kappes 2011): Firstly, the visualization of each single hazard/risk separately, secondly, the reduction in the multi-dimensionality to visualize a combined hazard or risk variable such as the overall hazard or risk, and thirdly, the presentation of more than one process displayed in one map.

In addition to the conventional mapping approach, web-mapping applications provide an alternative visualization method as they offer an interactive definition of the visible layers. Consequently, they gain in importance. In the following, the different approaches are presented:

(1) Single-hazard visualizations refer to sets of maps that display the single hazards or risks one by one. Their advantage is that they offer the possibility to observe and interpret the patterns for each process and in detail. Their main disadvantage, however, is a separation of information, a problem which can at least partly overcome with the method of small multiples (Tufte 2001): Small images are arranged next to each other so that the user is able to compare attributes of several maps. Bartel and Muller (2007) applied this method and juxtaposed the annual occurrence probability of any of the investigated hazards and the most probable hazard type. Thus, it provides information on the specific hazard that is responsible for the threat hotspots. Mostly, single-hazard presentations are followed by the visualization of merged or joined hazards or risks (e.g., Odeh Engineers Inc. 2001; Bell 2002; Dilley et al. 2005). This visualization form is often only the first step, followed by maps that present joint variables.

(2) Maps that visualize a joint variable show, for example, summed, multiplied, counted or maximum hazards, or risks, thus reducing the multi-dimensionality to one parameter. Further approaches are to display the number of relevant processes per pixel (Dilley et al. 2005) or to visualize the annual occurrence probability of any of the hazards (Bartel and Muller 2007). Odeh Engineers Inc. (2001) depict a combined hazard map that results from the sum of all single-hazard scores. In the Swiss hazard zone maps, the highest hazard class is adopted and displayed (Heinimann et al. 1998; Borter and Bart 1999).

For multi-hazard risk, examples include the global distribution of multiple hazards' mortality risk classified from low to high (UN-ISDR 2009). Bell (2002), on the other hand, visualizes the individual risk to life, object risk to life, and the economic risk emerging from multiple hazards calculated by summing the single risks.

(3) In contrast to the previous two options, maps visualizing multiple hazards or risks at once provide simultaneous information on their individual patterns and on spatial coincidences. However, this may impair readability and clearness of the maps: The more components are included, the more difficult it is to differentiate these components by means of different colors, patterns, or sizes. This situation is further aggravated by overlapping hazards or risks.

However, there are a number of approaches that aim at reducing the problem of readability and increasing the benefits. One option is to subdivide the considered range of processes into hazard-type classes. This approach has been followed by the UN-ISDR (2009) where weather-related hazards (floods, tropical cyclones, and droughts) and tectonic hazards (tsunamis, landslides, and earthquakes) were distinguished. Although the assignment of the different processes to the respective class can be questioned and is user- and objective-dependent, the advantage of this procedure is that it reduces the dimensionality from, in this case, six hazards per map to three. Instead of reducing the number of hazards per map, an alternative is to decrease the amount of information per hazard. This then allows to focus on the *most important information* (which varies with respect to the different stakeholders, study objectives, etc.) to be transmitted. For example, in order to provide “a clearer message” concerning those areas that “deserve most attention for mitigation efforts,” BGR and DESDM (2009, p. 46) only show the high (and possibly moderate) hazard zones in their multi-hazard map.

Bell and Glade (2004) depict the outlines of the hazard zones (as lines) within a map showing the total economic risk as areas (as areas; see Fig. 8). Thus, apart from the possibility to identify economic risk hotspots, it is possible to determine the contributing processes.

In the ARMONIA project, a new two-dimensional color scheme has been proposed with which two variables can be simultaneously depicted. Figure 9 gives an example for a color scheme that presents risk, based on monetary and on nonmonetary values (Klein et al. 2006). Nevertheless, this approach can also be applied to the risk emerging from two different hazards to indicate which process contributes to which proportion to the overall hazard or risk.

Garcin et al. (2007) provide a similar approach for the joint visualization of two parameters. They apply a color scheme where each color represents two characteristics: high, medium, low, or no hazard by the first and the second hazard. In their resulting *composite hazard map*, they display the combined sea level rise and tsunami hazard.

In summary, each of the three presented approaches exhibits certain advantages and disadvantages. On the one hand, single-hazard/risk maps allow interpreting each hazard/risk pattern, but it is very difficult to grasp spatial relationships between hazards. On the other hand, those maps with reduced dimensionality offer exactly this joint view, but information on single factors is missing. Finally, multi-dimensional maps that are displaying several hazards/risks might be able to bridge the gap between the two aforementioned approaches; however, they face the problem that the readability of the map

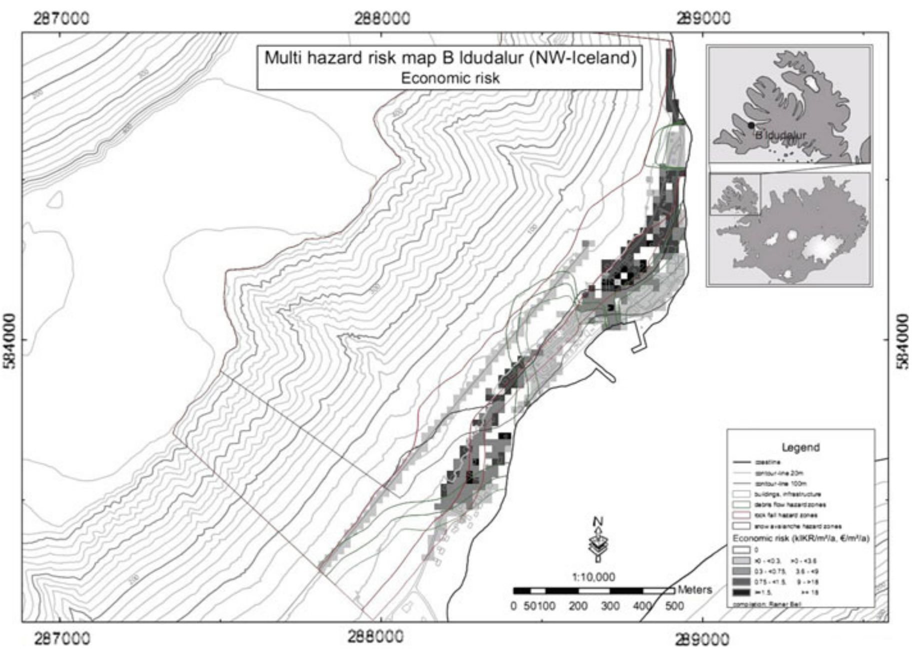

Fig. 8 Multi-hazard risk map after Bell and Glade (2004) showing the outlines of hazard zones and as areas the emerging risks

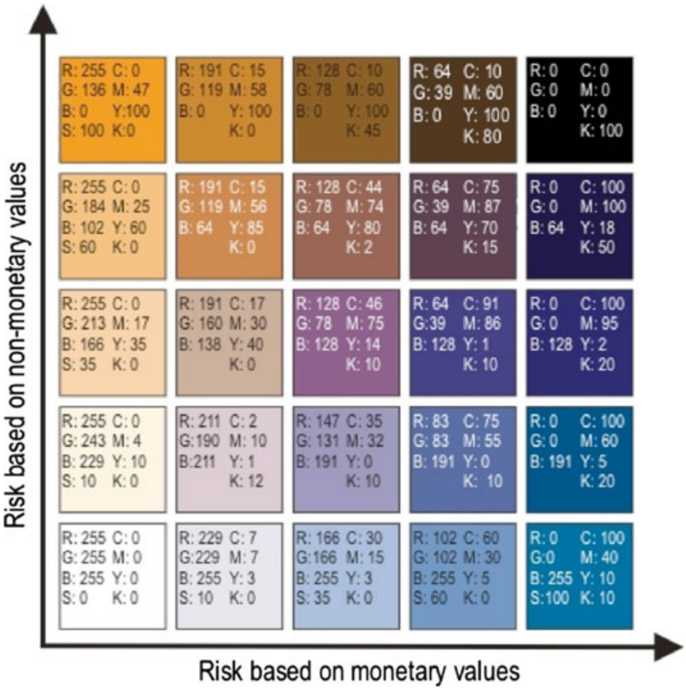

Fig. 9 Color scheme for simultaneous visualization of two aspects (Klein et al. 2006)

decreases with its dimensionality. Thus, only a limited number of different aspects can be visualized in a cognizable way. Thus, we yet have to face the challenge of how to arrange and depict them has to be faced.

(4) In the era of GIS and web-mapping, an alternative to static analog maps are digital interactive and flexible visualizations. Examples include the CEDIM Risk Explorer, Munich Re's NATHAN, CalEMA's MyHazards, or local applications such as the HazardBrowser of the Provincial Office of South Tyrol, Italy (Autonome Provinz Bozen Südtirol 2012). According to Kunz and Hurni (2008), this technique provides a solution to the difficulty of dealing with large data sets in one multi-hazard or multi-risk map.

Within web-mapping applications, it is possible to provide the whole range of single-hazard layer information without loss of content, while at the same time the user is free to choose any hazard or risk combination, and to define a specific area. Furthermore, the user can zoom in and out, and she/he can utilize a stepwise exploration of the provided complex information. However, the advantage of free interactive choice has to be implemented under application of cartographic standards, since negligence of such standards might result in misinterpretation, confusion, and missing readability (Kunz and Hurni 2008). An appropriate graphic user interface may serve as suitable prevention against this negligence, and supplying further information and suggestions might even enhance comprehensibility.

So far, the three different components of multi-hazard risk analyses were reviewed and discussed: multi-hazard, vulnerability for multiple processes, and multi-hazard risk. Additionally, different approaches for the visualization of the results were presented. A number of challenges became apparent within each of the steps and will be recapitulated in the following section.

3 Facing the challenges

Evidently, the analysis of multi-hazard risk is not a simple task. As an important part and basis of risk management, it consists of a number of steps and poses a variety of challenges. A multitude of methodologies and approaches is emerging to cope with these challenges, each with certain inherent advantages and disadvantages. Whatever approach is chosen, it has to be adjusted according to the objectives (e.g., which results are required?) and to the inherent issues (e.g., stakeholder interests), respectively. Thus, the adjustment of the whole framework toward the aspired result, considering the inherent issues, is a fundamental necessity. Hence, right from the beginning, several principal choices have to be made:

The first major choice is the definition of the expected outcome: multi-hazard or multi-hazard risk. This does not only depend on the research objective, but is also a question of data availability. Furthermore, it has to be decided whether a qualitative, semiquantitative, or quantitative outcome is needed. While multi-hazard analyses are commonly restricted to qualitative and semiquantitative approaches, the whole range from qualitative to quantitative methods is available for multi-hazard risk research.

Based on the previous review of different methods and concepts, the following paragraphs summarize the difficulties as well as the related solution approaches:

3.1 Multi-hazard

a. Computation of the overall hazard due to multiple natural processes is difficult since the single processes are generally quantified in different units and measures. Typically, the development of a common standardization scheme (classification or indices, qualitative, or semiquantitative) is used to overcome this difficulty. The standardization procedure is a rather useful approach. Also, in the case of few input data, it is an adaptive method. However, it has to be kept in mind that due to the specificity of the scheme, it is only applicable for the aim it was developed for.
b. If hazards are understood as interacting processes within geosystems, a new perspective has to be adopted. From this point of view, hazard relations might lead to hazard patterns that cannot be captured by summing up separate single-hazard analyses. Rather, multi-hazards can be assessed either by identification of coincidences (overlay) or by detailed scenario development. Moreover, in the development of further approaches, newer concepts such as nonlinearity, complexity, self-organization, and/or self-organized criticality should be considered.

The next step toward risk is the examination of the exposure of elements at risk and their vulnerability for a given process intensity. In this study, the exposure of elements at risk is not investigated in detail since no additional challenges arise in a multi-hazard context and rather, the vulnerability is explored with its inherent challenges and available solutions:

3.2 Vulnerability for multiple hazards

a. Vulnerabilities of elements at risk for multiple hazards vary just as hazard characteristics vary. Thus, the same is true for the methods to assess them, not only with regard to approaches for social and physical vulnerability, but also toward the single threats. Typical approaches in the natural sciences are vulnerability curves, matrices, or indicator-based methods.

b. In case of simultaneously occurring hazard events, the overall vulnerability might be different from single vulnerabilities. A possibility to describe this combined vulnerability is the extension of, for example, two-dimensional vulnerability curves to three-dimensional vulnerability surfaces.

3.3 Multi-hazard risk

The comparison of quantitative risks is much easier than the comparison of hazards as the single risks can be expressed in hazard-independent units. However, a general analysis framework defining which parameter to compare is needed. This framework can be qualitative (classification), semiquantitative (indices), or quantitative (monetary values, probabilities, etc.). Finally, the issue of hazard interactions resulting in amplified risk or differing patterns has to be considered.

3.4 Visualization

The communication of the multi-dimensional results poses a final major challenge. One single map for all kinds of stakeholders and showing all types of hazards within the respective area will surely not match the needs of the involved parties. Several options could be identified, each highlighting another aspect: (a) separate visualization of single hazards/risks, (b) visualization of the overall hazard, risk, probability, etc., (c) joint visualization of a number of hazards and risks according to a certain criteria, and (d) the use of web-mapping tools to let the user choose the combination.

In summary, multi-hazard risk analyses are multipartite and pose a lot of challenges. The choice to compute either multi-hazard or multi-hazard risk, to use a qualitative, semiquantitative, or quantitative approach, respectively, and the selection of the method depend primarily on the objective. However, also practical issues as method availability, scale issues, and data availability complicate the selection. Finally, the decision has to be guided by the awareness of all strengths, weaknesses, and inherent generalizations of the method and possible alternatives. An informed choice is also needed for the decision whether hazard interactions and cascading effects are to be considered or to be neglected. Their implementation is surely difficult, but they obviously have the potential to alter the results of risk analyses considerably. This article presented a range of possible approaches to deal with the challenges, hopefully serving as basis for the development of further (more) coherent multi-hazard (risk) analysis methods.

Acknowledgments The authors are grateful to the European Commission for funding the Marie Curie Research Training Network "Mountain Risks" (http://mountain-risks.eu, contract MCRTN03598) within which this review has be written. The authors also want to thank several persons who contributed to discussions, critics, and explanations: Cees van Westen, Stefan Greiving, Bernard Loup, Stephan Wohlwend, and Ronald Pöppl. We would also like to thank four anonymous reviewers for their constructive and helpful comments on earlier drafts of the paper.

References

Alexander D (2001) Natural hazards. In: Alexander D, Fairbridge R (eds) Encyclopedia of environmental science. Kluwer, Dordrecht, pp 421–425

Altenbach T (1995) A comparison of risk assessment techniques from qualitative to quantitative. In: ASME pressure and piping conference, Honolulu, Hawaii

Ancey C, Gervasoni C, Meunier M (2004) Computing extreme avalanches. Cold Reg Sci Technol 39:161–180
Autonome Provinz Bozen Südtirol (2012) http://www.provinz.bz.it/wasserschutzbauten/wildbachverbauung/hazardbrowser.asp, access 29 January 2012
Baker M, Little A, Hilson J (1997) Multi hazard: identification and risk assessment—the cornerstone of the national mitigation strategy. Tech. rep., FEMA, http://www.fema.gov/library/viewRecord.do?id=2214, available at: http://www.fema.gov/library/viewRecord.do?id=2214
Bartel P, Muller J (2007) Horn of Africa natural hazard probability and risk analysis. Tech. rep, USAID
Bell R (2002) Landslide and snow avalanche risk analysis—methodology and its application in Bíldur. Rheinische Friedrich-Wilhelms-Universität Bonn, NW-Iceland. Master's thesis
Bell R, Glade T (2004) Multi-hazard analysis in natural risk assessments. International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation, Brebbia, C.A., Rhodes, Greece, In, pp 197–206
Bernal G (2010) CAPRA: Multi-hazard approach, http://www.understandrisk.org/ur/node/4573, access 10 June 2011, conference presentation in the Understanding Risk Forum
Besson L, Durville JL, Garry G, Graszk E, Hubert T, Toulement M (1999) Plans de prévention des risques naturels (PPR)—risques de mouvements de terrain: guide méthodologique. Tech. rep., Ministère de l'aménagement du territoire et de l'environnement & Ministère de l'équipement, des transports et du logement
BGR, Desdm (2009) Guidebook for assessing the risks to natural hazards—case study: Province of Central Java. Tech. rep, Bundesanstalt für Geowissenschaften und Rohstoffe and the Geological Agency of Indonesia
Bommer J, Rodríguez C (2002) Earthquake-induced landslides in Central America. Eng Geol 63:189–220
Borter P (1999) Risikoanalyse bei gravitativen Naturgefahren—Methode. Umwelt-Materialien 107/I, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland
Borter P, Bart R (1999) Risikoanalyse bei gravitativen Naturgefahren—Fallbeispiele und Daten. Umwelt-Materialien 107/II, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland
Bovolo CI, Abele SJ, Bathurst JC, Caballero D, Ciglan M, Eftichidis G, Simo B (2009) A distributed framework for multi-risk assessment of natural hazards used to model the effects of forest fire on hydrology and sediment yield. Comput Geosi 35(5):924–945
Bründl M (2008) Risikokonzept für Naturgefahren—Leitfaden. Tech. rep., Nationale Plattform für Naturgefahren PLANAT, Bern, www.riskplan.admin.ch, access 24 January 2009
Bründl M, Bartelt P, Schweizer J, Keiler M, Glade T (2010) Snow avalanche risk analysis—review and future challenges. In: Alcántara-Ayala I, Goudie A (eds) Geomorphological hazards and disaster prevention. Cambridge University Press, Cambridge, pp 49–61
Büchele B, Kreibich H, Kron A, Thieken A, Ihringer J, Oberle P, Merz B, Nestmann F (2006) Flood-risk mapping: contributions towards and enhanced assessment of extreme events and associated risks. Nat Hazard Earth Syst 6:485–503
Calvi G, Pinho R, Magenes G, Bommer J, Restrepo-Vélez L, Crowley H (2006) Development of seismic vulnerability assessment methodologies over the past 30 years. ISET J Earthq Technol 43:75–104
Cannon S, deGraff J (2009) The increasing wildfire and post-fire debris-flow threat in western USA, and implications for consequences of climate change. In: Sassa K, Canuti P (eds) Landslides—disaster risk reduction. Springer, Berlin, pp 177–190
Cariam (2006) Plans de prévention des risques naturels prévisibles (PPR)—cahier de recommandations sur le contenu des PPR. Tech. rep., Ministère de l'Écologie et du Développement durable
Carpignano A, Golia E, Di Mauro C, Bouchon S, Nordvik JP (2009) A methodological approach for the definition of multi-risk maps at regional level: first application. J Risk Res 12:513–534
Carrasco R, Pedraza J, Martin-Duque J, Mattera M, Sanz M, Bodoque J (2003) Hazard zoning for landslides connected to torrential floods in the Jerte Valley (Spain) by using GIS techniques. Nat Hazards 30:361–381
CEPREDENAC, ISDR, IDB, the World Bank (2011) CAPRA Portal (Central American Probabilistic Risk Assessment). http://www.ecapra.org/en/, access 2 July 2011
Chang KT, Chiang SH, Hsu ML (2007) Modeling typhoon- and earthquake-induced landslides in a mountainous watershed using logistic regression. Geomorphology 89:335–347
Chiesa C, Laben C, Cicone R (2003) An Asia Pacific natural hazards and vulnerabilities atlas. In: 30th international symposium on remote sensing of environment
Christen M, Bartelt P, Gruber U (2007) Modelling avalanches. GEO connexion International Magazine pp 38–39
CRED (2009) EM-DAT: Emergency Events Database. http://www.emdat.be/, access 15 July 2009

Dai FC, Lee CF, Ngai YY (2002) Landslide risk assessment and management: an overview. Eng Geol 64(1):65–87
Delattre A, Garancher T, Rozencwajg C, Touret T (2002) Jurisque—prévention des risques naturels. Tech. Rep. 3, Ministere de l'Écologie et du Développement durable
Delmonaco G, Margottini C, Spizzichino D (2006) ARMONIA methodology for multi-risk assessment and the harmonisation of different natural risk maps. Deliverable 3.1.1, ARMONIA
Delmonaco G, Margottini C, Spizzichino D (2006) Report on new methodology for multi-risk assessment and the harmonisation of different natural risk maps. Deliverable 3.1, ARMONIA
dePippo T, Donadio C, Pennetta M, Petrosino C, Terlizzi F, Valente A (2008) Costal hazard assessment and mapping in Northern Campania, Italy. Geomorphology 97:451–466
DHS (2011) Integrated Rapid Visual Screening of buildings. Tech. report, Department of Homeland Security. http://www.dhs.gov/xlibrary/assets/st/st-bips-04-irvs.pdf, access 18th March 2012
Dilley M, Chen U RS Deichmann, Lerner-Lam A, Arnold M (2005) Natural disaster hotspots: a global risk analysis. In: Disaster Risk Management Series, 5, The World Bank
DIN (2009) ISO/IEC 31010: Risk management—risk assessment techniques. Tech. rep., Deutsches Institut für Normung e.V., http://www.previ.be/pdf/31010_FDIS.pdf, access 31st August 2011
Douglas J (2007) Physical vulnerability modelling in natural hazard risk assessment. Nat Hazard Earth Syst 7:283–288
Egli T (1996) Hochwasserschutz und Raumplanung. Schutz vor Naturgefahren mit Instrumenten der Raumplanung—dargestellt am Beispiel von Hochwasser und Murgängen. vdf Hochschulverlag AG, ETH Zürich, oRL-Bericht 100
El Morjani Z, Ebner S, Boos J, Abdel Ghaffar E, Musani A (2007) Modelling the spatial distribution of five natural hazards in the context of the WHO/EMRO Atlas of Disaster Risk as a step towards the reduction of the health impact related to disasters. Int J Health Geogr 6:1–28
Erlingsson U (2005) GIS for natural hazard mitigation—experiences from designing the HazMit GIS expert system suggests the need for an international standard. In: GIS Planet, Portugal
European Commission (2011) Risk assessment and mapping guidelines for disaster management. Commission staff working paper, European Union
Ewen J, Parkin G, O'Connell PE (2000) SHETRAN: distributed river basin flow and transport modeling system. J Hydrol Eng 5:250–258
Fell R, Ho K, Lacasse S, Leroi E (2005) A framework for landslide risk assessment. In: Proceedings of the International Conference on Landslide Risk Management, Vancouver, Canada, pp 3–25
FEMA (1995) National mitigation strategy: Partnerships for building safer communities. Tech. rep., Federal Agency Management Agency, Washington, USA
FEMA (2009) U.S. Department of Homeland Security: FEMA. http://www.fema.gov/, access 19 August 2009
FEMA (2010) HAZUS-MH analysis levels. Department of Homeland Security, Federal Emergency Management Agency. http://www.fema.gov/plan/prevent/hazus/hz_levels.shtm, access 4 July 2012
FEMA (2011a) Getting started with HAZUS-MH 2.1. Tech. rep. U.S. Department of Homeland Security, Federal Emergency Management Agency http://www.fema.gov/library/viewRecord.do?id=5120, access 2 July 2012
FEMA (2011b) Multi-hazard loss estimation methodology: flood model. HAZUS-MH. Technical manual, U.S. Department of Homeland Security, Federal Emergency Management Agency
FEMA (2011c) Multi-hazard loss estimation methodology: hurricane model. HAZUS-MH 2.1. Technical manual, U.S. Department of Homeland Security, Federal Emergency Management Agency
FEMA (2011d) Multi-hazard loss estimation methodology: earthquake model. HAZUS-MH 2.1—Technical Manual. U.S. Department of Homeland Security, Federal Emergency Management Agency
Foerster E, Krien Y, Dandoulaki M, Priest S, Tapsell S, Delmonaco G, Margottini C, Bonadonna C (2009) Methodologies to assess vulnerability of structural systems. Del. 1.1.1., ENSURE, http://eea.eionet.europa.eu/Public/irc/eionet-circle/airclimate/library?l=/public/2010_citiesproject/interchange/project_deliverables/ensure_del111pdf/_EN_1.0_&a=d, access 24 March 2011
Fuchs S, Keiler M, Zischg A (2001) Risikoanalyse—Oberes Suldental, Vinschgau: Konzepte und Methoden zur Erstellung eines Naturgefahrenhinweis-Informationssystems. Innsbrucker Geographische Studien
Garcin M, Prame B, Attanayake N, de Silva U, Desprats J, Fernando S, Fontaine M, Idier D, Lenotre N, Pedreros R, Siriwardana C (2007) A geographic information system for coastal hazards—application to a pilot site in Sri Lanka. Final report BRGM/RP-55553-FR, Bureau de recherches géologiques et minières (BRGM)
Garcin M, Desprats J, Fontaine M, Pedreros R, Attanayake N, Fernando S, Siriwardana C, de Silva U, Poisson B (2008) Integrated approach for coastal hazards and risks in Sri Lanka. Nat Hazard Earth Syst 8:577–586

Garry G, Graszk E, Dupuy JL (1997) Plans de prévention des risques naturels prévisibles (PPR): Guide général. Tech. rep., Ministère de l'Écologie et du Développement durable, http://catalogue.prim.net/146_plans-de-prevention-des-risques-naturels-ppr-guide-general.html, access 8 July 2009

GFDRR (2010) Reducing vulnerability to natural hazards. http://gfdrr.org, access 15 July 2010

Glade T (2003) Vulnerability assessment in landslide risk analysis. Erde 2:123–146

Glade T, Crozier M (2004) A review of scale dependency in landslide hazard and risk analysis

GNS, NIWA (2010) RiskScape—user manual. http://riskscape.org.nz/system/files/Riskscape%20Manual.pdf, access 8 December 2010

Granger K, Jones T, Leiba M, Scott G (1999) Community risk in Cairns: a multi-hazards risk assessment. Tech. rep., Australian Geological Survey Organisation (AGSO), http://www.ga.gov.au/hazards/reports/cairns/, access 19 Febuary 2009

Greiving S (2006) Integrated risk assessment of multi-hazards: a new methodology. In: Schmidt-Thomé P (ed) Natural and technological hazards and risks affecting the spatial development of european regions, geological survey of Finland, vol 42, pp 75–81

Greiving S, Fleischhauer M, Lückenkötter J (2006) A methodology for an integrated risk assessment of spatially relevant hazards. J Environ Planning Manage 49(1):1–19

Grünthal G, Thieken A, Schwarz J, Radtke K, Smolka A, Merz B (2006) Comparative risk assessment for the city of cologne—storms, floods, earthquakes. Nat Hazards 38(1–2):21–44

Harp E, Wilson R (1995) Shaking intensity thresholds for rock falls and slides: evidence from 1987 whittier narrows and superstition hills earthquake strong-motion records. Bull Seismol Soc Am 85:1739–1757

Heinimann H, Hollenstein K, Kienholz H, Krummenacher B, Mani P (1998) Methoden zur Analyse und Bewertung von Naturgefahren. Umwelt-Materialien Nr. 85, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland

Helmer O (1966) The use of the Delphi Technique in problems of educational innovations. Tech. Rep. P-3499, The Rand Corporation, http://www.rand.org/pubs/papers/2006/P3499.pdf, access 3 September 2010

Hewitt K, Burton I (1971) Hazardousness of a place: a regional ecology of damaging events. Toronto Press, Toronto

Hufschmidt G, Glade T (2010) Vulnerability analysis in geomorphic risk assessment. In: Alcántara-Ayala I, Goudie A (eds) Geomorphological hazards and disaster prevention. Cambridge University Press, Cambridge, pp 233–243

Huggel C, Kääb A, Salzmann N (2004) GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery. Nor J Geogr 58:61–73

Hunter N, Bates P, Horritt M, Wilson M (2007) Simple spatially-distributed models for predicting flood inundation: a review. Geomorphology 90:208–225

Kappes M (2011) Multi-hazard risk analyses: a concept and its implementation. PhD thesis, University of Vienna

Kappes M, Keiler M, Glade T (2010) From single- to multi-hazard risk analyses: a concept addressing emerging challenges. In: Malet JP, Glade T, Casagli N (eds) Mountain risks: bringing science to society. Proceedings of the international conference, florence, CERG Editions, Strasbourg, pp 351–356

Kappes M, Papathoma-Köhle M, Keiler M (2011) Assessing physical vulnerability for multi-hazards using an indicator-based methodology. Appl Geogr 32:577–590

Keefer D (2002) Investigating landslides caused by earthquakes—a historical review. Surv Geophys 23:473–510

Keylock C, Barbolini M (2001) Snow avalanche impact pressure—vulnerability relations for use in risk assessment. Can Geotech J 38(2):227–238

Klein J, Greiving S, Jarva J (2006) Integrated natural risk legend and standard for harmonised risk maps for land use planning and management. Deliverable 3.2, ARMONIA, http://arkisto.gtk.fi/UT/ut_europe_2007_81.pdf, access 30 January 2009

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

Lateltin O (1997) Berücksichtigung der Massenbewegungsgefahren bei raumwirksamen Tätigkeiten. Tech. rep., Bundesamt für Raumplanung (BRP), Bundesamt für Wasserwirtschaft (BWW), Bundesamt für Umwelt, Wald und Landschaft (BUWAL)

Lee K, Rosowsky D (2006) Fragility analysis of woodframe buildings considering combined snow and earthquake loading. Struct Saf 28:289–303

Lee CT, Huang CC, Lee JF, Pan KL, Lin ML, Dong JJ (2008) Statistical approach to earthquake-induced landslide susceptibility. Eng Geol 100:43–58

Liévois J (2003) Guide méthodologique plans de prévention des risques d'avalanches. Tech. rep., Ministère de l'Écologie et du Développement et de l'Aménagement

Lin CW, Liu SH, Lee SY, Liu CC (2006) Impacts of the Chi–Chi earthquake on subsequent rainfall-induced landslides in Central Taiwan. Eng Geol 86:87–101

Loat R (2010) Risk management of natural hazards in Switzerland. Tech. rep., Federal Office for the Environment FOEN, http://www.cenat.ch/ressources/planat_product_en_1308.pdf, access 23 July 2010

Loat R, Petrascheck A (1997) Berücksichtigung der Hochwassergefahren bei raumwirksamen Tätigkeiten. Empfehlungen 1997, Bundesamt für Wasserwirtschaft (BWW), Bundesamt für Raumplanung (BRP) and Bundesamt für Umwelt, Wald und Landschaft (BUWAL)

Luino F (2005) Sequence of instability processes triggered by heavy rainfall in the northern Italy. Geomorphology 66:13–39

Marzocchi W, Mastellone M, Di Ruocco A (2009) Principles of multi-risk assessment: interactions amongst natural and man-induced risks. Tech. rep., European Commission, http://www.scribd.com/doc/16902233/Principles-of-MultiRisk-Assessment, access 19 July 2009

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

MEDD (1999) Guide méthodologique plans de prévention des risques d'inondations. Tech. rep., Ministère de l'Écologie et du Développement durable, http://www.prim.net/professionnel/documentation/guide_inond/page01.html, access 25 November 2009

MEDD (2002) Guide méthodologique plans de prévention des risques sismique. Tech. rep., Ministère de l'Écologie et du Développement durable, http://www.prim.net/professionnel/documentation/guide_sismique/page01.html, access 25 November 2009

MEDD (2003) Plans de prévention des risques naturels (ppr)—risques d'inondations. Tech. rep., Ministère de l'Écologie et du Développement durable

Menoni S (2006) Integration of harmonized risk maps with spatial planning decision processes. Deliverable 5.1, ARMONIA

Meyenfeld H (2008) Modellierung seismisch ausgelöster gravitativer Massenbewegungen für die Schwäbische Alb und den Raum Bonn und Erstellen von Gefahrenhinweiskarten. PhD thesis, University of Vienna

Middelmann M, Granger K (2000) Community risk in Mackay: a multi-hazard risk assessment. Tech. rep., Australian Geological Survey Organisation (AGSO), http://www.ga.gov.au/hazards/reports/mackay/, access 19 February 2009

Miles S, Keefer D (2009) Evaluation of camel—comprehensive areal model of earthquake-induced landslides. Eng Geol 104:1–15

Moran A, Wastl M, Geitner C, Stötter J (2004) A regional scale risk analysis in the community of Ólafsfjödur, Iceland. In: Internationales Symposium—INTERPRAEVENT, Riva, Trient

Munich Re (1998) Weltkarte der Naturgefahren. Tech. rep., Münchner Rückversicherungs-Gesellschaft

Munich Re (2000) Topics 2000: natural catastrophes—the current position. Tech. rep., http://www.imia.com/downloads/external_papers/EP17_2003.pdf, access 23 January 2009

Odeh Engineers, Inc (2001) Statewide hazard risk and vulnerability assessment for the state of Rhode Island. Tech. rep., NOAA Coastal Services Center, http://www.csc.noaa.gov/rihazard/pdfs/rhdisl_hazard_report.pdf, access 09 March 2010

Papathoma-Köhle M, Kappes M, Keiler M, Glade T (2011) Physical vulnerability assessment for Alpine hazards—state of the art and future needs. Nat Hazards 58:645–680

Perles Roselló M, Cantarero Prados F (2010) Problems and challenges in analyzing multiple territorial risks. methodological proposals for multi-hazard mapping. Boletín de la Asociación de Geógrafos Españoles 52:399–404

Porter K, Scawthorn C (2007) OpenRisk: open-source risk software and access for the insurance industry. In: 1st International Conference on Asian Catastrophe Insurance (ICACI), Kyoto University, Japan

Puissant A, Malet JP, Maquaire O (2006) Mapping landslide consequences in mountain areas: a tentative approach with a semi-quantitative procedure. In: SAGEO 2006, Strasbourg, France

Reese S, Bell R, King A (2007a) RiskScape: a new tool for comparing risk from natural hazards. Water Atm 15:24–25

Reese S, King A, Bell R, Schmidt J (2007) Regional RiskScape: a multi-hazard loss modelling tool. In: Oxley L, Kulasiri D (eds) MODSIM 2007 International Congress on Modelling and Simulation, pp 1681–1687

Risk Frontiers (2008) PerilAUS II—relative risk ratings for postcodes and CRESTA/ICA zones. Website link to a PowerPoint presentation, http://www.riskfrontiers.com/perilaus.html, access 20 August 2008

RMS (2009) Risk management solutions. http://www.rms.com/, access 16 November 2009

Schmidt J, Matcham I, Reese S, King A, Bell R, Smart G, Cousins J, Smith W, Heron D (2011) Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. Nat Hazards 58: 1169–1192

Schneider P, Schauer B (2006) Hazus—its development and its future. Nat Hazards Rev 7:40–44
Schneiderbauer S, Ehrlich D (2006) Social levels and hazard (in)dependence in determining vulnerability. In: Birkmann J (ed) Measuring vulnerability to natural hazards—towards disaster resilient societies. TERI Press, New Delhi, pp 78–102
Sedan O, Mirgon C (2003) Application ARMAGEDOM. Notice utilisateur BRGM/RP-52759-FR, Bureau de recherches géologiques et minières (BRGM)
Shi P (2002) Theory on disaster science and disaster dynamics. J Nat Disasters 11:1–9
SLF (1984) Richtlinien zur Berücksichtigung der Lawinengefahr bei raumwirksamen Tätigkeiten. Tech. rep., Eidgenössisches Institut für Schnee- und Lawinenforschung & Bundesamt für Forstwesen
Sperling M, Berger E, Mair V, Bussadori V, Weber F (2007) Richtlinien zur Erstellung der Gefahrenzonenpläne (GZP) und zur Klassifizierung des spezifischen Risikos (KSR). Tech. rep., Autonome Provinz Bozen
Tarvainen T, Jarva J, Greiving S (2006) Spatial pattern of hazards and hazard interactions in Europe. In: Schmidt-Thomé P (ed) Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, vol 42, Geological Survey of Finland, pp 83–91
Thierry H (2003) Les plans de prévention des risques naturels ppr. Tech. rep., Ministere de l'Écologie et du Développement durable
Thierry P, Stieltjes L, Kouokam E, Nguéya P, Salley PM (2008) Multi-hazard risk mapping and assessment on an active volcano: the GRINP project at Mount Cameroon. Nat Hazards 45:429–456
Tufte E (2001) Envisioning information. Graphics Press, Cheshire
UN (2002) Johannesburg plan of implementation of the world summit on sustainable development. Tech. rep., United Nations, http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImpl.pdf, access 03 September 2009
UNDHA (1992) Internationally agreed glossary of basic terms related to disaster management. Glossary, United Nations Department of Humanitarian Affairs
UNEP (1992) Agenda 21. Tech. rep., United Nations Environment Programme, http://www.un.org/esa/dsd/agenda21/res_agenda21_07.shtml, access 03 September 2009
UN-ISDR (2005) Hyogo framework for action 2005–1015: Building the resilience of nations and communities to disasters. In: World Conference on Disaster Reduction, Kobe, Hyogo, Japan
UN-ISDR (2009) Global assessment report on disaster risk reduction. Tech. rep., United Nations—International Strategy for Disaster Reduction, http://www.preventionweb.net/english/hyogo/gar/report/index.php?id=9413, access 1 September 2009
vanWesten C (2004) Geo-information tools for landslide risk assessment. an overview of recent developments. In: Lacerda W, Erlich M, Fontoura S, Sayao A (eds) Landslides : evaluation and stabilization—glissement de terrain: Evaluation et Stabilisation: proceedings of the 9th international symposium on landslides, Balkema, London, UK, Rio de Janeiro, Brazil, pp 39–56
vanWesten C, Montoya A, Boerboom L, Badilla Coto E (2002) Multi-hazard risk assessment using GIS in urban areas: a case study for the city of Turrialba, Costa Rica. In: Proceedings of the regional workshop on best practices in disaster mitigation: lessons learned from the Asian urban disaster mitigation program and other initiatives, Bali, Indonesia, pp 120–136
Varnes DJ (1984) Landslide hazard zonation: a review of principles and practice. United Nations Educational, Scientific and Cultural Organisation, Paris
Wichmann V, Becht M (2003) Modelling of geomorphic processes in an alpine catchment. In: Martin D (ed) 7th international conference on geo computation. University of Southampton, Southampton
Wichmann V, Heckmann T, Haas F, Becht M (2009) A new modelling approach to delineate the spatial extent of alpine sediment cascades. Geomorphology 111:70–78
WMO (1999) Comprehensive risk assessment for natural hazards. Technical document 955, World Meteorological Organisation, http://www.planat.ch/ressources/planat_product_en_198.pdf, access 05 May 2010
Zezere J, Garcia R, Oliveira S, Reis E (2008) Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal). Geomorphology 94:467–495
Zuccaro G, Leone M (2011) Volcanic crisis management and mitigation strategies: a multi-risk framework case study. Earthzine 4
Zuccaro G, Cacace F, Spence R, Baxter P (2008) Impact of explosive eruption scenarios at Vesuvius. J Volcanol Geoth Res 178:416–453