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Conceptual Frameworks of Vulnerability Assessment for Natural Hazard Risk Reduction

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1. Introduction

The last few decades have demonstrated an increased concern for the occurrence of natural disasters and their consequences for leaders and organizations around the world. The EM-DAT International Disaster Database [1] statistics show that, in the last century, the mortality risk associated with major weather-related hazards has declined globally, but there has been a rapid increase in the exposure of economic assets to natural hazards.

Looking into more detail, UNISDR's Global Assessment Report 2011 (GAR11) [2] indicates that disasters in 2011 set a new record of \$366 billion for economic losses, including \$210 billion as a result of the Great East Japan Earthquake and the accompanying tsunami alone, and \$40 billion as a result of the floods in Thailand. There were 29,782 deaths linked to 302 major disaster events including 19,846 deaths in the March earthquake/tsunami in Japan (figures presented by other disaster databases for 2011 summary e.g. NATCAT Service – MunichRE, are slightly different but in general agreement). Disaster databases, such as the ones referred to above, represent key resources for actors involved in policy and practice related with disaster risk reduction and response. However, considering their diversity and recognizing their different roles, one can identify at least one limitation in their use i.e. the inclusion criteria which inherently results in many hazard events not being registered. Compiling and analyzing an extensive natural disaster data set for the period 1993 – 2002, Alexander [3] showed that, for example, in the Philippines in 1996 there were 31 major floods, 29 earthquakes, 10 typhoons and 7 tornadoes. Due to population pressure, large areas of Luzon and other islands were denuded of their dense vegetation cover resulting in landslide prone slopes. Twelve major episodes of slope failure causing high damages to infrastructure and build up areas were registered in the archipelago during 1996. Although documentation of the Government expenditures to finance relief efforts for natural disasters during the 1996 – 2002 period is not

completely contained in Figure 1 [4], one can observe that 1996 stands out as a particular year with high costs of rehabilitation.

Experience has shown that considering the frequency of disasters affecting the Philippines, its socio-economic context, and risk culture, the disaster management system tends to rely on a response approach. However, studies indicate that efforts are being made to engage more proactive approaches, involving mitigation and preparedness strategies [4]. In order to achieve this it is thus important to investigate not only the nature of the threat but also the underlying characteristics of the environment and society that makes them susceptible to damage and losses – in other words, the role of *vulnerability* in determining natural hazard risk levels.

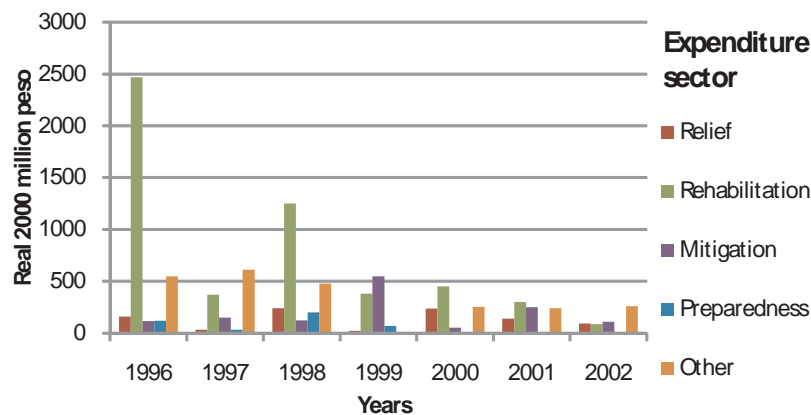


Figure 1. Philippines – annual expenditure under the National Calamity Fund (1996 – 2002) (Based on GDP at price market) [4]

BOX 1: Vulnerability – One term many meanings

In everyday use of language, the term vulnerability refers to the inability to withstand the effects of a hostile environment. The definition of vulnerability for the purpose of scientific assessment depends on the purpose of the study – is it to get a differential picture of global change threats to human well-being in different world regions? Is it to inform particular stakeholders about adaptation options to a potential future development? Is it to show that likelihood of harm and cost of harm have changed for a specific element of interest within the human-environment system? In scientific assessment the term vulnerability can have many meanings, differentiated mostly by (a) the vulnerable entity studied, (b) the stakeholders of the study.

The design of scientific assessment (as opposed to scientific research) has to respond to the scientific needs of the particular stakeholder who might use it [5]. An integral part of vulnerability assessment therefore is the collaboration with its stakeholders [6], [7]. Thus, the specific definition and the method of vulnerability assessment is specific to each study and needs to be made transparent in the specific context. An example set of definitions on vulnerability used in natural hazards risk assessment and global change research is presented in section 2.2, Table 1.

The objective of this work is to discuss and illustrate different approaches used in vulnerability assessment for hydro-meteorological hazards (i.e. landslides and floods, incl. flash floods) taking into account two perspectives: hazard vulnerability and global change vulnerability, which are rooted in the technical and environmental as well as social disciplines. The study is based on a review of recent research findings in global change and natural hazards risk management. The overall aim is to identify current gaps that can guide the development of future perspectives for vulnerability analysis to hydro-meteorological hazards. Following the introduction (section 1), the second section starts with a definition of vulnerability within the context of risk management to natural hazards (sub-section 2.1). Subsequently, various conceptual models (sub-section 2.2) and vulnerability assessment methodologies (sub-section 2.3) are analyzed and compared based on their different disciplinary foci. In the third section, the importance of addressing uncertainty in vulnerability analysis is discussed and lastly general observations and concluding remarks are presented.

2. Conceptual frameworks

2.1. Vulnerability and risk management to natural hazards

According to the UN International Strategy for Disaster Reduction (UNISDR) Report [8], there are two essential elements in the formulation of risk (Eq. 1): a potential event – hazard, and the degree of susceptibility of the elements exposed to that source – vulnerability.

$$\text{RISK} = \text{HAZARD} \times \text{VULNERABILITY} \quad (1)$$

In UNISDR terminology on Disaster Risk Reduction [9], «risk» is defined as the combination of the probability of an event and its negative consequences”. A «hazard» is “a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage”.

Within the risk management framework, vulnerability pertains to consequence analysis. It generally defines the potential for loss to the elements at risk caused by the occurrence of a hazard, and depends on multiple aspects arising from physical, social, economic, and environmental factors, which are interacting in space and time. Examples may include poor design and construction of buildings, inadequate protection of assets, lack of public information and awareness, limited official recognition of risks and preparedness measures, and disregard for wise environmental management.

BOX 2: Risk management frameworks are generally designed to answer the following questions [10]:

What are the probable dangers and their magnitude? (*Danger Identification*)

How often do the dangers of a given magnitude occur? (*Hazard Assessment*)

What are the elements at risk? (*Elements at Risk Identification*)

What is the possible damage to the elements at risk? (*Vulnerability Assessment*)

What is the probability of damage? (*Risk Estimation*)

What is the significance of the estimated risk? (*Risk Evaluation*)

What should be done? (*Risk Management*)

2.2. Vulnerability models

There are multiple definitions, concepts and methods to systematize vulnerability denoting the plurality of views and meanings attached to this term. Birkmann [11] noted that ‘we are still dealing with a paradox: we aim to measure vulnerability, yet we cannot define it precisely’. However, there are generally two perspectives in which vulnerability can be viewed and which are closely linked with the evolution of the concept [12]: (1) the amount of damage caused to a system by a particular hazard (technical or engineering sciences oriented perspective – dominating the disaster risk perception in the 1970s), and (2) a state that exists within a system before it encounters a hazard (social sciences oriented perspective – an alternative paradigm which uses vulnerability as a starting point for risk reduction since the 1980s). The former emphasizes ‘assessments of hazards and their impacts, in which the role of human systems in mediating the outcomes of hazard events is downplayed or neglected’. The latter puts the human system on the central stage and focuses on determining the coping capacity of the society, the ability to resist, respond and recover from the impact of a natural hazard [13]. While the technical sciences perspective of vulnerability focuses primarily on physical aspects [14], the social sciences perspective takes into account various factors and parameters that influence vulnerability, such as physical, economic, social, environmental, and institutional characteristics [8]. Other approaches emphasize the need to account for additional global factors, such as globalization and climate change. Thus, the broader vulnerability assessment is in scope, the more interdisciplinary it becomes.

The different definitions of vulnerability can also be viewed from a functional and subject/object-oriented perspective i.e. considering the end-user of the scientific assessment results (e.g. technical boards, administration officers, representatives from the civil protection, international organizations, etc.) and the vulnerable entity (e.g. critical infrastructure, elderly population, communication networks, mountain ecosystems, etc.).

| Working definitions(s): Vulnerability is... | Source |
|--|------------|
| The degree of loss to a given element at risk or a set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage) | [14] |
| The conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards | [8] |
| The characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from impacts of a hazard | [13] |
| The intrinsic and dynamic feature of an element at risk that determines the expected damage/harm resulting from a given hazardous event and is often even affected by the harmful event itself. Vulnerability changes continuously over time and is driven by physical, social, economic and environmental factors | [11] |
| The degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change | [15], [16] |

Table 1. General definitions of vulnerability used in risk assessment due to natural hazards and climate change

Vogel and O'Brien [17] emphasize that vulnerability is: (a) *multi-dimensional and differential* (varies for different dimensions of a single element or group of elements and from a physical context to another); (b) *scale dependent* (with regard to the unit of analysis e.g. individual, local, regional, national etc.) and (c) *dynamic* (the characteristics that influence vulnerability are continuously changing in time and space). With regards to the first characteristic, there are generally five components (or dimensions) that need to be investigated in vulnerability assessment: (1) the physical/functional dimension (relates to the predisposition of a structure, infrastructure or service to be damaged due to the occurrence of a harmful event associated with a specific hazard); (2) the economic dimension (relates to the economic stability of a region endangered by a loss of production, decrease of income or consumption of goods due to the occurrence of a hazard); (3) the social dimension (relates with the presence of human beings, individuals or communities, and their capacities to cope with, resist and recover from impacts of hazards); (4) the environmental dimension (refers to the interrelation between different ecosystems and their ability to cope with and recover from impacts of hazards and to tolerate stressors over time and space); (5) the political/institutional dimension (refers to those political or institutional actions e.g. livelihood diversification, risk mitigation strategies, regulation control, etc., or characteristics that determine differential coping capacities and exposure to hazards and associated impacts).

During the last decades, various schools of thinking proposed different conceptual models with the final aim of developing methods for measuring vulnerability. The following sub-sections give a short overview of some of the conceptual models presented in [11], such as the double structure of vulnerability, vulnerability within the context of hazard and risk, vulnerability in the context of global environmental change community, the Pressure and Release Model and a holistic approach to risk and vulnerability assessment. Other models not discussed herein are: The Sustainable Livelihood Framework, the UNISDR framework for disaster risk reduction, the 'onion framework', and the 'BBC conceptual framework', the last two developed by UNU-EHS (UN University, Institute for Environment and Human Security).

2.2.1. The double structure of vulnerability

According to Bohle [18] vulnerability can be seen as having an external and internal side (Figure 2). The *external* side is related to the exposure to risks and shocks and is influenced by Political Economy Approaches (e.g. social inequities, disproportionate division of assets), Human Ecology Perspectives (population dynamics and environmental management capacities) and the Entitlement Theory (relates vulnerability to the incapacity of people to obtain or manage assets via legitimate economic means). The *internal* side is called coping and relates to the capacity to anticipate, cope with, resist and recover from the impact of a hazard and is influenced by the Crisis and Conflict Theory (control of assets and resources, capacities to manage crisis situations and resolve conflicts), Action Theory Approaches (how people act and react freely as a result of social, economic or governmental constraints) and Model of Access to Assets (mitigation of vulnerability through access to assets). The conceptual framework of the double structure indicates that vulnerability cannot adequately be considered without taking into account coping¹ and response capacity².

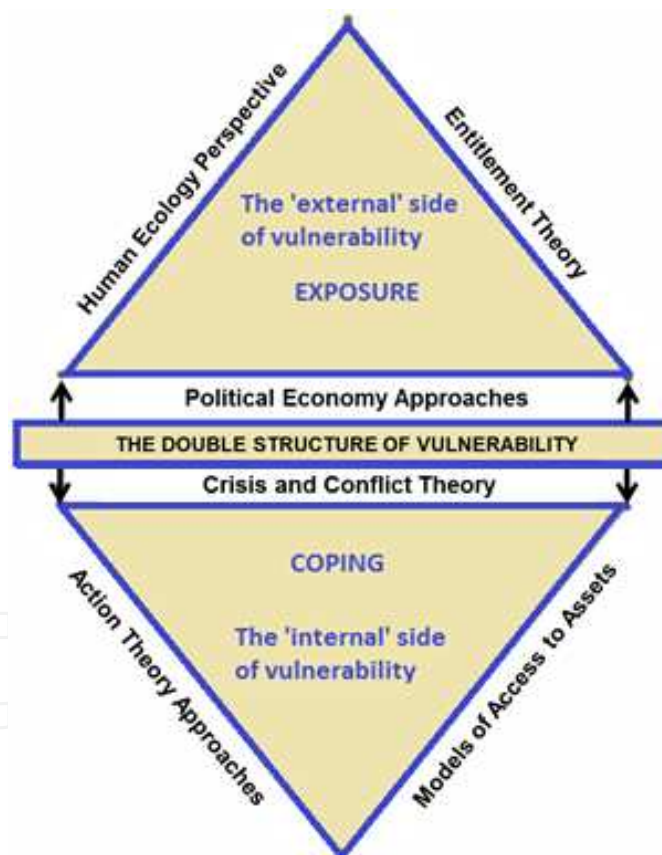


Figure 2. Bohle's conceptual framework for vulnerability analysis [18] in [11]

1 Coping capacity is the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters [8]

2 Capacity is the combination of all the strengths attributes and resources available within a community, society or organization that can be used to achieve agreed goals [8]

2.2.2. Vulnerability within the framework of hazard and risk

The disaster risk community defines vulnerability as a component within the context of hazard and risk. This school usually views vulnerability, coping capacity and exposure as separate features. One example within this approach is Davidson's [19] conceptual framework, adopted in [20] and illustrated in Figure 3. This framework views risk as the sum of hazard, exposure³, vulnerability and capacity measures. Hazard is characterized by probability and severity, exposure is characterized by structure, population and economy, while vulnerability has a physical, social, economic and environmental dimension. Capacity and measures are related with physical planning, management as well as social – and economic capacity.

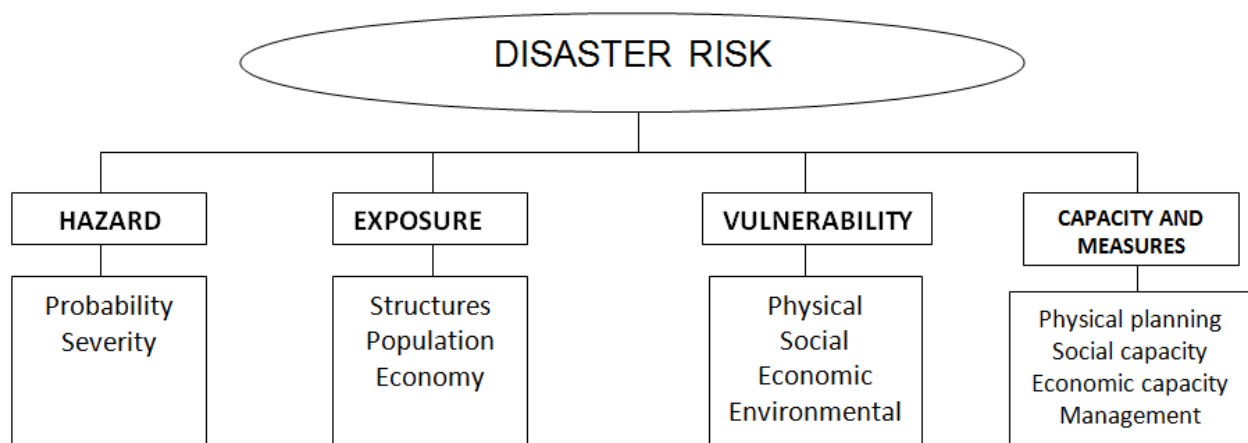


Figure 3. Conceptual framework to identify risk [20] in [11]

2.2.3. Vulnerability in the global environmental change community

Turner [21] developed a conceptual framework considered representative for the global environmental change community primarily due to its focus on the coupled human-environment systems. Their definition of vulnerability encompasses exposure, sensitivity and resilience. Exposure contains a set of components (i.e. threatened elements: individuals, households, states, ecosystem, etc.) subjected to damage and characteristics of the threat (frequency, magnitude, duration). The sensitivity is determined by the human (social capital and endowments) and environmental (natural capital or biophysical endowments) conditions of the system which influence its resilience⁴. The last component is enhanced through adjustments and adaptation.

A system's vulnerability to hazards consists of (Figure 4) (i) linkages to the broader human and biophysical (environmental) conditions and processes operating on the coupled system in

³ Exposure is defined as the totality of people, property, systems or other elements present in hazard zones that are thereby subject to potential losses [8]

⁴ Resilience is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions [8]

question; (ii) perturbations and stressors/stresses⁵ that emerge from this conditions and processes; and (iii) the coupled human – environment system of concern in which vulnerability resides, including exposure and responses (i.e. coping, impacts, adjustments, and adaptation) [21].

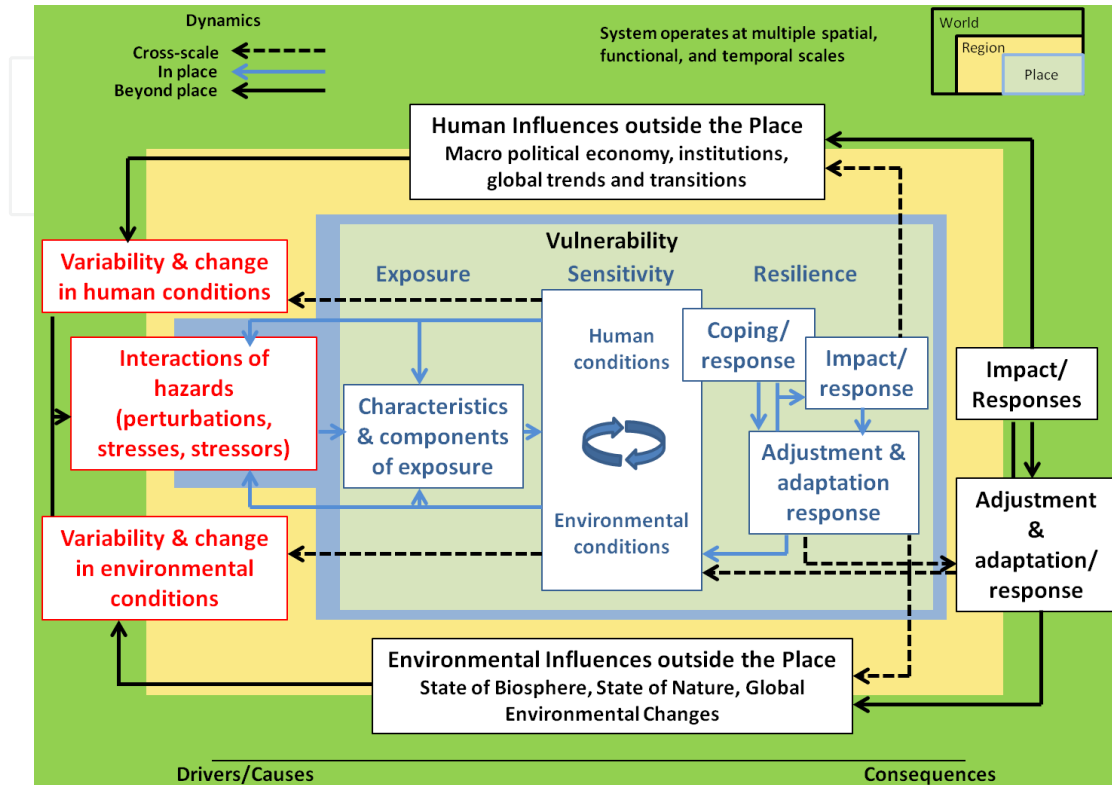


Figure 4. Vulnerability conceptual framework [21] in [11]

2.2.4. The Pressure and Release model (PAR model)

The model operates at different spatial (place, region, world), functional and temporal scales and takes into account the interaction of the multiple perturbations and stressor/stresses [22]. Hazards are regarded as being influenced from inside and outside of the analyzed system; however, due to their character they are commonly considered site-specific. Thus, given their complexity, hazards are located within and beyond the place of assessment. The Pressure and Release model (PAR model) is based on the commonly used equation which defines risk as a function of the hazard and vulnerability (Eq. 1). It emphasizes the underlying driving forces of vulnerability and the conditions existent in a system that contribute to disaster situations when a hazard occurs. Vulnerability is associated with these conditions at three progressive levels: (1) *Root causes*, which can be, for example, limited access to power, structures or resources; or related with political ideologies or economic systems; (2) *dynamic pressures* represented, for example, by demographic or social changes in time and space (e.g. rapid population decrease, rapid

⁵Stress is a continuous or slowly increasing pressure, commonly within the range of normal variability. Stress often originates and stressors (the sources of stress) often reside within the system [21]

urbanization, lack of local institutions, appropriate skills or training); and (3) *unsafe conditions* posed by the physical environment (e.g. unprotected buildings and infrastructure, dangerous slopes) or socio-economic context (e.g. lack of local institutions, prevalence of endemic diseases). In Birkmann's opinion [11], this conceptual framework is an important approach which goes beyond identification of vulnerability towards addressing its root causes and driving forces embedded in the human-environment system.

2.2.5. A holistic approach to risk and vulnerability

In this approach vulnerability is conditions by three categories of factors [23]:

- Physical exposure and susceptibility – regarded as hazard dependent
- Fragility of the socio-economic system – non hazard dependent
- Lack of resilience to cope and recover – non hazard dependent

The authors emphasize the importance of measuring vulnerability from a comprehensive and multidisciplinary perspective. The model (Figure 5) takes into account the consequences of direct physical impacts (exposure and susceptibility) as well as indirect consequences (socio-economic fragility and lack of resilience) of potential hazardous event. Within each category, the vulnerability factors are described with sets of indicators or indices. The model includes a control system which alters indirectly the level of risk through corrective and prospective interventions (risk identification, risk reduction, disaster management, risk transfer).

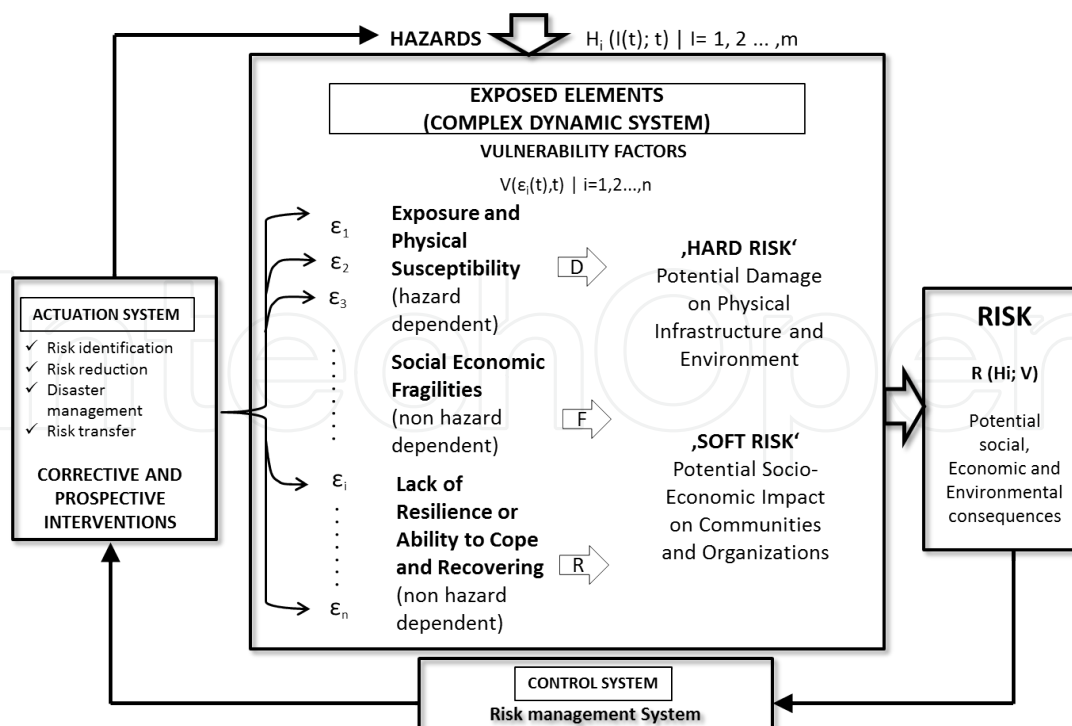


Figure 5. Conceptual framework for holistic approach to disaster risk assessment and management [23] in [11]

The conceptual frameworks described above are different in scope and thematic focus. The vulnerability definition encompasses exposure, coping capacities, sensitivity and adaptation responses in the model of double structure of vulnerability [18] and the global environmental change school model [21], while within the framework of hazard and risk, vulnerability is separated from these characteristics. The holistic approach and the PAR Model indicate factors and conditions of vulnerability able to measure direct physical impacts as well as indirect consequences of disasters. It is obvious that different vulnerability frameworks serve for different disciplinary groups and consequently there is no generally applicable model that can satisfy all specific needs. While our ability to understand vulnerability is enhanced by these conceptual models, only some of them result in paradigms of quantitative or qualitative vulnerability assessment. An illustration of the methods used in physical and social vulnerability evaluation is presented below.

2.3. Vulnerability assessment methods

In the last decades, methods of vulnerability assessment have been developed and tested within the framework of risk analysis, most of them designed for a specific hazard. Research has demonstrated that irrespective of the type of assessment (natural - or social science based), there are some key issues related with the definition of the vulnerable system that must be addressed. Of particular importance is to establish the objective and (time/space) scale of analysis. This will dictate the type of approach (method) employed taking into account data and resource availability. The most detailed vulnerability assessments are conducted at local level, often of individuals or households, but the data required at this level is not readily available. For decisional purposes, regional or national-level assessment can be employed, resulting though in inherent loss of information. An additional issue is the problem of down or up-scaling which implies different levels of generalization and assumption making. This is particularly important when the quality and quantity of data is low because it influences greatly the certainty of the outcome.

Vulnerability is not only site-specific and scale dependent but also varies for different types of hazards (e.g. floods, landslides, earthquakes, tsunamis), due to process characteristics (e.g. generation mode, rate of onset, intensity, area affected, temporal persistence in the environment, etc.) and type of element (or set of elements) at risk. Consequently, the methods used for the evaluation of earthquake vulnerability are not directly transferable to droughts, for example. Vulnerability of exposed objects or systems may vary also for similar processes ([24], [25]). Furthermore, it is acknowledged ([3], [24], [26]) that various types of the same process (e.g. debris flow vs. rock falls for landslide processes, fluvial floods vs. pluvial floods for flood processes) can result in different damage patterns.

An additional factor that must be considered in vulnerability assessment is the target of analysis i.e. the elements at risk. In general terms, these are the objects or systems which pose the potential to be adversely affected [27] by a hazardous event. In [28] the elements at risk are defined as the objects, population, activities and processes that may be differently affected by hazardous phenomena, in a particular area, either directly or indirectly.

Damages or losses caused by the occurrence of hazards can be manifold. In short term, when a disaster strikes, the primary concern are the potential losses due to casualties (fatalities, injuries and missing persons), physical (functional) consequences on services, buildings and infrastructure and direct economic loss. In long term, indirect economic consequences, social 'disturbance' and environmental degradation may become of greater importance. Many consequences cannot be measured or quantified easily. These are referred to as intangible losses (e.g. loss of social cohesion due to disruption of community, loss of reputation, psychological consequences resulting from disaster impacts, cultural effects, etc.). In vulnerability assessment, tangible losses (which can be measured, quantified) are mostly evaluated whereas intangible losses are at best described. The difference between the two types of losses makes their aggregation in a comprehensive consequence analysis very challenging.

In general vulnerability can be measured either on a metric scale, e.g. in terms of a given currency, or a non-numerical scale, based on social values or perceptions and evaluations [24]. Direct human-social and physical losses can be described and quantified using different methodological approaches. A non-exhaustive description of frequently used methods for physical and social vulnerability assessment is given below.

2.3.1. Social vulnerability assessment

The concept of social vulnerability is complex. A number of studies developed within research projects specifically dedicated to measuring social vulnerability to natural hazards (for example, see [29]) showed that there are fundamental differences between the main types of assessment approaches. These are largely based on qualitative or quantitative research traditions which have important differences in their related paradigms.

There are two distinct perspectives on the social dimension in vulnerability assessment: (1) one refers to *intangible losses* and the related elements at risk whose value cannot be easily counted or valued in economic terms. Such factors may be categorized, for example (but are not limited to) in environmental (biodiversity, natural scenery/tourist attractions, environmental assets used in economic activity, etc.), cultural (structures, historical material, sites of particular cultural value/importance, etc.), institutional (loss of both human and material resources related to the functioning of public institutions including health, law enforcement, education and maintenance). Another interpretation refers to (2) *the underlying socio-economic factors in a society causing or producing vulnerability*. Methods in this category may look into the fabric of society to assess its preparedness and coping/adaptive capacity. A wide range of factors may be considered and there is no generally accepted methodology that covers all aspects of social vulnerability. A review of methodologies can be found in [11].

One central role in social vulnerability assessment is attributed to indicator based methods. In [11] a vulnerability *indicator for natural hazards* is defined as 'a variable which is an operational representation of a characteristic or quality of a system able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of an albeit ill-defined event linked with a hazard of natural. Social and environmental indicators research is common in the field of sustainable science. For example, United Nations Development Program's Human Development Index [30], proposes a composite indicator of human well-

being, as well as gender disparity and poverty among nations. Similarly, the World Bank develops indicators that stress the links between environmental conditions and human welfare, especially in developing nations, in order to monitor national progress toward a more sustainable future [31]. In natural hazards risk management framework, many of the indicator based vulnerability studies are relying on measuring attributes or factors influencing vulnerability rather than understanding relationships or processes [32].

The composition and selection of vulnerability indicators is complex. Ideally, there are nine different phases in the development of indicators (Figure 6) [33]: first, a relevant *goal* must be selected and defined. Then, it is necessary to perform a *scoping process* in order to identify the target group and the associated purposes for which the indicators will be used. The third phase presumes the identification of an appropriate *conceptual framework*, which means structuring the potential themes and indicators. The fourth phase implies the definition of *selection criteria* for the potential indicators (see below). The fifth phase is the *identification of a set of potential indicators*. Finally, there is the evaluation and selection of each indicator (phase 6) taking into account the criteria developed at an earlier stage, which results in a final set of indicators. The outcome of previous phases must be validated against real data, which in many cases proves to be the most challenging part of the process due to difficulties in measuring or quantifying some of the intangible elements or aspect of vulnerability (e.g. social cohesion, confidence, etc.). The last phases of the indicator development imply the preparation of a report and assessment of the indicator performance which may results in a re-evaluation of the results (iterative process).

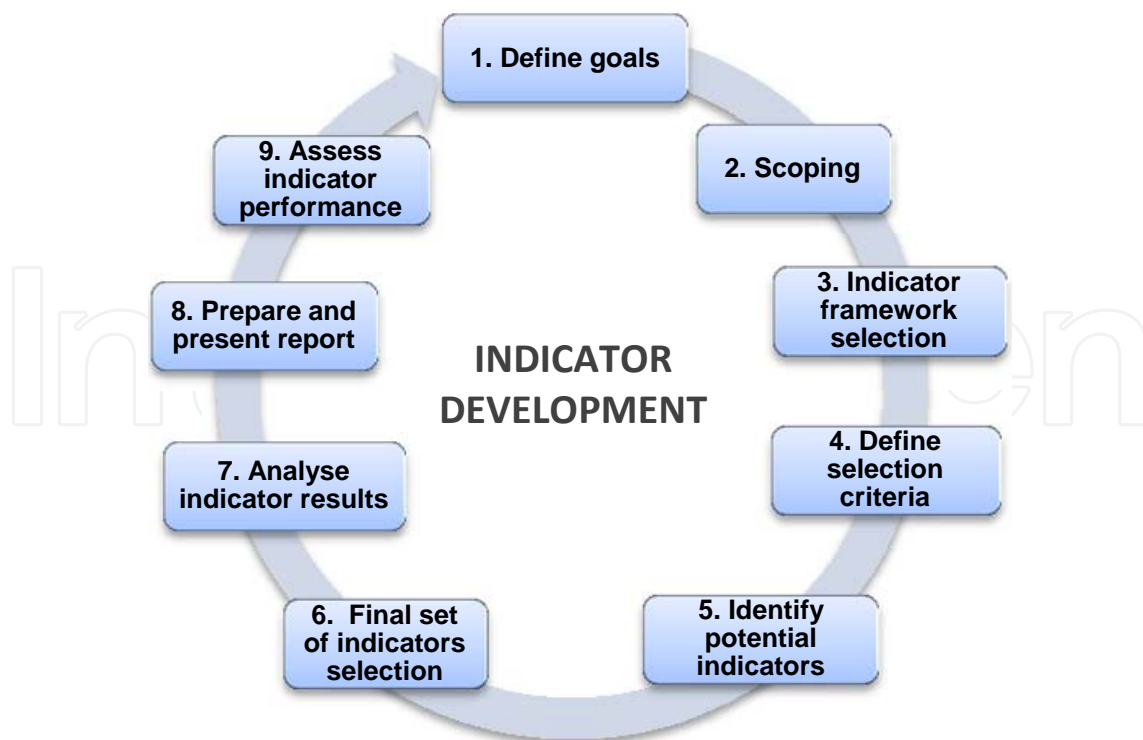


Figure 6. Development process of vulnerability indicators (based on the general figure according to [33] in [11])

Some important quality criteria for indicator and indicator development, as presented in [34], are: sensitivity (sensitive and specific to the underlying phenomenon), relevance, measurability, analytical and statistical soundness, validity/ accuracy, reproducibility, and cost effectiveness. The indicators should also measure only important key-elements instead of trying to indicate all aspects, and permit data comparability (across areas and/or over time).

In order to facilitate the use of indicators for decision-makers and summarize complex or multi-dimensional issues, sets of indices or composite indicators were developed. These are mathematical combinations of sub-indicators that can be easier to interpret than trying to find a trend in many separate indicators. However, there are no generally accepted methods of index aggregation (index construction) and their interpretation is not unique. An extensive description of construction methods and issues related with the combination of indicators is presented in [34].

An example set of factors used to assess social vulnerability at country level based on four main indices is [11]:

- *Disaster Deficit Index* (DDI; expected financial loss and capacity). The key factors describing economic resilience are insurance and reinsurance payments, reserve funds for disasters, aid and donations, new taxes, budgetary reallocations, external credit and internal credit.
- *Local Disaster Index* (LDI; cumulative impact of smaller scale natural hazard events). A uniform distribution of disasters in the area under consideration gives a high value, whereas a high concentration of disasters in a low number of places a low value.
- *Prevalent Vulnerability Index* (PVI; composed of exposure, socio-economic fragility and lack of social resilience). Each of the three components has eight sub-indices. The indices are for example related to population and urban growth, poverty and inequality, import/exports, arable land/land degradation, unemployment, debts, human development index, gender inequality, governance and environmental sustainability.
- *Risk Management Index* (RMI; disaster management/mitigation strategies/systems). This index is composed of four factors estimating capacity related to risk identification, risk reduction, disaster management and financial protection. Sub-indices are related to the quality of, amongst others, loss inventories, monitoring and mapping, public information and training, land use planning, standards, retrofitting, emergency planning and response, community preparedness, reconstruction, decentralized organization and budget allocation.

2.3.2. Physical vulnerability assessment

If in social vulnerability assessment the focus is on determining the indicators of societies' coping capacities to any natural hazard and identifying the vulnerable groups or individuals based on these indicators, in physical (or technical) vulnerability assessment the role of hazard and their impacts is emphasized, while the human systems in mediating the outcomes is minimized. In the technical/engineering literature for natural hazards, physical vulnerability is generally defined on a scale ranging from 0 (no loss/damage) to 1 (total loss/damage),

representing the degree of loss/potential damage of the element at risk (see Table 1). The evaluation of vulnerability and the combination of the hazard and the vulnerability to obtain the risk differs between natural phenomena. However, the majority of models see vulnerability as being dependent both on the acting agent (physical impact of a hazard event) and the exposed element (structural or physical characteristics of the vulnerable object). The most common expressions of physical vulnerability for different types of hazards (landslides, floods, earthquakes) are: vulnerability curves (stage-damage functions), fragility curves, damage matrices and vulnerability indicators [35]. In recent decades, research on flood vulnerability assessment has advanced substantially (especially with the aid of computational techniques) and different modeling approaches ranging from post-event damage observations to laboratory-based experiments and physical modeling have been developed. One major applications of flood vulnerability analysis is the development of guidelines for reducing structural vulnerability for different types of properties. Likewise, the results of these studies are used in spatial development strategies (spatial planning) and for identification of the elements or areas where damages would be expected in case of flood occurrence. There are two main approaches of flood vulnerability assessment: one (1) focuses on the economic damage and is essentially a quantification of the expected or actual damages to a structure expressed in monetary terms or through an evaluation of the percentage of the expected loss; (2) the other, deals with the physical vulnerability of individual structures and on the estimation of the likelihood of occurrence of physical damages or collapse of a single element (e.g. a building). Within the last category, two general methods can be identified:

Empirical methods are based on the analysis of observed consequences (collection of actual flood damage information after the event) through the use of interviews, questionnaires and field mapping. The main advantage of these methods is the use of real data. However, the results are very much dependent on the respondents' risk perception for the first two - and data availability (especially for deriving stage-damage curves) for the last collection method.

In **analytical methods** (i) different flood parameters (duration, velocity, impact pressure, etc.) are directly controlled during laboratory experiments and their effects on the structures are quantified; (ii) numerical models and computer simulation techniques are used to estimate the reliability of a structure and/or calculate its probability of failure (usually hydrologic and hydraulic modeling of the floodplain is a pre-requisite) [36]. This type of approaches are resource demanding (time and money) but allow for a better understanding of the relation between flood intensity and degree of damage for an exposed structure with definite characteristics. Moreover, due to data/resources requirement, they can only be used for assessment of individual structures.

The key parameters used in order to quantify physical vulnerability to floods are related with the forces (buoyancy, hydrostatic pressure and dynamic pressure) that flooding is likely to exert on a structure (e.g. building, bridge, dam, etc.). Directly linked with these forces are the characteristics of the damaging agent (water) which are reflected in a number of actions on the exposed structure: hydrostatic, hydrodynamic, erosion, buoyancy, etc. ([37] in [38]).

The most used approach for assessing and modeling direct flood damages is the stage-damage functions which relates the relative or absolute damage for a certain class of objects

to the inundation depth (Figure 7). One limitation in their use is the assessment of the degree of damage based solely on one characteristic of the exposed element/group of elements (e.g. building type). Likewise, the flood damage influencing parameter e.g. inundation depth, may not be the only hazard indicator that contributes to the quantity of losses [39]. In [40] the importance of further influencing factors like ‘duration of inundation, sediment concentration, availability and information content of flood warning and the quality of external response in a flood situation’ are emphasized. For static floods (slow moving water) the depth is considered to be sufficient for the analysis, but for dynamic floods, velocity is regarded as more important.

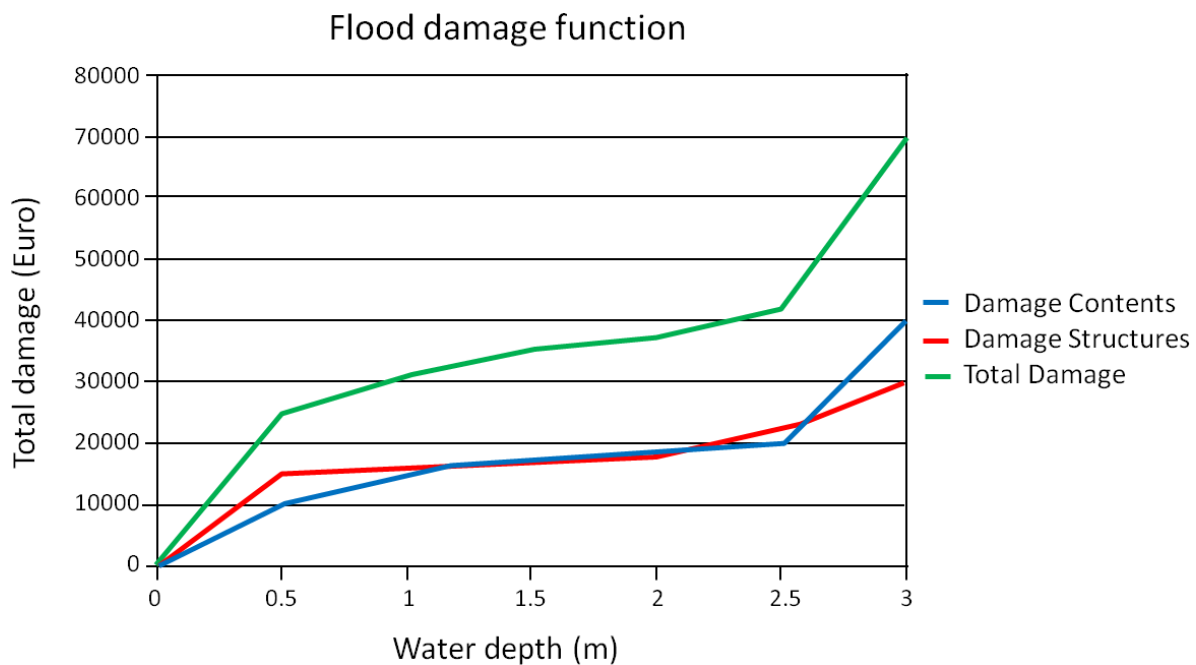


Figure 7. Example of flood damage curves showing damage to structures, contents and total damage as a function of inundation depths [41]

In HAZUS-MH Flood Model [42] the latter parameter is directly considered. A velocity-depth function is included indicating if building collapse has to be assumed. A threshold for collapse corresponding to 100% damage is set, while below this threshold the damage is estimated based on the inundation level only. The model also takes into account the effect of warning which is assessed based on a ‘day-curve’. If a public response rate of 100% is assumed, a maximum of 35% of damage reduction can be achieved depending on the time of warning [26]. The flood hazard module addresses both riverine and coastal floods; flash-floods are not included in the model’s capability.

The Swiss risk concept from the Nationale Plattform Naturgefahren (PLANAT) defines three intensity classes for flood vulnerability analysis, based on flood depth and velocity which are used in spatial planning regulations (Table 2).

| Intensity class | Criteria | Description |
|-----------------|---|--|
| Low | $h < 0.5 \text{ m}$ or $v \times h < 0.5 \text{ m}^2/\text{s}$ | Persons are barely at risk and only low damages at buildings or disruption have to be expected |
| Middle | $2 \text{ m} > h > 0.5 \text{ m}$ or $2 \text{ m}^2/\text{s} > v \times h > 0.5 \text{ m}^2/\text{s}$ | Persons outside of buildings are at risk and damage to buildings can occur while persons in buildings are quite safe and sudden destruction of buildings is improbable |
| High | $h > 2 \text{ m}$ or $v \times h > 2 \text{ m}^2/\text{s}$ | Persons inside and outside of buildings are at risk and the destruction of buildings is possible or events with lower intensity occur but with higher frequency and persons outside of buildings are at risk |

Table 2. Intensity classes based on flood depth and velocity from PLANAT in [26]

Damages caused by landslides to population, environment and built-up areas are significantly less than for other natural hazards due to the inherent characteristic of the process. However, the extent of these losses is frequently underestimated especially when landslides are associated with the occurrence of floods or earthquakes (their consequences tend to be aggregated). Generally, vulnerability to landslides depends on a variety of factors like: runout distance; volume and velocity of sliding; pressure caused by the movement; height of deposition; elements at risk (e.g. different structures), their nature and their proximity to the slide; elements at risk (e.g. persons), their proximity to the slide, the nature of the building/roads they are in [43].

Research in the field of landslide hazard and risk ([24], [44], [45],[46]) has demonstrated that in contrast to other natural processes (flooding, earthquakes) landslide vulnerability is more difficult to assess due to a number of reason, such as:

- i. The complexity and the wide range of variety of landslide processes (landslides are determined by different predisposing and triggering factors which results in various mechanisms of failure and mobility, size, shape, etc.)
- ii. The lack of systematic methods for expressing landslide intensity - there is no general indicator of landslide intensity (e.g. for rock falls, impact pressure or volume can be used whereas for debris flow deposit height is common; other indicators such as flow velocity are rarely considered) and in practice data scarcity reduces their number significantly
- iii. The quantitative heterogeneity of vulnerability of different elements at risk for qualitatively similar landslide mechanisms due to their intrinsic characteristics (here, human life constitutes a special case)
- iv. The variability in spatial and temporal vulnerability

- v. The lack of historical damage databases – usually only events which cause extensive damage are recorded and data about the type and extent of damage is often missing
- vi. Non-physical factors influence the vulnerability of people (e.g. early warning, hazard and risk perception, etc.)

Landslide vulnerability assessment approaches range significantly due to various foci and objectives addressed. Some consider vulnerability within the landslide risk management framework, others evaluate exclusively physical vulnerability. Three general types of methodologies can be identified (without excluding the possibility of other classification schemes):

Qualitative methods ([47], [48], [35]) - given a particular landslide type and the characteristics of the elements at risk, the appropriate vulnerability factor is assessed by expert judgment, field mapping or based on historical records. These methods are flexible (e.g. indicator based methods) valuable and easy to use/understand by decision makers. However, a major limitation of this approach is that most of the data have to be assumed and there is no direct (quantified) relation between hazard intensities and degree of damage.

As an example, in [47] an empirical GIS-based geomorphological approach for landslide and risk analysis was proposed, using stereoscopic aerial photographs and field mapping in order to represent the changes in distribution and shape of landslides and assess their expected frequency of occurrence and intensity. The damages were classified in three classes using a qualitative relationship between landslide intensity/type and their consequences: *superficial* (aesthetic, minor) damage where the functionality of the elements at risk is not compromised and damage can be repaired, rapidly and at low costs; *functional* (medium) damage, where the functionality of the structures is compromised, and the damage takes time and large resources to be fixed; *structural* (total) damage, where buildings or transportation routes are severely or completely damaged, and require extensive (and costly) work to be fixed (demolition and reconstruction may be required).

Semi-quantitative methods are reducing the level of generalization in comparison with qualitative methods. They are flexible and can, to a certain degree, reduce subjectivity, compared with the methods mentioned above. Within this category, damage matrices, for example, are composed by classified intensities and stepwise damage levels. In [49] damage matrices were suggested based on damaging factors and the resistance of the elements at risk to the impact of landslides. Figure 8 shows a correlation, in terms of vulnerability, between exposed elements and the characteristics of the hazard. The applicability of this method, requires statistical analysis of detailed records on landslides and their consequences [50]. This proves to be a challenge in data scarce environments.

Quantitative methods ([51], [52], [53], [54]) are mostly applied at local scale (often, for individual structures) due to complexity of procedures involved and detailed data requirements. Quantitative methods are usually employed by engineers or actors involved in technical decision making, as they allow for a more explicit objective output. The results can be directly integrated in a Quantitative Risk Assessment (QRA) also taking into account the uncertainty in vulnerability analysis. The procedures involved can rely on i) expert judgment (heuristic), ii) damage records (empirical) or iii) statistical analysis (probabilistic).

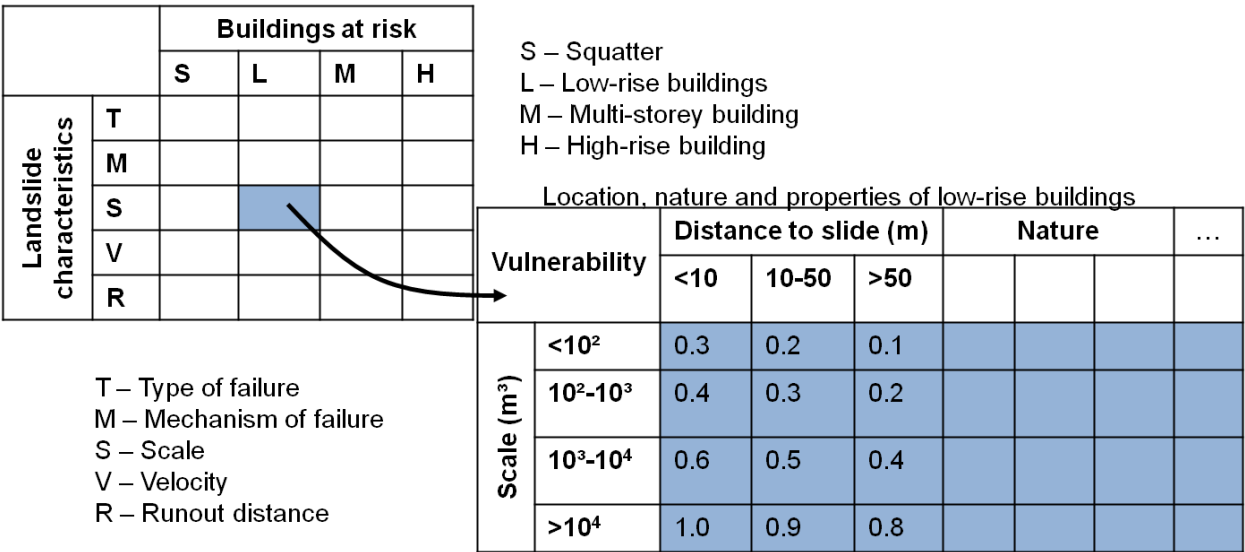


Figure 8. Structural vulnerability matrix [49]

One example of quantitative expert judgment used to evaluate physical vulnerability of roads to debris flows was used in [55]. 147 respondents from 17 countries were asked to use their expert knowledge to assess the probability of a certain damage state being exceeded given that a volume of debris impacts a road (Table 3).

| Description of probabilities | | |
|------------------------------|---|---------------------|
| Descriptor | Description | Values for analysis |
| Highly improbable | Damage state almost certainly exceeded, but cannot be ruled out | 0.000001 |
| Improbable(remote) | Damage state only exceeded in exceptional circumstances | 0.00001 |
| Very unlikely | Damage state will only be exceeded in very unusual circumstances | 0.001 |
| Unlikely | Damage state may be exceeded, but would not be expected to occur under normal circumstances | 0.001 |
| Likely | Damage state expected to be exceeded | 0.01 |
| Very likely | Damage state almost certainly exceeded | 0.1 |

Table 3. Damage state definition [55]

Based on the questionnaire results, fragility curves were produced which relate the flow volume to damage probabilities (Figures 9). It should be noted that in this study probabilities were derived based on the respondents experience only (qualitative data) with no statistical processing of damage observations or analytical/numerical modeling. The results were compared to known events in Scotland (UK) and the Republic of Korea. The major limitation of this method is the high degree of subjectivity, however it advances expert knowledge which might be in some cases the only/most appropriate source of information about damages caused by the impact of landslides.

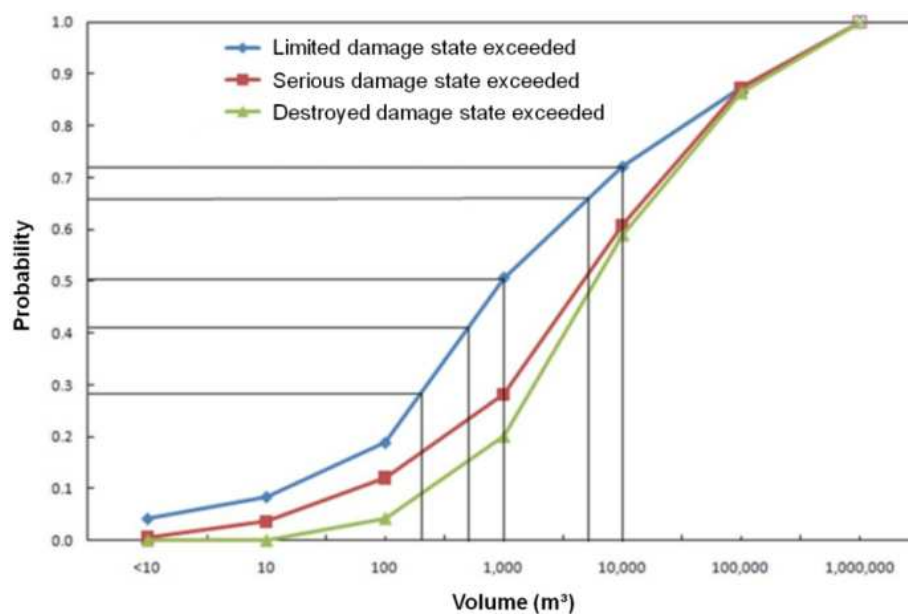


Figure 9. Fragility curves 'forced' to unity and manually extrapolated to the next order of magnitude for volume (local roads). The vertical lines are added at 200, 500, 1000, 5000 and 10000 m³ (illustration only for 'limited damage' curves) [55]

In reference [53], the author performed a study of a well-documented debris flow event which occurred in the Austrian Alps (August, 1997) and derived vulnerability curves for buildings located on the fan of the torrent based on the intensity of the phenomenon and the damage ratio. The intensity was approximated by deposit height and the susceptibility of the element at risk (i.e. buildings) by material of construction (brick, masonry, and concrete). Figure 10 shows the curve produced together with other existing curves for comparison. The application of this vulnerability function is limited to process intensities expressed as deposit height $\leq 2.5 - 3$ m which means that the curve is not relevant for intensities which exceed this value. Nevertheless, the authors argue that such high process intensities generally result in a total loss of the building since the reparation costs will exceed the expenditure necessary for a new construction [53].

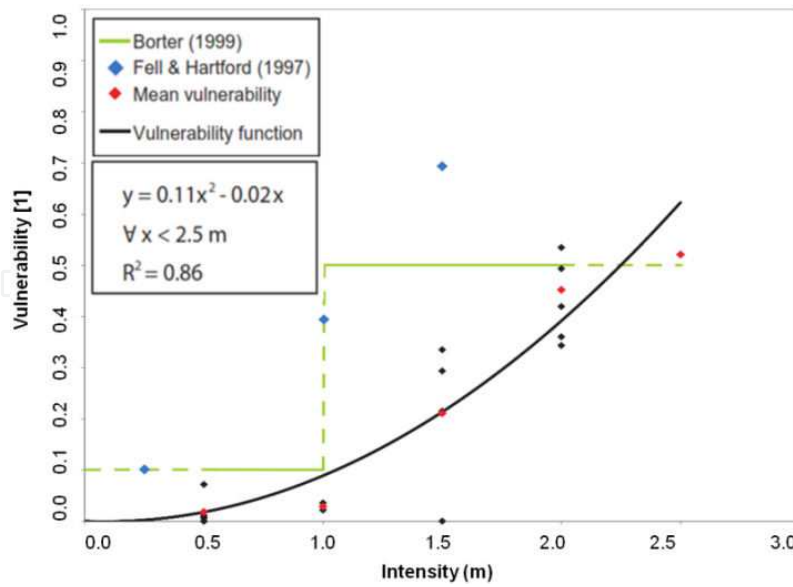


Figure 10. Relationship between debris flow intensity and vulnerability is expressed by a second order polynomial function for flow height > 2.5 m. Results from the study are indicated by black dots, the corresponding mean vulnerability is indicated by red dots [53]

In another study [51], a scenario-based method derived from a probabilistic approach to regional vulnerability assessment [56] was used. The authors defined vulnerability as a function of landslide intensity and the susceptibility of vulnerable elements (see Eq. 2).

$$V = I \bullet S \quad (2)$$

Susceptibility is defined as ‘the lack of inherent capacity of the elements in the spatial extension under investigation to preserve their physical integrity and functionality in the course of the physical interaction with a generic sliding mass’ and is independent of the characteristics of the landslide [51]. The susceptibility model is able to accommodate any factor dictated by the analyzed category of elements at risk. In this study, the susceptibility factors taken into account are: (a) resistance and state of maintenance for structures, and (b) persons in open space and vehicles, population density, income, age, and persons in structures, for individuals. For landslide intensity, a composite parameter is derived based on the kinetic – (related with the damage caused by the impact energy of the sliding mass) and kinematic (accounts for the effects of size-linked features of a reference landslide) characteristics of the interaction between the sliding mass and the reference area proposed. Models for quantification of susceptibility (Eq. 2) and intensity (Eq. 3) are illustrated below:

$$S = 1 - \prod_{i=1}^{ns} (1 - \vartheta_i) \quad (3)$$

where,

ϑ_i is the i -th on n_s susceptibility factor (each defined in the range) contributing to the category susceptibility

and,

$$I = k_s \cdot (r_K \cdot IK + r_M \cdot IM) \quad (4)$$

where,

k_s is the spatial impact ratio (equal to the ratio between the area pertaining to the category that is affected by the landslide and the total area pertaining to the category); r_K and IK are kinetic factors and r_M and IM are kinematic factors. The proposed methodology provided a framework for the quantification of uncertainties in vulnerability assessment.

3. Uncertainty in vulnerability analysis

In natural hazards risk management, decisions regarding the risk associated with a particular hazard are essentially enacted based on limited information and resources. In order to improve this process, experts started to investigate the effects of uncertainty on risk (and its determinants) qualitatively or quantitatively and communicate their results to decision-makers. This one-way approach toward finding solutions for advancing decision making proves out to be insufficient in contrast to the complexity of the problems at hand, especially when dealing with inherent uncertainties or unforeseen changes in the human-environmental system. Nevertheless, effort are being made to reduce the effects of uncertainty on vulnerability (and consequently, risk), particularly related with the data and models used. For example, representing hazard damage potential by only one parameter (e.g. for floods – depth of inundation) can result in overestimations of vulnerability and subsequently in un-economic investments in mitigation countermeasures. One possibility to overcome this problem would be to reduce the uncertainty in the input data by using data-mining approaches (e.g. tree-structured models) for the selection of the most important damage-influencing parameters [39]. Other examples would be the use of scenario analysis for seismic vulnerability and its probable damages in order to develop a hierarchy of effective factors in earthquake vulnerability [57] or testing the performance of different structures (reliability analysis) subjected to the impact of landslides with various intensities through the use of traditional methods like Monte Carlo Simulation (MCS), First Order Second Moment (FOSM), First Order - /Second Order Reliability Method (FORM/SORM). However, the selection of the most appropriate uncertainty modeling approach depends on the level of complexity required by the scope of analysis or the use of the final results.

Generally, uncertainties in decision and risk analysis can be divided into two categories [10]: those that stem from ‘real’ variability in known (or observable) processes or phenomena (e.g. height or the ethnicity of an arbitrary individual in a specified population or the distribution of velocities in a sliding mass, etc.) and those which reside from our limited knowledge about fundamental phenomena (e.g. the nature of some earthquake mechanism, the effect of water

level fluctuation on clay slope stability, etc.). The former is known as aleatory (inherent or stochastic) uncertainty and cannot be reduced. The latter, epistemic uncertainty, includes measurement uncertainty, statistical uncertainty (due to limited information), and model uncertainty, which can be reduced, for example, by increasing the probing samples or by improving the measurement methods or modeling algorithms. Other types of classification systems, together with a review of methods and simulation techniques for uncertainty treatment are critically discussed and illustrated in a work performed by the Norwegian Geotechnical Institute (NGI), in [34]. Uncertainty can be addressed from (1) an integrative perspective, where vulnerability is registered by exposure to hazards but also resides in the resilience of the system experiencing the hazard [58] (bottom-up oriented vulnerability assessment). In this context, uncertainty is associated with future changes (in frequency and magnitude of hazards but also in climatic, environmental and socio-economic patterns) characterized by unknowable risks to which communities must learn to adapt. This approach is centered on the human systems' coping capacity and promotes vulnerability reduction through enhancing resilience to future change. Conversely, (2) a direct approach towards reduction of (epistemic) uncertainty is developed within the technical field (assimilated to deductive, top-down vulnerability assessments), where uncertainty models are defined for each component of vulnerability and the sources of uncertainty categorized [45]. Figure 11 shows how these two approaches of dealing with uncertainty can inform climate adaptation policy: one is (epistemic) uncertainty 'reducer' while the other is uncertainty 'accepting' (due to issues like, for example, timescale and planning horizons, the unit of analysis being considered and the development status of the region or country) [59].

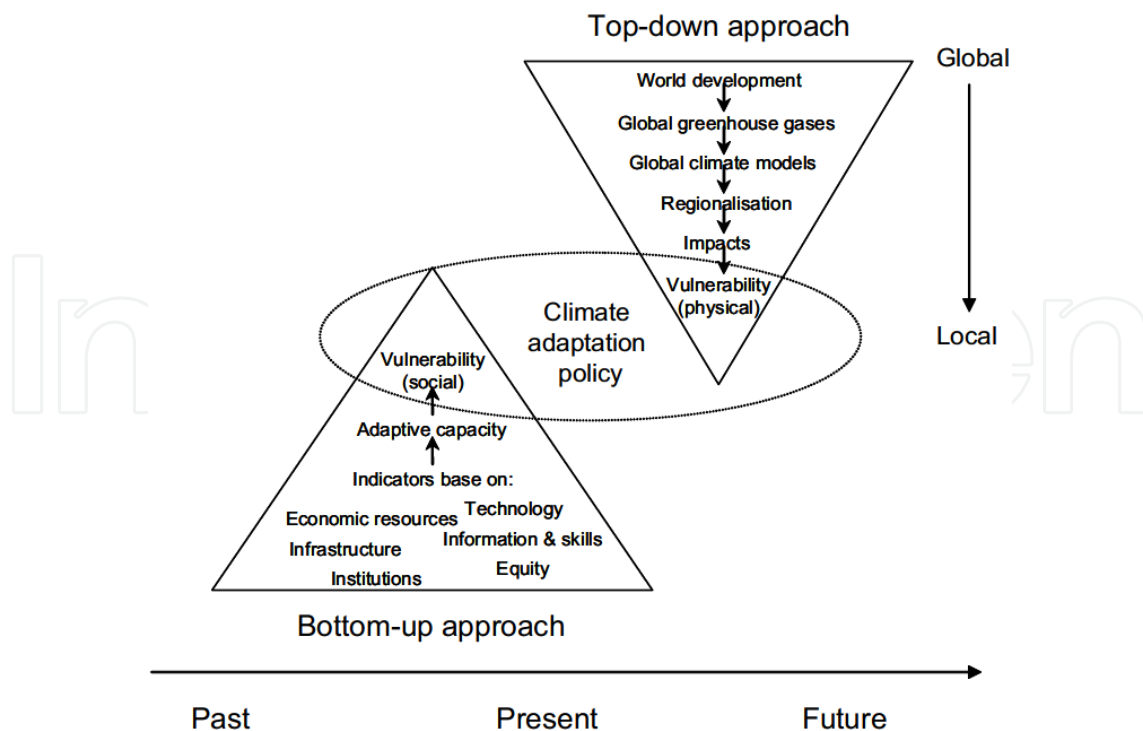


Figure 11. “Top-down” and “bottom-up” approaches used to inform adaptation to climate change [59]

Table 4 illustrates an example of uncertainty sources in physical vulnerability analysis of buildings. It is obvious that these will vary with the methodology used and the quality and quantity of data available.

| Type | Source |
|------------------|---|
| Epistemic | Intensity assessment (using proxies e.g. depth of material, velocity, volume, impact pressure, etc.) Characterization of elements at risk (e.g. structural-morphological characteristics, state of maintenance, strategic relevance, etc.) Estimations of buildings' value and damage costs Vulnerability model (selection of parameters, mathematical model, calculation limitations) Expert judgement |
| Aleatory | Spatial variability of parameters* (e.g. landslide intensities, population density, etc.) |

*also related with the scale of investigation

Table 4. Sources of uncertainty in physical vulnerability to landslides (e.g. for buildings)

Within the general risk assessment framework, uncertainty propagates not only from one component of risk to another but also within the process stages of vulnerability analysis. This is schematically described in a classification system for vulnerability estimation proposed in [34] and represented in Figure 12.

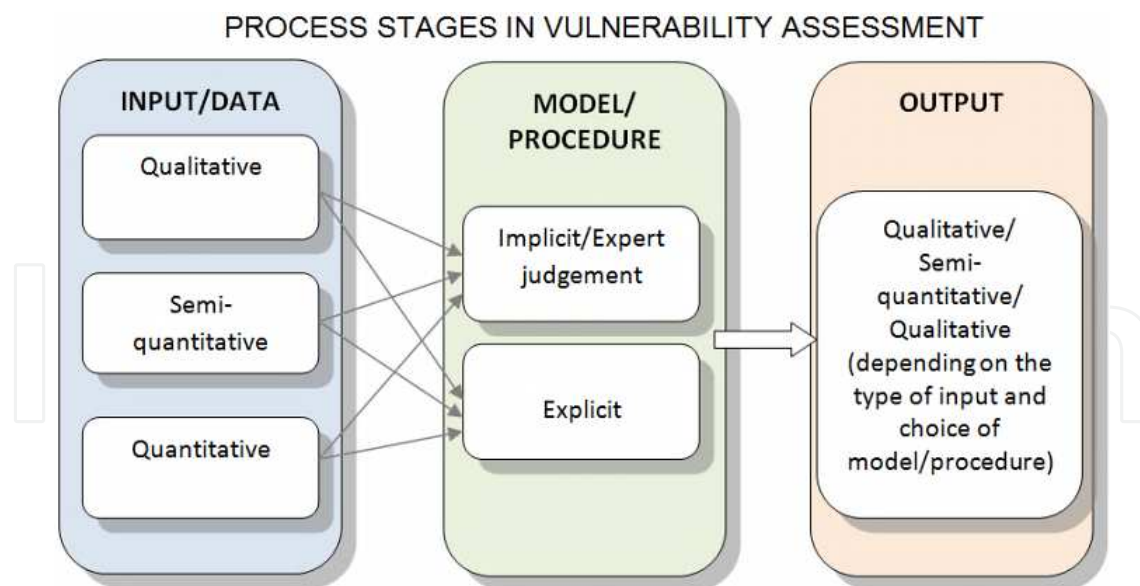


Figure 12. Classification system for vulnerability estimation. Uncertainty is associated with each process stage [34]

According to the authors, uncertainty associated with the input data (depending on the type, quantity and quality), propagates through the model, which also contains a degree of uncertainty due to, for example, expert judgment, mathematical model or basic assumptions. The

uncertainty in the output depends on the two previous process stages as well as the uncertainty related with the interpretation of the results.

4. Conclusions

The most important goal in developing tools for measuring vulnerability is their use in natural hazards risk reduction strategies, thus applying them in decision making processes. In this context, it is necessary to know what is the objective of the assessment, what is the target group of any particular approach, who is using the results and what is their understanding of the outcome. The methods of vulnerability assessment presented herein are mere exemplification of the complexity and wide range of approaches that can be applied in natural hazards disaster risk management. However, based on these a number of observations may be formulated.

Vulnerability defined considering physical exposure or social-economical determinants only cannot encompass the complexity of effects caused by the impact of a natural hazard on an element or group of elements at risk (especially for systems like urban developments, communities, etc.). In an editorial for vulnerability to natural hazards [60] addressed the question of integration between natural and social scientific approaches based on a number of research studies. Their findings show that, studies that are dedicated to different components of vulnerability (e.g. frequency and magnitude of a hazard, elements at risk, exposure, coping and adaptation capacities, etc.) and therefore use different methodological approaches, are relatively similar in scope. Hence it is important to clearly describe and define which components of risk and/or vulnerability assessment are considered in each individual case study. The aim is to communicate without losing the perspective either of the approaches advances. Thus, a step forward towards an integrative vulnerability assessment might be to strengthen the dialogue between different groups of experts in natural hazard vulnerability/risk assessment through exchange of views about definitions, concept and underlying worldviews and values [60].

In terms of vulnerability/risk assessment outcomes, there are three main types of methods (results) - quantitative, semi-quantitative and qualitative, all with benefits and drawbacks. The main difference between quantitative and qualitative methods lies in the fact that quantitative assessments provide a more explicit objective framework which may be conducive to improving decision making process. However, the most appropriate tool depends on the decision problem at hand (for example, qualitative vulnerability assessment can be more cost effective, less time consuming and easier to understand for non-technical stakeholders), the objective (including scale) of the analysis and the quality/quantity of available data. Hence there is no general preference for qualitative, semi-quantitative or quantitative approaches [61]. One must also acknowledge that there is no quantitative vulnerability/risk assessment totally devoid of expert judgment; quantitative vulnerability/risk analysis rather provides a framework for making systematic judgment [62]. It is the quality and quantity of subjectivity that affects the overall outcome of the analysis.

With regards to uncertainty in vulnerability analysis, Gall [63] emphasizes the importance of knowledge quality assessment - 'uncertainty and sensitivity analysis are mandatory for maximizing methodological transparency and soundness, and hence the acceptance of research findings; despite this demand, both analyses are often missing in vulnerability assessment'. However, progress has been done, for example, in the field of technical (structural) vulnerability (mostly, for hazards like floods and earthquakes), where empirical as well as statistical (probabilistic) methods aided by GIS and advanced computational models are used to estimate uncertainty in vulnerability and its components.

To allow for an improved decision making process through the treatment of uncertainty, first the joint effort between end-users and experts must shift towards a more transparent, participative and open process. The role of the scientist seen as 'speaking truth to power' is defective as it implies that all uncertainties can be treated. Conversely, experts should clearly communicate the limitations of their findings as well as continue to investigate the effects of uncertainty on risk and its determinants in order support the community to face future challenges in dealing with natural hazards and risk and global change.

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