ISGSR2007 First International Symposium on Geotechnical Safety & Risk
Oct. 18~19, 2007 Shanghai
Tongji University, China

Quantification of vulnerability to natural hazards

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ABSTRACT: Risk is recognized in both the social sciences and natural sciences as some combination of hazard, vulnerability, exposure and coping capacity. How (and which) components are defined, measured, and evaluated differs greatly between these disciplines, especially in the case of vulnerability and coping capacity. Methods in the natural sciences are generally quantitative. However, an incomplete view of vulnerability and coping capacity is provided because consideration of vulnerability is limited largely to structural fragility and fatality, while consideration of coping capacity is non-existent. Vulnerability and coping capacity are considered in broader detail in social sciences, but due to the resulting complexity qualitative methods are favoured. Risk analysis in the physical sciences could benefit from introduction of simplified and more quantitative adaptations of approaches in the social sciences. Understanding of vulnerability and coping capacity requires clear and consistent risk terminology, which is often lacking between (and within) disciplines. Critical terms related to the conceptualization of risk are identified, explicitly defined, and integrated into a detailed conceptual model of risk. Aspects related to vulnerability and coping capacity not typically addressed in the natural sciences are discussed with consideration of developments in the social sciences. With the context provided by these aspects and the conceptual risk model, a semi-quantitative conceptual framework for vulnerability and coping capacity analysis is proposed. The framework is divided into simplified components considered to holistically represent vulnerability and coping capacity of a system composed of social and physical features. Differentiation of components by theme and unit of quantification facilitates more realistic quantification of individual components. Based on the logical organization of the framework, research priorities relating to vulnerability and coping capacity are identified.

1 INTRODUCTION

There are two fundamentally different perspectives for assessing vulnerability: those that have their roots in natural sciences and those that are based on the social science concepts. In the first perspective, the hazard event is the active agent while the human system is the passive agent in the vulnerability assessment. Thus, an element at risk has a different vulnerability to different hazardous event magnitudes. The natural science perspective of vulnerability dominates the engineering literature, where the emphasis in on the assessment of hazards and their impacts, while the role of human systems in mediating the consequences is often not considered. In natural science approaches, vulnerability is defined as the physical vulnerability of the elements at risk, and it is an important component of consequence evaluation. The engineering approach quantifying the vulnerability of the elements at risk is most advanced in earthquake loss estimation models. "Technical vulnerability", as defined above, is referred to as "fragility" for different types of structures and elements of the built environment. Similar models are being developed for floods and landslides, but they have proved to be much more difficult than for earthquakes due to the extent of the event in time and space.

Ocial science approaches of vulnerability refer to the human system. Attention is directed to the underlying structural factors that reduce the capacity of the human system to cope with a range of hazards, rather than the negative impacts following one specific hazard. There is no unique definition of vulnerability in social sciences. In the recent studies carried out by the UN organisation (UNEP [United Nations Environment Program], ISDR [International Strategy for Disaster Reduction], UNDP [United Nations Development Program]), and the World Bank, vulnerability with respect to natural hazards is assessed on the basis of a series of socio-economic indicators (e.g., Gross Domestic Product [GDP] per inhabitant, Human Poverty Index [HPI], inflation rate, population characteristics such as density, growth, age, life expectancy at birth, illiteracy rate). It is generally accepted that resilience and coping capacity are important factors in societal vulnerability, and that they are difficult to measure and quantify. The approach used when required (for lack of anything better) is to include them as a subset in the vulnerability assessment while acknowledging the fact that social vulnerability cannot easily be expressed in numbers.

It is important, however, not to confuse vulnerability with risk or consequence. Vulnerability assessment is only one component of loss estimation and risk assessment. Risk involves forecasting of loss (and/or gain) and is composed of several components – hazard, vulnerability, exposure, and coping capacity. It is through these proximal features that risk must be addressed. Risk and its components are not specific to any feature or field, but are instead ubiquitous notions applicable to any situation or experience. It is the conceptualization of these components (how they are considered, defined, divided, measured, and recombined) that differs. The notion of risk in this paper follows primarily from views developed in the natural sciences, specifically with regard to natural dangers (often termed natural hazards), with substantial consideration of views from the social sciences and, to a lesser degree, from development and climate change literature.

Which components are considered to contribute to risk and how they are evaluated varies between disciplines. Disparity in consideration of risk reflects differences in the types of losses and sources of hazard of interest. For example, investigations in the social sciences consider a more general view of risk for societies at large and for individuals, while investigations in the natural sciences and engineering give detailed consideration to structural damage to the built environment and to life-loss. In the natural science paradigm emphasis is placed on characterization of hazard and exposure, which is quantitatively strong. Vulnerability is considered a static factor that modifies the amount of loss caused by threats. Coping capacity receives little, if any, attention. In the social science paradigm emphasis is placed on vulnerability and, increasingly, coping capacity, which are considered as dynamic complex properties of a (social) system. Due to the complexity with which these components are considered, qualitative methods are favoured. Hazard is viewed as a static state of the physical/cultural environment and receives minimal attention.

Accurate representations of risk are required to aid loss reduction. Combining the multiple components of risk requires a quantitative approach. Such an approach would utilize the detailed quantitative understanding of hazard and exposure available from the natural sciences and engineering. To reliably contribute to understanding of risk, vulnerability should be realistically and quantitatively represented. Complementary strengths of natural science and social science paradigms can improve understanding and, therefore, analysis of vulnerability. This will be best achieved through an adaptation of comprehensive views of vulnerability in the social sciences to the more quantitative approaches typical of the natural sciences. Simplification of the social science view of vulnerability required for this adaptation is a necessary concession given the benefits of quantization and is justifiable if a realistic characterization of vulnerability can be maintained.

2 CONCEPTUALIZING RISK AND VULNERABILITY

2.1 Terminology

Consistency of risk terminology lacks between the social science and natural science paradigms, but also within each (Lavell, 2003). These trends are exemplified by comparison of the numerous glossaries of risk-related terms that have been developed (c.f. ICG, 2004; IPCC, 2001; ISDR, 2004; ISSMGE, 2004; NOAA, 2007; Thywissen, 2006; UNDHA, 1992). Inconsistencies in terminology and concepts can result from inattention, differing interpretations, differing usage of the terminology, and use of outdated concepts (in light of more recent developments) (Lavell, 2003). Avoidance of these problems would be aided by clear and effective communication of concepts, and explicit definition of the intended use of the terminology. The core definitions used in this paper are listed below.

Threat: potentially detrimental phenomenon described in terms of its geometry, mechanical and other characteristics (without forecasting).

Hazard: probability that a particular threat occurs within a given period of time (e.g., spatial-temporal forecasting of a threat).

Exposure: spatial-temporal intersection between threat and vulnerable elements.

Physical exposure: joint consideration of hazard and exposure.

Vulnerability: latent state of an element representing susceptibility to impact from a threat; and revealed only through occurrence of a threat causing negative impact.

Risk: probability of loss to an element resulting from impact of a threat (expressed in terms of hazard, exposure, vulnerability and coping capacity).

2.2 Representation of risk

Initial representations of risk were in the form of various equations. Prior to O'Keefe et al.'s (1976) assertion that vulnerability is a requisite of risk, equations were not genetic and took the form of the product of frequency and magnitude of loss (c.f. Hammer, 1972):

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

Even after the initial suggestion of the importance of vulnerability, many definitions retained this form (NRC, 1989), but eventually genetic forms emerged in which vulnerability and hazard were used (UNDHA, 1992):

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability}$$

As other concepts of risk were developed, such as exposure, they were integrated into genetic definitions and included elements at risk (e.g., Alexander, 2000), disaster management (e.g., Benouar and Mimi, 2001), and coping capacity (Villagrán de León, 2006):

$$\text{Risk} = \text{Elements at risk} \times \text{Hazard} \times \text{Vulnerability}$$

$$\text{Risk} = \frac{\text{Hazard} \times \text{Vulnerability}}{\text{Disaster Management}}$$

$$\text{Risk} = \frac{\text{Hazard} \times \text{Vulnerability}}{\text{Coping Capacity}}$$

Such formalizations of risk and vulnerability are basic generalizations that provide little conceptual understanding of risk or vulnerability. Additionally, they cannot, alone, jointly consider losses with different metrics. A conceptual model is required to address the issues.

2.3 Conceptual models of vulnerability

Conceptual models have the potential to explain and communicate the process and components of risk. In addition, conceptual models of vulnerability facilitate the choice of appropriate indicators of vulnerability and are, therefore, integral in vulnerability analysis, whether quantitative or qualitative. In this context Birkmann (2006) provides an overview of vulnerability models, which he groups into six types: double structure models; vulnerability in the context of risk; global environmental change; political economy models; holistic model; and the BBC (Bohle-Bogardi-Cardona) model.

Chambers (1989) introduced an early formal definition of vulnerability: "exposure to contingencies and stresses and the difficulty which some communities experience while coping with such contingencies and stresses". He also identified two 'sides' to vulnerability: external vulnerability, which relates to exposure to external shocks (impacts due to sudden on-set events) and stresses (impacts of slow on-set events); and internal vulnerability, which relates to defencelessness or incapacity to cope. He suggested that vulnerability (with regard to livelihood) is determined by access to assets and how assets are managed. Watts and Bohle (1993) further developed Chambers' model through discussion of food supply (a stress). Watts and Bohle (1993) state vulnerability results from three conditions: exposure, coping capacity, and recovery potential. The 'social space' in which they discuss vulnerability is a result of economic, political, and institutional capabilities of people. Later, Bohle (2001) provided a clearer graphical representation of the model (Fig.1). In the model of vulnerability developed by Chambers (1989) and expanded by Watts and Bohle (1993) and Bohle (2001), assets are considered to reduce vulnerability. The model – termed the Bohle Model by Villagrán de León (2006) – was expected to provide insight into the causal structure of vulnerability (Bohle, 2001). This, in addition to the organization of vulnerability, gives the model potential to assist vulnerability analysis. However, the model is not functional as interaction between the various components is not described.

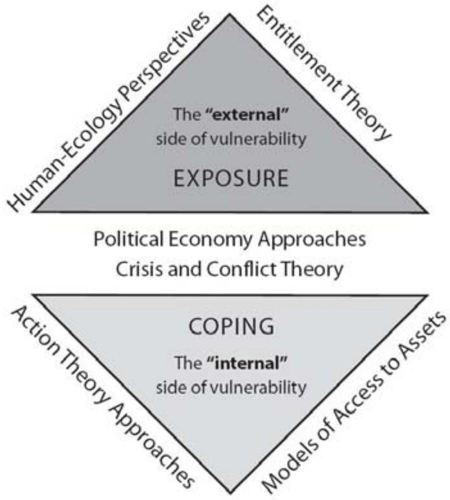

Fig.1 The Bohle model of vulnerability (Bohle, 2001)

In the Bohle model, coping capacity is explicitly included as a component of vulnerability. Exposure, as used in the Bohle model, is not equivalent to the spatial-temporal form considered in the natural science paradigm. Rather, it represents ability to resist initial impact of stresses or shocks and includes aspects of human ecology (population dynamics and capacities), entitlement (ability to access and manage assets), and political economy (inequalities). On account of this, the Bohle model includes exposure under the umbrella of vulnerability. Due to this fundamental difference with the natural sciences views on vulnerability and risk, double structure models do not fit into the natural science paradigm.

In the so-called 'disaster risk community', vulnerability is considered within the broader context of risk, with vulnerability, coping capacity, and exposure being separate elements that contribute together to produce risk and, potentially, disasters (Birkmann, 2006). Naturally, this arrangement fits best within the natural science paradigm of risk and vulnerability, which is not entirely coincidental as several of these models come from that paradigm (c.f. ISDR, 2004). Examples provided by Birkmann range from the very simplistic and inoperable plot of Villagrán de León (2006) to more complex flow net of ISDR (2004). The flow net (ISDR, 2004) attempts to provide a complete view of risk reduction through assessment, and does not conceptually represent risk or it components. Mitigation is disregarded as the authors have failed to illustrate movement back towards vulnerability and hazards (Birkmann, 2006). Due to either oversimplification or incomplete addressing of the problem, none of the disaster risk models presented by Birkmann (2006) are appropriate for a holistic conceptualization of vulnerability and risk in the natural sciences. One such example is the model proposed by Davidson (1997; Fig.2).

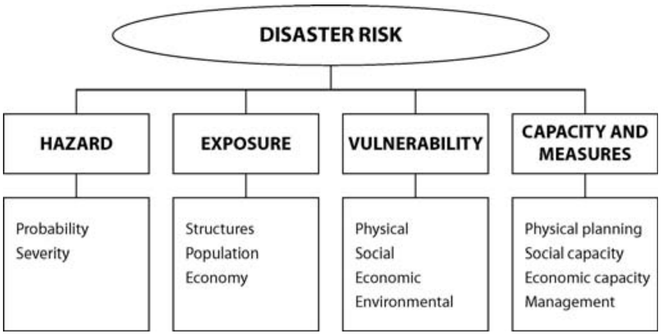

Fig.2 An example of a conceptual model for risk from the natural science paradigm (Davidson, 1997)

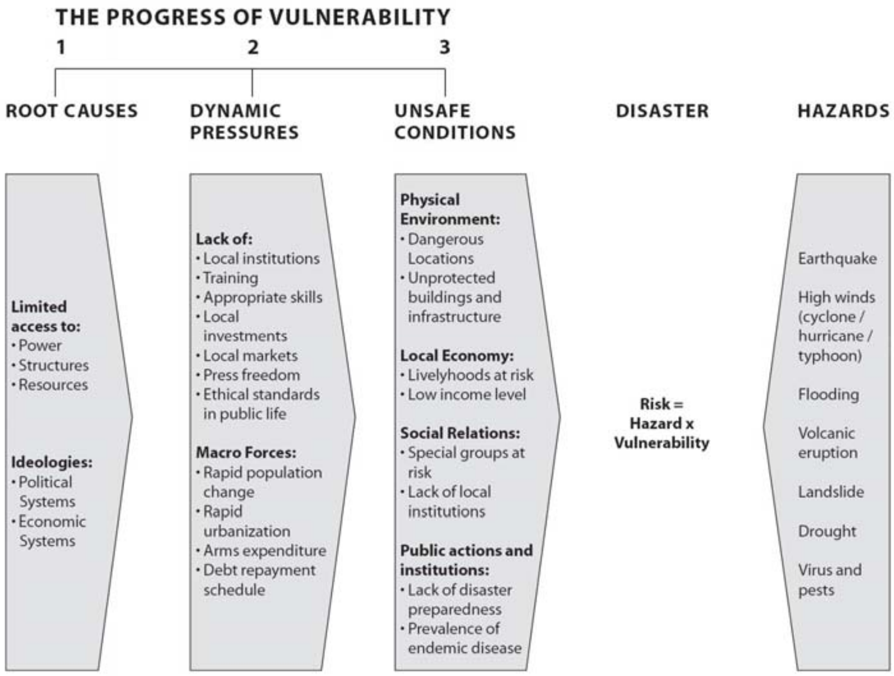

Fig.3 The pressure and release model (Wisner et al., 2004)

In the Pressure and Release Model (Fig.3) proposed by Blaikie et al. (1994) and further developed by Wisner et al. (2004) vulnerability is considered for a specific element (a person or group of persons) applied to a specific threat (natural 'hazards'). A unique aspect of the model is the progression of vulnerability, which outlines three stages contributing to development of vulnerability: root causes, dynamic pressures, and unsafe conditions. Root causes are processes (economic, demographic, and political) of a society representing distribution and inequality of power and assets. When impacted by dynamic pressures (attributes of a society such as population growth or urbanization) root causes become unsafe conditions (or circumstances resulting in the expression of vulnerability in the presence of hazard). Despite its restrictive nature, the Pressure and Release Model is an important contribution to conceptualization of vulnerability and, therefore, risk as it treats vulnerability as a process, rather than a state. The general form of the model follows the premise that risk is the product of vulnerability and hazard. Exposure is not considered. Structure of the model does not facilitate quantitative operability as only the general relation between parts of the progression of vulnerability is provided.

The BBC Model integrates exposure and coping capacity into the risk equation and, specifically, into the vulnerability component of the risk equation (Fig.4). In addition, the BBC model differentiates between different components of vulnerability (social, economic, and environmental). Physical vulnerability is not included in the model as it is assumed to lead to economic loss, fatalities or both. A reasonable approximation of total vulnerability could be achieved provided these aspects of physical vulnerability are integrated into social and economic vulnerability, respectively, in an appropriate way.

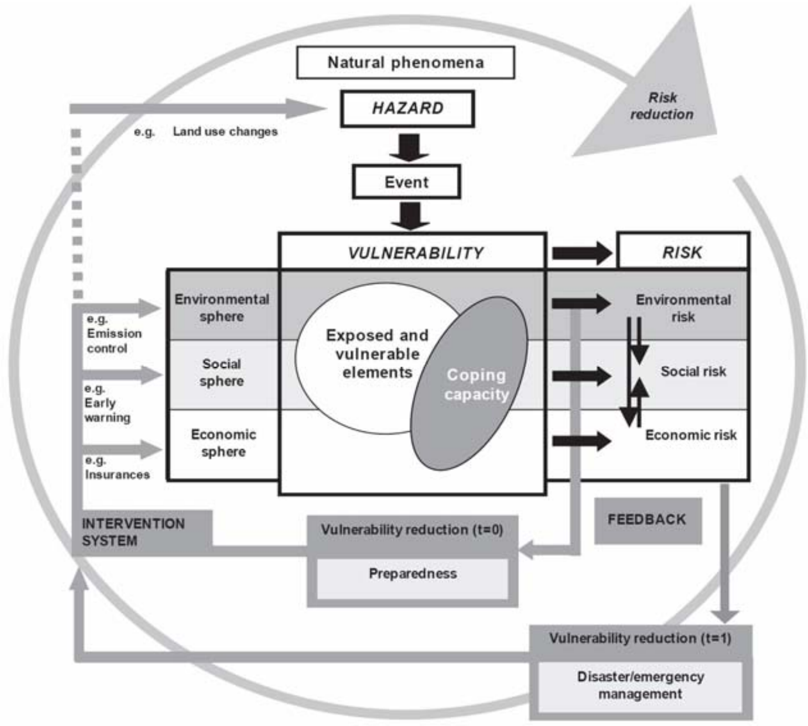

Fig.4 The BBC model (Birkmann, 2006)

3 PROPOSED MODEL FOR VULNERABILITY ASSESSMENT

Because none of the existing models were deemed appropriate for conceptualization of risk in the natural science paradigm, a new model has been developed (Fig.5). In contrast to the aforementioned models, the model presented here includes all properties required for conceptualization of risk in the natural sciences in an operable way: exposure and coping capacity are separated from vulnerability; ambiguity in the (double) meaning of vulnerability is addressed by introduction of *vulnerability factors*; and relevant relationships between components of the model are explicitly represented.

A comprehensive view of vulnerability requires numerous considerations typically not addressed in the natural sciences, but that are commonly addressed in the social sciences. Many such considerations have been recognized by recent reviews of vulnerability literature. Such considerations are also necessary in development of a vulnerability analysis framework. Villagrán de León (2006) mentions the following considerations:

- tangible versus intangible losses (and related vulnerabilities)
- controlled versus theoretical methods for measuring vulnerability
- receptor and process considered
- dependency on threat type
- dependency on threat magnitude
- relative versus absolute vulnerability (the latter requires benchmarks as a measuring tool, but can be considered as a linear scale)
- whether evaluation is based on historical outcomes? (if so inclusion/exclusion of extreme events, and the quality of the record will bias outcomes)
- implicit (e.g., using proxies) versus explicit (e.g., using directly representative data) embodiment
- consideration of separation form hazard
- simplicity, robustness and repeatability (temporally and at other scales) of the calculation

- capability for up- and down-scaling of the model (reasonably good application at various scales of consideration)

Further considerations not mentioned by Villagrán de León (2006) include:

- discrimination between 'scale' and 'level' (discussion of vulnerability)
- vulnerability versus exposure (not always a clear division)
- discrimination between vulnerability and vulnerability factors
- discrimination between poverty and vulnerability
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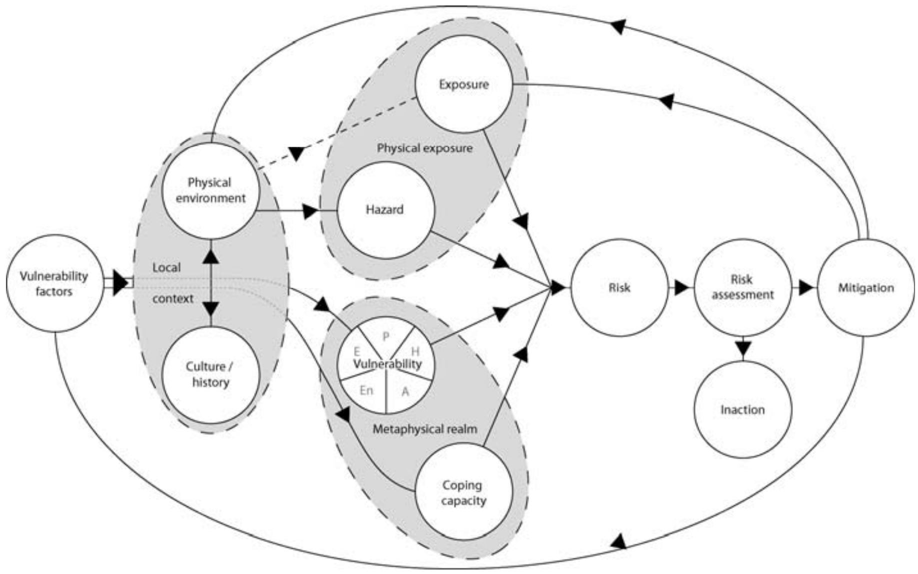

Fig.5 The proposed model for vulnerability conceptualization within risk assessment context

3.1 Vulnerability versus vulnerability factors and the importance of context

As is the case for *risk* and other terms used in risk analysis, meaning of *vulnerability* is highly varied. In the current literature vulnerability has been used both to describe the degree of susceptibility and to identify characteristics describing susceptibility. Double-meaning of vulnerability produces confusion and ambiguity, especially when both are considered by the same source. The International Society of Soil Mechanics and Foundation Engineering, for example, defines vulnerability as "…the degree of [potential] loss to a given element…" as well as "…conditions and processes…[that] increase the susceptibility of a community to the impact of hazards," (ISSMGE, 2004). This dual interpretation is reproduced throughout the literature (c.f. Fell et al., 2005; LESSLOSS, 2006).

Anderson-Berry and King (2005; 372) inadvertently applied the term vulnerability factor to characteristics that limit access to resources and, consequently, lead to increased vulnerability (in the sense of increased susceptibility). Here the term is developed further and formally applied to identify any characteristic of an element capable of influencing vulnerability. Vulnerability, as is used in the present discussion, is an abstract concept, whereas vulnerability factors are concrete objects or ideas. Alteration of vulnerability does not occur through direct action, but rather through changes made to vulnerability factors or the context of the system.

As stated by Anderson-Berry and King (2005), context is crucial, although more than just societal context should be considered. Environmental (ultimately determining threat and exposure) and social (cultural and historical background) contexts determine specific effects of vulnerability factors on vulnerability. In this way, vulnerability factors are 'filtered' through environmental and social contexts when influencing vulnerability (Fig.5). Thus, the exact same set of vulnerability factors present in two different scenarios (e.g., different locations or times) will yield different vulnerabilities due to contextual differences.

A similar 'filtering' concept is used in the 'geographic perspective' as described by Cutter (1996) and Cutter et al. (2000). Vulnerability factors (social fabric) and environmental context (geographic context) influence hazard, with effects of mitigation also considered (hazard potential). Joint consideration of hazard and environmental context determines physical exposure (biophysical vulnerability), and joint consideration of hazard and social context determines vulnerability (social vulnerability). In this way, environmental and social contexts are considered separately (although exchange by influence of one on the other is recognized) as each influences hazard and vulnerability, respectively, with the latter implicitly included in consideration of vulnerability factors. As in models in the physical sciences, joint consideration of vulnerability and physical exposure determines risk (termed 'vulnerability of place' by Cutter [1996]).

In contrast to Cutter and co-workers, the current risk model explicitly and realistically shows the roles of environmental and social context as well as the interaction of these with contexts with vulnerability factors, vulnerability, and mitigation. Consequently, a more detailed and realistic conceptualization of risk is provided. Such representation facilitates better understanding of the types and consequences of mitigation techniques possible as wells as realization that values of vulnerability factors (used often as proxies) are independent of context while their importance is context-dependant.

3.2 Scale versus level

Scale is a fundamental consideration in any geographic context. It indicates spatial magnitude of consideration and, due to trade-off between spatial extent and resolution, determines representation of physical detail. Conceptual complexity of a system introduces further detail in the form of additional information. Many fields considering vulnerability and risk are inherently geographic and, therefore, commonly consider scale. In addition, vulnerability and risk are regarded as complex conceptual systems. Explicit differentiation between spatial extent and system complexity is, therefore, crucial for understanding vulnerability and risk. Here, we apply *scale* to describe spatial extent and *level* to describe degree system complexity.

As scale increases (e.g., from local to regional to national) the degree of physical detail is reduced, but the possible level of conceptual complexity observed in the system increases. Scale is used here to indicate the level of investigation or consideration and is inversely proportional to map scale. The term small scale in this context indicates a localized investigation represented cartographically by a large map scale (representative fraction). Conversely, large scale indicates a more spatially-extensive investigation represented by a small map scale. The number of levels that are under consideration depends on scale. The amount of conceptual detail is determined by which and how many of the observed levels are considered. Consequently, while physical detail is directly related to scale, type and amount of conceptual detail is largely a function of level of consideration, which is ultimately limited by scale.

These trends are best illustrated with an example. A larger scale (e.g., regional) vulnerability analysis considers a larger geographic area than a smaller scale (e.g., house-specific) analysis, but is not necessarily more detailed. Local scale (e.g., households and individuals) analysis could consider only vulnerability of elements at the household level and below, while regional analysis could consider vulnerability of elements at more numerous levels of structure (region, town, community, household, and individual) independently. Consequently, the regional analysis would be more detailed if all levels were considered. However, consideration of all the levels possible for large scale analyses is rarely feasible or possible; only the highest levels are usually considered. Local analysis considering multiple lower levels (e.g., households and individuals) would be regarded as more detailed than regional analysis considering only a few higher levels (e.g., towns). Detail has the potential to change with scale, but whether detail increases, decreases, or changes in type depends on the levels being considered.

Whether characteristics (e.g., vulnerability factors) of a type of feature change with the level considered depends on the nature of the feature. On this basis of inter-level relationships two types of features are recognized: level-dependant and level-independent features. Characterization of level-independent features does not change with structural level. Consequently, vulnerability of features at a higher level (e.g., physical vulnerability of buildings of a city) is representative of typical vulnerabilities of features at a lower level (e.g., physical vulnerability of a single building) and provides a realistic generalization about vulnerability at a lower structural level. The type of information provided does not differ between analyses across different levels.

Conversely, characterization of level-dependent features changes with structural level. Vulnerability of features at a higher level (e.g., social vulnerability of a community) is not representative of vulnerability of lower level (e.g., social vulnerability of an indavidual). This disparity is due to aspects not considered at lower levels (e.g., community networks). For level-independent features the type of information provided by analysis is different at different levels and each level considered, therefore, provides additional information.

Inter-level relationships provide a useful basis for classification for vulnerability components. Components showing level-dependant behaviour (e.g., physical and environmental vulnerability) are composed mainly of material features and tend to be more easily quantified, and can reasonably be represented by consideration at one level (although spatial variability would not be represented). Components showing level-independent behaviour (e.g., social, economic, and organizational vulnerability) are composed mainly of immaterial (and often intangible) features, and tend to be more difficult to quantify and require consideration at many scales.

This is exemplified by characterization of vulnerability to tropical cyclones for the community of Cairns, Australia. Anderson-Berry and King (2005) reported that while individuals were relatively robust, the social capital and characteristics of the overall community increased vulnerability. Cleary, both scale and level determined how vulnerability factors, vulnerability components, and overall vulnerability have been considered.

4 QUANTIFICATION OF VULNERABILITY

The conceptual model of risk (Fig.5) allows vulnerability to be considered as a contributor to risk in an appropriate and communicable context. Deeper understanding of vulnerability, however, requires a more detailed consideration of vulnerability factors, local context, and the metaphysical realm. A conceptual model of vulnerability quantification including these elements has been developed to aid this understanding (Fig.6). The model can be considered as a module that fits into the more general conceptual model of risk (Fig.5).

In the model each component of vulnerability is composed of several subcomponents. Ideally, the collection of subcomponents, each representing a vulnerability factor, will realistically represent a vulnerability component. Subcomponents indicated in the model should be considered only as possible combinations. Consideration of more and/or different subcomponents may be required. Various subcomponents are combined through application of weights (entered in the upper left corner of each subcomponent as values of 0 to 1) to represent a component. Similarly, components are combined using weights to approximate overall vulnerability. Weights are, consequently, required for application of the model in a semi-quantitative way. Determination of weights is, initially, most realistically achieved by expert judgment. Later, however, some back analysis using disaster case studies could be used to justify adjustment of weights.

Although components represent vulnerability, subcomponents actually represent vulnerability factors and must, therefore, be considered in local context. Consequently, weighting of subcomponents is expected to vary with context. Interestingly, it was very difficult to separate subcomponents representing vulnerability from those representing coping capacity, suggesting that while differentiation of these elements may be useful in improving conceptual understanding, differentiation between them during analysis can be a hindrance.

Spaces in components and subcomponents provide a means to include indicators for vulnerability or vulnerability factors, respectively. Weights applied to these indices, should more than one be applied (in the case of only one index a weight of 1 is applied), are used to determine the value of the component or subcomponent that they describe. Use of weights and indices in the model will yield some quantitative estimation of overall vulnerability. How well this value represents actual overall vulnerability depends on the selection of weight and indices, appropriate consideration of relevant subcomponents, and consideration of local context.

An added and perhaps, at this early stage of development, more useful application of the model is in the conceptual organization. Organization of the model aids consideration of appropriate vulnerability factors. Subsequently, appropriate indices representing this is also aided. During construction of the model (e.g., consideration of what factors to include) an overview of the state of knowledge about various components and subcomponent is achieved. Those features clearly identifiable as important and easily explained will tend to be those about which the most knowledge and understanding has accumulated. Conversely, features providing more difficult will likely be suggested as those for which knowledge is lacking. These latter features should be priorities for further work.

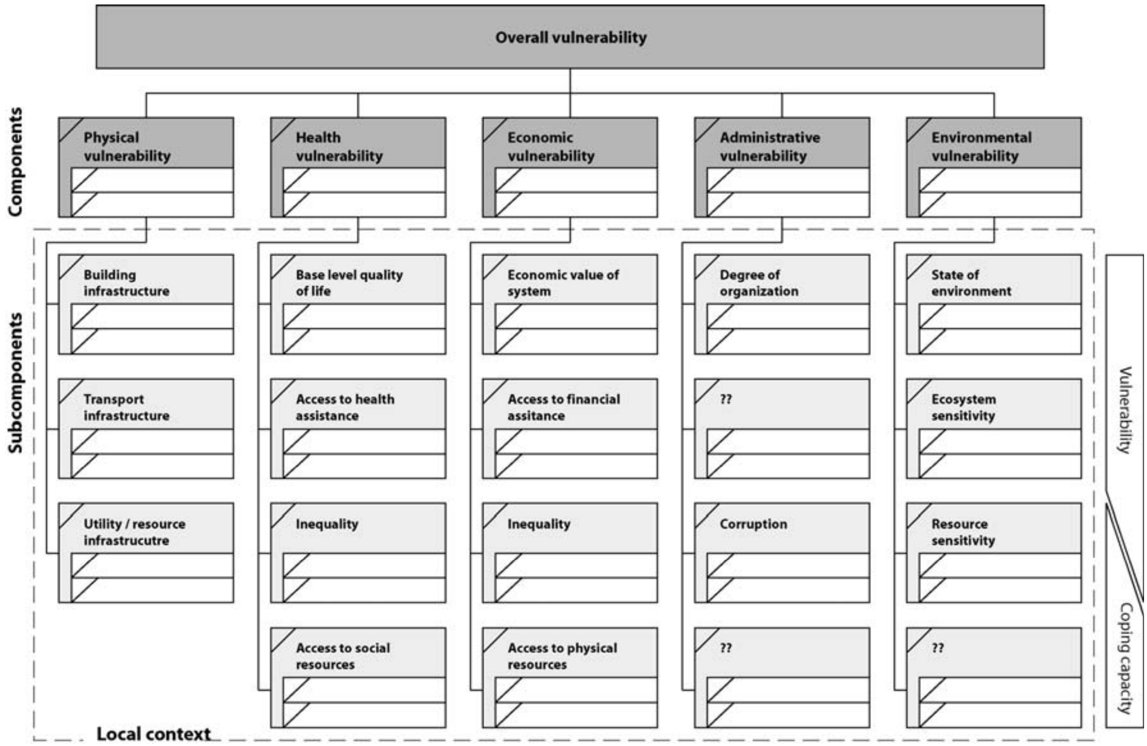

Fig.6 Components of the conceptual model for quantification of vulnerability

5 CONCLUDING REMARKS

Understanding of the structure of vulnerability and its role in risk according to the natural science paradigm has been improved through a combination of approaches. Terms crucial to understanding vulnerability, and risk, in the natural sciences were identified and explicitly defined. Using these, a functional conceptual model of risk was developed to give appropriate context for the discussion of risk.In creation of the model, new terminology was developed – vulnerability components, vulnerability factors, and metaphysical realm – that should assist understanding of both vulnerability and risk. Using the relationship between vulnerability factors, vulnerability components, and local context, a conceptual model for vulnerability and coping capacity was developed. This vulnerability model aids not only in understanding the structure of vulnerability, but also in the identification and organization of factor (and indicators of these) influencing vulnerability. Given the determination of appropriate weight, the vulnerability model has the potential to facilitate semi-quantitative vulnerability analysis.

ACKNOWLEDGEMENT

The work presented in this paper was supported by the Research Council of Norway through the Centre of Excellence “International Centre for Geohazards” (ICG). The authors gratefully acknowledge this support. Financial support was provided to Nick Roberts during the exchange at ICG through grants Natural Science and Engineering and Research Council of Canada to Nick Roberts and to Stephen Evans (Department of Earth and Environmental Sciences, University of Waterloo). Zenon Medin-Cetina (Norwegian Geotechnical Institute) was active in useful discussion during the work and Stephen Evans provided comments and suggestions on an earlier manuscript. These contributions were crucial in production of the final manuscript.

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