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Stefan Kienberger, Thomas Blaschke & Rukhe Zehra Zaidi

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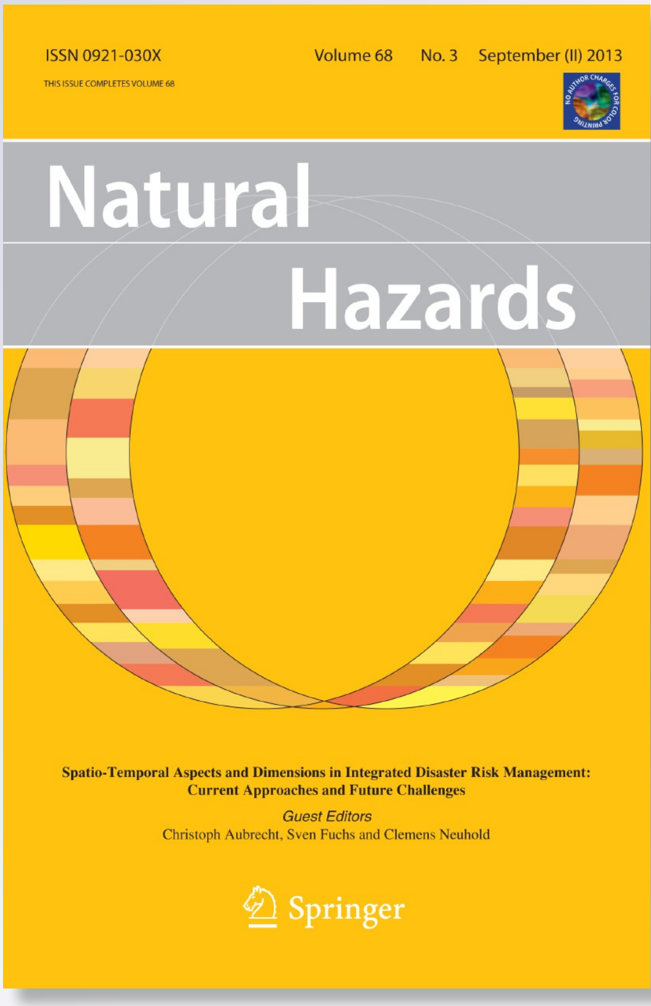

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ORIGINAL PAPER

A framework for spatio-temporal scales and concepts from different disciplines: the 'vulnerability cube'

Stefan Kienberger · Thomas Blaschke · Rukhe Zehra Zaidi

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Abstract The concept of vulnerability is increasingly used in the fields of disaster risk reduction and climate change adaptation, as well as socioeconomic studies. This paper reviews research inputs into the concept of vulnerability and highlights the challenges of resolving its spatial and temporal variability with building resilience and adaptation. We hypothesise that a clear understanding of scale is key to integrating these related issues, by differentiating three dimensions of scale when analysing relationships between the observed and the intrinsic scale of a given phenomenon, namely space, time and dimensional level. The paper analyses 20 vulnerability assessment approaches, ranging from the global down to the local scale, and positions them with regard to their integration of the spatial component. We then develop a vulnerability cube as a framework to position existing approaches and to map them in a three-dimensional space. The three axes represent space, time and dimension and provide a structure for the different notions of scales and ultimately for a spatial analysis workflow. The vulnerability cube framework helps us to position different vulnerability assessments and to identify overlaps, differences and specific characteristics. Additionally, this three-dimensional conceptualisation allows the identification and discussion of appropriate scaling issues.

Keywords Scale · Risk · Vulnerability assessment · GIScience · Integrated methods

S. Kienberger (✉) · T. Blaschke
Interfaculty Department of Geoinformatics, Z_GIS, University of Salzburg, Schillerstrasse 30, 5020 Salzburg, Austria
e-mail: stefan.kienberger@sbg.ac.at
URL: www.uni-salzburg.at/zgis/kienberger

T. Blaschke
e-mail: thomas.blaschke@sbg.ac.at
URL: www.uni-salzburg.at/zgis/blaschke

R. Z. Zaidi
Hazards and Risk Research Group, Department of Geography, King's College London, Strand Campus, London WC2R 2LS, UK
e-mail: zehra.zaidi@kcl.ac.uk
URL: http://www.kcl.ac.uk/sspp/departments/geography/people/researchstaff/ZaidiRukheZehra.aspx

1 Introduction

There is widespread agreement within the scientific community regarding the interdisciplinary nature of vulnerability assessments and their integration of risk, bringing together social and natural science perspectives (e.g. Hewitt and Burton 1971; Wisner et al. 2004; Adger 2006; Birkmann 2006a, b; Cannon 1994; Gallopín 2006). Within the assessment of risk and vulnerability, the scale issue has been identified as an important research question and has been discussed recently in several papers (e.g. Leichenko and O'Brien 2002; Birkmann 2007; Cutter and Finch 2008; Fekete et al. 2010; Preston et al. 2011). However, so far, the discussion has been primarily focussed on the importance of certain (key) indicators for different scale domains and how challenges such as scaling issues, could be overcome. Indicators are currently employed at different scales and used to measure and map different dimensions of vulnerability across space and time. This can facilitate comparisons between place as well as highlighting the multi-faceted nature of vulnerability. Such approaches have undoubtedly helped enable the inclusion of social sciences within disaster research, which has been traditionally hazard-centric and was once dominated by natural/technical sciences. Due to the interdisciplinary notion of vulnerability, confusion on scale concepts continues to exist and established understandings are often overlooked. Many different conceptions of scale persist and terms are often used interchangeably and in a confusing manner. This is on one hand due to the very interdisciplinary character of vulnerability science, but also the result of a lack of a common understanding of scale issues. We will exemplarily highlight some concepts in Sect. 2 such as the hierarchical patch dynamics paradigm.

This paper seeks to contribute to the discussion by providing a brief review of existing concepts and their importance, applicability and current use. As a way of furthering the scholarship on the subject, we propose a guiding framework to conceptualise different scale challenges in a vulnerability assessment. This should be of use to not only researchers, but also policy-makers and practitioners by providing clarity on the terms, and also highlighting the requirements and limitations for vulnerability assessments.

A discussion on conceptual approaches towards vulnerability is not central to the objectives of this paper. However, a certain weight is given to some approaches from the disaster risk reduction community (such as Hewitt and Burton 1971; Cutter 1996; Wisner et al. 2004; Birkmann 2006a; MOVE 2010), where vulnerability is an integral component—next to hazard—for determining risk. Therefore, a specific definition of vulnerability is not provided, but includes the assessments and conceptual scope used mainly in the disaster risk reduction community such as the Pressure and Release Model, the social ecology perspective and the holistic perspective on vulnerability (Cardona et al. 2012). Minor emphasis is given to the concept as understood in the IPCC climate change adaptation community (ibid.) as well as the more physical/geomorphological approach towards vulnerability (e.g. Fuchs 2009; Kappes et al. 2012). Both qualitative and quantitative aspects of vulnerability assessments are considered, where the measuring or mapping of vulnerability is not understood to be in contradiction with a more broad view of vulnerability research that incorporates wider adjacent aims of process-driven and empowering approaches.

We start from the hypothesis that scale is a very central and well-explored concept both in geography and landscape ecology. We claim that the term scale is often used less accurately in more technical and/or more applied realms. Scale issues are examined in Sect. 2, highlighting concepts established in geography and landscape ecology. Tracing their roots helps to reduce the current confusion regarding vulnerability and scale. This will be followed by a comprehensive discussion of spatial vulnerability assessment concepts and a general review of spatial approaches applied (Sect. 3). Section 4 proposes the 'vulnerability cube' as a way to characterise different vulnerability assessments with respect to spatial, time and dimensional dimensions.

2 Scale issues within quantitative and qualitative indicators

An examination of scale and space has been central in the discipline of geography as well as within interdisciplinary sciences. Early works on the topic include investigations by Stevens (1946) and Torgerson (1958). Since then, the theoretical debate on scale has been quite dynamic and vital, most notably between the physical and human geographical domains (e.g. Allen and Starr 1982; Meentemeyer 1989; Cox 1998; Brenner 2001; Sayre 2005; Blaschke 2006; Neumann 2009). Guttman (1944) provides an early review on scaling qualitative data. The field of ecological studies has also addressed the issue through the use of established concepts and developed the central approach of hierarchies (Simon and Ando 1961; Allen and Starr 1982; Blaschke 2006). This is further developed by Wu (1999) into hierarchical patch dynamics, which integrates hierarchy theory with the theory of patch dynamics. The central concept underlying the theory of patch dynamics is the patch, defined as a spatial unit differing from its surroundings in nature or appearance. The patch is the fundamental structural and functional unit of a landscape, and is scale and context-dependent. While hierarchy theory focuses on the vertical structure of the landscape composed of a limited number of discrete hierarchical levels, patch dynamics theory explicitly deals with spatial heterogeneity and hierarchical interactions among system components in a horizontal way (Marceau 1999). By merging the two theories, ecological systems can be described as hierarchical systems of patches that differ in composition and spatial configuration at particular scales.

Marceau (1999) provides a review of scale in social and natural science disciplines and introduces the metaphor of scale as a 'window of perception' which is seen as the filter or measuring tool through which a phenomenon (e.g. landscape or vulnerability) may be viewed or perceived (see also Levin 1992). Blaschke (2006) provides a more recent review of concepts of scale within the domain of landscape ecology. Current debates on the notion of scale in human geography are vital and target the issue of whether or not the notion of scale should be abandoned in the discipline. The proposed alternative would be a more 'site-based' ontology which flattens space into multiple sites of practices, relations, events and processes, which are both situated in place and extended through space (Marston 2000; Howitt 2002; Marston et al. 2005; Jonas 2006).

2.1 Scale concepts in landscape ecology: a more quantitative approach

One of the reasons scale is a complex problem is that patterns, processes and scale are often inseparable. Conceptual and methodological issues related to spatial (and temporal) scale have always been a central research topic in landscape ecology and other spatial sciences such as geography and regional science. In fact, it can be argued that scale is still the one of the most debated concepts in landscape ecology. Since Meentemeyer and Box (1987) proposed the term 'science of scale' to emphasize the critical role of scale in spatial research designs, hierarchy theory has been used to formalize the recognition that landscapes are spatially heterogeneous and composed of a variety of patterns and processes, which predominantly operate at different spatial and temporal scales, and simultaneously affect each other (O'Neill et al. 1989). Several subsequent and increasingly comprehensive refinements and extensions to this theory have since been developed.

Landscapes are considered complex systems because they are composed of a large number of spatially heterogeneous components that interact in a nonlinear way and exhibit emergence, self-organisation, path dependence and adaptive properties over time (Wu and Marceau 2002). Complex systems are also hierarchically structured, which further emphasizes the central role of scale in landscape studies.

According to the definition put forward by Wu and Harbin (2006, p. 3) 'scale usually refers to the spatial or temporal dimension of a phenomenon, and scaling is the transfer of information between scales'. Specific research domains include the issues of characteristic scales (levels in hierarchy and scale breaks), scale effects (e.g. modifiable areal unit problem) and scaling (in conjunction with accuracy assessment and uncertainty analysis).

Wu and Harbin (2006) propose a three-tiered concept of scale (adapted in Fig. 1), combining the more general classification of dimensions of scale, with different kinds of scale and most specifically the components of scale. Within these dimensions of scale, a phenomenon can be associated with a temporal, spatial and organisational level, which is mainly constructed by the observer and links to hierarchy theory. The time–space component has been discussed widely in the literature for both natural and socio-economic systems. It can be observed that large-sized events are characterised by lower frequencies and slower rates. Smaller ones tend to be faster and more frequent. This links strongly to the discussion on scales within vulnerability assessments by Fekete et al. (2010) who observe a coupling effect between the memory times linked to flood frequency. They argue that more frequent flood events tend to be less perceived as hazards, and instead as events which are unusual and unexpected (see also early work by Geipel 1982). Wu and Harbin (2006) also state that, especially for scaling purposes, the levels of organisation have to be consistent with spatial and temporal scales. Here, hierarchy theory states that higher levels of organisation tend to be faster and smaller than lower ones, which is in accordance with the space–time principle. This notion is taken up in the proposed 'vulnerability cube' which is presented in Sect. 4 for characterising vulnerability.

As a second classification of scale, Wu and Harbin (2006) describe various kinds of scale (Fig. 1), with arrows signifying the relationships and feedbacks that take place between these different levels. It is important to note that that 'the observed scale of a given phenomenon is the result of the interaction between the observer and the inherent scale of the phenomenon' (p. 7). Definitions of the different kinds of scales are provided in Table 1. They stress that 'only when the scales of observation and analysis are properly chosen, may the characteristic scale of the phenomenon of interest be detected correctly; only when the scales of experiments and models are appropriate, may the results of experiments and models be relevant; only when the scale of implementation of policies is commensurate with the intrinsic scale of the problem under consideration, may the policies be effective'.

To compensate for a mismatch between these different scales, scaling is applied (Bierkens et al. 2000). Following Wu and Harbin (2006), components of scale, as the third classification of scale (Fig. 1), include grain (e.g. resolution, such as the pixel size in remote sensing images), extent (e.g. spatial/temporal expanse, such as the number of rows and columns in raster data), coverage (e.g. sampling intensity, such as the repeat rate of satellites over the same place) and spacing (e.g. interval between samples). Within a vulnerability assessment, the issue of the intrinsic scale and establishing a match to the policy scale is essential, in addition to data being available at the right scale level and properly observable (observational scale). The combination of the modelling scale and the

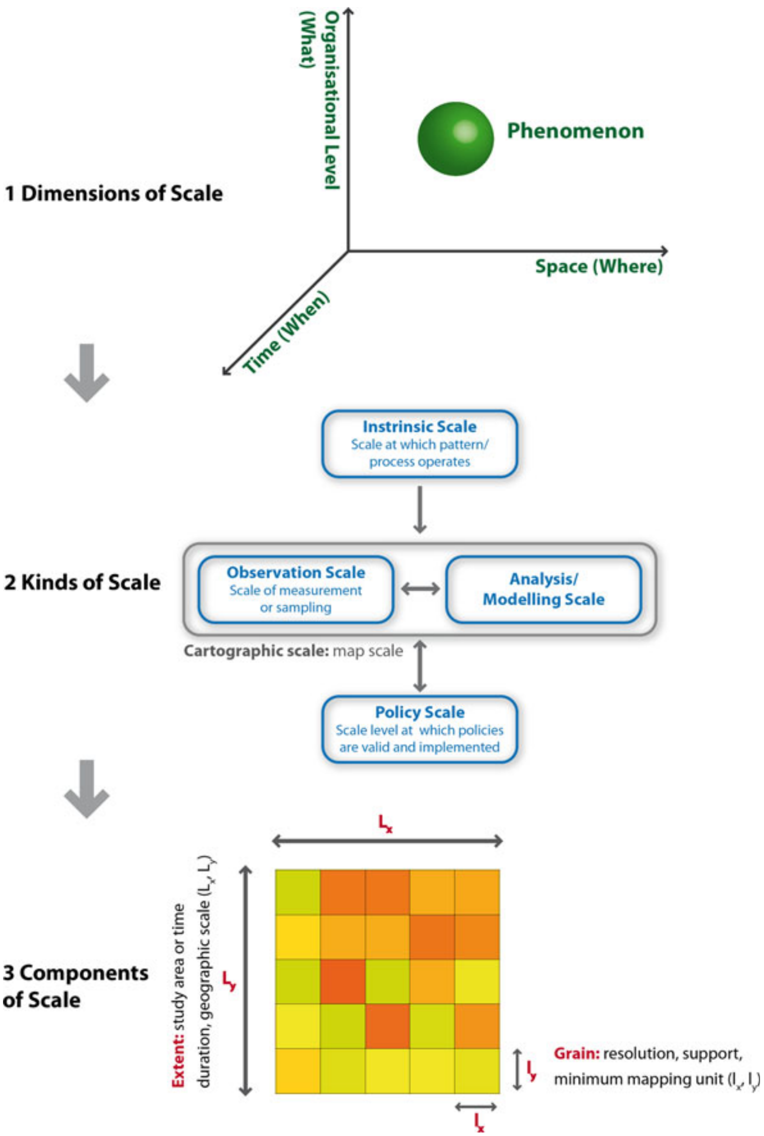


Fig. 1 Modified hierarchy of scale concepts according to Wu and Harbin (2006) which was based on Bierkens et al. (2000) and Dungan et al. (2002)

observational scale can also be expressed as the final cartographic scale or map scale, as this is the one where the final products are then presented.

2.2 Scale and scaling of qualitative data

When considering qualitative data, which can be represented as nominal or ordinal data, different challenges arise. While the framework provided by Wu and Harbin (2006) can also be transferred of course to socio-economic domains, the challenge with qualitative

Table 1 Definition of core terms based on Wu and Harbin (2006) with own modifications

Term	Definition
Scale	Usually refers to the spatial or temporal dimension of a phenomenon, and scaling is the transfer of information between different kinds and dimension of scales
Dimensions of scale	A phenomenon can be characterised by a temporal, spatial and organisational level
Intrinsic scale	Scale at which the pattern/process typically operates and is defined by pattern/process itself
Observational scale	Scale of measurement and sampling of the phenomena. Ideally, the observational scale is closely linked to the intrinsic scale, but may be adjusted if appropriate
Modelling scale	Scale level at which the analysis is carried out. Data derived from the observational scale may be scaled to the appropriate modelling scale in a valid manner
Policy scale	Scale level for which policies (such as laws and regulations) are valid and implemented

data (in the sense of descriptive data with non-numerical values) arises as it is greatly affected by the scale or spatial level from which it is extracted; for instance, the perception of household flood risk is not consistent across a number of individuals, or between individuals and the entire community. Two methodological issues are important to note here. First, the grouping of individuals and organisations into socially constructed classifications or scales of national, local or community is a normative exercise that does not necessarily correspond to the locations or scales where vulnerability is experienced and manifests itself. Second, although data can be aggregated or sampled from a finer scale to a broader scale to provide methodological guidance or policy relevant information, as is the case in community assessments of vulnerability, this scaling-up of local level data to produce a broader scale analysis is generally representative but not precisely indicative of individual inputs. For example, a recent study on heat wave vulnerability in London assessed risk management of elderly care provision at the national and local scale (Zaidi and Pelling forthcoming). The national level assessment highlighted institutional preparedness, robust risk management and policy engagement, indicating low levels of vulnerability. Local level assessments, however, revealed lack of awareness and disjointed risk management practices among at-risk individuals and care managers. In this particular context, the different definitions, sources and perceptions of vulnerability present at each scale highlight the limited utility of scaling data upwards or downwards for the construction of representative hypotheses. In addition, the grouping of different types (public, private and third sector) and levels (nursing, sheltered, and in-community) of care into local capacity resulted in the combination of several different forms of vulnerability being aggregated into one category. Classifications of scale reveal the limitations up- and downscaling data, which results in loss of data resolution and specificity. As such, qualitative data which have been scaled up cannot then be downscaled back to the original level of data collection without loss of accuracy and meaning.

We may also state that the same process of data transposition is not feasible when applied in the reverse direction. Qualitative data cannot be downscaled to produce information of a greater descriptive value (in much the same way that a nominal measurement cannot be disaggregated to produce interval measurements; see Table 2), unless qualitative

Table 2 Possible directions of scaling for qualitative data

	Data	Indicators	Methods
Upscaling	Possible for aggregation and indicative sampling but not for synthesis	Possible with modifications to input variable to suit context/scale	Possible with modifications or alterations to suit context/scale
Downscaling	Not possible without loss of accuracy	Possible with modifications to input variable to suit context/scale	Possible with modifications or alterations to suit context/scale
Crosscaling	Possible for comparative output but not representative results	Possible with modifications to input variables to suit research objectives	Possible with modifications or alterations to suit research objectives

and quantitative methods are to be mixed, but the accuracy of the data obtained and the accuracy and reliability of the resulting indicator will be low (OECD 2008).

Unlike qualitative data, however, it is potentially possible to downscale methods and/or qualitative indicators when applied at different scales under a common conceptual framework. For example, a framework developed at the national level can include vulnerability indicators such as access to information or availability of health resources that can be used at multiple scale classifications, and employ a participatory methodology that can be applied at all scales of vulnerability analysis. Similarly, data, indicators and methods can all potentially be utilized across scales, but depending on the direction, context, and purpose of extrapolation, each scaling attempt will require adaptation and modification to the original data set or method and produce outcomes with a varying degree of accuracy or relevance to the overall aims of the research project. A methodological framework for assessing risk can be utilized in multiple communities with comparable characteristics, providing that there is a modification undertaken to tailor methods and indicators to suit the specific features of every site. The issue of up–downscaling of qualitative data can be also related to the space in which the organisations take actions and develop activities. Gillespie (2004) presents up–downscaling examples in the following perspectives: institutional, geographical/spatial, technological, temporal and economic and he comments on the upscaling approach of Myer (1984), which consist of expansion, explosion and association.

As Evans et al. (2002) describe, the process of 'scaling-up necessitates the introduction of some heterogeneity within the social unit'. It can therefore lose the nuance, relevance and rich quality of data and methods derived from a finer scale of qualitative analysis. Similarly, scaling down or across does not necessarily produce comparative or representative outcomes. The same input variables employed across different scales can produce varying or potentially incommensurate outcomes. Therefore, as Birkmann (2006b) explains in reference to quantitative data, any exercise in scaling qualitative data or indicators will similarly require a certain amount of 'contextualization' or alteration to account for variations in the new scale to which they are being transposed or applied.

Boundaries of scales are often undefined and empirically problematic (e.g. between national and sub-national). In addition, parallel scales of relevance in different systems rarely overlap completely, for example, watershed and flood management. This adds a challenge when moving across scales. Smith (1992) contends that there is nothing ontologically given about the traditional division between home and locality, urban and regional, national and global scales and scale is, instead, a socially constructed phenomenon. This view is supported by Purcell and Brown (2005) who warn that 'we cannot assume a priori anything about the extent, characteristics and functions of a particular scale or scalar arrangements' (p. 281) in the social science. Hence, there exists a need for greater consideration of the definition and use of scales when referred to in vulnerability studies. Indeed, the interaction of natural and human systems in analysis can be a challenge where units operate at equal scales—for example, nation states have greatly differing spatial characteristics and so are exposed to different kinds of natural hazard. This is a concern for all scaling issues, not just those involving qualitative methods, data collection or indicators. According to Marceau (1999), 'in the natural sciences, the development of concepts such as domain of scales and scale thresholds are crucial to the understanding of the hierarchical organisation of the geographic world. Such concepts can also be applied in the social sciences to explain the strength of a relationship between specific variables at one scale and their disappearance at another, or the dominance of one variable at a specific scale only (p. 11)'.

The scaling-up of methods, data and indicators raises questions about the ethics of research and representation. Both the collection of data and the process of data production and representation introduce potential bias on the part of the researcher. This is especially potent in qualitative (but also quantitative) scaling exercises since decisions about the weight assigned to responses, what is to be included and scaled up, and what is excluded are crucial in affecting the outcome of data and even the indicators that are scaled up.

3 Review of vulnerability (and risk) assessments in regard to their spatio–temporal dimensions

Aside from the conceptualisation of vulnerability and the development of specific indices or metrics, spatial modelling of vulnerability, in a strict sense, is not always approached as a central element of the assessment. The integration of scale in geographic information science (GIScience) has been primarily discussed by Cutter (2003) and cannot be viewed as a strongly investigated concept in qualitative vulnerability assessments as in the domain of landscape ecology for example, which integrates spatial components in its concepts. Leichenko and O'Brien (2002), Turner et al. (2003), Birkmann and von Teichman (2010), and MOVE (2010) discuss the importance and dynamics of scale approaches in the context of vulnerability assessments. Vulnerability is a phenomenon which is strongly related to the specifics of place (e.g. Cutter et al. 2008; November 2008; Fekete et al. 2010) and—as we claim here—to GIScience as a scientific framework. GIScience deals with scientific principles on the development, use and application of geographic information systems (GIS) and is concerned with people, hardware, software and geospatial data (Goodchild 1992).

Table 3 summarises different existing vulnerability assessments, ranging from the global down to the local scale. The review has been structured according to three domains—as presented in the vulnerability cube (see Sect. 4)—of spatial (global to household), temporal validity of indicators for a time period or for a specific moment only

Table 3 Analysis of different vulnerability assessment methodologies among different scales and domains of application/research (including evaluation results of Villagrán de León (2006) and Gall (2007))

Author	Spatial	Temporal	Dimension of vulnerability	Hazard	Scope	Method	Map products/analysis
UNDP (2004)	Global	Time period (~yearly)	Risk, vulnerability (social)	Earthquake, floods, tropical cyclones, droughts	Decision support at global level/ support to policies	Human vulnerability and risk index (ranking) based on human exposure to earthquakes, tropical cyclones, droughts and flooding. Based on proxy measures (not by a theoretical framework or expert opinion)	Global map provided with indicators at country level
Dilley et al. (2005)	Global	Time period (~yearly)	Risk	Cyclones, drought, earthquakes, floods, landslides, volcanic eruptions	Decision support at global level/ support to policies	Assessing risk in relation to disaster-related mortality and economic losses. Assumes the condition of vulnerability depending on hazards	Global map (2,5 km grid) Integration of indicators GIS based
Schneiderbauer (2007)	Global	Time period (~yearly)	Risk, vulnerability (socio-economic)	Hazard (earthquake)	Research	Risk as an equation of exposure (based on population data), risk (through a specific hazard map), and vulnerability (integrating socio-economic indicators); selection and weighting through factor analysis	Strong support of GIS to analyse and model vulnerability
Cardona (2005a, b)	Global	Time period (~yearly)	Risk, vulnerability (socio-economic)	'hazard'	Research focus/ support to policies and monitoring purposes	Captures inherent conditions between risk and development in terms of exposure and susceptibility, socio-economic fragility and lack of resilience regarding possible events. Rooted in political–ecological traditions of vulnerability science; expert-based analytical hierarchy process (AHP)	Maps at national scale

Table 3 continued

Author	Spatial	Temporal	Dimension of vulnerability	Hazard	Scope	Method	Map products/analysis
Adger et al. (2004)	Global	Time period (~yearly)	Vulnerability (social)	Climate change	Research/policy support	Social vulnerability indicators based on historic hazard mortality. Links social vulnerability with climate adaptation (climate variability and climate change).	N/A
UN/ISDR (2009)	Global	Time period (~yearly)	Risk, vulnerability (socio-economic)	'hazards'	Decision support at global level/support to policies/share global risk data	Modelling of hazards, exposure (population and economic assets), loss for hazard events and vulnerability (country-level indicators). Identification of multi-risk hot spots at the global level (relative and absolute risk) Development of multi- risk index	Global hazard maps and different risk maps (1 km) Support and integration of spatial data (download)
Birkmann et al. (2011)	Global	Time period (~yearly)	Risk, vulnerability (socio-economic, institutional)	'hazards'	Decision support at global level/support to policies (NGO driven)	WorldRiskIndex WRI: disaster risk for countries and regions. i.e.. exposure a) natural hazards and climate change, b) 'social vulnerability' (vulnerability of population, its susceptibility as well as coping and adaptation capacities). Focus: 'governance and civil society'. Ranking at per country for risk and associated sub-domains	Global risk index map and maps for different domains Statistical analysis of indicators; maps as visualisation

Table 3 continued

Author	Spatial	Temporal	Dimension of vulnerability	Hazard	Scope	Method	Map products/analysis
Schmidt-Thomé et al. (2006)	Regional	Time period (~yearly)	Risk, vulnerability (socio-economic)	Europe (NUTS3 level)/natural and technological hazards	Application/ research/policy support	Integration of hazard research results to obtain information comparable for EU 27 + 2 area based on Delphi weighting method (population, GDP (national and regional) and the proportion of fragmented natural areas to all natural areas)	Strong support of GIS to analyse and model hazards and vulnerabilities
Cutter et al. (2003)	National	Time period (~yearly)	Vulnerability (social)	Environmental hazards	Research	US-wide county-level index of social vulnerability index (SoVI) to environmental hazards based on socio-economic and demographic data. Using a factor analytic approach while reducing 42 variables to 11 independent factors	Visualisation of calculated indicators
Vincent (2004)	Regional	Time period (~yearly)	Vulnerability (social)	Water availability	Research focus/ support to policies	Expert weighted index of five indicators; however, the indicators (indirectly) related to 'water availability' Aligns social vulnerability with adaptation capacity	Visualisation of indicators for Africa (country level)
Briguglio (2003/2004)	Regional	Time period (~yearly)	Vulnerability (social)	Focusing on developing small island states/'hazard'	Reveal vulnerabilities of small states	Intrinsic vulnerability of small island states in comparison with large countries which may possess several advantages due to their size. Weighted least square (regression) routines to integrate 4 basic indicators	N/A

Table 3 continued

Author	Spatial	Temporal	Dimension of vulnerability	Hazard	Scope	Method	Map products/analysis
Pelling and Uitto (2001)	Regional	Time period (~yearly)	Vulnerability (social)	Focusing on developing small island states/hazard independent	Reveal vulnerabilities of small states	Combines five indicators using equal weights to an index: The method applies a hazard-independent index	N/A
Cutter et al. (2000)	Sub-national	Time period (~yearly)	Vulnerability (biophysical, social)	Hazard (flood, chemical accidents, hurricane, earthquake)	Research	Follows the conceptual framework of Cutter to assess the biophysical and social vulnerability, which can be integrated in 'place vulnerability maps': different risk maps through spatial analysis and a biophysical hazard score for each intersected polygon. Social vulnerability consists of different socio-economic indicators, which have also been chosen for specific hazard zones	Strong support of GIS to analyse and model place vulnerability
WFP (2004)	Sub-national	Time period (~yearly)	Vulnerability (food security)	Food security	Application/implementation	Standardised methodology to assess food security: integrates also different hazards through secondary data analysis, literature review, household and community survey (integration of data on education, health, demographics, agriculture, income sources, remittances, food consumption, nutrition, etc.). Final product is a CFSVA report targeting WFP preparedness, food security monitoring system, WFP emergency needs assessment targeting humanitarian assistance	Visualisation/online mapping tools available, strong integration of GIS and remote sensing (VAM spatial information environment)

Table 3 continued

Author	Spatial	Temporal	Dimension of vulnerability	Hazard	Scope	Method	Map products/analysis
Munich Re Group (2003)	Local	Time period (~yearly)	Vulnerability (economic)	'hazard'	Insurance (economic) oriented	Vulnerability index based on the combination of one hazard-dependent and two hazard-independent parameters	N/A
Clark et al. (1998)	Local	Time period (~yearly)	Vulnerability (socio-economic)	Storm	Research	Integration of classic causal hazard models with social, environmental and spatial dynamics reveals differential ability of people to cope with hazards (poverty; disability). Uses Census data, factor analysis, data envelopment analysis, and floodplain maps to understand the compound social and physical vulnerability of coastal residents	Strong support of GIS to analyse and model hazards and vulnerabilities
Hahn (2003)	Local	Time period (~yearly-monthly)	Vulnerability (physical, social, economic, environmental)	'Hazard' (floods, storms, earthquakes, landslides, droughts, volcanic eruptions)	Application and implementation oriented/community empowerment	Application of several indicators to assess vulnerability (physical/demographic, social, economic, environment). Data integrated from municipal and national sources. Remaining data acquired through a questionnaire	N/A

Table 3 continued

Author	Spatial	Temporal	Dimension of vulnerability	Hazard	Scope	Method	Map products/analysis
IFRC (2007)	Local	Point in time (~monthly)	Vulnerability (socio-economic)	'Hazard'	Application and implementation	VCA investigates the risks that people face in their locality, their vulnerability to those risks and their capacity to cope with and recover from disasters. It is part of a community programming strategy, integration of participatory methods. 12-step participatory investigation method, with a focus on the process and the community engagement; qualitative indicators for project monitoring are developed	Community mapping is integrated within the methodology
Villagrán de León (2004, 2005)	Household	Point in time (~monthly)	Vulnerability (physical, social, economic)	Case study 'volcanic eruptions', can be adjusted to different hazards	Application and implementation oriented/ research focus	Procedure to assess four different types of vulnerabilities associated with the housing sector at the local level: physical or structural, functional, social, and economic income. Each type of vulnerability is measured through parameters which are directly related to the type of vulnerability in question, classifying the different types of options commonly available in communities for these variables (low, medium and high)	Household maps (but aggregation to higher level theoretically possible)

Table 3 continued

Author	Spatial	Temporal	Dimension of vulnerability	Hazard	Scope	Method	Map products/analysis
Dwyer et al. (2004)	Household	Point in time (~monthly)	Vulnerability (socio-economic)	Individual-household level (Australia)/Natural hazards	Application/research/policy support	Methodology measuring attributes of individuals/household that contributes to their vulnerability to a natural hazard impact. Steps: indicator selection, integration of a risk perception questionnaire, decision tree analysis synthetic estimations. Vulnerability indicators are strongly in the socio-economic domain, whereas hazard indicators are associated with residence damage and injuries; decision tree analysis applied to combine the indicators with the outcomes (perceptions) of the questionnaire	Modelling and visualisation within a GIS

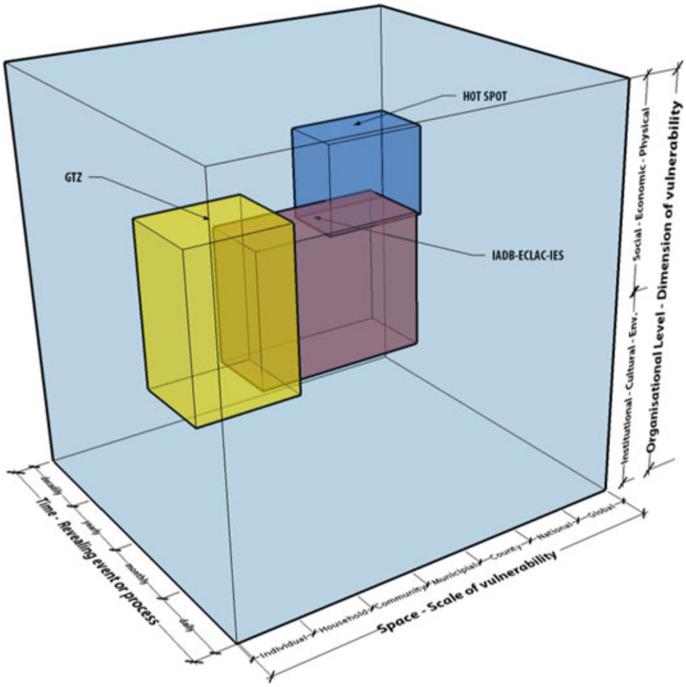
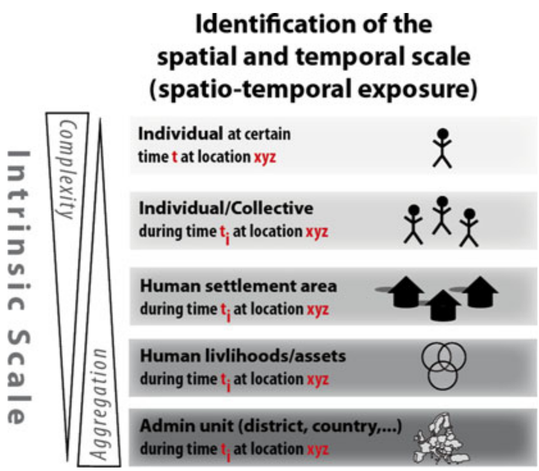


Fig. 2 Vulnerability cube for the positioning and characterisation of different vulnerability assessments with a spatial, time and dimensional characterisation. Here, the example assessments of GTZ (Hahn 2003), the hot spots analysis (Dilley et al. 2005) and IADB (Cardona et al. 2004) are visualised

and the dimensions of vulnerability (physical, social, etc.). Additionally, the scope of the study, its targeted hazards, applied methods and spatial analysis range have been analysed. The table includes a selection of key assessments in the past, but does not prove to be complete.

Fig. 3 The integration of the intrinsic scales towards spatio–temporal conceptualisations of our real-world environment



Many of the identified assessments integrate country-level data, especially in the context of the global/regional assessments. This is mainly due to the fact that in conjunction with the assessment of vulnerability, indicators such as GDP or the distribution of population have been used. However, the hot spot assessment approach of Dilley et al. (2005) and more recently the PREVIEW Global Risk Data Platform developed by UN/ISDR (2009) and other UN agencies employ disaggregated approaches down to a 1×1 km^2 resolution. As these risk indices are quite aggregated and therefore simple proxies of vulnerability, the results have to be interpreted with care especially when 'zooming in'; for instance, indices such as 'government accountability' or 'per capita income' are straightforward and understandable but are less suited for downscaling to completely different scales. This raises a general issue concerning the complexity of such modelling approaches, as methodological limits might be considered by experts but non-experts/policy-makers might interpret such results incorrectly when considering inherent uncertainties or limits when zooming into the finest pixel resolution. It can also be observed that a larger number of such spatio–temporal assessments are embedded within the global and regional scale than on the very local scale level, where a large number of case studies exists as well (as once collected on the ProVention website). This may be because global/regional assessments tend to be more quantitative with easier access to relevant data. Local assessments with an increasing level of complexities and a lesser degree of abstraction tend to be generally embedded in qualitative research domains.

In regard to the methodologies, quite different approaches exist. The number and the choice of indicators for indices vary significantly, but the weighting methods and the construction of combined indices are quite different as well (see also Gall 2007). The local level integrates household data, whereas in the approaches developed by Villagrán de León (2004) and Dwyer et al. (2004), a GIS component can be identified. A literature study reveals that a significant diversity exists with respect to the spatial dimension within existing vulnerability assessment approaches (Table 3).

In certain cases, highly sophisticated spatial analysis methods can be identified and the spatial dimension is explicitly considered, whereas in other cases, no spatial component is reflected, even if the study has assessed different countries/cities. The reason behind this omission may not necessarily be explained out of an ignorance of spatial concepts. Rather, it originates from different traditions of schools of thought. Only few of the approaches studied and listed in Table 3 are methodologically bound to a spatial assessment of vulnerability. It may also depend on the 'tools' available in the different scientific fields. The spatial component is seen by the authors as an essential aspect in the assessment of vulnerability at different scale levels, and therefore requires serious consideration of concepts and approaches developed in GIScience.

Additionally, it can be observed that the temporal dimension is also associated with the spatial scale, whereas global towards national (and sub-national) assessment tends to integrate available statistical data. These data are then perceived to be valid for a certain time period (e.g. last 2–3 years or even longer). Local studies in the context of an integrated vulnerability approach strongly rely on interviews and participatory approaches, which may also be seen as a snapshot of a specific point in time during the assessment but can also account for the temporal process through the use of participatory calendars, timelines and other tools. In mere natural and physical sciences approaches (e.g. Totschnig et al. 2011), quantitative approaches may be sufficient (Papathoma-Köhle et al. 2011).

Temporal issues also become more important in the overall development and evolution of vulnerability, which could create different 'windows of vulnerability' as stated by Dow (1992). Assessments (even on the global scale) are very difficult to compare, as underlying concepts and methods applied do not allow for a direct comparison of identified vulnerabilities. This may also underline the notion that vulnerability assessments can be seen as process (see also Birkmann 2007) which in turn requires that the identification of trends in the increase or decrease of vulnerability over time and within a spatial component. Therefore, it is an essential prerequisite within the design of (spatial) vulnerability assessments to allow for the integration of a monitoring component which should effectively support decision-making over a continuous time span, as opposed to single assessments which are not spatially, temporally and attributively (within their underlying concepts and selected indicators) comparable.

4 Vulnerability in a spatio–temporal and dimensional context

4.1 Vulnerability cube: a framework to integrate the where, when and what

As pointed out earlier, the concept of vulnerability is seen here more in the tradition of disaster risk reduction concepts than the one embedded in the traditional climate change community (Cardona et al. 2012). However, the proposed scale framework is valid for a wider range of vulnerability frameworks (which probably may already include spatio–temporal concepts), as it does not address the critical issue of stringent conceptualisation, but helps to provide a three-dimensional 'reference system' to position the vulnerability assessment itself. The integration of climate change-related vulnerability may also be possible, especially since it is expected that the two poles of hazard- and climate change-oriented vulnerability may converge in the future (see IPCC 2012).

Keeping in mind this variety of vulnerability concepts, some important general characteristics can be defined which help to integrate the framework into a GIScience relevant context (see also Kienberger 2007):

- WHERE: Vulnerability differs spatially and is place-specific
- WHEN: Vulnerability changes within time
- WHAT: Vulnerability has different dimensions (such as environmental, physical, economic, social, institutional and cultural)
- WHY: Vulnerability assessments are policy-oriented with the overall objective of mitigating/avoiding the negative impacts of disasters
- HOW: Vulnerability is currently measured indirectly and is described through specific indicators which should allow the representation and monitoring of the different dimensions of vulnerability

In Sect. 3, the integration of the spatial component in a vulnerability assessment was discussed and existing approaches were analysed. Following the characteristics set out above, it is assumed that the final manifestation of the combination of risk with hazard and vulnerability as a disaster can be spatially delineated. Therefore, vulnerability and its measurement and characterisations depend on the principles of scale as discussed above. Vulnerability has a spatial characteristic changing within its quantitative and qualitative manifestation in space.

In addition to the spatial component and its variation, vulnerability has a specific time component (see also Dow 1992). This becomes even more evident when assessing vulnerability as it is often based on data which have been acquired at a certain time (e.g. census results from a certain year, population distribution at a certain time). A strong relationship here exists with regard to the temporal character of the associated hazard. As for sudden-onset hazards such as earthquakes, this can be related to a specific time within a minute's resolution, whereby long-onset disasters such as droughts might need a different timescale (e.g. several years). It is therefore acknowledged that the temporal characteristic of the hazard shapes the temporal scale of at which vulnerability could be understood, but also accounts for the role of the hazard in revealing, triggering or causing vulnerability.

As already pointed out in the definition above, vulnerability is characterised by different dimensions. This links to the concept of sustainable development which identified the economic, social and ecological/environmental dimensions, but also integrates physical, cultural and institutional dimensions (MOVE 2010; Cardona et al. 2012) The structuring and separation of different dimensions underlies human reasoning and conceptualisation of our 'real-world environment' and therefore serves as a model for how we perceive reality and abstract it. These dimensions are strongly interlinked and are separated for the purpose of gaining a more simplified understanding of complex, so-called coupling mechanisms. The identification of dimensions, or as Villagrán de León (2006) calls them, sectors, helps to target specific user needs in the context of the policy dimensions. This means that actors involved in social, economic or environmental domains can be addressed. This may help to clearly adapt vulnerability assessment to the specific needs of certain actors.

Policy orientation is the central objective for conducting a vulnerability assessment. The assessment of vulnerability has to be designed to meet the needs of policy and decision-makers in order to minimise risk through the identification of where, and what is vulnerable, to which extent. In this case, the policy scale is essential as it influences the design of a vulnerability assessment and needs to be adequately chosen.

Finally, and in regard to the measurement/quantification of vulnerability, we face the challenge of identifying appropriate indicators, which allow for the measurement of vulnerability. Vulnerability cannot be measured directly; it is not expected that in the foreseeable future, there will be sensors developed to measure vulnerability.

We have to rely on the appropriate choice and the appropriate methods of integrating various datasets/indicators (e.g. expert-based approaches through weightings or mere statistical approaches) into a reliable and representative vulnerability assessment. However, the above-mentioned points should help to guide and select the appropriate indicators to address specific needs in developing a valid and suitable assessment.

Linking this discussion of the concept of scale, which was developed by Wu and Harbin (2006), to the concept of vulnerability and the guiding questions identified above, three axes for the positioning and characterisation of vulnerability can be defined by the following and visualised in a 'vulnerability cube' (Fig. 2):

- Time/When—Revealing event or process (e.g. daily, monthly, yearly and decadal)
- Space/Where—Scale of vulnerability (local to global)
- Organisational Level/What—Dimensions of vulnerability (e.g. social, economic, environmental, physical, institutional and cultural)

The questions on the 'purpose' (why) and the methodology ('how') are independent from the cube itself. However, putting an assessment in this coordinate space, questions on the relevance for policy (is my intended scale level the right one?) or the appropriate method (e.g. including participatory approaches) can be more easily answered.

Within the 'vulnerability cube', the time component is seen as the temporal validity of the assessment. Is the assessment carried out at a specific cut-off date or does it cover a longer period/time interval? This is also essential for the purpose of monitoring vulnerability to identify trends over time when comparing different time series. The next axe defines the spatial scale of the assessment. This is often referred to as the one which is most considered within a vulnerability assessment. It could be either designed for the local scale or for the global scale. Processes or the underling causal relationships we try to capture through the different dimensions of vulnerability are presented as the third axe (e.g. social, economic and environmental)

Within the spatio–temporal relation, it is essential to consider the different 'kinds of scale' (Wu and Harbin 2006). This includes the appropriate choice of the adequate policy scale (for whom is the assessment of use and under which regulations?), as well as the related observational/modelling scale (which data/indicators can be included and modelled at a certain scale?). Additionally, to this, the dimensional axes refer to the intrinsic scale of the phenomena; for instance, if a district has certain responsibilities in disaster risk reduction activities (=policy scale), the specific requirements need to be addressed through the appropriate choice of the modelling scale including data derived from an adequate observational scale with a valid choice of the dimensions considering the intrinsic scale of the phenomena in reality (e.g. is the identified indicator on poverty appropriate to (partially) describe the social dimension of vulnerability at this scale level). To answer these essential questions, the 'vulnerability cube' should serve as a guiding framework to gain clarity on the appropriate scale levels and the proper design of a vulnerability assessment.

Building on this, the three-dimensional conceptualisation allows the identification and discussion of appropriate scaling issues. This follows, once again, the argument of Wu and Harbin (2006) who define the three different types of scales as important characteristics for identifying appropriate scaling procedures and their validity. The possible divergence between the policy scale and observation/modelling scale with the intrinsic scale is an important consideration when designing a vulnerability assessment. Therefore, it might be necessary to not only extend the 'grain' size of the sample but also to change the underlying indicator as the intrinsic scale characteristic might be not valid for a certain policy scale anymore.

Subsequently, this framework helps us to position and compare different vulnerability assessments and to visualise/define overlaps, differences and specific characteristics (see also Fig. 2).

4.2 Integration of scale concepts within a vulnerability assessment

Drawing on the conceptualisation of the three-dimensional model, where a vulnerability assessment or the causes of vulnerability are defined by a spatial and temporal scale and the dimension under observation, different hierarchies associated with the three axes can be identified. In other disciplines, such as landscape ecology, these conceptualisations are applied to address hierarchical structures. Burnett and Blaschke (2003) have demonstrated that through the application of object-based image analysis (OBIA; Blaschke 2010) and the integration of remote sensing data, these hierarchical relationships can be applied to monitor and model ecological research questions. OBIA aims to generate image objects which not only make use of spectral reflectance values of satellite-based data but also include other attributes such as the shape, texture, neighbourhood relationships and scale hierarchy of image objects. In the domain of disaster (risk) management, these approaches are currently applied for damage assessment with very high-resolution satellite data or for population monitoring for humanitarian aid (see, e.g., Lang et al. 2006; Tiede et al. 2011).

As already stated above, the concept of vulnerability also exhibits a hierarchical structure (see Fekete et al. 2010). As vulnerability can be seen as a human-centred issue (see the notion that there are no 'natural disasters'; e.g. Smith 2006), we can also define which 'human system' has to be addressed (see Fig. 3). Theoretically, the vulnerability of an individual could be assessed, defined by a specific location at a specific time (see, e.g., Rieken 2010). However, the individual level might be for our purpose the most complex one and one which might be less 'relevant' for policy support. It can be simplified to examples such as physical vulnerability (e.g. ability to swim) or issues related to the social status of a person (e.g. income and education) which determines susceptibility or coping/adaptive capacity. At a next level, individuals could be 'aggregated' to a 'collective' such as population at locations and within certain time intervals. Here, the location of the population can be determined in a spatio–temporal relationship which might not be as 'chaotic' as an individual but still exhibits diurnal fluctuations (e.g. day- vs. night-time population). This question is manifested in the research needs identified by Cutter (2003), where the daily and diurnal occupation of certain areas with people/population should be more closely investigated. This spatio–temporal distribution, which characterises the spatio–temporal exposure of the population as well, is defined through the different 'attributive' dimensions of vulnerability, such as physical issues (e.g. being within a house at a certain time and place which is less earthquake resistant) or socio-economic conditions which characterise certain 'groups' of the population (which links to the social science definition of exposure).

A possible next level, the permanent settlement area could be of interest. Here, the temporal dimension is more stable (fewer time fluctuations) compared to the lower level and involves a longer period of time (such as years). The spatial dimension therefore is 'wider' and includes next to the real 'housing locations' the surrounding area which is of use to people. This approach can then be extended beyond the individual/settlement to the capabilities, assets (including both material and social resources) and activities required for a means of living, and what is here referred to as the livelihoods approach (e.g. DFID 2001). Finally, this can be again aggregated to arbitrarily define administrative boundaries, such as district, provincial, national and regional entities. All these levels are defined by an intrinsic scale which defines specific characteristics to be considered in the modelling and observational scale (see Fig. 4).

In general, it can be observed that the spatial and time variability of vulnerability increases when looking towards the individual and is more generalised towards the more aggregated, societal assessments. Interestingly, we see here a link to the intrinsic scale of hazards, which are defined by a certain speed of onset, temporal spacing and recurrence; for instance, droughts require a longer period of time to be considered as 'drought',

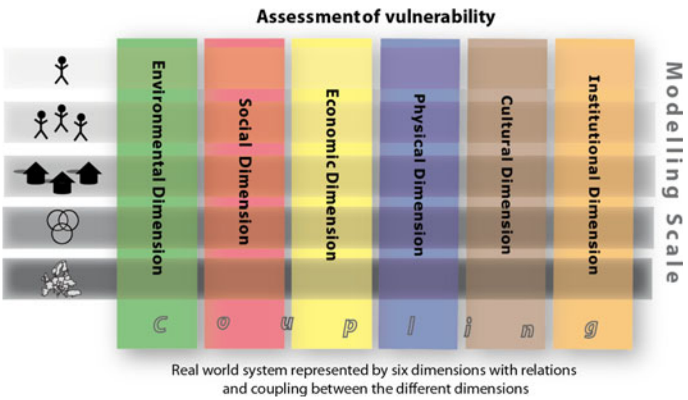


Fig. 4 From the intrinsic scale towards the modelling scale: integration of different dimensions of vulnerability and representative indicators

whereas an earthquake realises itself in a very short time period and where for instance diurnal population changes may play an important role. These characteristics are essential when considering the different levels presented above and defining the spatio–temporal scale of vulnerability.

Next, vulnerability can be considered in relation to the different dimensions of vulnerability, such as social, economic, environmental, physical, institutional and cultural (Fig. 4). In this case, we go beyond the spatio–temporal characterisation of the intrinsic scale and integrate an ordering system in regard to different causal relationships of our real-world environment. This helps us to target certain dimensions (e.g. social) of vulnerability (and risk) and further help in reducing the complexity (see also the axes of the 'vulnerability cube'). It is of course strongly acknowledged that the different dimensions are coupled with each other. This level of abstraction can also be seen at the modelling scale, which considers the previously identified characteristics of the intrinsic scale. This again requires the appropriate choice of input data at an adequate observational scale (e.g. poverty indicators for the district level assessment).

As stated earlier, vulnerability assessments have a strong focus on policy support. Therefore, it is required to link the intrinsic and modelling scales towards the appropriate policy scale (Fig. 5). Here, on one hand, the policy scale is predefined by laws and regulations, but also is characterised by the need to represent vulnerability in an appropriate way including its spatial, temporal and dimensional context. This can be done in a spatial, quantitative manner through the integration of different spatial methods. One such approach is the geon approach proposed by Lang et al. (2008). The term is used to describe generic spatial objects that are homogenous in terms of changing spatial phenomena under the influence of, and partly controlled by, policy actions. In this model, it is proposed that each dimension is represented separately which is a comprehensible and tractable approach. However, the question of an overall vulnerability (and also an overall risk when evaluating the hazard/vulnerability equation) arises. From a methodological point of view,

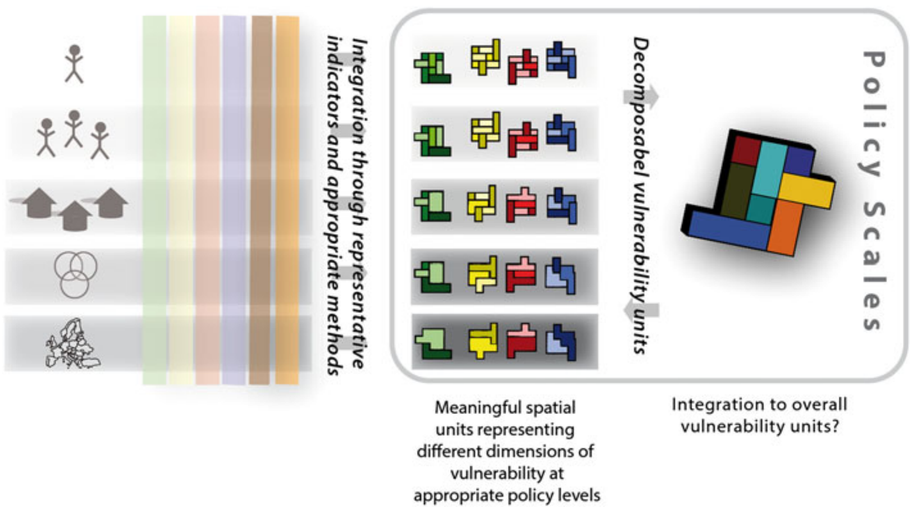


Fig. 5 Towards policy relevant provision of information products (e.g. spatial modelling of vulnerability)

it may be possible to integrate these different dimensions, but as already indicated, the relationships are still difficult to understand and integrate quantitatively.

The methodology has been currently applied for assessing vulnerability in a climate change (Kienberger et al. 2009) and flood hazard-related context (Kienberger 2012).

5 Conclusions

It has been demonstrated with the 'vulnerability cube' framework—and the underlying conceptualisation of the 'kinds of scale'—that a characterisation of vulnerability assessments in regard to its spatial and temporal scale, temporal validity and its associated dimension is possible. We further conclude that this approach provides a comprehensive and powerful way for structuring future vulnerability assessments according to different spatial, temporal and dimensional resolutions. Furthermore, this characterisation can be usefully translated into a useful methodological tool to coordinate future research as well as practical implementation of vulnerability assessments.

The definition of the appropriate modelling scale remains critical. It depends on the policy support objective of a vulnerability assessment at the policy level, since this is the scale at which decisions are made and implemented. Additionally, the scale issue is linked to the availability of suitable input data and to a clear evidence of the intrinsic scale characteristics of underlying drivers and characteristics of vulnerability.

Based on this, it is possible to approach the challenge of up–downscaling and to identify processes which characterise certain scale levels. In addition to the identification of different inter-linkages, the requirements for (geospatial) data and its availability within certain timescales need to be identified. This relates to the appropriate spatial resolution of data (e.g. census data) but also to the establishment of services which are available continuously in time and allow for the regular monitoring of vulnerability. Monitoring is seen as a central objective of any vulnerability assessment. In addition to analysing the present state, the identification of critical changes and trends over time at the appropriate scale level is crucial. While the technological realms such as earth observation and GIS are well advanced, methodological differences and inconsistent use of terms and concepts have so far hindered both the transferability and re-applicability of approaches. In this respect, the authors believe that the 'vulnerability cube' is more than a metaphor: it provides a structure for the different notions of scales and ultimately for a spatial analysis workflow. It integrates supporting application tools and capabilities, providing a more holistic solution for spatial analyses of vulnerabilities and risks to hazards.

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