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Assessment of urban vulnerability towards floods using an indicator-based approach – a case study for Santiago de Chile

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Abstract. Regularly occurring flood events do have a history in Santiago de Chile, the capital city of Chile and study area for this research. The analysis of flood events, the resulting damage and its causes are crucial prerequisites for the development of risk prevention measures. The goal of this research is to empirically investigate the vulnerability towards floods in Santiago de Chile as one component of flood risk. The analysis and assessment of vulnerability is based on the application of a multi-scale (individual, household, municipal level) set of indicators and the use of a broad range of data. The case-specific set of indicators developed in this study shows the relevant variables and their interrelations influencing the flood vulnerability in the study area. It provides a decision support tool for stakeholders and allows for monitoring and evaluating changes over time. The paper outlines how GIS, census, and remote sensing data as well as household surveys and expert interviews are used as an information base for the derivation of a vulnerability map for two municipalities located in the eastern part of Santiago de Chile. The generation of vulnerability maps representing the two different perspectives of local decision makers (experts) and affected households is exemplified and discussed using the developed methodology.

1 Introduction

Floods in Santiago frequently affect numerous people, buildings, and infrastructure across the city. The dramatic and ongoing urbanization process in Santiago is leading to an increase of the flood hazard and an increase of population and infrastructure in flood-prone areas. Hazard maps for Santiago de Chile for floods resulting from river and canal overflow, high ground water tables, and accumulation of storm water on streets were published in the scope of several studies (AC Ingenieros, 2008; Antinao et al., 2003; CADE IDEPE, 2001; Ayala et al., 1987). The amount and type of damage that the affected elements within these hazard zones suffer, however, is heterogeneous and not recorded in any inventory. The extent of damage depends on the vulnerability of the affected people and infrastructure. Flood vulnerability has its origins in various dimensions that are sometimes hard to capture and to describe precisely and even harder to measure and to evaluate. What is lacking for the study area is information about the vulnerability of the people, buildings, and infrastructure in the flood-prone areas in order to be able to derive flood risk reduction measures. So far, vulnerability assessment in the study area has only focussed on land use as the sole determinant of vulnerability (Perez, 2009). More specific research on coping capacities and exposure issues to further characterize and analyze vulnerability to floods has not been carried out yet. Thus, this study investigates vulnerability to floods in Santiago de Chile, i.e. in a semi-arid environment with rather low flood heights, for the first time and discusses them with respect to their importance for flood risk both from the perspective of the affected population and regional decision makers. Hence, this paper compares the evaluation of vulnerability from different perspectives.

Vulnerability is embedded into the concept of risk as shown in Eq. (1).

$$\text{Risk} = \text{Vulnerability} \times \text{Hazard (Wisner et al., 2004; UNDP, 2004)} \quad (1)$$

Next to the hazard, vulnerability contributes to the generation of risk. That means that risk evolves where a hazard zone spatially interferes with areas that are vulnerable to the particular thread. The assessment of vulnerability through its fuzzy nature remains an ill-structured problem. This has been stated numerous times in literature (Taubenböck et al., 2008; Villagran, 2006; Rashed and Weeks, 2003). Findings from the Expert Working Group 'Measuring Vulnerability' show that there are basically two approaches to measure

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vulnerability, (i) expert approaches, such as indices based on expert knowledge (see listing below) and (ii) participatory approaches, e.g. self assessment that fosters raising awareness of the negative situation that people might get into (Birkmann, 2005a; Kienberger and Steinbruch, 2005).

This research applies an indicator-based expert approach. In order to be measured, the dimensions, characteristics or variables that define and influence vulnerabilities have to be assigned with a crisp value, i.e. they need to be scaled using indicators (Atteslander et al., 2008). Birkmann (2005a) states that the employment of indicators requires an overall goal and guiding vision, which is in this case the reduction of flood vulnerability. Birkmann (2005a) names the ability to set priorities, to give a background for action, to raise awareness and analyze trends as the most important function of indicators. For the practical analysis and assessment of vulnerability to floods in Santiago, a set of relevant indicators was developed in the scope of this study. For the validation of these indicators, expert opinion as well as the perception of the (potentially) affected population was taken into consideration. The different opinions on the generation of vulnerability, the data collection for the indicators and the generation of vulnerability maps based on the selected indicators are presented from Sect. 4 onwards.

2 The concept of vulnerability

2.1 Theoretical framework

Vulnerability has its origin in poverty research and, generally spoken, explains why the same hazardous event has different effects on each element at risk, i.e. people and infrastructure. A variability of types of vulnerability exists: social, physical, ecological, economic, individual, and urban vulnerability amongst others (compare Adger, 2006; Luers et al., 2003). The high amount of definitions for vulnerability that can be found in literature is a corollary. The common baseline of all approaches is that they refer to the conditions that make an individual or a system susceptible to experience harm as a consequence of an external shock. What differs is the explanation for that aforementioned susceptibility, as that depends on the type of shock, the considered scale, the reference objects and the location-specific conditions. The concept of vulnerability is non-tangible and it is a practical challenge to quantitatively capture it. A range of elementary concepts have been generated which all have a high explanatory value and represent interdependencies that are more or less universally valid. They can then be specified for individual case studies by choosing vulnerability indicators accordingly (Bogardi, 2006; Birkmann, 2005b; Brooks, 2003; Cutter et al., 2003; Turner et al., 2003). A very prominent concept to capture the multi-dimensional character of vulnerability is the “Pressure and Release (PAR) Modell” developed by Blaikie et al. (1994) and republished by Wisner et al. (2005) that emphasizes the diversity of relevant scales for vulnerability research. Besides physical and social characteristics of an individual or household level, institutional, economic, and systemic conditions that influence vulnerability are included in the proposed concept. Encompassing two dimensions, Clark et al. (1998) define vulnerability as “people’s differential incapacity to deal with hazards, based on the position of groups and individuals within both the physical and social worlds”. During field surveys it was investigated whether or not there is a relation between the geographic location of a household, its social position and the level of coping capacities and risk knowledge of its inhabitants. Thus, the definition given by Clark et al. (1998) also coincides with the research direction followed in this study.

The definition that is found appropriate for this research is based on the previous findings:

Vulnerability results from the social and physical conditions that make parts of an urban system susceptible to experience damage from a flood event (modified after Wisner et al., 2005 and Clark et al., 1998).

Physical conditions comprise, for example, exposure to the hazard. People and buildings are only exposed if they do not have sufficient structural or private measures against flooding (e.g. walls, backflow flaps). In other words, a building is not exposed if it is surrounded by a solid high stone wall that keeps all water out. Social conditions refer to the characteristics of an element at risk that make it less susceptible to suffer damage from floods, i.e. knowledge about the hazard or the age of the affected people. The means by which people or organizations use available resources and abilities to face adverse consequences that could lead to a disaster are defined as *coping capacities* (UN/ISDR, 2004).

Pelling (2003) understands vulnerability as a concept comprising exposure (location relative to hazard, environmental surrounding), resistance (livelihood, health), and resilience (adjustments, preparation). Especially the consideration of resistance - referring also to the economic, psychological, and physical health of individuals - make the approach very realistic, but at the same time very costly and complex as in-depth household studies are needed. While indicators referring to exposure and resilience are included in this study, indicators referring to the resistance are left out (a) because respective data were not available, (b) because for an appropriate evaluation they require expert knowledge that was not available in the scope of this study, and (c) because it was found during field surveys that floods with the comparably low magnitude as occurring in Santiago de Chile can predominantly be explained using physical exposure and resilience indicators.

It has to be stressed here that vulnerability is a highly dynamic component. The level of vulnerability can change rapidly, e.g. after the impact of a disastrous event or slowly with changing personal, communal or national conditions (e.g. individual ageing process, political changes, economic development, ...). Vulnerability is to a large part dependent on the hazard: In terms of construction material, for example, this means that a certain construction material shows a higher fragility towards floods than earthquakes.

2.2 Practical vulnerability assessment using indicators

Vulnerability assessment helps to identify people or property that is susceptible to suffer harm. However the variables that cause this vulnerability cannot be generalized. Reasons for the vulnerability of a modern Global City can differ remarkably from those e.g. in a fast growing megacity in a developing country. It is also widely recognized that individuals, households, and neighbourhoods are able to influence their level of vulnerability (Kuhlicke, 2008; Heijmans, 2004). Through the development and application of indicators and parameters, relevant aspects and contexts can be examined and integrated into practical tools (Wisner, 2003).

To practically assess vulnerability in a specific study area, it is of utmost importance to identify those factors and variables that make a specific urban system vulnerable to a certain hazard and to explore how these factors take effect. Once these variables that cause social phenomena are identified, they need to be converted into indicators to enable the assignment of values and a consequent measurement. Indices are then developed to allow at minimum a relative evaluation of vulnerabilities among different people or places, i.e. to determine if one area is more or less vulnerable than another. Besides this, the use of indices allows assessment of vulnerability and its comparison amongst places also for an analysis over time in the same area.

2.3 State of the art in vulnerability assessment

The importance of vulnerability assessment in the scope of disaster management has been recognized: Numerous approaches to assess vulnerability using indicator-based top-down methods can be found in literature (te Linde et al., 2011; Taubenböck et al., 2011; Huttenlau et al., 2010; Kienberger et al., 2009; Fekete, 2009; Kubal et al., 2009; Meyer et al., 2009; Ebert et al., 2009; Taubenböck et al., 2008; Fedeski and Gwilliam, 2007).

Taubenböck et al. (2008) investigated on the potential of remote sensing data (IKONOS, Landsat, SRTM) for vulnerability and risk assessment in the earthquake-prone area of Istanbul. Ebert et al. (2009) used Quickbird data for a study area in Tegucigalpa (Honduras) to map elements at risk (roads, buildings, green spaces) and their social vulnerability to landslides and floods using proxy variables. Taubenböck et al. (2011) highlighted the added value of multi-temporal and multi-scale remote sensing and high-resolution elevation data for the assessment of flood risk in urban areas as they can be applied to address a range of vulnerability-related questions. Te Linde et al. (2011) combined various digital data sources to assess vulnerability to floods in the Rhine catchment. Meyer et al. (2009) developed a GIS-based multi-criteria flood risk assessment and mapping approach implemented in the software tool FloodCalc. Kubal et al. (2009) applied the approach developed by Meyer et al. (2009) to an urban area, to the city of Leipzig (Germany). The study likewise focuses on estimating the damage potential with regard to economic, social, and environmental aspects after a flood event. Fekete (2009) applied census data validated with a second independent data set about damage after flood events in 2002 to analyse social vulnerability in Germany. Kienberger et al. (2009) developed a raster cell based object-oriented approach for the assessment of vulnerability to floods in Austria.

Applying a bottom-up approach, Pelling (1997) published a study on vulnerability to floods where field surveys were conducted seven days after a flood event in Georgetown, Guyana, in order to find out what type of people was affected by floods. The findings showed that those households experienced the highest damage were the ones that had a low income, poor housing quality and little community organization (Pelling, 1997).

Several studies apply indicators to evaluate the success of measures for the reduction of vulnerability or structural flood control measures (Brouwer and van Ek, 2004; Bana Costa et al., 2004). In contrast to the present study which focuses on the analysis of reasons for vulnerable conditions which are not yet known for the case of Santiago, those studies go one step ahead and aim at judging concrete measures for the reduction of vulnerability and risk but do again emphasize the importance of including stakeholders.

These and other studies have led to important scientific and practical knowledge about vulnerability and vulnerability assessment. Besides specific projects, several national and international programs and institutions, such as the Helmholtz EOS Natural Disasters Networking Platform (NaDiNe), the DLR (German Aerospace Centre) disaster management centre, the RISKEOS network (a network of European service providers, which is part of the GMES (Global Monitoring for Environment and Security) Service Element Program), the Dresden Flood Research Centre, the UK Flood Risk Management Research Consortium, several national research agencies such as the British Environment Agency, and the United States Geological Survey (USGS) that focus on flood risk management do exist and work on different spatial levels.

The challenges that always remain are (i) the selection of appropriate variables that are capable of representing the sources of vulnerability generation in the specific study area, (ii) the determination of the importance of each indicator, (iii) the availability of data to analyze and assess the indicators, and (iv) the validation of the results.

Table 1. Overview about available geodata.

Content	Format	Data source
Contour lines and derived , digital elevation model (DEM) 1:2500 and 2.5 m, respectively	Polyline shape, raster file	AC (2008), own derivation of DEM
Administrative units (building blocks)	Polygon shape	INE (2002)
Classification results containing 17 urban land use/land cover classes from Quickbird satellite image	Raster with 2.4 geometric resultion in channels Blue, Green, Red and NearInfrared, 0.6 m geometric resolution in panchromatic channel and classification result	Own classification
Census data	Pre-processed, in table format	INE (2002)

3 Study area and data base

3.1 Study area

This research focuses on Santiago de Chile, the economic center and largest agglomeration of the country. With 6.8 million inhabitants it accommodates 40 % of the total Chilean population (INE, 2008). The city is located in the central region, where the climate is characterized by long dry summers and a clearly marked rainy season with few but intense precipitation events. Santiago is built in a depression between the Coastal Range and the massive Andes Main Range. Several creeks or so-called "quebradas" characterized by sporadic alluvial discharge drain the ranges towards the city. Chile's economic boom of the last three decades has transformed Santiago into one of Latin America's most modern capitals within a short period of time. Due to the growing demand of space the urban area is continuously expanding, especially towards the slopes of the Andean foothills. From 1940 to 2002, the urban built-up body grew from 11 017 ha to 64 140 ha (Galetovic and Jordan, 2006). In the particular study area, i.e. the municipalities La Reina and Peñalolén, the analysis of land-use/land-cover (LULC) changes shows a growth of the amount of built-up area by 7.47 % in La Reina and by 13.46 % in Peñalolén between 1993 and 2009 (our own calculations based on the analysis of remote sensing data with a spatial resolution of 15 m). The loss of vegetation cover and the sealing of the slope regions mean that surface water rapidly enters the urban area, resulting in frequent floods at times of heavy precipitation events. The situation becomes even more problematic as urban planning cannot keep up with the significant growth of the city and also parts of the natural drainage systems have been claimed for the construction of housing and infrastructure. To allow for a more detailed study, this research was carried out for a specific part of the city. The chosen study area comprises two communities situated at the western slope of the Andes (Fig. 1).

Both are crossed by several creeks and are regularly affected by floods. Peñalolén is one of the most densely populated communities of the metropolitan area. The settlement of the originally rural area of Peñalolén started with processes of spontaneous and illegal land takes by low-income groups. Still today, the community is marked by great socioeconomic diversity. In comparison, La Reina has a much smaller population and building density and is considered as a middle to upper middle class community.

The floods in Santiago are typically slow (i.e. no flash floods), carrying large amounts of sediments and branches from deforested slopes that remain on the streets after the water disappears (Reyes Paecke, 2003). Other characteristics of these floods are the different and partly overlapping sources of danger. Unchanneled rainwater entering the city from the creeks as well as water from overloaded channels flows into town and causes danger zones, mainly along the roads. Besides that, rain water accumulations resulting from topographic sinks and/or a malfunctioning or missing stormwater infrastructure cause local flooding. For the irregularity of the flood sources, it becomes challenging to select appropriate indicators. The floods occur rather regularly (almost annually) and people have in most cases adapted to a certain hazard level or do adopt as sooa as they have suffered damage once. However, information about the cost of these flood events is not available for the study area.

Investigations of the Inter-American Development Bank have prooved that predominantly small and medium hazardous events have a cumulative negative impact on daily life and on local and regional capital accumulation (Wisner,

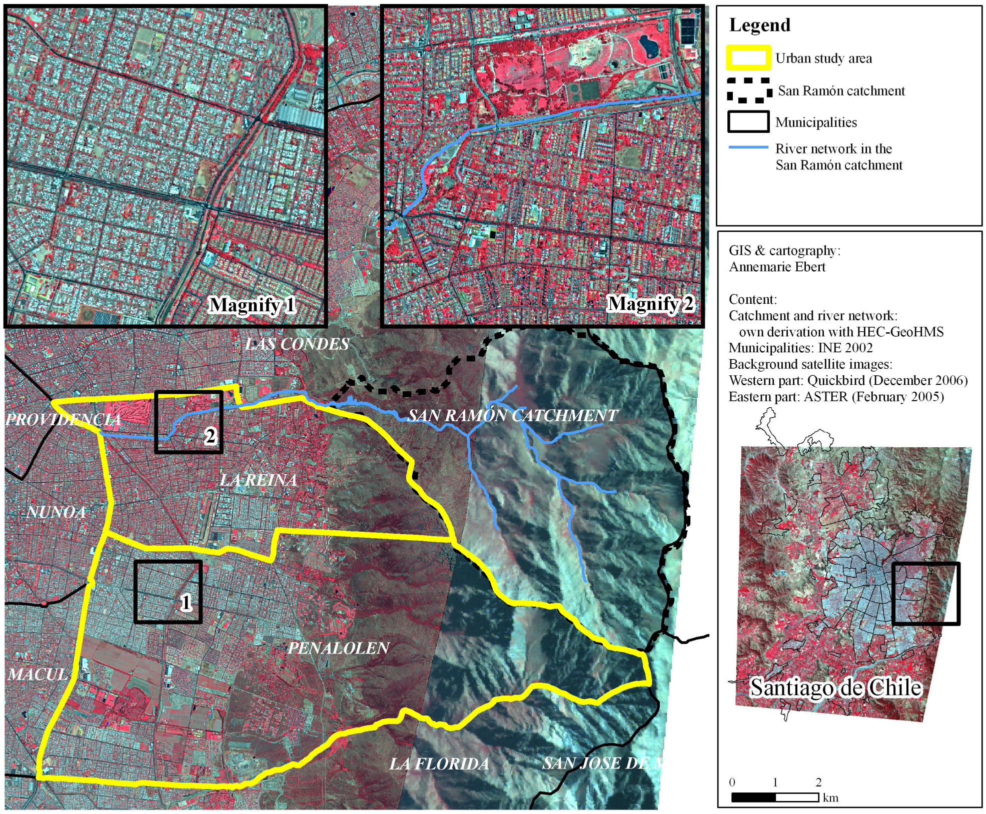

Fig. 1. Location of the study area.

2003). Also in the study area, floods – even with a lower intensity – cause monetary costs as well as alternative costs, e.g. if people are hindered from going to work and the quality of life decreases. The flood height seldom exceeds 20 cm but regularly interrupts urban functioning and harms vulnerable households in one or the other way. Due to the hilly topography, material damage to private homes often occurs quite selectively. Most frequently, front yards, outer walls, floors, and furniture are affected, moisture remains in the walls (physical damage) or people are trapped in gated communities and cannot go to work (immaterial and economic damage).

3.2 Data base

The information used in this study is based on the analysis of geodata, such as land-use and land-cover maps derived from satellite data and GIS data as well as census data. In addition to the available database, field surveys were carried out to obtain more detailed information about coping capacities and specific household characteristics in the selected communities.

The following data is available for the study area (Table 1):

Geodata are used for this study as they are readily available from different points in time without the need for carrying out extensive field studies. This clearly eases the multi-temporal assessment of vulnerability homogeneously over larger areas. The available Quickbird data were classified to derive LULC maps using an object-based analysis approach. The broad applicability of object-based image analysis of remote sensing data has been highlighted by Blaschke (2010). A range of studies prooved the great advantages of this approach for building extraction in the context of urban flood risk management (Taubenböck et al., 2011; Jacquin et al., 2010; Ebert et al., 2009; Banzhaf and Höfer, 2008). The delineation of built-up areas and green spaces as they are most relevant for this article; in the following it is used as input data for vulnerability indicators. The classification accuracy is 0.88 for built-up areas and 0.95 for green spaces. The applied digital elevation model (DEM) was derived from 2.5 m contour lines using an adapted inverse distance weighted algorithm after Hutchinson (1989). The information of the land-use map and the DEM were then combined using a GIS to obtain information about the location of the buildings in relation to the street level. Therefore, buildings as they were derived during the object-based analysis from the Quickbird data and streets as they were manually digitized for the highest possible accuracy were assigned with average elevation values. This analysis was then completed by carrying out a spatial query to identify those built-up areas that are located at or below the level of frequently flooded streets. While information derived from geodata (GIS, remote sensing data) or from census data cover large areas and are mostly readily available, they generally have not been acquired specifically to obtain information about flood risk. Especially for the analysis of vulnerability, additional data sources were required to get more causal information on how vulnerability is being generated. Additionally, geodata alone only provide a limited level of spatial detail, i.e. individual characteristics cannot be delineated. Therefore, further specific information was collected during field surveys and expert interviews.

To obtain knowledge on why and how households are vulnerable to flood events, which characteristics and dimensions are most important, and how the affected people personally evaluate the issue of floods, interviews were carried out with households in flood- prone areas according to the regional development plan (PRMS). The most appropriate method to obtain the desired information is a structured interview using a standardized questionnaire (Atteslander et al., 2008). A pre-test carried out in the field ensured that the closed and open questions that were posed in the Spanish language were clear and understandable. Possible additional questions were clarified during the interview as all questionnaires were completed personally with the interviewees. The face-to-face interviews also allowed the participation of illiterate persons and a detailed mapping of the living situation.

In 2002, 27.8 % (approx. 26 900 people) of the population in La Reina and 17.99 % (approx. 38 900 people) of the total population in the municipality Peñalolén were living in areas that are flooded at least once every two years. The household size in the study area is in average 4.06 (our own calculations based on census data (INE, 2002)). As in the scope of this research it was practically impossible to interview all households potentially affected by floods, stratified samples were selected in order to prevent possible under-representation of relevant characteristics even with a small sample. Following the theoretical discussion (Adger, 2006; ISDR, 2004; Pelling, 1997; Chambers, 1989), a strong link between vulnerability and socio-economic characteristics is assumed, thus the distribution of household characteristics and capabilities that can serve as indicators vary between groups of different social status. For the analysis, an even distribution (disproportionate stratification) between socio-economic groups was aimed at. For the final selection of households, a systematic random sampling was conducted, backed up by available maps of the distribution of Social Economic Groups (Grupos Socioeconomicos – GSE, Adimark, 2003). In practice, the selection of the household was mainly dependent on the accessibility, the presence of a household member at different times of day and their willingness to participate in the survey. Due to increased criminalization in parts of the municipality of Peñalolén, some districts were not accessible. Furthermore, the increasing crime in neighbourhoods leads to a strong isolation which made it even more difficult to get in contact with upper class residents in these areas. For these reasons, the implementation of systematic random selection of households was not always possible. It has to be noted, however, that people's willingness to answer the questionnaire differed depending on their experience with floods. People that were regularly and/or strongly affected by the floods tended to agree to participate rather than people without any flood experience. For that reason, the sample contains proportionally more affected households. With regard to the content, this has no impact on the indicator analysis. It is more critical that due to these difficult conditions, the sample size was even smaller than planned. A total of 82 household surveys was conducted in the municipalities of La Reina and Peñalolén. The sample cannot withstand any hard criteria of representativeness. Besides the question of being representative, small samples face the hazard of rejecting theoretically plausible hypotheses or of not being able to non-ambiguously verify these hypotheses. However, having only small samples available for certain fields of research should, according to Prein et al. (1994), not hinder empirical research in the respective research areas. For that reason, this research includes next to statistical analyses the application of plausibility criteria that are supported and verified particularly through the statements of the actors. This research has a predominantly exploratory character but provides valuable quantitative data at the micro level at the same time that could only have been gathered using the presented methodology with its limitations. The main goal of this research is, consequently, to work out tendencies in a small area that allow for testing the relationship between household characteristics and vulnerabilities towards floods.

An additional questionnaire was designed to inquire into the specific importance of vulnerability indicators from the expert's point of view. During the household surveys, a range of variables and characteristics related to flood vulnerability were obtained but their importance and weights that need to be known for the calculation of a vulnerability index did not entirely and reliably become clear from the household survey alone. Therefore, a standardized questionnaire with closed and open questions (Atteslander et al., 2008, p. 136 ff.) was designed. The closed questions comprise a list of vulnerability variables and five possibilities to rank their importance (100 % = very important, 75 % = important, 50 % = medium important, 25 % = little important and 0 % = not important). Open questions in the questionnaire left the opportunity to add comments to the experts' evaluation of each indicator and to list further aspects and variables relevant for the analysis of vulnerability. The Spanish questionnaires were sent out together with a cover letter by email to experts that were found to have relevant knowledge about flood-related vulnerability in the study area. Eleven out of 50 questionnaires were returned by email within a period of three months between November 2009 and February 2010, whereby a reminder was sent out after seven weeks leading to a doubling of the previous response rate. The comparably low initial response rate might be interpreted in such a way – amongst other probable reasons – that the topic of flood risk and especially of vulnerabilities was not considered very relevant to the actors. All closed questions were always completely answered; the open (voluntary) questions were only partially answered.

4 Indicator development

4.1 Selection of relevant variables

While a range of widely-accepted relevant characteristics and indicators is being presented in literature, the actual conditions that determine flood vulnerability are to a certain degree very site-specific, location-, and hazard-dependent. The review of relevant literature and the field surveys and interviews carried out in the scope of this research showed that the variables compiled in Table 2 are most relevant for flood vulnerability analysis in the study area. These indicators fit the local conditions and the flood characteristics best. At the same time, data for their assessment are available. Data availability limited the application of further indicators that prooved to be applicable in previous studies: While flood risk assessment is based on state-damage functions in most European countries, respective data are not available for the study area (Meyer et al., 2009). For that reason, the inclusion of asset values in the vulnerability assessment was not feasible and the vulnerability analysis is predominantly based on the aspect of coping capacities.

The selection of the indicators is backed up by the outcome of the expert survey. This survey brought up cultural aspects as the only other variable that should be considered in the vulnerability assessment. Besides providing a list of suitable indicators, Table 2 also lines out the relevance of the indicators for the specific case study and provides further references for each indicator.

4.2 Evaluation of the variables based on the household surveys

The household surveys carried out in the municipalities of La Reina and Peñalolén were meant to proove the ability of the identified variables to explain flood vulnerability in Santiago, taking into account the local knowledge and perception of the affected people. On the one hand, the questionnaire contained information about the household characteristics identified as relevant for vulnerability assessment (compare Table 2, except of Variable 4). On the other hand, interviewees should define damages or limitations suffered from flood events and evaluate their own affectedness on a scale with three values (not affected/moderate affected/heavily affected) based on their experience of the annual flood events and the current capacities to cope with these events. Against the background of the repeatedly occurring events, the assessment of their own affectedness from the people's point of view defines which households are vulnerable to floods. To verify the variables, correlation analysis was applied.

Answers from the residents about material and immaterial damages they suffered during flood events improved the understanding about what it practically means to be affected and to suffer damage from floods. 34 out of 82 households declared they suffered physical damage, i.e. that parts of the exterior (garden furniture, plants) or interior equipment (floor, documents, electric equipment, furniture, etc.) got wet and were destroyed to different degrees. Three cases reported that the sewer system broke and excrements could enter their houses. In total, 53 households declared they suffered immaterial damage. With more than one answer possible, 24 suffered limited mobility, 18 isolation, eight had financial losses as they could not go to work or as their shops were inundated, and four in each case declared power and water outages, illness, and mental stress.

According to the local residents, the location of a building in relation to the street level (above, at or below street level), the employment status (none, sporadic or permanent occupation) and the number of dependent people (household size) best explain the households' evaluation of their own affectedness.

Looking at variables such as structural flood protection measures, the relation to affectedness is diverse: On one hand, it prevents from material damage, on the other hand it results that people are captives in their buildings (mostly in the case of gated communities) and suffer immaterial damage. In the questionnaires, 37 households stated they apply temporary mitigation measures such as sandbags (23 people) and cleaning of drains and gutters before the raining season starts (22 households).

A central finding from the field surveys that for methodological reasons could not statistically be proven is that the experience with floods plays a central role for the level of vulnerability. Households that had suffered any type of damage during floods did take precaution measures, as it is widely known that floods are a regularly reoccurring phenomenon. The survey showed that the first flood protection measures (mostly requiring financial investments) were taken after a building or household suffered damage and not in advance. That means that preventive protection measures were not considered important. Twenty of the households then took permanent measures: Six heightened their houses, e.g. with cement, 15 constructed walls or watergates, four constructed a private drainage system on their property (multiple answers possible). However, none of the households that had never experienced harm took permanent prevention measures. The statistical lack of correlation between affectedness and experience as well as affectedness and protection measures can be explained amongst others by the small sample and the diverse dimensions of damage. For instance, a household that built a watergate to protect the property from water outside can still be affected e.g. because the residents are isolated and have no possibility to buy food and to go to

Table 2. Variables relevant for the assessment of flood vulnerability in the study area.

No	Variable	Relevance	Reference
		Physical vulnerability	
1	Main construction material for roof, walls and floor	determines the physical fragility towards flood events and indicates the resistance to damage and also the social status	Schneiderbauer (2007); Taubenböck (2007); Clark et al. (1998); Cutter et al. (2003)
		some types of construction material allow humidity to remain in the walls or floor after flood events which can lead to health problems	Field surveys
2	Position of buildings in relation to the street level	determines the likelihood of constructions to suffer damage in case of a flood event,	Schneiderbauer (2007)
		people that live below or at street level show a much higher exposure to the floods	Field surveys
3	Proportion of green spaces per building block	used to describe the social status	Stow et al. (2007)
		the higher the amount of green spaces in an area, the higher the retention potential and the lower the flood hazard	Niehoff et al. (2002)
4	Availability or application	small walls and backflow flaps of flood protection infrastructure	Schneiderbauer (2007) reduce the exposure
		Social vulnerability	
5	Age	the young and the elderly people are vulnerable to natural hazards both because of their physical condition and their financial dependence	Schneiderbauer (2007); Haki et al. (2004); Cutter et al. (2003)
		the vulnerability of the elderly is minimized by their experience	Clark et al. (1998)
6	Gender	women are generally described as more vulnerable to natural hazards than men because of their stronger involvement in family life, sector-specific jobs and lower wages	Wisner et al. (2004); Haki et al. (2004); Cutter et al. (2003)
		women are more emotional which makes them more vulnerable	Field surveys
7	Level of education	strong relation to income and social status contributes to a better knowledge about natural extreme events and their origins and about methods to reduce and mitigate the hazard	Schneiderbauer (2007); Velasquez and Tanhueco (2005); Haki et al. (2004)
8	Household size	the higher the household size, the lower the social status and the higher the amount of people affected – and therewith the damage	Haki et al. (2004); Cutter et al. (2003)
		large households embody intrinsic social networks and manpower which can be valuable in emergency situations	Velasquez and Tanhueco (2005)
9	Employment status	Indicates the regularity of income and therewith the possibilities of a household to save money for flood mitigation measures or to cope with negative affects. It is distinguished between no employment, permanent employment and sporadic employment	Field surveys (modified after Dwyer et al., 2004)
10	Experience with floods	Increases people's sensitivity to the problem, leads to the generation of private flood mitigation measures; positive influence on preparedness	Birkmann (2005a), Velasquez and Tanhueco (2005), Wisner et al. (2004), Cardona (2003)
11	Knowledge about flood hazard	The more knowledge and information available, the lower the vulnerability	Cardona (2003)
12	Knowledge about private protection measures	diminishment of vulnerability, financial resources are not real constraint for the construction of protection measures – at least not for short-term protection measures such as sandbags	Wisner (2003), field surveys

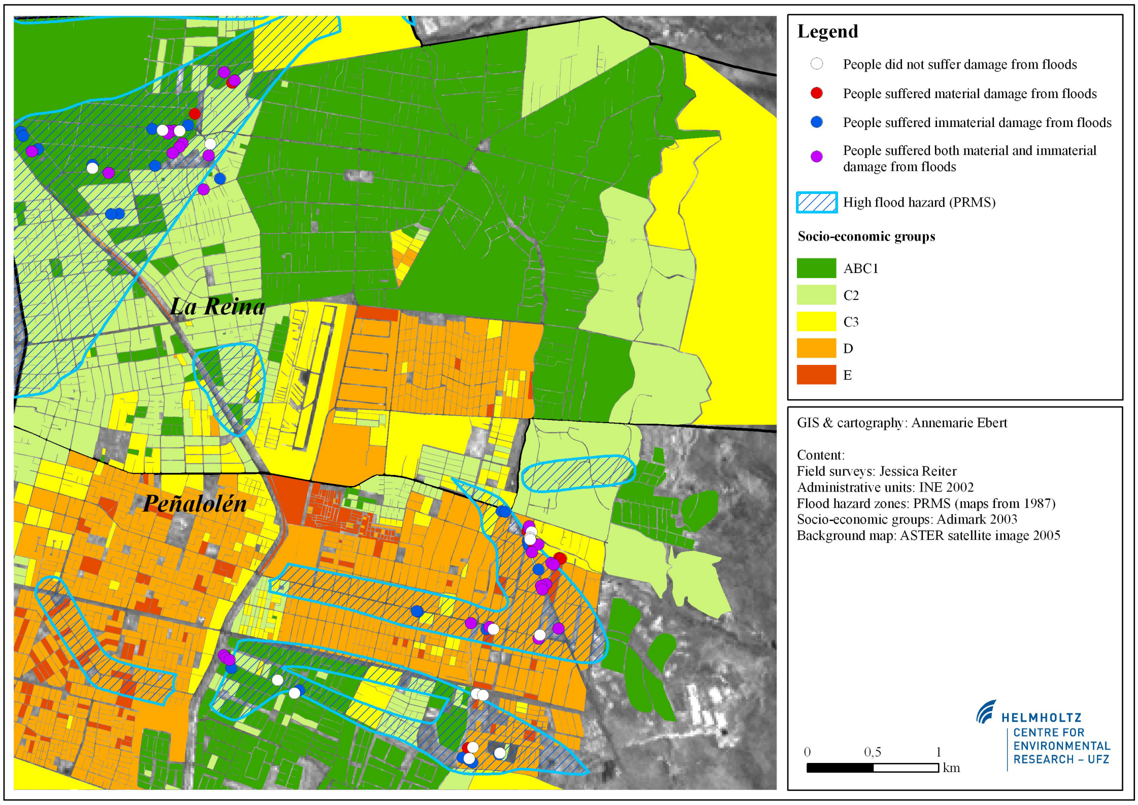

Fig. 2. Location of the surveyed households with their predominant type of flood-related damage and location of the flood hazard β-zones after according to the Regional Development Plan.

Table 3. Most explanatory variables: experts' and residents' perspective.

Experts' perspective	Local residents' perspective
Position of buildings in relation to the street level	Position of buildings in relation to the street level
Main construction material for roof, walls and floor	Employment status
Proportion of green spaces per building block	Household size

work or the electricity breaks down etc. Additionally, this lack of correlation can be interpreted as advice that in some cases, private measures do not provide sufficient protection.

No relation could be shown for the variables level of education and income groups with knowledge about protection measures and taking of measures. The reason is most likely that information is largely circulated on informal networks working independent of social status. Finally, it can clearly be stated that the frequently used socio-economic indicators are not sufficient for the explanation of the generation of vulnerability (compare Adger, 2006; ISDR, 2004; Pelling, 1997; Chambers, 1989).

Figure 2 shows the location of the interviewed households, the flood hazard zones as contained in the Regional Development Plan (PRMS), the average socio-economic group of each building block in the background, and the type of damage the households predominantly suffered. It becomes obvious that by trend, the damage in areas with a higher socio-economic level is immaterial. The damage is more likely to be material in areas where more households from the lower social level are found.

4.3 Evaluation of the variables based on the expert interviews

While the relevance of variables related to hazard and elements at risk can be defined physically or mathematically, the relevance of the variables referring to vulnerability with respect to flood risk is more challenging to evaluate. Interviews carried out with local decision makers allowed a broader estimation of respective information and deeper insight into the local, site-specific conditions. Questionnaires sent out to experts working in the regional government or branches of ministries, in non-governmental organizations as well as communal planning institutions in the research area produced the findings reported in the following.

The evaluation of eleven questionnaires completed by experts working in the fields of urban development and planning on municipal and regional levels, in natural conservation and the Ministry of Public Works showed that parameters referring to the location of a building (position of building in relation to street level, and distance to water way) as well as the construction material of a building, and the availability of private protection or mitigation measures are expected to be most relevant for the assessment of vulnerability (Table 3). This questionnaire survey introduced in Sect. 3.2 asked the participants to rate the vulnerability variables as shown in Table 2 according to their relevance in the study area with values between 0 and 1 (1 means 100 % important). The average ranking result was then calculated as the arithmetic mean of the 11 questionnaires for each variable. The following listing provides information about the ranking and rating in average (short names of the variables, number of the respective variable from Table 2 in brackets):

- Position of building in relation to street level: 0.85 (variable 2)
- Availability of flood protection measures on building: 0.85 (variable 4)
- Construction material of building: 0.75 (variable 1)
- Experience with floods: 0.725 (variable 10)
- Knowledge about floods: 0.725 (variable 11)
- Knowledge about flood protection measures: 0.7 (variable 12)
- Socio-economic level of household: 0.65 (variable 7)
- Proportion of green spaces per building block: 0.675 (variable 3)
- Age: 0.425 (variable 5)
- Building usage (commercial, residential, industrial): 0.4
- Occupation status: 0.325 (variable 9)
- Gender: 0.3 (variable 6)

Building usage was introduced as a new variable in the expert survey to find out its importance. In the household survey, only residentially used building were considered. While age groups, gender and building type/usage were rated as little important 42.5 %, 30 % and 40 %, respectively), the socio-economic level of a household was in average evaluated to be of (in this case only) 65 % importance. This last value and the interpretation of comments from the expert interviews show that not only the low income groups, but also middle and high income groups are affected by floods, a fact supported by the results from the household surveys. The difference between the socio-economic groups is rather the type of damage. Household size was not part of the expert questionnaire as it strongly correlates with the socio-economic level of the household. In order to avoid redundancy of information, this variable was left out in the expert survey. Only in the analysis phase, it was discovered that it is a relevant variable in the vulnerability analysis of the households.

4.4 Comparison of the evaluation results

The comparison between the results from the expert survey and the household survey is interesting: Although the results cannot be compared directly as the applied methods were different and the set of variables taken into consideration was not identical, some findings can be highlighted: While the location of a building in relation to the street level and the slope of the street as a hazard indicator have in both cases been ranked important, the employment status of the people (permanent contract or sporadic work) was ranked as very important in the household survey but only a little important (32.5 %) in the expert survey. The same applies for the availability of private protection measures. While experts rank this parameter as very important (85 %), the household survey showed no significant relation between the households that have private flood mitigation measures (e.g. walls or watergates) and households that suffered damage. Although not statistically significant, the high relevance of this indicator was experienced during the field survey. For further analysis, only those variables were considered where sufficient data for their quantitative assessment were available.

As stated before the ranking of the importance of each characteristic varies amongst the experts, depending on their professional background, the administrative level they are working on and possibly also the interests that each institution follows. That shows the different viewpoints and also the knowledge gaps in the scope of vulnerability assessment.

4.5 Final selection of variables and conversion into indicators

Taking the relevance of each flood-related characteristic, the knowledge obtained during field stays and data availability into account, a set of 12 variables (Table 2) was selected to get an estimation of the flood vulnerability in Santiago de Chile.

However, using all indicators also the ones with a low weight according to the evaluation of the experts leads to a rather homogeneous distribution of vulnerability. The reason for that is that variables such as gender and age show a very balanced content over the study area. With that they

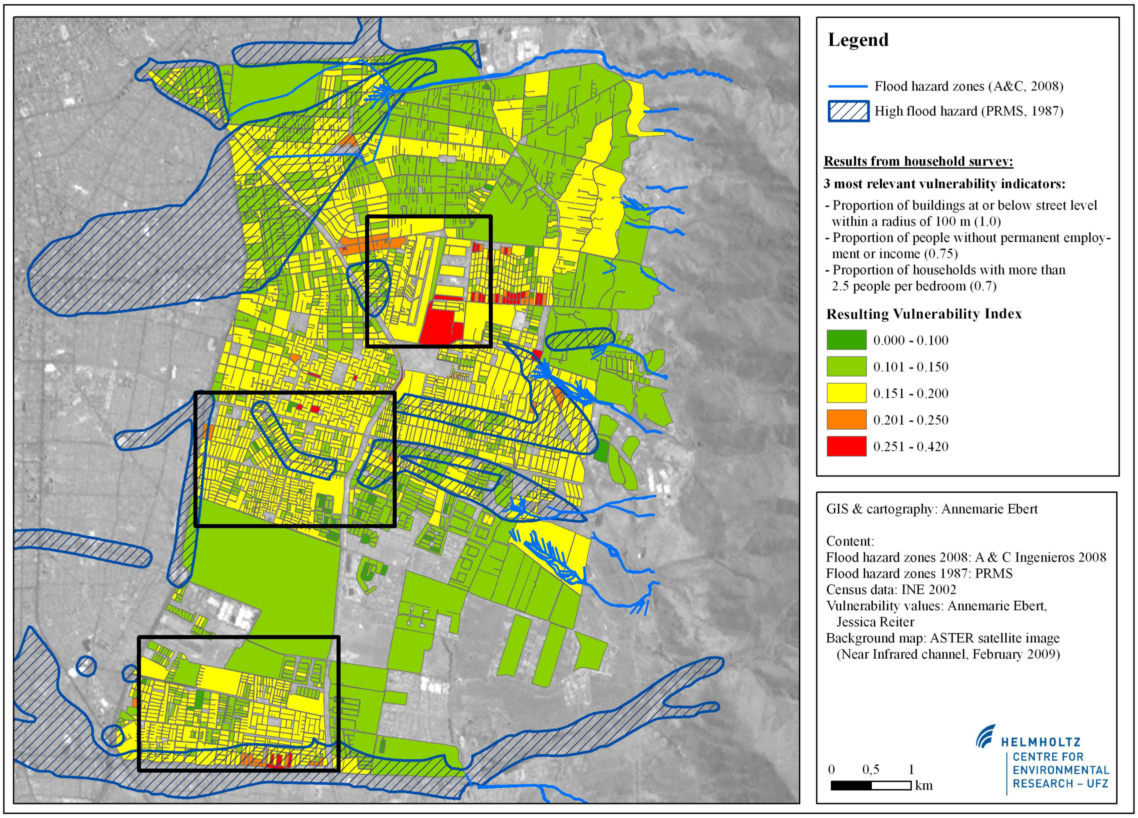

Fig. 3. Vulnerability map of the study area according to the indicator weight evaluations of the affected households.

statistically level out the vulnerability values. For that reason, only those three variables that are according to (i) the affected households and (ii) the experts most relevant for the determination of vulnerability were used and converted into indicators (Table 3 and Table 4). According to the household survey, it concerns the variables position of buildings in relation to street level (variable 2), the employment status (variable 9), and the household size (variable 8). In the case of the experts, they are the variables position of buildings in relation to street level (variable 2), the construction material (variable 1) and the amount of green spaces (variable 3).

For practical risk analysis, all variables need to be transformed into indicators and can then be applied in a GIS-based multi-criteria analysis. The vulnerability variables show a very diverse nature. To make all of them comparable, they are best translated into ratio scale indicators, i.e. all indicators are expressed as relative frequencies per building block in order to treat them as quantitative measures in a vulnerability index. The indicators are thereby always formulated in such a way that a high indicator value represents high vulnerability. The variable construction material as an example was transformed into the indicator "Proportion of buildings with poor construction material per building block" to capture those building groups that show a higher vulnerability to floods.

Several variables were only available for a small part of the study area, i.e. for those households that were interviewed. They comprise (i) the availability of flood protection on buildings, (ii) the experience with floods, (iii) knowledge about the flood hazard, and (iv) knowledge about private protection measures. Thus, these variables were omitted for the final vulnerability analysis.

4.6 Assignment of information to the indicators

GIS data, census data and the classification results of the remote sensing data are used to derive information to feed the indicators. This section presents the methodologies to derive data for each indicator. Table 4 shows the indicators and the respective data source and methodology to derive information content for each indicator (compare Sect. 3.2).

4.7 Application of the vulnerability index

A vulnerability index adapted from Haki et al. (2004) and also used by Kienberger et al. (2009) was applied to calculate the vulnerability of each building block to flood events using the selected indicators. For the practical implementation, the index was normalized by dividing the vulnerability score by the number of vulnerability items, i.e. the maximum

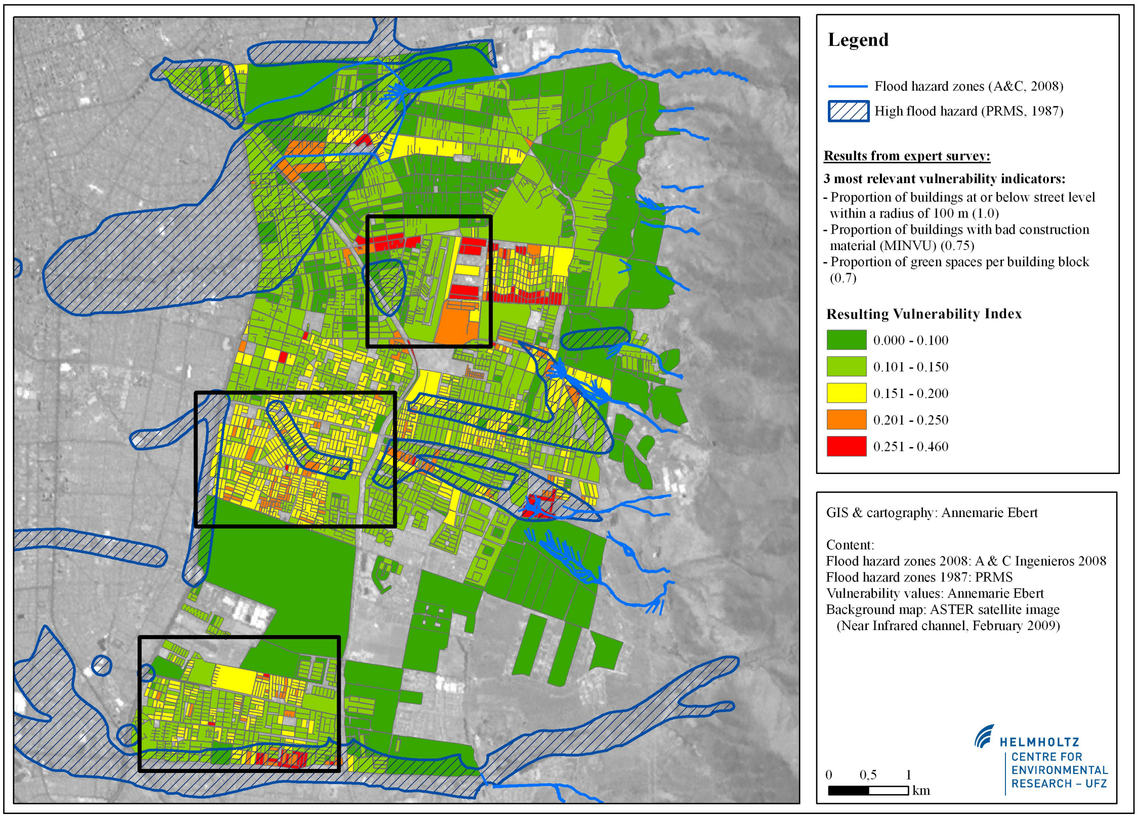

Fig. 4. Vulnerability map of the study area according to the indicator weight evaluations of the experts.

vulnerability value is 1. The normalized composite vulnerability was then calculated based on the equation:

$$\mathrm{VI} = \sum_{i=1}^{m} v_i \times q_i \tag{2}$$

with VI as the value of the vulnerability index, v_i as the weight of each variable (ranging from 0 to 1) and q_i as the relative frequency of the variable per building block (ranging from 0 to 1), i as the interval count, and m as the total number of indicators.

The index was applied using a GIS with all relevant input data being available in a digital spatial database (polygon shape file). As a tool for the application of the vulnerability index was previously not available in a GIS, it was created using the ArcGIS Model Builder. Using pre-defined components from the library, a tool was created that asks the user to enter weights for each vulnerability indicator. After all weights are entered in a valid format (ranging from 0 to 1) the index is calculated on the fly based on Eq. (2) and a vulnerability map can be displayed. The weights that need to be entered for this calculation are derived (i) from the household surveys and (ii) from the expert surveys.

4.8 Sensitivity analysis for the weighting

Figures 3 and 4 show that the vulnerability maps change with changing indicators. It still needs to be determined how sensitive the applied weights are. Therefore, a sensitivity analysis was carried out for the weights of the three most relevant indicators based on the evaluation of the experts. The weights of the indicators "Proportion of buildings located at or below street level per building block" (Weight 1), "Proportion of buildings with poor construction material per building block" (Weight 2), and "Proportion of green spaces per building block" (Weight 3) were altered and the resulting vulnerability scores were analyzed. The weights were altered according to the weighting options in the questionnaire: 1.0, 0.75, and 0.5 for the two first indicators, 1.0, 0.75, 0.5, 0.25, and 0 for the last indicator. These values cover the answer ranges given by the experts in the questionnaire and are therefore regarded as being plausible. As none of the interviewed people considered values below 0.5 being realistic for the first two variables, these low weighting options were left out.

The resulting vulnerability indices were then analyzed statistically using a correlation analysis. Table 5 displays the results. The first column indicates the name for the weight combination, columns 2, 3, and 4 show the respective

Table 4. Data source and methodology applied for the derivation of information for each vulnerability indicator.

No	Indicator	Data source	Methodology
Physical vulnerability			
1	Proportion of buildings with poor construction material per building block	The data base is the composite index referring to the construction material of each building developed by the Ministry for Housing and Urbanism (MINVU, Arriagada and Moreno, 2006). The index defines garbage, adobe, clay bricks, and soil as poor construction materials for roof and walls. Plastics, concrete, and soil are classified as poor construction materials for floors.	The relative frequency of respective buildings was calculated for each building block.
2	Proportion of buildings located at or below street level per building block	The required processing operations comprise the delineation of a building mask from the results of the land use/land cover classification of the Quickbird satellite image, the determination of the flood prone street network and the spatial analysis of digital elevation data at a very high spatial resolution. Flood prone streets were digitized using 2.5 m contour lines, Quickbird satellite data, results from previous flood hazard studies (AC, 2008) and local knowledge. The building mask comprises all image objects that are classified as buildings during the LULC classification.	Elevation values from the DEM delineated from 2.5 m contour lines were assigned to the building mask (average elevation for each building) and to the hazard prone street network. Using spatial analysis applications, the distance of a building to the closest street was determined within a radius of 100 m. The radius was chosen in that size to also include the front yards that are part of the property and might take damage but are not included in the building mask. Data of lot limits/outlines were not available.
3	Proportion of green spaces per building block	The GIS-based combination of all types of vegetated areas as derived from the analysis of the Quickbird data, i.e. trees, grassland, dry vegetation, and bushland leads to one class 'vegetation'.	The relative proportion of green spaces per building block was calculated from the LULC classification results.
Social vulnerability			
8	Proportion of households with more than 2.5 people per bedroom per building block	Arriagada and Moreno (2006) from the Ministery of Housing and Urbanism in Chile delineated an index expressing the number of people sharing one bedroom. The threshold value of 2.5 people was hereby defined as a critical value for overcrowding.	Secondary information delineated from the index after Arriagada and Moreno (2006) was used to populate the indicator.
9a	Proportion of people without employment per building block	Those people that are according to the census seeking employment and have worked before, seeking employment without having worked before, or are permanently unemployable were extracted from the census data base (INE, 2002).	The relative proportion of the sum of all people belonging to the defined groups was delineated from the census data base.
9b	Proportion of people without permanent income per building block	The people in each building block that are according to the census working for the family, students, retired, homemaker or that have employment but are not working were extracted from the census data base (INE, 2002).	The relative proportion of the sum of all people belonging to the defined groups was delineated from the census data base.

weights for the three indicators, and the last column indicates the correlation coefficient with the original values, i.e. the average values that were delineated from the expert questionnaires and that were then used for the vulnerability analysis.

The results of this analysis prove that the correlation between the resulting vulnerability scores is very high, except for the alternative 3-D (last row of Table 5), where the weight of the third indicator was set to zero. That means that the indicators are not very sensitive to the weights as long as the weights are larger than zero. Only if certain indicators are left out of the analysis (i.e. if their weight is set to zero), or if the applied indicators change (e.g. household survey vs. expert survey), do the relative vulnerability results change significantly. While the absolute values differ, the differences between the regions remain stable; that is the relative vulnerability pattern remains. For the combination of this information with a hazard map to a final risk map, however, more research on bringing the weights in an appropriate range of numbers would be required. This could be achieved by carrying out more field surveys and expert interviews or by selecting validation data after the next flood event.

Table 5. Results from the sensitivity analysis: The weights for the vulnerability indicators and the resulting correlation coefficient r^2 with the vulnerability scores applying the original set of weights.

Alternative	Weight 1	Weight 2	Weight 3	r^2
Original	1.0	0.75	0.7	1.00
1A	0.75	0.75	0.7	0.99
1B	0.5	0.75	0.7	0.96
2A	1.0	1.0	0.7	1.00
2B	1.0	0.5	0.7	1.00
3A	1.0	0.75	1.0	0.99
3B	1.0	0.75	0.5	0.99
3C	1.0	0.75	0.25	0.91
3D	1.0	0.75	0.0	0.72

5 Results

Applying the vulnerability index results in a map with vulnerability values assigned to each building block. Green colours indicate low, yellow-orange colours medium and red colours high levels of vulnerability.

Figure 3 shows the vulnerability map derived using the vulnerability index after Eq. (2) with the weights as determined from the household surveys, i.e. from the point of view of the affected population. According to this evaluation, the building blocks along the aforementioned flood-prone streets are rated vulnerable and some of the building blocks located in higher-lying regions of the Andean piedmont. These regions were not included in the household survey, but have a comparably high number of inhabitants without permanent employment. In this case however, this is not an indicator for a low social status of the household; rather the opposite is the case as these people prefer an independent lifestyle which is not necessarily associated to a low social status.

Figure 4 shows the vulnerability map based on the evaluation of the indicators by the experts for the two municipalities La Reina and Peñalolén. Most vulnerable to suffer damage from floods are those building blocks along the roads that are constructed in former creek beds and that are located on the lower-lying part of that street. Those building blocks that contain a low amount of green spaces and a high amount of buildings with bad construction material show likewise a high level of vulnerability, whereby the number of buildings with poor construction material is comparably low in the study area. The vulnerable areas are the low-income settlements in the south-western and north-western part of Peñalolén and several building blocks located along those afore- mentioned large streets that do not have a functioning storm water drainage system until now.

Comparing this map with the results obtained during the household surveys (point data, Fig. 2), it can be seen that vulnerability is generally lower in areas where the inhabitants suffered predominantly immaterial damage (higher socio-economic level in the northwestern part of the study area) and generally higher in the regions where people suffered material damage (lower social strata living in the central and eastern parts of the study area).

A finding from the comparison of the vulnerability maps with the punctual household surveys is that the vulnerability values for the households that suffered both material and immaterial damage range from 0.94 to 2.4 according to the evaluation of the households and from 1.02 to 2.99 according to the evaluation of the experts. The maximum vulnerability scores in the entire map are 2.4 and 3.1, respectively. That means that all affected people are rated in the vulnerability analysis as being vulnerable, but the maps generated on a building block level can only provide an orientation and are not sufficient to carry out a detailed vulnerability analysis.

6 Discussion

Experts and affected households rated different variables as being most relevant. Variables that were found very relevant in both cases obtained different weights. As a consequence, the resulting vulnerability is similar in some regions but differs in others. The main differences are in the region of the local airport in La Reina (upper box in Figs. 3 and 4) and in the northwestern and southwestern part of Peñalolén, with the low-income housing areas (lower boxes in Figs. 3 and 4). For the chosen level of investigation, the variables age and gender can generally not be considered to be a valuable contribution or input information for the vulnerability map. As the census data are aggregated on a building block level the proportion of male and female population is in almost all cases approximately 50 %. The data thus show a very high level of heterogeneity throughout the study area and average out the information content of each building block. Information about where exactly the “old, single, female” – classically exemplifying the most vulnerable individual – lives is impossible to obtain using the proposed methodology.

Having this methodological drawback in mind, it is all the more interesting to revise the evaluations of the experts: This group rates the personal statistical information with a rather low relevance. With respect to the individuals, their specific risk-relevant knowledge and experiences are rated to be more important, (even though this can for data availability reasons not be considered in this study). Besides the individual characteristics, the group of the professionals broadly agrees that the information that are available on a building or building block level, e.g. amount of green spaces, construction material, are most important for flood vulnerability. Going back to the definition of vulnerability, this proves that the physical (or exposure) side seems to have a much higher influence on vulnerability than the social characteristics. The possible reasons for this judgement are double-edged: It is either true in reality or the social aspects are not sufficiently perceived and considered in the experts' understanding. It is noteworthy, though, that at first sight practically no responsibility is shifted to the residents as many of the important factors are at least officially in the competence of the experts. Public projects, such as social housing projects, either provide a basic house constructed of proper material or support construction and renovation initiatives of poor families through financial aid. In practice however, some public and legal policies, especially with regard to construction permits, are not followed strictly enough. Likewise, the provision and conservation of green spaces – which is a public task – is insufficient.

Coming back to the social aspect, the results of the households' evaluation show that the importance of social characteristics is higher there. While the different viewpoints and perspectives might partially explain this finding, there is also a methodological explanation. The surveys were carried out with individuals; hence, the equipment of the building block with green spaces was not surveyed. The construction material, however, was part of the questionnaire but did not show a statistic significance in the analysis of the results. A reason for that might be that the construction material is rather heterogeneous amongst the interviewees so there was no direct link between the general damage that the affected people suffered and the individual building qualities. With respect to the type of the flood, it has to be recalled that the availability of private or public structural mitigation measures should be rated equally important but for data availability reasons, cannot be included in this study. During field work, the importance of social networks was highlighted as another variable that determines vulnerability: It minimizes vulnerability as it forms part of the coping capacities. This could also not be included in this study for data availability reasons.

With respect to the validation of the results, it has to be confessed that no data were available to test the accuracy of the vulnerability maps. As no insurance system exists for this regard, data about damage are not collected. However, accuracy data for the delineation of the relevant land-use classes built-up areas and green spaces prove that at least the input data for the indicators show a high level of precision. In order to enlarge the practicability of this approach and to foster the application through decision makers, a WebGIS-based tool was set up to allow for a very transparent and interactive communication of the research results (Ebert and Müller, 2010). The tool allows decision makers to carry out a vulnerability analysis using the data available for this study on the internet. Thereby, each vulnerability indicator can be weighted according to their knowledge and understanding.

7 Conclusions

The study presented here shows a methodology that uses indicators derived from geodata and census data to analyze the vulnerability to floods in a dense urban setting. It was shown how a complex set containing a large number of possibly relevant variables can be reduced to a small number of indicators that are distinctive for the study area. This selection was not only based on statistical analysis but also on the opinion and evaluation of local experts. Incorporating local specific knowledge into the analysis enlarged the credibility and acceptability of the research results, making the approach a modern transdisciplinary one. The set of proposed vulnerability indicators can be used on the one hand to show the complexity of this problem and to communicate it to relevant parties and involved people. On the other hand, it can be used to define and control development directions and to identify problematic areas, for example, areas with a high number of people exposed or areas with unfavourable usage. Furthermore, the proposed approach implies the possibility to present and compare different viewing perspectives (experts and affected people). Field work and expert surveys proved the validity of the approach. The chosen methodology allowed for a repeatable vulnerability analysis and thus for a monitoring of its development over time. As the approach can be transferred, e.g. to other regions of the city, it can be used as a decision-making tool that helps risk managers and land-use planners to develop and plan measures for vulnerability reduction. Spatial priorities can be set easily when planning the practical implementation of the measures. This study reveals the site-specific conditions for the first timethat lead to vulnerabilities and consequently to flood damage in the city of Santiago de Chile. The study is another proof of the diversity of vulnerabilities in that it shows that socio-economic characteristics are not sufficient for explaining different levels of vulnerability. It also proves that the causes of vulnerability to the same hazard are rated differently amongst the involved parties (affected households vs. decision makers), proving that it is of utmost importance to include different perspectives in the vulnerability assessment. The empirically collected information and the incorporation of expert knowledge of local decision makers substantiate these findings. In addition to this, the presented study provides a significant practical value as it clearly enhances risk-relevant knowledge and helps to minimize further damage. As a general conclusion, the study clearly shows that variables referring to the physical exposure of the affected population are ranked as much more important for the present case than social characteristics, such as age and gender, which again underlines the suitability of the selected method. The study can be further improved by complementing it with data from more extensive field surveys to include individual characteristics, such as knowledge about the hazard or risk perception in the analysis.

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References

AC Ingenieros Consultores Ltda.: Diagnóstico de cauces naturales, sector pie Andino. Región Metropolitana. Technical report, 2008.

Adger, W.: Vulnerability. Global Environmental Change, 16, 268–281, 2006.

Adimark: Mapa socioeconómico de Chile. Modelo estimativo del N.S.E. en los hogares de Chile, Adimark, Investigaciones de Mercado y Opinión Pública, Santiago de Chile, 2003.

Antinao, J., Fernandez, J., Naranjo, J., and Villarroel, P.: Peligro de remociones en masa e inundaciones de la cuenca de Santiago. Carta Geologica de Chile, Servicio Nacional de Geología Ambiental, No. 2. 1 mapa escala 1:100.000, Servicio Nacional de Geología y Minería. Santiago de Chile, 2003.

Arriagada, C. and Moreno, J.: Atlas de la evolución del déficit habitacional en Chile 1992-2002. Tech. Rep. 323, Ministerio de Vivienda y Urbanismo. División Técnica de Estudio y Formento Habitacional – DITEC, Santiago de Chile, 2006.

Atteslander, P., Cromm, J., Grabow, B., Klein, H., Maurer, A., and Siegert, G.: Methoden der empirischen Sozialforschung, Erich Schmidt Verlag, 12, 359 pp. 2008.

Ayala, L., Espinoza, G., and Saragoni, R.: Estudio de Áreas de Riesgo por Inundación. Segunda Parte. Tech. rep., Ministerio de Vivienda y Urbanismo, Santiago de Chile, 1987.

Bana, E., Costa, C. A., and Da Silva, P. A.: Nunes Correia F Multicriteria Evaluation of Flood Control Measures: The Case of Ribeira do Livramento, Water Resour. Manag., 18(21), 263–283, 2004.

Banzhaf, E. and Höfer, R.: Monitoring urban structure types as spatial indicators with CIR aerial photographs for a more effective urban environmental management, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS) 1, 129–138, 2008.

Birkmann, J.: Danger need not spell disaster. But how vulnerable are we? Research Brief, 1, 8 pp., 2005a.

Birkmann, J.: Report on the 1st meeting of the expert working group “Measuring Vulnerability”. Working Paper No. 1, United Nations University, UNU EHS, 2005b.

Blaikie, P. M., Cannon, T., Davis, I., and Wisner, B.: At Risk: Natural Hazards, People’s Vulnerability and Disasters. Routledge, London, 320 pp., 1994.

Blaschke, T.: Object based image analysis for remote sensing, ISPRS J. Photogramm., 65, 1, 2010.

Bogardi, J.: Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies, edited by: Birkmann, J., Introduction, United Nations University Press, 1–6, 2006.

Brooks, N.: Vulnerability, risk and adaptation: A conceptual framework. Tyndall Centre Working Paper 38, Centre for Social and Economic Research on the Global Environment (CSERGE), School of Environmental Sciences, University of East Anglia, 01/06, 2003.

Brouwer, R. and van Ek R.: Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands, Ecol. Econ., 50(1–2), 1–21, 2004.

CADE IDEPE Consultores en Ingeniería: Plan Maestro de Evacuación y Drenaje de Aguas Lluvias del Gran Santiago. Ministerio de Obras Públicas, Dirección de Obras Hidraúlicas, Santiago de Chile, 2001.

Cardona, O.: Indicators for disaster risk management, in: First expert meeting on disaster risk conceptualization and indicator modelling, 37 pp., March 2003, Manizales, 2003.

Clark, G. E., Moser, S., Ratick, S., Dow, K., Meyer, W. B., Emani, S., Jin, W., Kasperson, J. X., Kasperson, R. E., and Schwarz, H. E.: Assessing the vulnerability of coastal communities to extreme storms: the case of Revere, MA., USA, Mitigation and Adaptation Strategies for Global Change 3, 1, 59–82, 1998.

Chambers, R.: Vulnerability: How the poor cope, IDS Bulletin, Institute of Development Studies, edited by: Chambers, R., 20, 2, 1989.

Cutter, S., Boruff, B., and Shirley, W.: Social vulnerability to environmental hazards, Soc. Sci. Quart, 84, 2, 242–260, 2003.

Dwyer, A., Zoppou, C., Nielsen, O., Day, S., and Roberts, S.: Quantifying Social Vulnerability: A methodology for identifying those at risk to natural hazards, Geoscience Australia, 92 pp., available at: http://www.ga.gov.au/image_cache/GA4267.pdf 2004.

Ebert, A., Kerle, N., and Stein, A.: Urban social vulnerability assessment with physical proxies and spatial metrics derived from air- and spaceborne imagery and GIS data, Nat. Hazards, 48, 275–294, 2009.

Ebert, A. and Müller, A.: Bewertung von Vulnerabilität gegenüber Hochwasser in Santiago de Chile Mithilfe einer dienstebasierten WebGIS-Anwendung – reviewed paper, in: Angewandte Geoinformatik 2010, edited by: Strobl, J., Blaschke, T., and Griesebner, G., Beiträge zum 22. AGIT-Symposium Salzburg, Berlin, Wichmann Verlag, 840–849, 2010.

Fedeski, M. and Gwilliam, J.: Urban sustainability in the presence of flood and geological hazards: The development of a GIS-based vulnerability and risk assessment methodology, Landscape Urban Plan., 83, 50–61, 2007.

Fekete, A.: Validation of a social vulnerability index in context to river-floods in Germany, Nat. Hazards Earth Syst. Sci., 9, 393–403, doi:10.5194/nhess-9-393-2009, 2009.

Galetovic, A. and Jordán, P.: Santiago: ¿dónde estamos? ¿hacia dónde vamos?, in: Santiago, Dónde estamos y dónde vamos, edited by: Galetovic, A., Centro de Estudios Publicos, Santiago de Chile, 25–71, 2006.

Grunwald, A. and Kopfmüller, J.: Nachhaltigkeit. No. 978-3-593-37978-4. Campus Verlag, Frankfurt/Main & New York, 2006.

Haki, Z., Akyuerek, Z., and Duezguen, S.: Assessment of social vulnerability using geographic information systems: Pendik, Istanbul case study. In: 7th AGILE Conference on Geographic Information Science (Heraklion, Greece, 2004), Middle East Technical University of Ankara, Turkey, 413–423, 2004.

Heinrichs, D., Rodriguez, J., and Welz, J.: Migration and residential segregation in Santiago de Chile: Trends, relations and implications for policy on social integration, in 5th International Conference ’Private Urban Governance and Gated Communities’ of the Research Network, Santiago de Chile, 2009.

Heijmans, A.: From Vulnerability to Empowerment, Mapping Vulnerability, Disasters, Development, and People, edited by: Bankoff, G., Frerks, G., Hilhorst, D., London, 115–127, 2004.

Hutchison, M.: A new procedure for gridding elevation and stream line data with automatic removal of spurious pits, J. Hydrol., 106, 3–4, 211–232, 1989.

Huttenlau, M., Sttter, J., and Stiefelmeyer, H.: Risk-based damage potential and loss estimation of extreme flooding scenarios in the Austrian Federal Province of Tyrol, Nat. Hazards Earth Syst. Sci., 10, 2451–2473, doi:10.5194/nhess-10-2451-2010, 2010.

Jacquin, A., Misakovab, L., and Gay, M.: A hybrid object-based classification approach for mapping urban sprawl in periurban environment, Landscape Urban Plan., 84, 152–165, 2008.

Kienberger, S., Lang, S., and Zeil, P.: Spatial vulnerability units – expert-based spatial modelling of socio-economic vulnerability in the Salzach catchment, Austria, Nat. Hazards Earth Syst. Sci., 9, 767–778, doi:10.5194/nhess-9-767-2009, 2009.

Kienberger, S. and Steinbruch, F.: P-GIS and disaster risk management: Assessing vulnerability with P-GIS methods – Experiences from Buzi, Mozambique, in: International Conference on Participatory Spatial Information Management and Communication, PGIS ’05, 2005.

Kubal, C., Haase, D., Meyer, V., and Scheuer, S.: Integrated urban flood risk assessment – adapting a multicriteria approach to a city, Nat. Hazards Earth Syst. Sci., 9, 1881–1895, doi:10.5194/nhess-9-1881-2009, 2009.

Kuhlicke, C.: Ignorance and Vulnerability – The 2002 Mulde Flood in the City of Eilenburg (Saxony, Germany), Dissertation, Potsdam, Institut fu¨r Geographie, Universität Potsdam, 2008.

Luers, A., Lobell, D., Sklar, L., Addams, C., and Matson, P.: A method for quantifying vulnerability, applied to the agricultural system of the Yakie Valley, Mexico, Global Environ. Chang., 13, 255–267, 2003.

Meyer, V., Scheuer, S., and Haase, D.: A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany, Nat. Hazards, 48, 1, 17–39, 2009.

Mitchell, J.: Earth System Analysis: Integrating Science for Sustainability. Springer, Chapter: Urban metabolism and disaster vulnerability in an era, 359–377, 1998.

Niehoff, D., Fritsch, U., and Bronstert, A.: Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany, J. Hydrol., 267, 1–2, 80–93, 2002.

Pelling, M.: What determines vulnerability to floods; a case study in Georgetown, Guyana, Environ. Urban. 9, 1, 203–226, 1997.

Perez, J.: Riesgo de inundación producto del cambio climático. Caso de estudio: Quebrada de Ramón. Master’s thesis, Universidad de Chile, Santiago de Chile, unpublished, 2009,

Prein, G., Kluge, S., and Kelle, U.: Strategien zur Sicherung von Repräsentativität und Stichprobenvalidität bei kleinen Samples, Arbeitspapier Nr. 18, Der Vorstand des SfB 186, 2nd Edition, Bremen, 1994.

Rashed, T. and Weeks, J.: Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas, Int. J. Geogr. Inf. Sci. 17, 6, 547–576, 2003.

Reyes Paecke, S.: Perspectivas del medio ambiente urbano, GEO Santiago, Technical report, PNUMA/UNEP, 2003.

Schneiderbauer, S.: Risk and vulnerability to natural disasters – from broad view to focused perspective. Theoretical background and applied methods for the identification of the most endangered populations in two case studies at different scales, Phd, Freie Universität Berlin, 2007.

Stow, D., Lopez, A., Lippitt, C., Hinton, S., and Weeks, J.: Object-based classification of residential land use within Accra, Ghana based on QuickBird satellite data, Int. J. Remote Sens., 28, 5167–5173, 2007.

Taubenböck, H.: Vulnerabilitätsabschätzung der erdbebengefährdeten Megacity Istanbul mit Methoden der Fernerkundung. PhD Thesis, Bayerischen Julius-Maximilians Universität Würzburg, 2007.

Taubenböck, H., Post, J., Roth, A., Zosseder, K., Strunz, G., and Dech, S.: A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing, Nat. Hazards Earth Syst. Sci., 8, 409–420, doi:10.5194/nhess-8-409-2008, 2008.

Taubenböck, H., Wurm, M., Netzband, M., Zwenzner, H., Roth, A., Rahman, A., and Dech, S.: Flood risks in urbanized areas multi-sensoral approaches using remotely sensed data for risk assessment, Nat. Hazards Earth Syst. Sci., 11, 431–444, doi:10.5194/nhess-11-431-2011, 2011.

te Linde, A. H., Bubeck, P., Dekkers, J. E. C., de Moel, H., and Aerts, J. C. J. H.: Future flood risk estimates along the river Rhine, Nat. Hazards Earth Syst. Sci., 11, 459–473, doi:10.5194/nhess-11-459-2011, 2011.

Turner, B., Kasperson, R., Matsone, P., McCarthy, J., Corell, R., Christensen, L., Eckley, N., Kasperson, J., Luerse, A., Martello, M., Polsky, C., Pulsipher, A., and Schiller, A.: A framework for vulnerability analysis in sustainability science, PNAS 100, 14, 8074–8079, 2003.

UN/ISDR (United Nations International Strategy for Disaster Reduction): Living with Risk. A Global Review of Disaster Reduction Initiatives. United Nations, Geneva, 2004.

UNDP: A Global Report. Reducing Disaster Risk. Challenge for Development, UNDP, New York, 2004.

van Herzele, A. and Wiedemann, T.: A monitoring tool for the provision of accessible and attractive urban green spaces, Landscape Urban Plan., 63, 109–126, 2003.

Vásquez, A., Salgado, M., and Romero, H.: Desigualdades socioeconómicas y distribución inequitativa de los peligros ambientales en las comunas de Peñalolen y San Pedro de la Paz. Coloquio Del Pas Urbano a Pas Metropolitano, 4 al 6 de Diciembre 2007.

Velasquez, G. and Tanhueco, R.: Know Risk. United Nations ‘World Conference on Disaster Reduction’, Chapter: Incorporating social issues in disaster risk assessment, 2005.

Villagrán de León, J.: Vulnerability. A conceptual and methodological review. Source 4/2006, United Nations University, UNU-EHS, 2006.

Wisner, B.: Turning knowledge into timely and appropriate action: Reflections on IADB/IDEA program of disaster risk indicators, IDB/IDEA Program of Indicators for Risk Management, National University of Colombia, Manizales, available at: http://www.manizales.unal.edu.co/ProyectosEspeciales/bid2/documentos/Ben%20Wisner%20EM%20Barcelona%20Nov%202003.pdf, 2003.

Wisner, B., Blaikie, P., Cannon, T., and Davis, I.: At Risk. Natural hazards, people’s vulnerability, and disasters, 2nd ed. Routledge, London, New York, 496 pp., 2004.