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ORIGINAL PAPER

Capturing the multifaceted phenomena of socioeconomic vulnerability

Linda Sorg[1] · Neiler Medina[2] · Daniel Feldmeyer[1] · Arlex Sanchez[2] · Zoran Vojinovic[2] · Jörn Birkmann[1] · Alessandra Marchese[3]

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Abstract Vulnerability and disaster risk assessment has been evaluated from different perspectives with focus on global or national scale. There is a lack of methodologies on city scale, which are able to capture inner-city disparities with regard to socioeconomic aspects. Therefore, the main objective was to develop a transparent and comprehensive indicator-based approach which is flexible in terms of data availability and is not tied to a specific case study side. This research proposes two flexible methodological approaches on how to perform socioeconomic vulnerability assessment. Susceptibility, Coping and Adaptation are the main elements of a modular hierarchical structure to capture the societal sphere of vulnerability. The first method is completely based on official census data at block scale. The second method is an expansion and includes data derived from a field

✉ Linda Sorg
Linda.sorg@ireus.uni-stuttgart.de

Neiler Medina
n.medina@unesco-ihe.org

Daniel Feldmeyer
Daniel.feldmeyer@ireus.uni-stuttgart.de

Arlex Sanchez
a.sanchez@unesco-ihe.org

Zoran Vojinovic
z.vojinovic@unesco-ihe.org

Jörn Birkmann
Joern.birkmann@ireus.uni-stuttgart.de

Alessandra Marchese
a.marchese@gisig.it

1 Institute of Spatial and Regional Planning, University of Stuttgart, Pfaffenwaldring 7, 70569 Stuttgart, Germany

2 Urban Water Systems, Environmental Engineering and Water Technology Department, UNESCO-IHE, Westvest 7, 2611 AX Delft, The Netherlands

3 GISIG – Geographical Information Systems International Group, Via Piacenza 54, 16138 Genoa, Italy

survey to add components of risk perception. The proposed methodologies were developed and applied in the city of Genoa (Italy). The results are displayed spatially explicit on maps. Furthermore statistical analysis, to reveal the driving forces which influence vulnerability, was performed. The census-based approach revealed that vulnerability is forced along the river by the inherent susceptibility, as well as the lack of adaptation. The two approaches can be used effectively in gaining different insights. The flexibility of the framework proved to be suitable to the objective of the research. However, the values computed in this research do not claim completeness, and the aim was to provide useful information for stakeholders in decision making process to reduce vulnerability and risk.

Keywords Vulnerability assessment · Socioeconomic vulnerability · Susceptibility · Coping · Adaptation · Disasters

1 Introduction

There is a change in thinking needed from a solely perspective on hazards to the inherent risk characteristic of social systems (UNISDR 2015). In the last 90 years exposure increased despite introduction of natural hazard management strategies (Fuchs et al. 2017). In order to understand the "*social construction of risk*" (Garschargen and Romero-Lankao 2013: 40) vulnerability is a key element (see e.g. Wisner et al. 2004; Adger 2006; Turner et al. 2003, Cardona 2005). Vulnerability can be seen as a complex multifaceted system (Birkmann 2013a; Maskrey 1993), which is not easily measurable (Adger 2006). However, the quantification of vulnerability is less developed than the mapping and quantification of hazards (Birkmann 2007). Natural disasters resulting from extreme hydrometeorological events occur almost daily (see e.g. Vojinovic and van Teeffelen 2007; Price and Vojinovic 2008; Mynett and Vojinovic 2009), and they represent a particular challenge when it comes to the assessment of hazards, vulnerabilities and risk. With numerical models it is possible to explore the generation of flood hazards and to simulate effects of different scenarios (Abbott and Vojinovic 2009). Next to the display of the hazard, the understanding and decoding of drivers of vulnerability are crucial to capture the societal components in the composition of risk (Wolf and McGregor 2013). Fuchs (2009: 348) stresses that a "*broader understanding of the concept of vulnerability is needed*" to reduce risk induced by natural hazards. In an analysis of paired flood events Kreibich et al. (2017) concluded that reduction in losses of second events was mainly due to reduction in vulnerability.

Turner et al. (2003) express the need for a better understanding of vulnerability and methods for its assessment. Furthermore they state that when it comes to coastal flood vulnerability, the link of theoretical concepts and their practical use in decision making has to be strengthened (ibid). Vojinovic (2015) highlights the requirement of a larger perspective and holistic approaches to assess risk and vulnerability to capture their complexity. This comprehensive view is needed to trace the roots of urban flood risk (Vojinovic and Abbott 2012). However, due to constraints related to real-world data it is impossible to achieve this entirely (Turner et al. 2003). Turner et al. (2003) demand a simplified, but consistent vulnerability assessment methodology.

The present paper deals with a flexible vulnerability assessment method which has been developed within the EC-funded project "Preparing for Extreme and Rare events in coastal regions" (PEARL, see e.g. Vojinovic et al. 2014 and Vojinovic 2015). The assessment on city scale focusses on societal factors of vulnerability besides a primary focus on the natural hazard.

In the context of this paper, risk is defined as the interaction of the natural hazard sphere and the social sphere of vulnerability (Wisner et al. 2004; UNISDR 2012). PEARL expands the definition of the term vulnerability as "*the propensity or predisposition to be adversely affected*" (IPCC 2012: 5) by further refining the terminology: The propensity of being affected depends on the underlying concept of susceptibility, as well as on the ability to recover from disastrous events and capacities to transformation.

The PEARL vulnerability assessment framework presented here consists of a quantitative approach, using statistical data and an extended semiquantitative approach, which enables to incorporate results from a household survey. This differentiation in the method proved to be flexible considering the availability of data in different case study areas. In the following the approach is introduced and applied to the city of Genoa, Italy.

2 Vulnerability assessment

The proposed methodology was developed to allow the combination of data from multiple sources and knowledge bases. The PEARL project has various case study sites with different preconditions. The proposed methodology can be adjusted to different levels of information to have a general assessment, based on standard census data, or an extended assessment with incorporation of local survey data.

The following section introduces some of the current vulnerability assessment frameworks (or, respectively, risk) of societies at different scales. It also reflects limitations of current methods and highlights the needs for a progress beyond the state of art.

2.1 Current methods

Literature in the context of vulnerability differs in the spatial scale being contemplated and in the type of hazard being analyzed. Recently, the number of publications related to the measurement of risk and vulnerability has increased. Birkmann (2013a) provides an extensive compilation of methodologies for different scales and levels.

There are methods for spatial vulnerability or risk assessments for different natural hazards and climate change in general at country level worldwide (*WorldRiskIndex*, e.g. Welle and Birkmann 2015; Birkmann and Welle 2016) and to multiple stressors (O'Brien et al. 2004). Moreover, there are assessment methods which incorporate socioeconomic aspects for specific hazards, like heat waves and flooding (Depietri et al. 2013; Welle et al. 2014), flash floods (Karagiorgos et al. 2016), tsunamis (Jelínek et al. 2012; Birkmann et al. 2010), or with focus on flood risk in areas with cultural heritage (Vojinovic et al. 2015).

There are numerous indices on national level (see e.g. Brooks et al. 2005; Welle and Birkmann 2015). However, taking a closer look at national level, cities are of major concern due to the high concentration of people and infrastructure assets. Balica et al. (2012) developed a Coastal City Flood Vulnerability Index, which is defined by exposure, susceptibility and resilience. The index was calculated for nine cities and results in a vulnerability value per city which makes the cities around the world comparable (despite different kinds of exposure). There are various publications on the risk assessment to tsunamis for the city of Cádiz, Spain (Birkmann et al. 2010; Jelínek et al. 2012), which built on an adapted *BBC framework* (*Bogardi, Birkmann, Cardona Framework* developed in 2004, for more details see Birkmann 2013b: 54). Here, vulnerability is measured based on exposure, susceptibility and coping capacity. Karagiorgos et al. (2016) combine physical and social vulnerability in the region of East Attica/Greece. Social vulnerability is assessed by a composite index based on survey data exclusively.

In order to develop strategies on city level a detailed resolution is required. Depietri et al. (2013) conducted a social vulnerability assessment to heat waves for the urban area of Cologne, Germany. The vulnerability assessment is based on the MOVE framework (Birkmann et al. 2013) and therefore encompassed the components of exposure, susceptibility and lack of resilience. The assessment considers not solely statistical data but also expert interviews, resulting in a broader set of drivers and elements of vulnerability for the 85 districts of Cologne. Another vulnerability index on city level was developed by Wolf and McGregor (2013). It conceptualizes vulnerability to heat for the city of London, UK, as a function of exposure and sensitivity. This comprises next to high temperature areas also societal aspects like demographics, adaptive aspects, and e.g., the behavior of citizens.

In order to provide valuable information for decision makers "*information on vulnerability to heat [is required] at spatial resolutions finer than the regional or city scale*" (Wolf and McGregor 2013: 59). Wilhelmi and Hayden (2010) proposed a framework for the analysis of local vulnerability to urban heat stress based on a multilayered, top-down and bottom-up approach, based also on household data through interviews. The integration of local practices and knowledge base is essential when aiming to strengthen climate change adaptation (IPCC 2014) since "*social capital influences households' perception of and coping with flood risks*" (Babcicky and Seebauer 2016: 1017).

The local scale is the most effective and, respectively, valuable scale for decision making processes (Wilhelmi and Hayden 2010). Wilhelmi and Morss (2013) state that the vulnerability patterns within ostensible homogeneous urban areas and neighborhoods may show significant variations.

The review discloses that there is a wide range of vulnerability and risk assessment methods on global and national scale, as well as on the level of a city as a whole. In cases where measures are available for city districts, the selection of indicators is rather limited and closely tied to the specific case study area and its data.

This research aims to close this considerable gap and aims to capture inner-city disparities with regard to socioeconomic aspects. One of the main advantages of the PEARL vulnerability assessment framework is its flexibility in terms of data. As such it can be applied in various case study areas and to different types of hazards. In addition, the index structure allows the incorporation of data from various sources and therefore encourages triangulation of knowledge.

2.2 PEARL vulnerability assessment framework

The PEARL vulnerability framework uses a robust index (called PeVI in the following) to get a multifaceted picture of the current status of the societal component of vulnerability. PeVI is based on a modular structure with three elements: S*usceptibility*, *Coping* and *Adaptation* and was developed based on the methodology of the *WorldRiskIndex* (see e.g. Welle and Birkmann 2015). However, it is adaptable and expandable to fit with local contexts and requirements. The assessment is primarily based on the secondary data available for social, environmental and economic indicators of vulnerability.

The PeVI aims to cover as many aspects as possible in order to have a proper insight into the vulnerability of a city or a region under analysis.

Table 1 Components of the PEARL Vulnerability Assessment (input from PEARL household survey *highlighted in italics and underlined*)

SUSCEPTIBILITY	COPING	ADAPTATION
1. DEMOGRAPHY 1.1. Vulnerable Age Groups 1.2. Elderly living alone 1.3. Population density 1.4. Language Ability / Origin	5. GOVERNMENT AND AUTHORITIES 5.1. Crime rates per X population 5.2. Turnout at local elections (%) *5.3. Trust in institutions* *5.4. Performance Perception*	12. EDUCATION AND RESEARCH 12.1. Education Level / Proportion of people holding higher qualification 12.2. NEETs 12.3. Literacy rate
2. HEALTH 2.1. Number of disabled or chronically ill persons	6. SOCIAL NETWORK 6.1. Household size	13. GENDER EQUITY 13.1. Gender parity in education (primary, secondary and tertiary education) 13.2. Gender parity in annual gross pay (female-male)
3. POVERTY AND INCOME 3.1. Dependency Ratio 3.2. Share of population living under national poverty line 3.3. Unemployment rate	7. ECONOMIC COVERAGE 7.1. Household income *7.2. Insurance (life insurances excluded)* *7.3. Financial Backup*	14. ENVIRONMENTAL STATUS 14.1. Air quality data 14.2. Green infrastructure *14.3. Climate Change Perception*
4. HOUSING 4.1. Building conditions 4.2. Type of building	8. MEDICAL SERVICE 8.1. Number of physicians / hospital beds 8.2. Access to medical service 8.3. Vaccination coverage *8.4. Medical Services Perception*	15. INVESTMENTS 15.1. Life expectancy 15.2. Flood protection measures 15.3. Risk awareness *15.4. Enhancement of Early Warning*
	9. IMMEDIATE ACTION 9.1. Multi-storey buildings	
	10. INFORMATION 10.1. Access to early warning and evacuation information *10.1.1. Dissemination of early warning* *10.1.2. Knowledge of evacuation* *10.1.3. Early Warning Lead time perception* 10.2. Internet access per X habitants 10.3. Smartphone user per X habitants	
	11. AWARENESS / PREPAREDNESS *11.1. Risk Knowledge* *11.2. Increased Preparedness* *11.3. Perception of Preparedness*	

The first element of PeVI is *Susceptibility*, which is defined as the current status of a society and its likelihood to be harmed. It refers to the condition of exposed citizens and infrastructure to a certain hazard. The susceptibility component for PeVI was defined by four major components: *Demography*, *Health*, *Poverty and Income* and *Housing* (Table 1).

The second element used in the computation of the index is *Coping*, which is evaluated by strengths and resources for direct actions which leads to a reduction in the consequences of a hazardous event (Birkmann and Welle 2015). This not only implies knowledge about local natural hazards and resources, but also the ability to react immediately when a disaster strikes to minimize harming impacts. In this context coping includes the following seven modules: *Government and Authorities, Social Network, Economic Coverage, Medical Service, Immediate Action, Information and Awareness/Preparedness*.

Finally, the third element of the PeVI represents adaptive capacities of a community. *Adaptation* in contrast to coping, which is linked to the impacts, is closer related to change (Birkmann 2011). In order to deal with negative impacts of future disasters, adaptive capacities enable societies to transform. Therefore, adaptive capacities include medium to long-term changes and a future-oriented view (Birkmann and Welle 2015). The following four categories were used to represent *Adaptation* for the PeVI: *Education and Research*, *Gender Equity*, *Environmental Status* and *Investments*.

The respective components of *Susceptibility*, as well as *Coping* and *Adaptation,* are further subdivided to ensure high flexibility to different requirements (see Table 1). Data sets are individually determined for each case study location with regard to local conditions. Since the availability of data is case specific, the definition of indicators can alter, both for inclusion or exclusion of new components. Whatever the case, the development of the compound index needs to be as comprehensive as possible. Data collection includes existing statistical data (e.g. census data, disaster loss data) at local and provincial levels. Therefore, the scale of the assessment is highly dependent on the availability of data from the case study area (Birkmann 2013a).

The PEARL vulnerability assessment has the purpose to display the composition of relative vulnerability in a specific case study area. Hence, all calculated indicators consist either of ratios, or are normalized between 0 and 100, and can only be seen with regard to the respective spatial entity. There are several normalization methods that can be applied in this context (e.g. OECD 2008). In the present research work the min–max normalization method was used. An equal weight scheme was applied to increase transferability and transparency but also to foster communication with stakeholders and decision makers (Birkmann and Welle 2016; Karagiorgos et al. 2016; Cutter et al. 2010; Rød et al. 2012). Due to the inherent characteristics of vulnerability it is not reasonable to define thresholds. Since the aim was to illustrate disparities within a case study site, the quantile method was used for spatial visualization.

2.2.1 Census-based vulnerability assessment framework

The content of Table 1 is based on the literature review and discussions among scientists during several project workshops. The PeVI has been designed in a way that a general analysis can be conducted by using census data. The census 2011 was the first joint assessment of census data in the member states of the European Union. The scope of the assessment can be altered and extended with regard to data availability. The indicators can be adjusted based on local conditions, but the process of elaboration needs to be transparent and reproducible.

2.2.2 Household survey enhanced vulnerability assessment framework

In addition to the PeVI based on census data an alternative and extended methodology was performed in the project. The in-depth analysis of vulnerability was possible through the inclusion of data from a household survey. The survey was carried out with the purpose of gaining knowledge about local vulnerability patterns and household perception on flood vulnerability and risks. Earlier research highlights the added value of the combination of census-based methods with "*mixed-methods*" (Wilhelmi and Morss 2013: 59). Information deriving from the household survey is highlighted in italics and underlined in Table 1.

3 Application to the city of Genoa

The proposed framework was applied and evaluated on the case study of Genoa, Italy. After introducing general conditions for the case study, the location, data availability and calculation of the indicators, as well as the PeVI, are presented and discussed.

3.1 Case study Genoa, Italy

Genoa is the Liguria county seat, situated in Northwestern Italy. It is located in the Gulf of Genoa on the Ligurian Sea and is the sixth largest city in Italy with an estimated population of 585.000 inhabitants and area of 240 km^2 (Faccini et al. 2015b; Sacchini et al. 2012). Genoa is one of Europe's largest cities on the Mediterranean Sea, and the largest seaport in Italy is located here. The PEARL project focusses on the last 5 km of the Bisagno, which is one of the most problematic rivers of the region in terms of floods (Faccini et al. 2016). The Bisagno river basin is set in an area with complex geomorphology and large elevation changes upstream which are the driving forces for flooding-related issues in its downstream urban area. The risk of flooding is further increased by the high degree of urbanization that over the years considerably modified the natural path of the river. Around 1930, the last 1.3 km of the river (from Brignole railway station to the mouth) was covered in order to construct buildings and streets. This resulted in a decrease in discharge capacity and increase in flood occurrence in the urban area (Faccini et al. 2015c).

The combination effects among Bisagno river basin morphology, man-made modifications to urban area and locally generated extreme hydrometeorological events (heavy precipitations, V-shaped storms) are the main causes of pluvial and flash floods that hit the city along the years (Acquaotta et al. 2017). The vulnerability assessment focusses on the flood event of October 2014. Besides this event, most recent flood events in Genoa city took place in 2010 and 2011. After the Second World War notable events occurred in 1951, 1953, 1970 and 1992 (Faccini et al. 2015a; Faccini et al. 2015c). All events resulted in displacement of people and high economic damage and in many cases also in fatalities.

3.2 Overview of data collection methods

Data collection methods included field surveys, as well as open access data bases and official information sources (e.g. public administrations). An overview of these methods and details of how there were used to assess vulnerability in Genoa are discussed in this section.

3.2.1 Census data

Data for the underlying indicator calculation were extracted from publicly accessible statistical data from the Italian National Institute of Statistics (ISTAT). The census reference date for the data obtained is October 9, 2011. The census data comprises personal information, as well as building information. With regard to the underlying entity this includes absolute values of residential population and information on age groups, level of education, number of illiterates and employment status. The respective data can be further divided by gender. In addition also information concerning the origin of the residential population and household size can also be obtained. Building information comprises aggregated values regarding the type of use, construction material and period, the number of floors and rooms, as well as the classification of building conditions. Additional information concerning Italian census data can be found in ISTAT (2016).

3.2.2 Household survey data collection

The household survey focusses on assessing vulnerability of a subsample of local population living in areas affected by hydrometeorological disasters. The examined case study area has been recently and recurrently affected by flood events.

Wilhelmi and Morss (2013) highlighted that there is a predominantly lack of data concerning coping and adaptive capacity on local level. On the basis of the questions covered in the survey the intention was to close this gap and to collect data with regard to these capacities.

Ten local interviewers with background in environmental engineering or geomorphology supported the researchers with the implementation of the survey. The extent of the survey was selected based on the extent of the 2014 flood event in the Bisagno area. The affected area was divided into ten sub-areas different in size but homogeneous in number of inhabitants. These were defined by census data of population distribution, elaborated with the support of GIS tools and related functionalities. Within each sub-area the interviewed households were chosen randomly. A total of 500 persons took part in the household survey. Spatial distribution of the survey is highlighted in Fig. 1 and referred to as the area of the 2014 flood event.

3.2.3 Spatial information

In order to map the PeVI and its components geo-spatial data from Open Street Map, ESRI ArcGIS, national open data servers and data sources from local administrations were sourced. The most relevant data sets are listed below:

- city, region and country administrative boundaries,
- polygons representing the census administrative areas,
- outline of the Bisagno river catchment,
- outline of the 2014 flood event.

3.3 Application of the census-based vulnerability assessment framework

The structure of the census data for the city of Genoa has two main administrative areas of interest: the census zones or polygons (SEZ—*Sezioni di censimento*), where each SEZ code uniquely identifies each section of the 2011 census within the municipal area (ISTAT

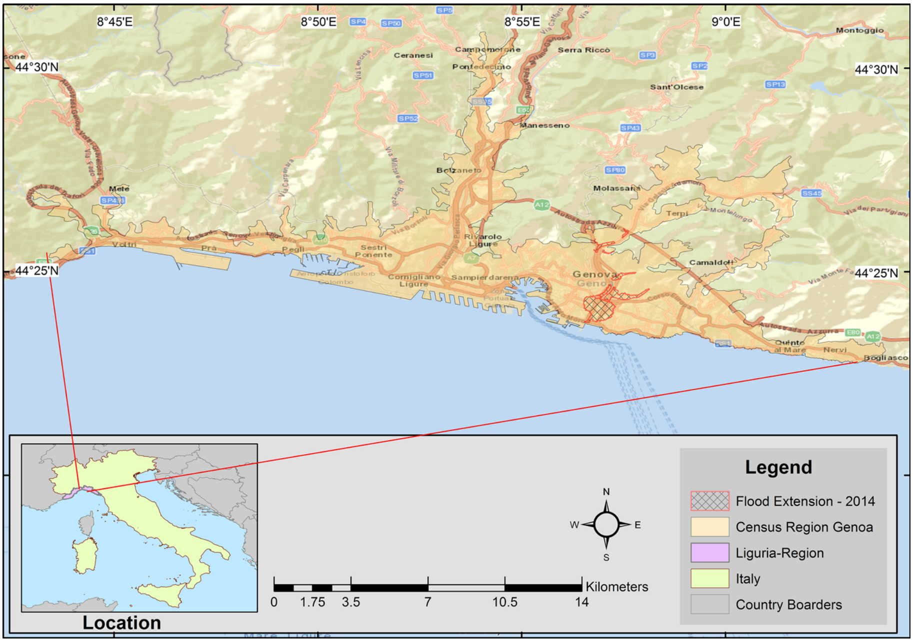

Fig. 1 Case Study Site Genoa, Italy

2016) and the census areas (ACE—*Area di censimento*). ACE corresponds to a collection of SEZ sections, and each polygon has one unique identifier within the municipality. The PeVI was calculated on the smallest scale possible. In this case the analysis was carried out on the basis of 3412 SEZ census sections. All computations for the indicators were done in MS Excel, and the results were transferred to the corresponding geographical unit in GIS using the *Join* functionality based on the unique SEZ identifier. The indicators of the PeVI predominantly were calculated as ratios. "No Data" fields were filtered and excluded from the computation of indicators. By applying this constraint the PeVI could be calculated for a total of 3083 of SEZ areas.

The analysis of the results obtained from SEZ areas was not conclusive and did not add an additional value to the map and the subsequent interpretation process. On the contrary a wide graphical dispersion of the results was obtained due to the level of detail and statistical differences between SEZ areas (see Fig. 2). It was considered that the representation on SEZ level is unpractical for stakeholders and the decision making process; therefore, the results of the PeVI were aggregated into the ACE areas, which in the case of Genoa corresponds to a total of 40 units. This level of representation gives a more clear view of the results. This process was done using the mean value as statistical variable using ArcGIS.

3.3.1 Susceptibility

The following section discusses the composition of *Susceptibility* and describes the data used for the calculation (Fig. 3). The respective indicators were carefully chosen based on data availability and local and theoretical relevance (Wilhelmi and Morss 2013).

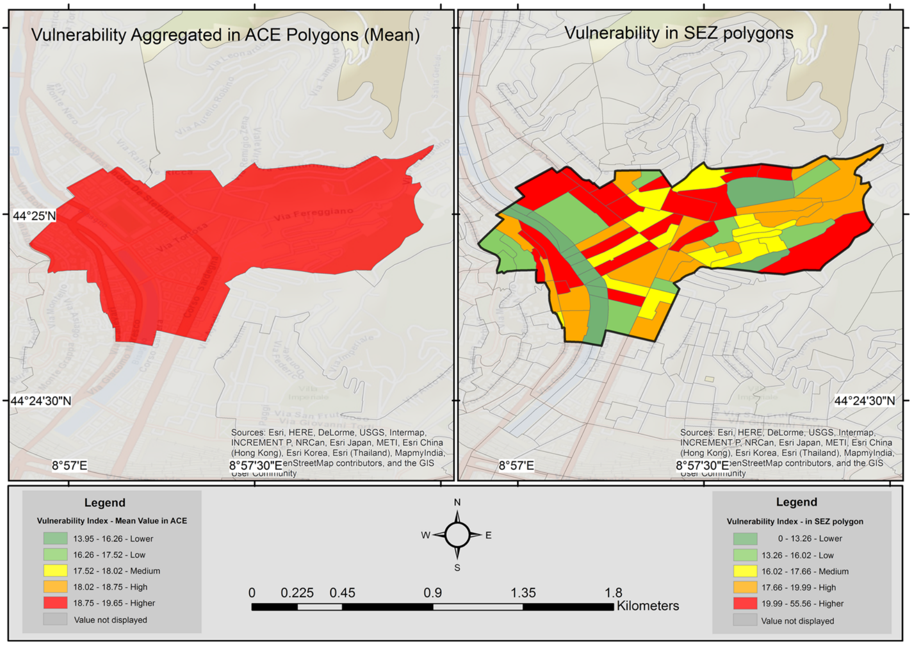

Fig. 2 Exemplary aggregation process

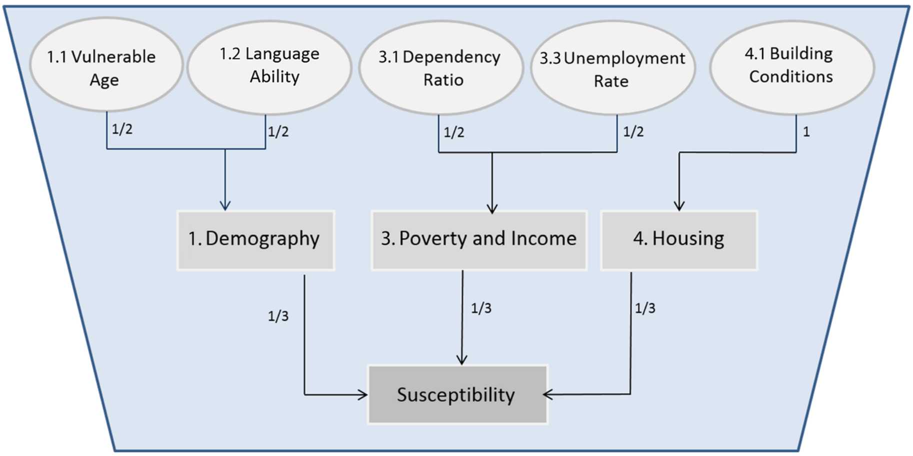

Fig. 3 Composition of Susceptibility including weights of indicators

From census data *Demography*, *Poverty and Income* as well as *Housing* were incorporated into the calculation scheme. *Demography* is thereby acknowledged by vulnerable age groups and share of foreign and stateless people. In the context of natural hazards vulnerable age groups are defined as people younger than five and older than 65 years (see e.g. Jelínek et al. 2012; Welle et al. 2014). Depietri et al. (2013: 106) considered the amount of immigrants per spatial unit as a "*proxy for low income and of disadvantageous* *condition due to difficulties in understanding warning messages*". Both indicators contribute equally to *Demography* and therefore have a weight of one half (see Fig. 3).

Poverty and Income is measured on the one hand by the unemployment rate and on the other hand by the dependency ratio. The dependency ratio is a measure which aims to capture economic reliance of parts of the community on other parts and as such it is defined as the sum of people younger than 15 years and older than 65 years. This is then divided by the number of people at working age in between. A high dependency ratio indicates that the working population group faces a major challenge to support the economically non-active population (United Nations 2007). The unemployment rate for Genoa was calculated by dividing the number of unemployed by the number of potential workers. More precisely, all persons are aged 15 or older, and the number of unemployed in this case includes only the persons who are registered as seeking employment.

Due to different building conditions, individual buildings are more or less resilient (Vojinovic et al. 2015). For the Genoa case study ISTAT (2016) provides necessary data describing the conservation status of the building with four classes (very good/good/medium/bad). The respective indicator was calculated by summing up the weighted different categories and dividing the sum by the total of residential buildings. Here the category *bad* was applied with the highest weight, since this increases the *Susceptibility* and consequently *Vulnerability*.

3.3.2 Coping

Vulnerability includes aspects which make people susceptible to the negative impacts of natural hazards and factors which increase their ability to cope and adjust to them. For the calculation purposes the lack of coping is taken into consideration, to assess negative impacts on vulnerability.

Coping consists of two components: *Social Network* and *Immediate Actions*. Social environment has a high impact on flood-risk behavior (Bubeck et al. 2013). Welle et al. (2014) state that an increase in household size decreases vulnerability due to mutual help. Following this line of arguments single households were weighted higher in the assessment than larger households, since the assumption was that smaller households increase vulnerability. The individual households were multiplied with the respective weights, summed up and divided by the total number of households.

Having a second floor to take refuge to is one way of an *Immediate Action* for getting to safety and having the possibility to store belongings securely from the hazard. Since the lack of coping is incorporated into the calculation scheme, the respective indicator is computed by the number of single floor houses divided by the total number of houses. *Immediate Action* and *Social Network* are weighted with one half (see Fig. 4).

3.3.3 Adaptation

In contrast to coping, adaptation processes include societal changes and mid- to long-term transformation processes. Hence, the focus is orientated toward the future.

In Genoa, two pillars of adaptive capacities were calculated based on census data (see Fig. 5).

Education can be viewed at two different levels, first by looking at the ratio of people holding a higher degree and second looking at the society and the basic level of education by means of literacy rate. Due to the structure of census data information concerning education is not linked with age. In order to graduate from secondary or tertiary level of

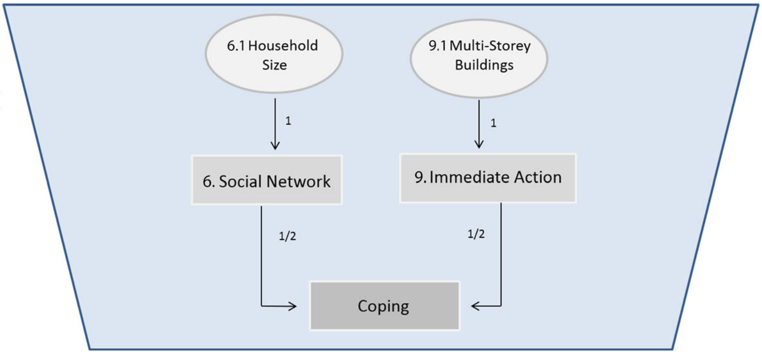

Fig. 4 Composition of Coping including weights of indicators

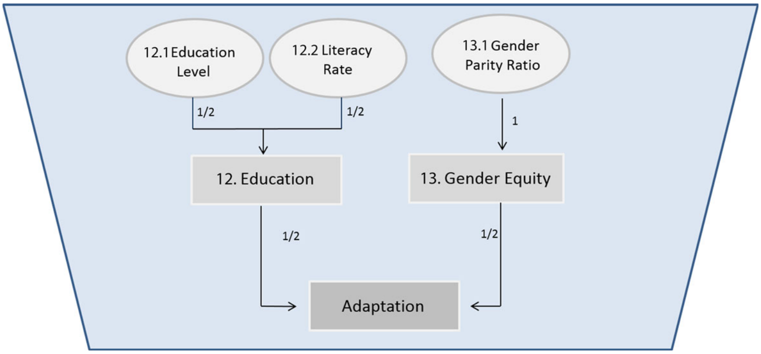

Fig. 5 Composition of Adaptation including weights of indicators

education it is assumed that the person has to be at least 20 years old. Therefore, the persons at the age 20 and higher are taken into consideration for the calculation. The indicator is calculated by summing up the number of people holding higher education (secondary and tertiary education), divided by the number of people at the age of 20 or higher. The indicator was inverted since indicators related to adaptive capacity were calculated in a way in which they increase vulnerability. Further the illiteracy rate was calculated. Due to the fact that the number of illiterates in the census data was not further categorized by age groups the respective indicator was calculated by dividing the number of illiterates by the population aged 15 or higher. Both pillars are multiplied by one half and summed to the *Education* indicator.

Gender parity in education is calculated by the ratio of the number of females holding primary, secondary or tertiary education and the number of males holding the respective education. The number ranges from zero to one in advantage of men, one for equality and larger than one in advantage of women. A high value of the ratio does not necessarily mean a high access of females to education, it could in turn mean that the participation of male is rather low (Bündnis Entwicklung Hilft 2015). Since *Gender Equity* was aspired, the value for the best case was one. As mentioned the lack of adaptive capacity is incorporated into the PeVI, and consequently, the calculated value of gender equity was reversed.

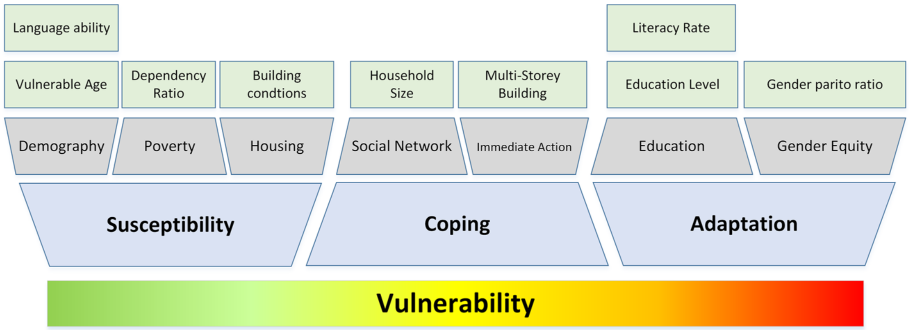

Fig. 6 Composition of the compound PEARL vulnerability index based on census data (Genoa)

3.3.4 Vulnerability Index

The aim of a vulnerability assessment is to get a comprehensive overview about the current state of a system. The vulnerability map that results from this process allows to draw conclusions at one glance, because every spatial entity is assigned to one value. The PeVI was calculated by combining *Susceptibility*, *Coping* and *Adaptation,* where equal weights were applied for each element. The availability of data concerning coping and adaptive capacities was found to be rather limited in the case study area. For both indicators only two of the initially proposed categories (Table 1) were taken into consideration. Figure 6 shows the structure of indicator development for the compound PeVI based on census data.

3.4 Application of the household survey enhanced vulnerability assessment framework

The household survey enhanced PeVI comprises the combination of statistical data, derived from census data (ISTAT 2016), geo-statistical data and information on household level.

As in other research projects (e.g. Kuhlicke et al. 2011: 799) the collection of household data was examined to also serve other work steps of the PEARL project with specific purposes and guidelines. The purpose of the questionnaire was twofold: to engage local stakeholders (Gourgoura et al. 2015) and to incorporate perception of the citizens into the index. A high proportion of questions with quantitative information was incorporated which can be categorized into three groups:

- Type (1): Questions on Likert Scale ranging from strongly agree to strongly disagree
- Type (2): Questions based on ratings from 0 to 10
- Type (3): Questions, which can be answered with yes or no.

As part of a workshop researchers agreed on three different schemes for the transfer of answers to numbers. For Type (1) it is assumed that a level of strong agreement to a statement (e.g., "*The climate change is adversely affecting the Liguria region*") can be captured with the value of "0," while the level of strong disagreement is transferred into a maximum value of "100". All intermediary steps are assumed to be evenly spread over the minimum and maximum value. For the questions of Type (2) the conversion into indices is also following an even distribution from 0 to 100 based on the 10 classes of response options. For the Type (3) questions all answers in affirmance were transferred into a value of “20,” while negations are assigned the value “80.”

The validation of data was performed by using two rank-based nonparametric test methods for independent samples (Mann–Whitney *U* and Kruskal–Wallis *H* test). The advantage of these methods is that the data does not require to be normally distributed. Both tests can be applied for variables on ordinal scale. However, there are assumptions for both methods that have to be met: The scale of the dependent variable has to be ordinal at least, and the independent variable has to consist of two or more categorical independent groups. Moreover, independence of observations has to be ensured. All respective assumptions can be met for the underlying data.

Consequently, vulnerability and its respective indicators were calculated for 500 respondents, geo-referenced through the address of the household. A point shapefile in ArcGIS was prepared using the addresses and geo-coding functionalities. For the cases where no address was available a point shapefile was randomly created within the area that was flooded in 2014 and it was used to undertake the computation. The household survey results were coupled with indicators obtained from the census-based vulnerability assessment in MS Excel, and all vulnerability indicators were then computed and incorporated into the ArcGIS shapefile of the household survey (building level). The next step was to aggregate the vulnerability assessment from the point shapefile into the respective polygon at SEZ level on the census data. This was done by applying the *Spatial Join* functionality in ArcGIS to link each respondent of the survey with their associated SEZ polygon. Once each point was given the attribute of the unique identifier (ID) for the SEZ polygon an aggregation of points was performed based on the SEZ ID attribute using the mean value. ArcGIS *dissolved* method was applied in this operation. In such SEZ polygons including the mean values for each one of the SEZ polygon that contains household data were obtained.

The following sections describe the process of incorporating household survey data for the 2014 flooding event. The inclusion of household data modifies the mathematical structure, and consequently the result and pattern of the PeVI. The PeVI is particularly enhanced by the personal assessment of *Coping* and *Adaptation* of local respondents, and this is evident from Table 1 and Fig. 7.

3.4.1 *Susceptibility*

Since no additional data from the household survey were incorporated into the calculation of the susceptibility component, the procedure and results from the census-based PeVI and the PeVI enhanced with survey data are identical (as discussed in Sect. 3.3.1).

3.4.2 *Coping*

The household survey contributed to an enriched depiction of coping capacities, adding to the multi-dimensional picture of societal vulnerability. Information was used for the development of five additional indicators related to *Coping*. These are *Government and Authorities, Economic Coverage, Medical Service, Information* and *Awareness/Preparedness*. Next to these five indicators, two census-based indicators (refer to description in Sect. 3.3.2) were used.

In terms of *Government and Authorities*, the data obtained from two survey questions were incorporated. The first survey question addressed whether the inhabitants trust the local administrative bodies, whereas the second survey question addressed the performance

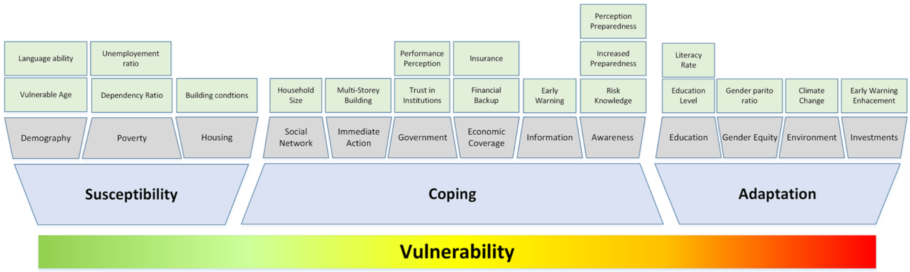

Fig. 7 Composition of the compound PEARL vulnerability index with household survey input (Genoa)

of flood-risk management authorities. By applying equal weights the answers were combined into the indicator. The *Economic Coverage* indicator looked on one hand at the institutional situation to recover from losses by the insurance coverage and on the other hand at the personal capacities by self-rating of financial resources. The *Medical Service* indicator was explored by the level of agreement to the question whether the supply with hospitals, ambulances and rescue units in Genoa is satisfactory.

Another important aspect of *Coping* is information flow, especially the access to early warning and evacuation information. Crucial parts of the information flow are dissemination time, knowledge of evacuation and lead time, which all three were considered explicitly in the questionnaire and contributing one-third each to the *Information* indicator.

The last important addition to the census-based coping component was given by the *Awareness/Preparedness* indicator. Here the flood risk knowledge was queried in addition to whether the respondents believe that they are now better prepared for future flooding events and a ranking of their perception of preparedness and expectance of damages.

Figure 7 illustrates the enrichment of the *Coping* indicator in the context of the overall compound index of social vulnerability.

3.4.3 Adaptation

When it comes to future orientated adaptation processes, the attitude of people affected is critical, as it determines whether or not someone is willing to invest or to take action. For the calculation of *Adaptation* two additional indicators were developed based on the household survey data.

Environmental Status was evaluated by the extent of approval to the statement that climate change is affecting the Liguria region.

Parker and Priest (2012: 2928) name "*human factors and related social issues*" as crucial for the success of early warning systems. For the *Investments* component the survey queried the *Enhancement of Early Warning*. This was assessed by the level of agreement of respondents to the statement: "*If the early warnings distributed to the population would be more precise and would reach me more directly I would follow them more than I do now*".

Adaptation supplemented by the household survey and combined with the census data (*Education and Research* and *Gender Equity*) consists of four indicators, each adding one quarter to the calculation of *Adaptation*.

3.4.4 Vulnerability Index

Since the incorporation of household survey results influence the structure and computation of the indicators, the final calculation of *Vulnerability* using the enhanced methodology was also affected. Figure 7 illustrates the modular structure of the compound index and visualizes the valuable input of the household survey data to the PeVI.

4 Results and discussion

In this section the results obtained from the calculation of the compound vulnerability index in Genoa are presented and discussed. As described above, the PeVI is the result of the combination of *Susceptibility*, *Coping* and *Adaptation*. In the census-based vulnerability assessment carried out for the entire municipality of Genoa the SEZ polygons were aggregated into ACE areas using the mean values. Based on five classes, the vulnerability values of the entities were translated into a qualitative classification. The quantile method represents each class equally in the map. This does not necessarily mean that a spatial entity, which was addressed to the "lower" (green) group, is not vulnerable and does not need any support. However, viewed relatively, it has a lower priority, with regard to the other entities, when it comes, e.g., to investments concerning vulnerability mitigation.

The spatial analysis map for the census-based PeVI is given in Fig. 8. The highest vulnerability value was calculated for the small polygon corresponding to the business and trade area of the city. For this particular polygon the underlying *Susceptibility* also achieved the maximum value and as such it was assigned as the red category. While the

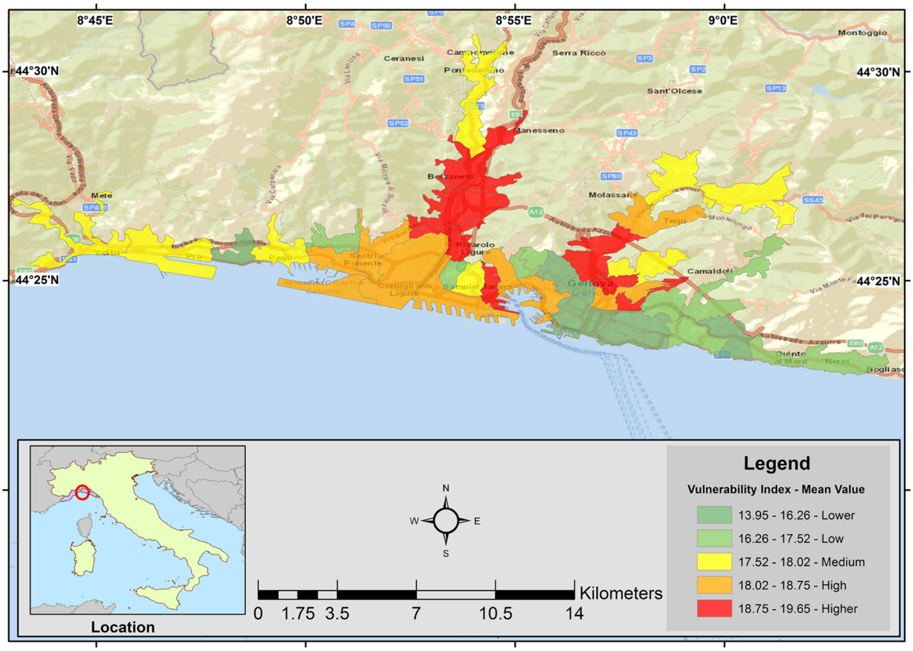

Fig. 8 Result of the census-based PeVI

related Coping and Adaptation values are presented in the orange category, indicating a high discrepancy in capacities. The western part of the harbor area also has higher vulnerability values, while the area of the airport is orange (high). Both areas have a relatively sparse population.

Along the river course of the Polcevera, which, together with the Bisagno stream represents one of the most flood prone areas of the city, the highest vulnerability category was calculated. The area is located in a city district with a former industrial characteristic, now densely populated, and is one of the most working-class zones in Genoa, with a high rate of immigrates and low incomes. Here the underlying values of *Coping* are in the middle range, while the maximum red categories were achieved for the lack of *Adaptation* and *Susceptibility*. Other red hot spots are located in the catchment area of the Bisagno. The area is characterized by residential buildings, as well as commercial/industrial sites. The Bisagno with its final reach predominantly covered by concrete poses a major threat to flooding (Faccini et al. 2016). The areas flooded in 2014 are marked with yellow color in the upper catchment, merge with a color gradient from yellow to red and then green color in the lower parts. The green area in the lower parts has the lowest PeVI values with underlying *Susceptibility*, *Coping* and *Adaptation* (all subindices, respectively, it the green category) due to its residential usage and the generally good social and economic conditions of its population. The green areas in the eastern part of the city are more prosperous areas, with the main focus on tourism. The area in the eastern edge is a former fishing village with a small touristic harbor. It shows predominantly very good *Susceptibility* and *Adaptation* values, and therefore, the PeVI is marked with green color.

While the result of the census-based PeVI covers the entire city of Genoa, the extent of the household survey enhanced PeVI focusses on the flooded area of the 2014 event. The spatial unit used for the enhanced approach was SEZ, which influenced the vulnerability values. Generally speaking, the mean aggregation process from SEZ into ACE smoothened the PeVI. The range of vulnerability values is wider for the assessment on SEZ basis. The color coding based on the quantile method relates to the areas covered by the survey (Fig. 9). For the spatial display only the SEZs, where the survey was conducted, were taken into consideration. Figure 9 depicts the *PeVI enhanced by household survey input* on the right side, while the map on the left displays the *census-based PeVI*.

Disparities are obvious at the first glance at both maps presented in Fig. 9. Hence, Fig. 10 selects exemplary polygons, to give more clarity in those SEZ polygons with higher differences. The SEZ with the ID '2007' can be referred to as an example. An increase in both pillars *Coping* and *Adaptation* results in a change in category from the lowest to the highest category. Based on the comparative approach of the quantile method the census area´s PeVI is pulled down, in objection to the good census rating, by the subjective rating of the inhabitants of the block. Compared to the other areas within the flood extent this leads to the category of higher vulnerability. The main driving force behind this is people's negative rating of *Climate Change* and *Investment*. That puts a spotlight on the future orientated development of the quarter. Similarly, SEZ with ID '1945' is also rated poorly by its inhabitants concerning *Coping* and *Adaptation,* contributing equally to the PeVI. Within *Coping* the relative worse ranking is forced on one hand by *Economic Coverage* and on the other hand by *Awareness/Preparedness,* indicating the expectation of financial support in case of losses. The other indicators, especially *Medical Service* and *Information*, clearly reach higher satisfaction among the respondents. Concerning *Adaptation* there is a general approval of the negative impacts of climate change but even surpassed by the perception of *Enhancement of early warning.* To summarize in short, the perception of the people outweighs the baseline of lower vulnerability (census based). The opposite dynamic

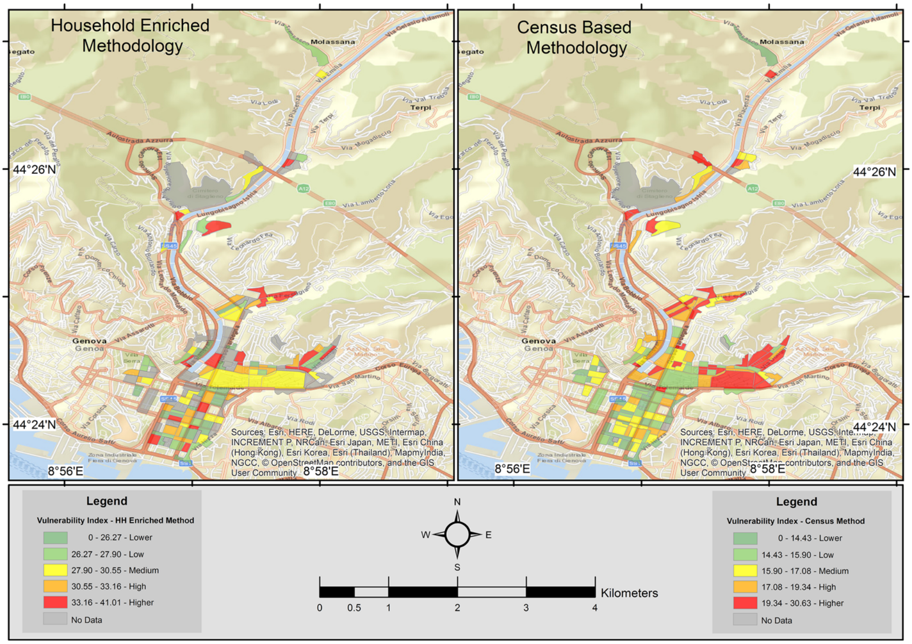

Fig. 9 Result of household survey enhanced PeVI and census-based PeVI

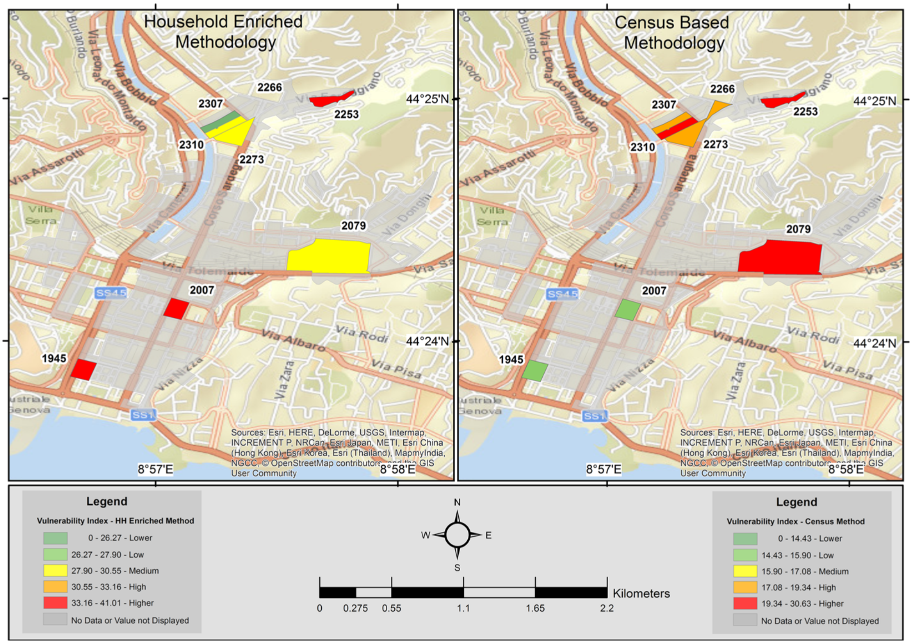

Fig. 10 Comparison of SEZ polygons with remarkable differences in both methodologies

of relative lower vulnerability based on household survey data shows lower perception of vulnerability, although higher susceptibility to vulnerability based on the census data. For instance SEZ '2079' improves its ranking from red to yellow by maintaining its vulnerability score but improving relatively to the other SEZs.

Other areas which obviously change are the SEZs with the IDs '2273', '2310' and '2307'. All three improved their ranking. It is interesting to observe that this is less related to the impact of *Adaptation*, but more connected to *Coping*, stating the peoples worry in inappropriate short-term strategies and capacities. The SEZs '2267' and '2253' mark a hot spot in vulnerability, building a cluster of high values. Local Morans I-Index categorizes both as a cluster with statistical significant high values surrounded by high values. Again the major concern pertains to the immediate action strategies.

Altogether, the results show a distinct spatial distribution and allow not only to identify clusters, but also to explore all the different facets and aspect of societal vulnerability.

4.1 Validation of the census-based approach using sensitivity analysis

The construction and development of a compound index, in order to assess complex matters to simplify them or to understand the broader picture, are challenging and require to consider a multitude of needs (Saisana et al. 2005). The framework, especially in this case, has to foster adaptability and transferability as straightforward as possible, but also taking into account the complexity of the topic and demands in terms of data requirements and mathematical construction. Important aspects of indicator construction are transparency, robustness and traceability (Welle and Birkmann 2015). To ensure the quality of PeVI the following part examines reliability, exploratory factor analysis and sensitivity analysis.

Reliability analysis scrutinizes if the indicators or items are suitable to describe the overall question: *Vulnerability*. Hence, the internal consistency and accordingly homogeneity of the items are tested. The most common measurement of reliability is the Cronbach Coefficient alpha, having values from *zero to one*, raising the questions of an adequate threshold concerning reliability. Depending on the literature and consulting different disciplines values from 0.6 to 0.8 are recommended (OECD 2008). Calculating Cronbach's alpha for the vulnerability indicators taking the whole bundle of ten census data input indicators into consideration the result displays a strong reliability with Cronbach's alpha of 0.982. Another measurement of reliability is Guttman Lambda which calculates a succession of six Guttman Lambdas for different versions of the model. The highest value of the succession can be interpreted as the minimum reliability (Janssen and Laatz 2013). Using the whole set of indicators the highest Guttman Lambda of the sequence is the sixth with 0.998, showing strong reliability.

In order to conduct exploratory factor analysis (EFA) a commonly used criterion to test the suitability of data for analysis is the Kaiser–Meyer–Olkin criterion (KMO). If the KMO is lower than 0.5, the data are not suitable for EFA and it should not be proceeded, due to the fact of little shared variance of the intercorrelation matrix. Values higher than 0.7 are suitable and higher than 0.8 are good (Bühner 2006). Resulting in a KMO of 0.75, a medium but still encouraging value to proceed is reached. To safeguard the robust outcome of the EFA the unweighted least square extraction method is chosen (Zygmond and Smith 2014). Following the procedure described in "Handbook on Constructing Composite Indicators" (OECD 2008) the eigenvalues of 0.952 for *Susceptibility*, 0.994 for *Coping* and 0.943 for *Adaptation* justify the implementation of equal weights of, respectively, one-third to each of it. Extracting only one factor no rotation is carried out.

Creating a complex model of an even more sophisticated topic can result in an abstract black box. Here sensitivity analysis is important to understand the response of the model, generating an understanding and hence a range of trust. Saltelli (2002: 579) define sensitivity analysis as "*the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input*". According to the definition, the analysis distinguishes which input has significant impact on the output and which variables do not. In general there is a distinction of global sensitivity, where all parameters are varied at the same time and local sensitivity analysis, where only one variable is changed and the others are kept constant. In contrast to the local global sensitivity also takes into consideration the uncertainty inherent to each single input factor and is therefore applied to PeVI. Typically for many compound indices a Monte Carlo method is the common way of assessing sensitivity. The weakness here is the high amount of computations and the computational effort needed. Moreover, the assumption of independent indicators can hardly be expected entirely in the field of social science. The advantage of using a Bayesian approach is to reduce the number of runs, while still achieving reliable results due to the fact that the standard deviation connected to the estimates is smaller (Oakley and O'Hagan 2004). This is attained by explaining each variable as a function and adding Gaussian noise to the function which is normally distributed. Figure 11 displays the result of the sensitivity analysis and consists of three parts. The left part shows the resulting curves of the sensitivity. The x-axis is hereby the original input scaled from − 0.5 to 0.5 and the *y*-axis the variance of the indicators. Discussing the curves a steep curve explains a strong effect on the output, whereas a flat or horizontal curve can be seen as low impact and consequently the indicator would be open for discussion whether to include or not, due to the limited impact and explanatory power of the variable. Following this line of argumentation all three indicators show strong impact on vulnerability and hence their justification. Considering the middle and right graphs of

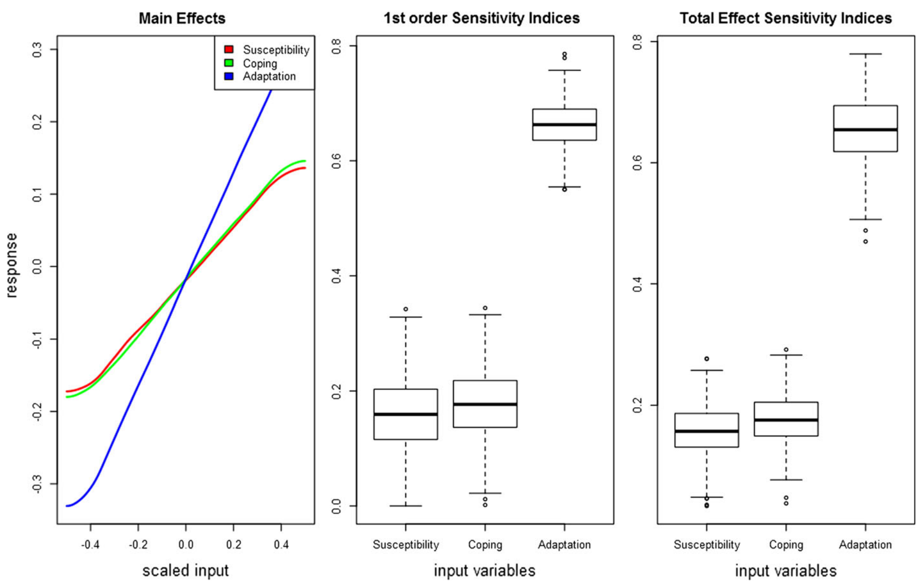

Fig. 11 Result of the sensitivity analysis for *Susceptibility, Coping* and *Adaptation* for the census-based assessment

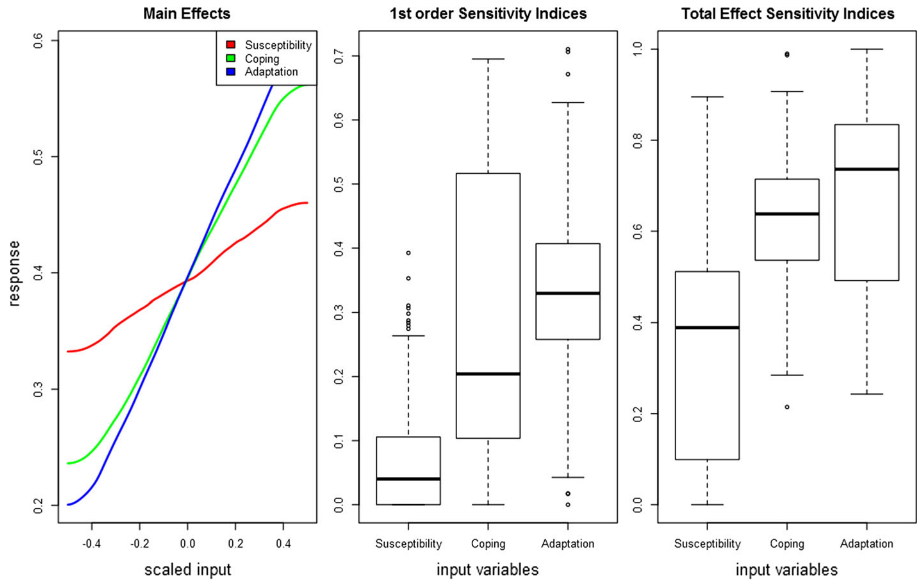

Fig. 12 Result of the sensitivity analysis for *Susceptibility, Coping* and *Adaptation* for the household enhanced assessment

Fig. 11 the size of the boxplot is showing how the respective indicators are influencing the PeVI, meaning an indicator with small box has a precise impact. All three indicators are having a median higher than zero and consequently contributing and increasing the statement of the overall indices. The right picture is showing the interaction of the indicators.

4.2 Validation of the household survey enhanced approach using sensitivity analysis

Incorporating the household survey into the model, it is important to reassess the performance and behavior of the complex system. In order to achieve transparency, robustness and traceability (Welle and Birkmann 2015) the model response needs to be understood.

The compound index achieves a lower reliability compared to the census data-based approach but still showing good values with Cronbach's alpha of 0,7 and Guttmans Lambda of 0,83. Looking at the sensitivity two aspects are interesting. Coping capacity increases its impact due to the merged and added data influence on the overall indicators. Obvious change is represented by the boxplots in the middle and right component of Fig. 12 having a much larger range, hence having a more diffused impact compared to the much clearer impact of the PeVI based on census data only.

5 Conclusions

In this paper we examined the multifaceted phenomena of socioeconomic vulnerability by deducting measurable proxy indicators from census data and a household survey of 500 flood-affected households. Prior studies have noted the importance of flexible methodologies in order to deal with the ever evolving complexity of vulnerability and risk in nowadays societies, especially when dealing with vulnerability to climate change and flood-related disasters. Therefore, the aim of this research is to identify key elements that contribute to the formation of vulnerability and risk in coastal cities and propose a flexible framework to compute vulnerability by open standard data sets such as census data and geo-spatial data. The proposed methodology was applied in a real case study to prove its feasibility and statistical methods were used for its validation.

Based on the census-based results it is evident that the most flood prone areas with the highest exposure and also have the highest vulnerability values. An example for this is the areas along the Polcevera river course, which is a former industrial district and now predominantly populated by working class and immigrants. Further the population density is high. In the respective areas *Susceptibility* and *Adaptation* show values, which demand for action. In contrast low vulnerability scores were calculated for prosperous areas in the eastern part of the city. Here a former fishing village is located which serves as a touristic hot spot nowadays.

Due to data limitations, uncertainties and other aspects it is not possible to capture the totality of vulnerability, as a multifaceted coupled system (Turner et al. 2003). With the calculation of an index only certain aspects of vulnerability can be taken into consideration, depending on the selected factors. Although attempts were made to assess a wide range of features, the result of the spatial vulnerability assessment is only one possible depiction of a complex societal system. The limits of its validity might also be explained by the fact that economical and technical factors can be measured easily, while the inclusion of societal factors like, e.g., neighborhood support, is much more multifaceted.

The possibility to assess coping and adaptive capacities with census data is limited in the Genoa case study. For both indicators only two of the initially proposed categories were taken into consideration. Solely reducing social vulnerability on cold facts like age, gender and education neglects the complexity of human nature. Driven by opinions, influenced by friends and family and living in our own realities, *Adaptation* and *Coping* rely heavily on the perceived threat shaping the willingness to follow instructions or implement safety measures.

The framework developed in this research was enhanced by field data from a survey. The *household survey enhanced methodology* compromises the perception of flood-affected inhabitants on the present state and future development of the case study. It is advisable to include these aspects in the computation of indices to reflect more adequately the real-world patterns of a particular case study. Also, by incorporating local knowledge in the process, communication and implementation of measures aiming to improve the vulnerability situation might be facilitated with reference to the findings of the study. In other words including survey data can be seen as a “self-assessment” of the people, which enriches the vulnerability maps with the perception of the respondents. Both information layers are crucial for people-centered risk management since they address different dimensions and aspects of vulnerability. The findings indicate a general concern on appropriateness of immediate action strategies.

The PeVI does not claim completeness, and the aim is to provide information and alternative approaches for trade-offs in decision making processes. The approach goes beyond a solely technical view on risk and bridges between different disciplines and perspectives. Therefore, it is important to communicate vulnerability assessments with stakeholders in terms of management, planning and the development of procedures and adaptation strategies (see e.g. Balica et al. 2012; Rosenzweig et al. 2015). With reference to the application in the Genoa pilot, results of the vulnerability assessment have been presented and shared with local administrations. The aim of the discussion was to compare and validate the findings with the perception of local stakeholders and other studies. By scientific exchange the uptake of methodology and use of socioeconomic components when dealing with risk reduction and urban resilience were encouraged. The external validation by local authorities supported the findings of the study and the spatial distribution of vulnerability within the city boarders of Genoa. Moreover, an internal validation was done by statistical testing which justify the robustness, reliability and sensitivity of the index.

All components of vulnerability and therefore the vulnerability itself are not static but highly dynamic. Consequently, the display of vulnerability in a static map can only provide a snapshot. The assessment as it is now can serve as a baseline scenario to monitor and evaluate future assessments of vulnerability detecting changes triggered by internal and external factors. Future research should focus on the development of an effective and transparent monitoring system to detect spatiotemporal patterns in vulnerability. This enables the identification of negative trends and avoidance of long-term deterioration of vulnerability in endangered city districts by implementing tailor-made adaptation measures leading to a climate resilient pathway.

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