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ORIGINAL PAPER

Assessing multifaceted vulnerability and resilience in order to design risk-mitigation strategies

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Abstract Vulnerability studies have evolved significantly in recent decades. Although not overly theoretical compared with some other fields of science, some important conceptual progress has been made. At the practical level, vulnerability indicators have been used either at a generic level or for particular hazard contexts. However, these indicators are often predictably too narrow in their coverage of aspects of vulnerability. An important need remains to produce more conceptually informed vulnerability indicators or parameters and more satisfactory operational tools to assess weaknesses and resilience in coping with natural risks. In this paper, we present the methodology developed in the context of a recently concluded EU funded project, ENSURE (Enhancing resilience of communities and territories facing natural and na-tech hazards). The resulting vulnerability and resilience assessment framework tool adopts a systemic approach embedding and integrating as much as possible the multifaceted and articulated nature of concepts such as vulnerability and resilience. The tool guides evaluators towards a comprehensive and context-related understanding of strengths and fragilities of a given territory and community with respect to natural extremes. In this paper, both the framework tool and its application to Sondrio in Italy, which is exposed to flash floods, are presented and discussed. The merits and demerits of the new tool are discussed, and the results of the application to Sondrio indicate where data are currently missing, suggesting the kind of data, which will need to be gathered in future to achieve more complete assessments. The results also suggest vulnerability reduction policies and actions and further ways of revising the existing framework tool in the future.

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1 Introduction

There is growing concern among scientists about their limited capacity to contribute, with better knowledge and more reliable information about hazards, to effective ways of addressing the trend towards increased damages and losses caused by natural and other disasters (Guha-Sapri and Santos 2012). As White et al. (2001) pointed out, the indisputable rise in threatening phenomena has not been matched by enhanced community and environmental response so that mitigation strategies and measures have been inadequate in addressing the threat. The underlying causes of this 'failure' are multifaceted and include an incomplete understanding of the probable influence of climate change on hazards (Kininmonth 2005) that are triggered by meteorological conditions and the impacts of rapid worldwide urbanisation of recent decades (Mitchell 1999). Importantly, there are also severe limitations in current methods of assessing risk and translating risk assessments into usable terms for policy and practical decision-making. Although progress has been made (e.g. Meyer and Messner 2005; Inter-American Development Bank 2010), ability to recognise, capture and measure the full range of potential or actual damages and losses related to hazards and disasters at local, regional and national levels is part of this problem.

This paper addresses the problem of the lack of predictability of the impacts of natural extremes and disasters by focusing upon vulnerability as a means of approaching, describing and measuring these impacts as potential ones. Compared with a focus upon hazard impacts as damages or losses, the concentration on vulnerability moves the analysis of hazards and disasters into a much broader and more appropriate framework for considering the underlying and less superficial, sometimes less visible causes of the effects of these phenomena. The first aim is to present a methodology, developed through the completion of the EU funded ENSURE research project (2008–2011), which builds in an integrated way on the role played by different facets of vulnerability in shaping the type, severity and chains of failures which induce direct and indirect damages and losses that are so common in disasters. The second aim is to apply this vulnerability assessment framework tool to the Italian town of Sondrio, which suffers from flash floods. The objectives are to demonstrate application of the tool in a single hazard assessment and to identify gaps in current data availability, which can guide enhancements in data capture for the future. The objective is also to briefly suggest ways in which the vulnerability assessment indicates policies and actions, which should be considered to reduce vulnerability to floods. The advantages and disadvantages of the tool and this application are discussed, as are ways in which they might be further enhanced in the future. The central issue that this paper seeks to address is the development of theoretically informed practical, operational vulnerability assessment methods for a single hazard setting. The ENSURE methodology also aims to provide a tool for multi-hazard vulnerability assessment, but this is beyond the scope of this paper.

2 Vulnerability and resilience assessment: in search of theoretically informed, practical operationalisation

Recognising the need to broaden the focus from the hazard, vulnerability is now a central concept in disasters research and in mitigation strategies at all scales. The origins of hazard vulnerability theory go back to dissatisfaction (see Torry 1978; O'Keefe et al. 1976) with natural hazard assessments focused mainly or solely upon geophysical or climatic causality. The report by an UNDRO expert group in 1979 (UNDRO 1979) was one of the first to address theoretical aspects and to point to the need for vulnerability analysis. The theory of vulnerability has evolved in many fields including structural engineering (e.g. Calvi et al. 2006), systems engineering (e.g. Perrow 1984), geography (e.g. Hewitt 1983), sociology (e.g. Beck 1992) and political ecology/development studies (e.g. Cuny 1983, Blaikie et al. 1994) and ecology (e.g. Holling 1973, 1996, 2001). Although disciplinary approaches originally contributed to overly narrow, dominant theorisations of hazard causality, the multi-disciplinary nature of contributions to vulnerability theory has now led to a particularly wide range of definitions of vulnerability and to little consensus about definition (Cutter 2006).

The ENSURE project draws on, and is informed by, many understandings and theories of vulnerability, particularly but not only those which seek to articulate the vulnerability of people, communities, their lifelines and their economies (e.g. Cutter et al. 2008; Hills 2005; Al-Kuwaiti et al. 2006). Vulnerability is an extremely complex concept. In the ENSURE project, vulnerability is defined as different to the potential for loss. It is defined in terms of the interaction of hazards and people's vulnerability and is a composite outcome of exposure, resilience and adaptive capacity.

'Exposure' contributes to vulnerability (Cutter 2006) and is part of vulnerability in the ENSURE methodology. It is defined as the physical assets (e.g. building stock, roads, power stations etc.), environmental assets (e.g. land, soil, ecosystems etc.) and people (i.e. individuals, households, communities etc.) located within the hazard zone. Assets and people have a differential 'susceptibility' to damage. For example, timber frame buildings are likely to be more susceptible to flood damage than brick built ones and may float off their foundations.

Vulnerability may be measured by physical and systemic susceptibility to loss. Vulnerability reflects fragility in the face of external stress. It also reflects the processes which deprive people of the means of coping without incurring damaging losses that leave them physically weak, economically poor, socially dependent and psychologically damaged. Vulnerability is multi-faceted with the principal facets being physical (natural and built environment), systemic, social/community/institutional and economic; in fact they all influence one another. Mitchell (1999) recognises the complexity of hazards and the increased tendency for 'coupled events'. Often natural and 'na-tech' hazards are combined as in the 2011 Japanese Tohoku earthquake and tsunami (Cyranoski 2011). Vulnerability to such coupled events has been considered as well in ENSURE.

Vulnerability is also a dynamic concept, being shaped over time throughout the 'disaster cycle' (Fig. 1) (Tobin and Montz 1997, 336). Vulnerability must also be considered across spatial scales. Impacts and vulnerability reduction measures may (a) vary and (b) be transmitted across local, regional or national scales. The IDNDR Program Forum (IDNDR 1999) placed a particular emphasis upon the need to build 'hazard-resilient' communities. The IPCC Third Assessment (2001) defined a resilient population as one that is able to adapt successfully to climate variability and change. In this definition, resilience represents the flip side of vulnerability, although the ENSURE team observed that in practice some mitigation measures designed to increase resilience may have unpredicted negative outcomes. On the other hand, some communities may be very vulnerable to the impact and the consequences of a hazard, while showing high levels of resilience in the response phase. Coherently, ENSURE interpreted vulnerability and resilience are two separated concepts (see Paton 2008). The first can be understood as synonym of the weaknesses and fragilities,

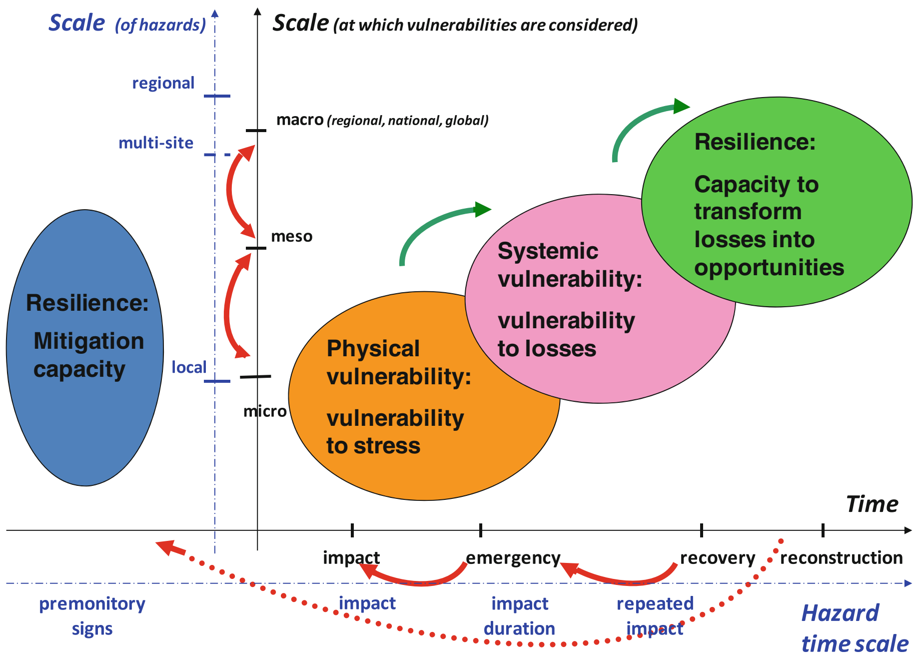

Fig. 1 The ENSURE general theoretical vulnerability framework

while he second entails the capacity to recover effectively by improving pre-event conditions (Norris et al. 2008).

2.1 ENSURE methodology

The ENSURE methodology is informed by theoretical studies and practical applications, three of which are discussed below. They have been selected because they are attempts to create a comprehensive framework, which organises, in an integrated manner, vulnerability of physical assets and systems and social and economic ones. Other studies include mostly vulnerability assessment methods addressing social, economic, and geographical components (see Cutter et al. 2000), or evaluations of response of physical systems but only to a limited extent coping capacity to individual hazards (e.g. Calvi et al. 2006 and Petrini 1996 for seismic risk; Fowler et al. 2003 and Messner and Meyer 2006 for flood risk; Rockström 2003 for drought; Spence et al. 2005 and Zuccaro and Ianniello 2004 for volcanic risk; Galli and Guzzetti 2007 and van Westen et al. 2006 for landslide risk).

The 'Pressure and Release (PAR)' and 'Access to Resources' models proposed by Blaikie et al. (1994) represented progress in explaining the nature of vulnerability to natural hazards. Blaikie et al. held that vulnerability is socially produced and is at least as important as an understanding of extreme natural events in understanding disasters. People's vulnerability is rooted in social processes and underlying causes. Only by bringing these social processes and causes together, under 'pressure', with an extreme event can we fully explain disasters. Root causes of vulnerability are limited access to power, structures and resources. Dynamic forces, such as lack of local institutions or rapid urbanisation, are added to root causes generating unsafe conditions manifested in fragile physical environments and local economies, vulnerable societies and lack of public actions such as disaster preparedness. The idea of 'release' conceptualises the relief of the pressure through disaster reduction in which vulnerability is reduced. The 'Access to Resources' model expands the PAR model and explains how vulnerability is related to household's access to resources, which affects their ability to recover from disasters. Importantly, Blaikie et al. recognised that disasters and vulnerability to them 'unfolds' over time. They also recognised that vulnerability and its reduction can only be understood within a multi-scale context, that is, that, for example, the vulnerability of a local community may be largely determined by international political and economic forces. Both of these temporal and scale elements are absorbed into the ENSURE methodology as well as the social causation philosophy.

The need to consider spatial multi-scale aspects was already recognised in the Armonia project, (see Armonia 2007 and Galderis and Menoni 2007) to which some ENSURE project partners contributed. Armonia provided spatial planners with a decision support system (DSS) to guide land uses choices in areas exposed to hazards. The DSS provides a path through which planners should pass to assess the compatibility of future land uses with existing levels of risk. A complete risk assessment, comprising hazard, exposure, vulnerability, and coping capacity evaluations, was recommended to be developed to inform land use planning decisions. Both hazard and vulnerability assessment methods had to be provided for the DSS to be operational. While it proved to be relatively easy to indicate standard hazard parameters at the regional and the local scales, identifying usable indicators for vulnerability and coping capacity assessments proved more challenging. Within the Armonia project a first attempt to identify such parameters for various threats was undertaken, coupling each proposed parameter with a bibliographical reference. The ENSURE project constitutes a logical continuation of Armonia.

The multi-hazard risk assessment of Cairns, Australia, undertaken by Granger et al. (1999) also informed the ENSURE methodology by suggesting aspects of vulnerability (e.g. physical, social etc.), which might be incorporated. Focusing on geohazards risk is viewed as a function of hazard and vulnerability elements, where the latter are assets exposed to risk. The analysis separates five 'S's: setting, shelter, sustenance (e.g. lifelines), security (e.g. protection measures) and society for which spatial and other data are assembled for spatial units (e.g. suburbs) within Cairns. The analysis identifies interdependencies between lifelines recognising that damage may be propagated through such connections. A number of assumptions are made about the linkages between indicators such as educational level, community services and indices of disadvantage and vulnerability and resilience (King et al. 2000). The multi-hazard risk assessment is achieved by combining data on community vulnerability according to the five 'S's so that overall simple vulnerability descriptors (e.g. high, significant, moderate and low vulnerability) are assigned to each suburb. Granger et al. (1999) present a practical framework in which physical, economic, social and institutional aspects of vulnerability can be integrated, presented and measured in various ways.

Longstaff et al. (2010) also employ a framework to identify relevant aspects of vulnerability (e.g. physical, economic and so on) and vulnerability parameters (i.e. indicators) that are necessary to formulate a vulnerability assessment. Such frameworks allow a useful bridge to be constructed between theory and assessment practice (see Ostrom 2005), and for this reason, the ENSURE methodology adopts a framework approach. The development of operational vulnerability assessment tools that are rooted in theory and research evidence may be progressed in practical terms by moving from the theoretical concept of vulnerability to a consideration of vulnerability factors (i.e. vulnerability aspects and parameters) which can be measured and appraised (Roberts et al. 2007).

3 The ENSURE vulnerability and resilience assessment framework and matrices

Figure 1 presents the ENSURE general theoretical framework that creates the basis for a set of four matrices which are a vulnerability and resilience assessment tool. The general theoretical framework reflects a desire to provide an interpretation of the relationship between vulnerability and related concepts (e.g. resilience) with a prevention orientation. The framework and related tool provide a basis for an integrated assessment of vulnerability before an event strikes, thereby aiding decision-makers and citizens to take appropriate anticipatory and mitigation measures.

The framework (Fig. 1) attempts to capture the most relevant features of vulnerability and resilience but is, inevitably, based upon a judgemental selection of aspects considered as important and representative of reality. The temporal and spatial scale axes form a space in which the principal dimensions of vulnerability and resilience are arranged. The scales at which (a) hazards and (b) vulnerability and resilience should be appraised are different and are represented by two distinct y-axes. The scale at which hazards are usually analysed is often different to the scale at which different types of vulnerability must be considered. For example, a landslide is considered by geologists a local event, but in terms of consequences, it may become a regional or even national event depending on the type of consequences (and therefore vulnerabilities) on relevant assets.

Physical vulnerabilities are mainly addressed at the local scale but systemic vulnerability can only be appropriately considered by linking the local scale to a larger scale. For recovery capabilities and resilience, all scales are relevant because resource needs usually cut across all levels of government. Following a disaster, the satisfaction of a local area's resource needs usually depend upon the type and quality of the relationships between the affected place and a much wider region.

The temporal dimension is punctuated by the principal phases of disaster (i.e. impact through to reconstruction) and also displays the potential dynamism of hazardous events as they evolve from a premonitionary signs stage to impacts (of variable duration), which may be manifested as single or repeated ones. Resilience is interpreted as mitigation capacity in advance of an event. Physical vulnerabilities play a dominant role at the impact stage. At this stage, the severity of the event is usually strongly correlated with direct physical damage. This type of vulnerability manifests itself mainly at the local level. After the impact, other forms of vulnerability gain prominence. Especially during the emergency phase, systemic vulnerabilities come to the fore. These express the response capacity, or lack of it, to the consequences of the event impacts, which may include the impairment of crucial infrastructure systems. During the phase of recovery and reconstruction, resilience gains prominence, not as a response to the stress, but the longer term induced, indirect and secondary effects it has generated. Here, it is important that assessment considers not only response capacity but also whether or not systems are able to recover by reducing pre-event vulnerabilities reflecting a process of learning. The red and green arrows in Fig. 1 represent various connections that exist among the different types of vulnerability and resilience, in space and time.

3.1 The vulnerability matrices

Each ellipsoid in Fig. 1 is translated into a matrix so that the vulnerability assessment tool comprises four such matrices. These matrices are the basis for the application to the Sondrio case study (Online Resources 1–4, Tables 1, 2, 3, 4). Each of the four matrices comprises a set of sub-matrices related to the natural environment, the built environment, the critical infrastructures and the social/economic systems. Within the first matrix (i.e. Mitigation Capacity, see Online Resource 1), the capacity to mitigate vulnerabilities to natural hazards is the focus. In this case, the aspects of natural environment, which are important, are their monitoring, forecasting and structural defences. These aspects are considered in both presence or absence terms and also according to their quality. With regard to the built environment, what is examined is whether or not vulnerability assessments were or were not undertaken and taken into account in planning and risk-prevention strategies. In the case of infrastructures, not only awareness of systemic vulnerability but also the capacity to reduce this vulnerability through ordinary maintenance programs is assessed. For social agents, their awareness of existing threats and fragilities is assessed as well as their willingness and capacity to address them during periods between hazard events when time has passed since the last event. In the second matrix (Online Resource 2), exposure and physical vulnerability of buildings, infrastructure, production sites and people are most important. In the third matrix (Online Resource 3), the potential reaction to first-level losses is addressed. Secondary effects in the natural environment are considered (the sort of coupled events addressed by Mitchell 1999). For artefacts, the capacity to keep functioning despite some level of physical damage is evaluated, considering the interdependencies among systems and their components. Regarding agents, the capacity to manage emergencies and to endure during periods of limited facilities and restricted access to resources and markets are considered. Finally, in the fourth matrix (Online Resource 4), recovery potential is appraised. Ecological resilience is referred to regarding the natural environment. For the built environment, the capacity to embed lessons learned while reconstructing artefacts and places is evaluated, as well as the capacity to couple physical reconstruction with symbolic reconstruction, which accompanies the healing process of a traumatised society.

In the ENSURE methodology, a set of four matrices is generated for each hazard. Each of the four matrices, and their sub-matrices, are organised by columns. In order from left to right, the columns identify the (a) system being assessed (e.g. natural hazards, critical infrastructures or people/individuals) and (b) components (e.g. critical infrastructure) (c) the aspect that is often addressed in the form of a question (e.g. what are the actors which make critical infrastructures vulnerable?). Next, (d) is the parameter (i.e. indicator) chosen for the aspect followed by (e) the criteria for parameter assessment, that is, how the parameters may be measured and assessed using what tools, such as maps) and then (f) descriptors (e.g. presence or absence, categories, quantitative measures). In the final column, the vulnerability assessment outcome of the application of each parameter is recorded or evaluated for the territorial area for which vulnerability is assessed as it relates to a particular hazard.

3.2 Parameters

As part of the ENSURE project, and extensive and searching approach was used to identify and describe parameters to measure mitigation capacity, vulnerability and resilience of the considered systems. Previously published and non-published research was examined in

Table 1 Extract from the ENSURE mitigation matrix: parameters for assessing and evaluating monitoring and forecasting systems

System	Component	Aspect	Aspect parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
Natural environment	Natural hazards	Are hazards monitored?	Dos a monitoring network exist?	Binary	Yes/no	YES
			If previous yes, quality and distribution of monitoring networks	Expert judgement upon the quality of networks, considering also the coverage of the geographical area	High/medium/low; density	MEDIUM The monitoring system is made up of 13 rain gauges which cover the whole river basin (1 gauges/25 km^2). Only one instrument is available to monitor water level. No instruments are in place to monitor sediments transport and river bed aggradation
			Does a weather radar exist?	Binary, quality	Yes/no; type of weather radar	YES, Data required in future
		Are hazards forecasted?	Does a precipitation forecasting system exist?	Binary, quality	Yes/no; deterministic/probabilistic	YES, Deterministic
			If previous yes, quality of the system	Expert judgment, Performance index	High/medium/low; value of the index	Data required in future
			Does a flood forecasting system exist?	Binary, type, quality	Yes/no; hydraulic/hydrologic; deterministic/probabilistic	YES, Deterministic rainfall-runoff model
			If previous yes, quality of the system	Expert judgment; performance index	High/medium/low; value of the index	LOW The accuracy (evaluated by means of common accuracy measures) is low. Moreover, the model does not take into account of river bed aggradation. See Molinari et al. (2011) for specific values

Table 1 continued

System	Component	Aspect	Aspect parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
			Which is the warning lead time?	Warning lead time	Very short (<30 min), Short (30–180 min), Medium (181 min—12 h), Long (>12 h)	SHORT (3 h)
		Integration among forecasting tools	Are precipitation and flood forecasting models connected to increase the warning lead time?	Binary, increased warning lead time	Yes/no, Increase	NO
			Are weather radar data implemented in forecasting system?	Binary	Yes/no	NO
			Are flood forecasts connected to a flood inundation model?	Binary	Yes/no	NO
			If previous yes, quality of information supplied by inundation model	Degree	Basic (water depth) Medium (water depth & velocity) High (further parameters, e.g. contamination, duration)	NO

Table 2 Extract from the ENSURE physical vulnerability matrix: example of parameters for assessing and evaluating the vulnerability of buildings and infrastructure/production sites

System	Component	Aspect	Aspect parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
Built environment	Exposure and vulnerability of built environment	What are the factors that make buildings, the urban fabric and public facilities vulnerable to the stress?	Buildings structural vulnerability	Material	Timber/mud/stone/bricks/reinforced concrete	Concrete and masonry buildings are predominant in the city and are of variable vulnerability to flooding
				Number of floors	1/2/>2	The majority of buildings are >1 storey
				Level of the first floor with respect to expected flood	Lower level/same/higher level	Higher level
				Existence of basement	Yes/no	The majority of buildings (68 %) have basement, which are highly vulnerable to flooding
			Properties within flood risk zone	Number and type of properties	Numbers from survey or secondary data	2000 (estimated)
			Resistance and resilience of structural mitigation measures	Vulnerability to stress, maintenance regimes etc.	Qualitative judgement; low/medium/high	MEDIUM Floodwalls protect the town reach of Sondrio and they currently do so to a high standard of protection but river bed aggradation can significantly reduce this level of protection. This risk reduces the high standard of protection to a medium one
			Camping facilities in hazardous areas	Binary and expected occupancy	Yes/no; number of tourists	NO
			Vulnerability assessment of public facilities	As for buildings but distinguishing by function	Type of critical facility in the hazardous zones	HIGH Most of public facilities are in the flood prone area and are susceptible to flood damage (see Fig. 2)

Table 2 continued

System	Component	Aspect	Aspect parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
			Vulnerability of the urban fabric	Position and pattern of roads, buildings and open area in the hazardous zones	Pattern allowing for rapid evacuation of mud/pattern creating barriers or channelling sediments against buildings	MEDIUM In the city centre there are both large open spaces as well as narrow streets. Narrow streets may concentrate floodwaters causing flux, which is potentially damaging to buildings and road surfaces
			Vulnerability assessment of monuments; ancient parts of the town; museums	As for buildings and urban pattern	Type of historical buildings/settlement parts in the hazardous areas	HIGH Most of the cultural heritage is in the flood prone area and by its nature is highly damageable
			Vulnerability of the archaeological sites	Position and defences in the hazardous zones	Archaeological sites in dangerous zones (yes/no) (high/medium/low); existent/non-existent defences	Yes, MEDIUM Most of the cultural heritage is in the flood prone area but archaeological sites are few. Flood defences exist offering some degree of protection to these sites
Infrastructure and production site	Critical infrastructures	What are the factors that make critical infrastructures vulnerable (mainly lifelines)	Water treatment plants; electrical power plants; other lifelines plants	Distance and position with respect to expected flood	In the most critical zone/in a rarely flooding zone	Lifelines cross the critical flood risk zone. Corresponding installations are also place in the high risk zone
				Ordinary maintenance	Yes/no	Data required in future
				Existence of emergency provisions to protect from floods	Yes/no	Data required in future
				'Na-tech' hazards are considered in emergency procedures	Yes/no	Data required in future

Table 2 continued

System	Component	Aspect	Aspect parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
	Production sites	What are the factors that make production sites vulnerable (including na-tech potential)	Vulnerability assessment of production sites	Distance and position with respect to expected flood	In the most critical zone/ in a rarely flooding zone	Different production sites are placed in the critical flood risk area (in the order of 300 units), one of which can be source of 'na-tech' events
				Existence of emergency provisions to protect structures from floods	Yes/no	Data required in future
				'Na-tech' hazards are considered in emergency procedures	Yes/no	Data required in future
				Existence of provisions to protect stocked material and machinery	Yes/no	Data required in future
			Vulnerability due to dependence on lifelines	Qualitative judgement	Low/medium/high	HIGH
			Proximity to dangerous land uses	Type of land use and distance	Estimate of distance: <500 m, 500-1000 m, > 1,000 m	<500 m: A petroleum storage facility is located in the flood risk area

Table 3 Extract from the systemic matrix: Parameters to assess/evaluate links among built environment, lifelines and agents

System	Component	Aspect	Aspect parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
Built environment	Exposure and vulnerability of built environment	What are the factors that make public facilities vulnerable to losses?	Existence of public facilities: hospitals, fire brigades, etc.	Yes/no; functional capacity of such facilities	Assessment of functional potential of facilities	YES most of public facilities are in the flood risk zone; their functional capacity can be badly affected in case of flood also considering their accessibility
			Range of service of public facilities	Importance of facilities in the stricken areas	Local facilities/regional/ national relevance	HIGH importance (regional) both in time of peace and during the emergency
		Accessibility to public facilities	Redundancy; quality of roads; expected travel time	Number of roads serving the various settlements; type of road; shape and width.	Low (few-narrow roads)/ medium/high (many-wide roads)	LOW internal connections among the two parts of the city through bridges (right and left side of the River Mallero) could be absent; the city centre could be inaccessible from the surrounding areas because most of roads could be flooded
			Usability of roads	Individuals/vehicle stability	High/medium/low	MEDIUM/LOW Usability of roads is limited for both pedestrians and vehicles, also in case of minor floods (see Fig. 2)
Infrastructure	Critical infrastructures	What are the factors that make critical infrastructures stop functioning?	Degree of interdependence among lifelines	Level of redundancy; binary	High redundancy; emergency devices exist/do not; autonomous capacity exist/does not	MEDIUM (provisional) Water supply, gas supply and sewerage system lines run along/under roads corridors, Dependency links exist among electricity supply system and other systems
Social system (agents)	Community and institutions	What are the factors that may hamper effective crisis management?	Overlapping responsibilities among agencies	Degree	Low/medium/High	HIGH A recent exercise highlighted that there is no a clear definition of roles and responsibilities
			Established protocols for information sharing	Binary	Yes/no	NO
			Established protocols for use of resources to manage the crisis	Degree	Yes/partially/no	Data required in future
			Warning skills	Degree	Low/medium/High	LOW warning skills are out-of-date

Table 4 Extract from the ENSURE resilience matrix: parameters to assess/evaluate recovery tools and social structure

System	Component	Aspect	Aspect Parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
Infrastructure	Critical infrastructures	Are there tools to recover critical infrastructures rapidly and at low costs?	Existence of protocols to proceed with repairs requiring inter-lifelines interventions	Degree; number of different stakeholders to be coordinated in repair efforts	Yes/partially/no; protocols among all companies or coordinated by authorities/limited agreements	A lot of agents are involved; there is no evidence about pre-arranged agreements both among private firms and between public authorities and private firms which would increase resilience to flooding Evaluation: Resilience is limited and less than desirable
			Existence of funds for fast repairs	Binary	Yes/no	Compensation schemes are available for repaying private owners and public authorities facing costs to deal with the emergency (and repairing damages) Evaluation: These schemes are of potential aid to the recovery process compared with a situation in which there are no such schemes. This situation may change owing to declining economic fortunes

Table 4 continued

System	Component	Aspect	Aspect Parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
Social system (agents)	Community and institutions	Is the affected community resilient to the consequences of a catastrophe?	Age structure	Age groups and fertility	Ageing population; low fertility rates/ young	Population of Sondrio in 2010: 22,131 47 % male, 53 % female aged over 65 years—5,036 (23 %): 37 % male, 63 % female aged below 14 years—2,849 (13 %) 51 % male, 49 % female Evaluation: Over one-third (i.e. 36 %) of the population is vulnerable in a flood emergency because of their age (i.e. under 14 or over 65 years of age) and 64 % are likely to be comparatively resilient on age grounds alone. King et al. (2000) found that the very young and the very old are more vulnerable than others to natural hazards
			Local condition of aged population	Percentage of autonomous and healthy population	Autonomous/not autonomous; relatively healthy/ not healthy	Car ownership in Sondrio in 2008—534 cars per 1000 inhabitants Households owned by occupier(s) (regional data 2009)—73.4 % People with long term illness (regional data 2009)—38.8 % Evaluation: Car ownership is reasonably high and might aid evacuation but research shows that many flood deaths are caused by people trying to drive through or away from floods. Household ownership is reasonably high providing an incentive to three-quarters of householders to protect their property through preparatory and emergency measures. The 40 % with a long term illness are likely to be among the least resilient in a flood emergency Illness and disablement are socio-economic indicators which research shows are important factors in vulnerability to natural hazards (King et al. 2000)

Table 4 continued

System	Component	Aspect	Aspect Parameters	Criteria for assessment	Parameter values and/or categories	Application to Sondrio's vulnerability assessment
			Employment rate	Degree	High/ medium/ low	HIGH : Total population in employment in 2009)—51.9 % Evaluation: The high unemployment rate will probably be associated with low incomes. Income level has been identified as an important socio-economic indicator of vulnerability to natural hazards (King et al. 2000)
			Annual population growth rate	Trend	High/ medium/ low/ negative	Annual population grow rate low/negative trend Evaluation: May be associated with an ageing population structure and limited resilience to disasters although exposure of people to floods will be less as a result compared to a high population growth rate situation
			Immigration index	New immigrants/ emigrants	High/ medium/ low/ negative	Annual population immigration index negative trend Evaluation: Immigrants may be less resilient to disasters than long term residents because they have less experience of local environmental conditions and are less likely to be well networked socially (except among their cultural peers) and emigration may make the community less resilient over time as local environmental experience and knowledge is lost
			Social networking	Qualitative judgement	High/ medium/ low/ negative	HIGH A lot of social, cultural, professional organisations exist in Sondrio among individual agents Evaluation: Level of engagement in social networks is usually associated with rapid access to warnings and to information about preparatory and emergency actions (Parker and Handmer, 1996)
			Criminality rate	Degree	High/ medium/ low	LOW: Crimes per 1000 inhabitants: 21.27 (about an half of national data) Evaluation: The degree of social coherence which may be expected to be positively associated with disaster resilience may be indicated by the crime rate
			Conflict among social/ethnic groups	Degree	High/ medium/ low	Data required in future Evaluation:The level of conflict within a community may well be associated with its ability to work together effectively during crises

order to systematise parameters that have been already proposed to assess vulnerability and resilience of places and communities to a variety of hazards. As an example, the review carried out for flood risk can be considered: parameters already proposed to assess buildings vulnerability (Schwarz and Maiwald 2008), critical facilities (Chaviteau and Vinet 2006; Ledoux 1999), and urban environments (Barroca et al. 2006) significantly inspired ENSURE as can be seen in following sections.

The scientific communities working on hazards have not reached the same level of development of vulnerability and resilience indicators. An effort has been carried out in ENSURE to provide a minimum level that can be considered satisfactory for all hazards, while achieving more specified and tuned parameters in cases where research is more mature. It must be also pointed out that some parameters are well suited for all hazards, particularly those that relate to systemic, social and economic aspects: with minor adjustments they can be transferred from one field to another.

A critical review of results was carried out by ENSURE teams according to their own expertise. When internal expertise was not sufficient, external advice was sought (interview with Xanthopoulos, see also Xanthopoulos 2003, 2007). Quality, cost, effectiveness and usefulness have been carefully considered in this selection process of the most appropriate parameters (Segnestam 1999).

In some cases, as for example, to identify the critical load of tephra on roofs, a ad hoc modelling was conducted to support the definition of sound thresholds to assess vulnerability categories (see Ensure site Del. 5.1 for more details).

4 Application of the vulnerability assessment tool to the Sondrio case study

4.1 Sondrio and the Mallero catchment

The town of Sondrio is located in the Mallero catchment, which is situated on the Southern flanks of the Alps in Northern Italy, near the Swiss-Italian border. The Mallero catchment has a surface area of 320 km^2 and is mountainous, and the highest point being at approximately 4,000 m above mean sea level. The lowest point in the catchment is at approximately 300 m at Sondrio. Sondrio is located on the alluvial fan of the River Mallero just upstream of where the Mallero debouches into the River Adda (Fig. 2). The Mallero is a ‘torrent river’ which passes through the centre of Sondrio generating flash floods, which are a serious risk facing the town and its approximately 22,000 inhabitants. The town is protected from flooding by dikes (i.e. concrete walls) the bankfull discharge of which (equivalent to 700 m^3/s) corresponds to an event with a return period of 1,000 years. However, the principal risk arises from the danger of river bed aggradation, which can significantly reduce this level of protection leading to the flood walls being overtopped. Landslides and mudslides are also a hazard throughout this region: it is the material from these slides which is carried downstream causing aggradation which in turn causes water levels and flood levels and flood frequency to increase.

Because of their length, it is only feasible in this paper to reproduce extracts of the vulnerability matrices prepared for the Sondrio vulnerability assessment. However, the full set of vulnerability matrices are available as Online Resources 1–4. Extracted aspects and parameters are selected according to (a) their significance in explaining how the ENSURE framework may be applied in practice and (b) their importance in explaining vulnerability to floods in Sondrio. The extracts illustrate the vulnerability assessment for Sondrio:

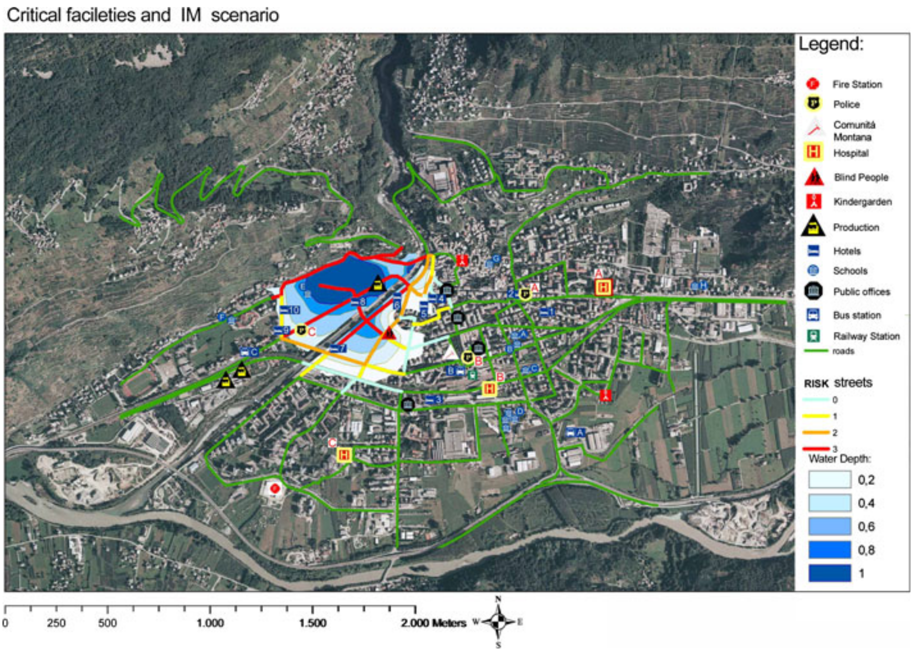

Fig. 2 The location of Sondrio and its public facilities on the River Mallero just above its confluence with the Adda River, showing expected floodwater depths. Streets are categorised according to an assessment of the risk, which they present to people and vehicles. Risk level 1 means instability for people; Risk level 2 means instability for both people and vehicles; Risk level 3 means instability for people and vehicles as well as likely collapse of buildings facing the street

references are also made to selected aspects of vulnerability, which only appear in the Online Resources.

4.2 Mitigation

The mitigation parameters (a) describe and (b) evaluate the set of resources and capacities in place to prevent a flood disaster (Table 1). Table 1 focuses upon crucial flood forecasting and monitoring aspects of mitigation capacity in Sondrio. Although short forecasting and warning lead times are likely, high-quality early flood forecasting and warning is important to avoid flood losses in Sondrio, particularly loss of lives.

Three aspects are evaluated: (a) whether hazards are monitored (b) whether forecasting is available and (c) integration among monitoring and forecasting tools. Different parameters are assessed, which synthesise information about each aspect. For monitoring, parameters aim to evaluate the quality and the distribution of the monitoring network as well as the presence and quality of weather radars. The latter were useful for the monitoring of flash floods, supplying real-time and detailed rainfall estimates (Cruetin et al. 2009). To assess the quality and distribution of the monitoring network, a field survey was undertaken. Data were also collected from the agency in charge of monitoring and through a literature review. Analyses suggest that the quality of the monitoring system may be assessed as 'medium' for Sondrio. One weather radar exists, but little information is currently available on the quality of outputs. Although the spatial coverage of rain gauges is good (1 gauge/25 km^2, covering the whole Mallero basin), only one hydrometer is available and no instruments are in place to monitor sediment transport and river bed aggradation, which are very important contributory causes of flood risk in Sondrio.

Flood forecasting parameters aim at evaluating the quality and the distribution of both precipitation and flood forecasts as well as the warning time they permit (Table 1). A review of literature reveals that a deterministic precipitation forecast is supplied, but no analyses were found about forecasting quality. Flood forecasts are supplied through a deterministic rainfall-runoff model, the accuracy of which has been assessed by a back analysis, comparing observed and forecasted data for 36 past events (Molinari et al. 2011). According to this, flood forecast accuracy is low; moreover, the model does not allow for river bed aggradation, leading to a 'low' assessment of mitigation capacity. The warning time provided is about 3 h, which corresponds to the concentration time of the basin. The reason for this is that precipitation and flood forecasting are not integrated—this and other features are evaluated using parameters related to the third aspect in Table 1—integration among forecasting tools. Weather radar is currently not used within the flood forecasting system. The analysis of the town's emergency plan reveals that inundation maps are not connected to the flood forecasting system. Instead, these maps are used only for emergency procedures.

The Built Environment section of the Mitigation matrix (Online Resource 1) focuses on the extent to which flood risk exposure and vulnerability are considered and acted upon in plans and whether flood mitigation rules exist and their efficacy and quality. Vulnerability assessment reveals slow progress in defining flood risk zones for planning purposes and building codes for flooding only exist for public buildings. Overall, the assessment reveals considerable scope in Sondrio to adopt flood mitigation measures through the spatial planning process. In the Social Systems section of the same matrix, the assessment reveals that Sondrio's population and community institutions are ill-prepared to face flood risk. Obvious suggestions for vulnerability reduction flow from these findings.

4.3 Physical vulnerability

The physical vulnerability matrix enables assessment of aspects related to the exposure and fragility of natural and social systems, buildings, infrastructures and production sites, which have potential for physical losses. For the structural vulnerability of buildings, parameters relate to critical features such as building materials, number of floors, the level of the first floor and the existence of basements (Kelman and Spence 2004) (Table 2). The assessment is based on a physical survey of buildings in Sondrio and on a statistical analysis of gathered data. The number of potentially directly flood-affected buildings in Sondrio is estimated to be 2000. It is evident that a building by building survey of features would be too costly for performing a vulnerability analysis for Sondrio, and so statistical inference methods were employed. Different sampling techniques and sample sizes were tested and their errors compared (not reported here), but the detail of such an analysis is beyond the scope of this paper. Results are summarised in the final column of Table 2, which highlights that the most critical parameter is the widespread existence of basements. Sondrio is currently protected from flooding by floodwalls, the design standard of which can be reduced by aggradation creating a higher risk than the current protection standards suggest (Table 2). Camping facilities are usually highly vulnerable to floods, but fortunately, there are currently none in the Sondrio flood risk zone. The remaining four built environment aspect parameters aim to assess the vulnerability of different aspects of the town's vulnerability, which is evaluated as medium to high (Table 2). As for the physical vulnerability of critical infrastructure and production sites, the assessment identifies the degree of exposure of these sites and parameters focus on the existence of measures to reduce breakdown and physical damage during a flood including routine maintenance, emergency actions and so on. As the assessment reveals, in Sondrio, a petroleum storage facility is located in the flood zone, which could potentially be damaged by flooding, leading to chemical pollution and other hazards. Here, data limitations come to the fore, as they do in various places throughout the vulnerability matrices, identifying the data gaps, which will need attention for future assessments of vulnerability to floods in Sondrio.

Factors that may lead to injuries and fatalities in a flood are represented by a number of parameters in the remaining part of Table 2 (Online Resource 2). These include exposure of people, levels of mobility impairment, flood depths and flood preparedness. Research shows that flood depths of 1 m or more pose a significant risk to life (Defra/Environment Agency 2006). The vulnerability assessment reveals a relatively high degree of vulnerability because a large number of people are exposed to floods, 68 % of buildings have basements, a relatively high proportion are likely to have mobility limitations either because of age or illness or both, flood depths exceed 1 m in central Sondrio, and people are largely unaware of how to respond appropriately to a flash flood warning. Preparedness was evaluated by means of a questionnaire survey, which is a suitable tool when social aspects are concerned: details and results are available in Ballio et al. (2010). The survey also revealed that individual preparedness is low; respondents manifested the need for more accurate flood risk information and for flood emergency exercises.

4.4 Systemic vulnerability

Table 3 displays illustrative extracts from the Systemic vulnerability matrix for Sondrio (Online Resource 3). This matrix seeks to evaluate the interconnectedness and interdependencies among systems and components. The first aspect in the table concerns factors, including exposure, that make public facilities vulnerable to losses. The inundation map (Fig. 2) reveals that floods could strike the entire city centre where educational, health, governmental, tertiary and other services are located. Such an event would have significant repercussions on a larger territory than the town itself, as Sondrio is the capital city of the homonymous Sondrio Province. Public facilities are assessed as being highly important both in time of peace and during a flood emergency because they provide potential shelter as well as access to the kind of resources (e.g. organisational, informational, health care and social welfare resources) required in a flood emergency. Even if public facilities can continue to provide services from their upper floors, physical accessibility to services is likely to be limited because of the low level of redundancy within Sondrio's road and bridge network and because road usability is problematic even in low severity floods (Fig. 2). Connections between the left and right banks of the town could be lost if bridges are damaged, or if they are too dangerous to cross. The assessment suggests that emergency preparedness plans are needed, which permit public business continuity during flood emergencies. In turn, this implies developing and locating emergency public facilities, and back-up data and other services on which they depend, in flood-free locations in the province.

As far as critical infrastructure is concerned, interdependencies exist particularly focused around power supply connections on which the continuity of other lifeline services in part depend. Continuity and back-up arrangements for electricity supplies during the periods of bad weather when floods and landslides are likely to be prevalent in the province are required to prevent a breakdown in lifeline services. Currently, vulnerability to lifeline service disruptions and related losses are provisionally assessed to be at a medium level. Data are not currently available to allow a full assessment to be made of critical infrastructure vulnerabilities, which also permit suggestions to be made about vulnerability reduction measures for the future. In the Social Systems, section of the systemic matrix extract (Table 3) the focus is upon the factors, which may hamper effective flood crisis management. Again, data insufficiency limits the assessment, but it is clear that effective management of flood crises would not be aided by the current lack of clear definition of the role of the key emergency response players. Fortunately, this shortcoming was identified in a recent exercise providing a foundation for improvement. Further, systemic shortcomings are revealed in another section of the Social Systems matrix (Online Resource 3) which reveals that currently the population has a low level of trust in flood risk and emergency information providers and that means of flood warning communication are omitted in Sondrio's contingency plan and are generally out-of-date (Ballio et al. 2010). Several flood risk plans at different spatial scales are currently available for Sondrio (e.g. region, municipal levels), and these represent a source of confusion among emergency planners relating to which of these plans they are committed to. However, a new multi-risk plan is being prepared for the municipality.

4.5 Resilience

Resilience is assessed and evaluated in the fourth matrix (Table 4) and also in Online Resource 4. Resilience is linked to a range of aspects such as ability to incorporate flood resilience and resistance measures into future urban redevelopment plans; ability to transfer production to alternative flood-free sites; the degree of community solidarity and support, and level of development and engagement in social networks. The first aspect in the matrix extract (i.e. Table 4) relates to the presence of tools to recover critical infrastructure facilities. Two parameters are assessed and evaluated. The first is the existence of protocols to proceed with repairs requiring inter-lifeline interventions. Not surprisingly, a field survey revealed that there are many infrastructure stakeholders in Sondrio, for example, water supply and sewerage companies, gas and electricity distribution and supply companies, telecommunications companies, local authorities, emergency services, etc. At present, there is no evidence that pre-arranged agreements or protocols exist among both private firms and between public authorities and private firms, which would help increase resilience to flooding. This suggests that opportunities to build resilience by, for example, having pre-arranged mutual assistance agreements, are currently lacking pointing the way towards ways of making Sondrio's infrastructure more resilient to floods in the future. The second parameter in Table 4 assesses instead whether funds exist for rapid repair, which might otherwise be delayed or infeasible. Compensation schemes are granted by Italian legislation to support both private owners and local authorities facing emergency costs and damage. From this perspective, there is currently a degree of resilience, but the economic fortunes of Italy have changed recently and so this may not continue to be the case if these compensation schemes become unfunded.

In the Built Environment section of the resilience matrix (Online Resource 4), the emphasis is upon whether or not new programs for building refurbishment include flood risk assessments, whether there is any detailed analysis of flood damage potential, whether building codes address flood risk and so on. These parameters are designed to reveal the extent to which Sondrio would be able to recover from a flood by reducing its pre-flood vulnerability. The assessment shows that current conditions are not well predisposed to this kind of constructive, vulnerability reducing potential suggesting obvious remedial policies and actions. These include the adoption of flood resistance and resilience codes for all building and refurbishment in Sondrio based upon an understanding of flood damage susceptibilities and potential.

In the second part of Table 4, the focus switches to parameters related to social systems and agents. Most of parameters in Table 4 are assessed by referring to available statistical and census data, although a field work survey could be used beneficially to supplement these data in future. The data reveal a very mixed situation in which elements of the social structure which support resilience exist alongside elements, which apparently weaken the social structure and its resilience to flood disasters. One of the strengths of Sondrio was revealed by a survey within public offices which discovered that several social, cultural and professional organisations are active. Such networks may be used, for instance, as privileged channels for educational campaigns as well as for flood warning dissemination, increasing resilience among those to whom the networks are open. The evaluations of the aspects of resilience suggest a number of resilience building measures which might be taken in future. These include developing flood preparedness plans specifically for the young and elderly; informing and warning the people of Sondrio about both the potential benefits and dangers of using cars in flood emergencies; developing ways to retain within the community the flood knowledge and experience of emigrants and providing user-friendly flood risk information for immigrants; promoting and developing useful social networks such as local flood action groups; and generally supporting policies designed to promote employment, prosperity and social coherence within the town.

5 Discussion and conclusions

The principal scientific contribution of this paper is a multi-faceted and integrated methodology for vulnerability assessment of natural hazards. This methodology comprises two key elements (1) a general theoretical framework, which identifies and articulates four principal components of hazard vulnerability and resilience as defined in the ENSURE project within time and space dimensions; and (2) a vulnerability and resilience assessment framework tool comprising four matrices based upon the theoretical framework. Unlike many previous vulnerability assessment tools, the theoretical framework and matrices are multi-faceted in that they articulate natural environmental, physical, systemic, social, economic and institutional vulnerability so that they are all assessed. The tool is integrated in that it brings together different vulnerability facets, including exposure and resilience within a framework. Time and space dimensions are incorporated and integrated through the time/space positioning of the principal components and related matrices (Fig. 1). The vulnerability and resilience framework assessment tool is prevention oriented so that the resulting assessments identify strengths and weaknesses of current mitigation policies and actions, which in turn leads naturally on to recommendations for vulnerability reduction improvements and resilience enhancement.

The choice and articulation of parameters is central to the performance of the vulnerability framework assessment tool. The tool articulates and combines a particularly wide range of parameters. They include simple exposure parameters as well as ones that seek to get at what factors make certain aspects vulnerable and the fragilities, qualities, susceptibilities and dependencies, which contribute to vulnerability. They also seek to reflect more complex aspects of vulnerability and resilience such as whether or not risk and vulnerability assessments are integrated into existing spatial planning and infrastructure planning processes. Parameters are also used to assess learning, response and recovery as part of resilience. However, the choice of parameters is not without problems, which will need further attention to further refine the tool. In some cases, data are not readily available to allow a parameter to be applied—this is particularly the case in the infrastructure sections of the matrices. On one hand, the identification of these data gaps is a step forward, but on the other hand, it may prove too costly to collect such data in future in which case some parameters might require replacing by ones for which data is or can become available.

The vulnerability assessments yield quantitative data of different types (e.g. categorical, interval) as well as qualitative information. They provide a profile of vulnerability without being combined into some kind of scores, which may be totalled. Totalled scores of this kind lose richness of meaning, oversimplify and may mislead—their use is therefore not preferred in the methodology presented here. What is important is that the each parameter leads to a vulnerability assessment, which in one way or another leads to identification of a strength or weakness in current vulnerability reduction strategy (assuming there is one—and there is often only an incomplete and non-comprehensive one) thereby leading to suggestions for improving the effectiveness of this strategy. There is the need to collect and structure more evidence than just physical damage to structures in order to better understand the real consequences of a complex disaster in a town such as Sondrio. The use of questionnaire surveys is one way forward and was adopted in the case of Sondrio to assess the vulnerability of social agents.

The application to the Sondrio area demonstrates how the ENSURE methodology works in practice. This application clearly identifies key strengths and weaknesses in the existing approach to flood hazard vulnerability, and the paper briefly indicates the implications of the vulnerability assessments for future improvement of flood vulnerability reduction. A more comprehensive set of vulnerability reduction strategy recommendations is certainly feasible but is beyond the scope of this paper. Because the ENSURE methodology integrates the time dimension, the vulnerability assessment for Sondrio includes this dimension. However, although in theory, the scale dimension is also integrated, the Sondrio application currently deals less well with scale aspects. A wider range of data at the provincial/regional and national levels is required to address this weakness.

There is no doubt that the construction of operational frameworks to assess vulnerability and resilience is a challenging task, which will in future require more work, similarly to what has been the case for example in sustainability 'science' (Mihelcic et al. 2003). ENSURE has paved the way for a methodology that aims at providing a reliable diagnosis of vulnerability and resilience with respect to a variety of factors and systems to better tune mitigation strategies. A balance had to be achieved between the need to come up with parameters and assessment criteria that can be generalised and considered as a 'standard' and the requirement to be context sensitive, being able to adapt measurement and appraisals at the specific context at stake. Further work with stakeholders on the ENSURE methodology may suggest ways to improve such balance and in the meantime make the application more user-friendly. In the meantime, while the large amount of data required to conduct the assessment may be seen as a detractor of the methodology, the latter also highlights fields in which more careful considerations have to be paid particularly during the phases of damage assessment and monitoring of the recovery process. A better understanding of the chain of damages and failures as well as of successful and unsuccessful response modes may gain from enlarged capacity to evaluate vulnerability and resilience (e.g. Pielke 2000); and vice versa the latter may greatly benefit from a more comprehensive understanding of the complexity of systems' behaviour under stress.

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