Upgrading of an index oriented methodology for consequence analysis of natural hazards: application to the Upper Guil Catchment (Southern French Alps)

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Abstract

Vulnerability is a complex concept involving a variety of disciplines from both physical and socio-economic sciences. Currently, two opposite trends exist: the physical approach in which vulnerability is analysed as a sum of potential impacts on elements at risk; and the social approach in which vulnerability is mostly viewed as a combination of socio-economic variables determining people's ability to anticipate, cope with and recover from a catastrophic event. Finding a way to combine these two approaches is a key issue for a global vulnerability assessment. In this paper we propose to combine elements from these two approaches through the analysis of the potential consequences of a high magnitude flood event (R.I. > 100 years) on human and material stakes. To perform our analysis, we choose to upgrade an existing index, the *Potential Damage Index* (PDI; Puissant *et al.*, 2013), by including social criteria. The PDI was originally developed to assess physical consequences of hazards on the elements at risk (people, building and lands). It is based on the calculation of 3 sub-indexes representing different types of direct and indirect consequences: Physical Injury Consequences (PIC), Structural and Functional Consequences (SFC), Indirect Functional Consequences (IC). Here, we propose to add a fourth sub-index representing the social consequences. This new sub-index, called Social Consequences (SC) is obtained by combining criteria derived from INSEE French census data and a risk perception survey conducted on the field. By combining the 4 indexes (PIC, SFC, IC and SC), we managed to create a new index called *Potential Consequences Index* (PCI). The new PCI was tested on the Upper Guil Catchment to assess the consequences of a high magnitude flood event (R.I. > 100 years). Results of the PDI were compared with the PCI and show significant differences. The upgrade made on the PDI method provided us with many inputs. The introduction of elements coming from social vulnerability added an extra-dimension to the Total Consequence map. It allowed to qualify the potential physical consequences (physical injury, structural and functional consequences) on element at risk by considering the global resilience of local communities.

Introduction

In Europe, small alpines communities are particularly exposed to natural hazards due to characteristics inherent to the physical and the socio-economic environment (Zingari and Fiebiger, 2002). Alpine areas are generally characterized by step gradient, tectonic activity and harsh climates resulting in dynamic gravitational and torrential processes causing hazards (Keiler and Fuchs, 2016; Papathoma-Köhle *et al.*, 2011). They are also characterized by a high level of vulnerability caused by scattered populations and resources (Hewitt and Metha, 2012), limited accessibility (Leone *et al*., 2014) and strong dependencies to seasonal tourism activities (Elsasser and Bürki 2002; Muhar *et al*., 2007). In addition, the lack of building zones leads to a concentration of stakes in areas exposed to natural hazards (debris fans, floodplains, unstable terrains etc.) causing risk (Arnaud-Fassetta *et al*., 2005; Puissant *et al.*, 2013). For communities with limited resources, risk management leads to important costs and has a significant impacts on the public opinion (Barroca *et al*., 2005). As the global climatic and socio-economic environment changes drastically, this concern is growing up (Pachauri *et al*., 2007; Papathoma-Köhle *et al.,* 2011; 2016; Aitsi-Selmi *et al.,* 2015; Alcántara-Ayala *et al*., 2015). The Alpines environment is in fact, very sensitive to global changes (IPCC, 2012). The impacts of such changes on hazards magnitudes and frequencies will be significant and may increase the probability of occurrence of catastrophic event (Schoeneich and De Jong, 2008; Keiler *et al.,* 2010; Lafaysse, 2011; IPCC, 2012; Papathoma-Köhle *et al.* 2016).

However, studies on risk assessment at regional or local scale are frequently hazard-centred. As a consequence, the vulnerability component is often limited (Reghezza, 2006; Reghezza and Rufat, 2015; Zahran *et al*., 2008; Jeffers, 2013). It is now recognized that risk assessment cannot be reduced by focusing solely on the hazards (Birkmann *et al.,* 2013). Vulnerability is also an essential part of the risk assessment (Varnes, 1984; Fuchs *et al.,* 2017). Vulnerability assessment related to natural hazards is a relatively recent research field (Totschnig and Fuchs, 2013). There is still no consensus on a single definition of vulnerability (Fuchs *et al.*, 2007; Birkmann *et al*., 2013). It is a complex concept involving a variety of disciplines from both physical and socio-economic sciences (Fuchs, 2007, Fuchs *et al*., 2009; Birkmann *et al*., 2013; Papathoma-Köhle *et al.,* 2017). If the number of vulnerability components is also debated (Tapsell *et al*., 2010; Ciurean *et al.,* 2013), two main research approaches dominate: the "physical approach" and the "social approach". For environmental researchers and engineers, vulnerability is defined as "a degree of loss to a given element within the area affected by a hazard" (UNDRO, 1984). Vulnerability is so considered as the total potential consequences of a process impacting human interests (Glade, 2003; Fuchs *et al*., 2007; Puissant *et al*., 2013). Social scientists define vulnerability as "the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from impacts of a hazard" (Blaikie *et al*., 1994; Cutter *et al*., 2003; Steinführer *et al*., 2009). It refers to socio-economic and demographic factors that may affect the resilience of communities (Clark *et al*., 1998; Cutter *et al*., 2003; Wu *et al*., 2002; Chakraborty *et al*., 2005; Flanagan *et al*., 2011). These two theories must be combined in order to reduce susceptibility to hazard and to create disaster-resilient communities (Fuchs, 2009; Fuchs *et al.*, 2012; Birkmann *et al.*, 2013). Recently, significant efforts were made to combine social and physical vulnerability. For example, Ebert *et al.* (2009) combined social vulnerability indicators with physical characteristics derived from airborne imagery and GIS data. Armas and Gavris (2013) and Armas *et al.,* (2017) combined social and economic vulnerability with housing quality. Koks *et al.,* (2015) combined hazard and exposure with a social vulnerability index to assess flood risk in the Netherlands. In the same way, Chang *et al.,* (2015) used vulnerability indicators considering the economic, social, built and natural capital. Karagiorgos *et al.* (2016) used vulnerability function and socio economic variables to assess physical and social vulnerability of the elements at risk face to a flash-floods event in East Attica, Greece. Eidsvig *et al.,* (2017) used a physical vulnerability indicator together with a social vulnerability indicator to assess the risk induced by natural hazards to infrastructures.

Currently, three different methods are commonly used to assess vulnerability: (1) vulnerability matrices, (2) vulnerability functions and (3) vulnerability indicators (Messner *et al.,* 2007; Papathoma-

Köhle *et al*., 2017). (1) Vulnerability matrices are a qualitative method which provides some advantages. The relationship between process and consequence is clearly expressed and easy to understand by non-experts. The information on the exact intensity of the processes is not needed and the costs of the exact damages expressed in monetary value is not requested (Fuchs *et al.*, 2007; Papathoma-Köhle *et al*., 2017). The main default of matrices remains in the description of damages. They may be very subjective making it difficult to replicate to another sector. By contrast, vulnerability functions (i.e. damage curves and fragility functions) (2) express vulnerability in a quantitative way by translating damage into monetary value (Fuchs *et al.*, 2007; Messner *et al.*, 2007; Tarbotton *et al.*, 2015). As a result, vulnerability function allows us to establish a clear relation between financial losses and hazard intensity and realize cost-benefit analysis (Tarbotton *et al.*, 2015; Papathoma-Köhle *et al*., 2017). On the other hand, vulnerability functions are dependent on the quality and the quantity of the data collected. They require a large number of the element at risk to be efficient and they cannot be transferred to areas with different housing types. Last but not least, important characteristics of the element at risk are not taken into account (Papathoma-Köhle *et al*., 2017). For Rygel *et al*., 2006, Birkmann, 2006, and Kappes *et al*. (2012) the more effective solution to assess vulnerability is to create an index from a suite of indicators (3). This approach provides many advantages: it includes the analysis of all the relevant types of consequences without monetary measures (Meyer *et al*., 2009), no empirical data is needed (Papathoma-Köhle *et al*., 2017), it considers the different characteristics of the element at risk (Puissant *et al*, 2013) and it is flexible enough to be adjusted to different hazards and places (Kappes *et al*., 2012). Furthermore, the improvement of GIS technology with the ability to integrate information from various fields makes it easy to develop high resolution vulnerability index with an operative perspective (Wood & Good, 2004; Nelson *et al*., 2015).

In the context of the French funded ANR project SAMCO (*Society Adaptation for coping with Mountain risks in a global change Context*), a comparative analysis on the topic of mountain risks was engaged on three mountain representative case studies: The Upper-Guil catchment (southern French Alps) prone to torrential floods, the Ubaye catchment (southern French Alps) predisposed to landslides and the Cauterets Valley (French Pyrenees) affected by rockfalls. The aim of the project was to develop methodological tools to characterize and measure societal resilience with an operative perspective (www.anr-samco.com, 2017). In this regard, studies were conducted with consideration to the different steps of risk analysis - i.e. hazard analysis, exposure analysis and consequences analysis (Bründl *et al*., 2009). The final product of the SAMCO project is a GIS-based demonstration platform for elected officials and local stakeholders. The present paper is focussed on a new method to assess physical and social vulnerability together. This method was developed to assess the vulnerability of elements at risk in the Upper Guil catchment (Fig.1) in front of a high magnitude flood event (R.I. > 100 years). To perform this work, we opted for an indicator-based vulnerability approach. The proposed indicator, called *Potential Consequences Index* (PCI) is oriented on potential consequences assessment. According to Fell *et al*. (2008), consequences may be defined as “the potential outcomes arising from the occurrence of a hazard expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life”. Consequence analysis is, together with hazard evaluation, one of the major steps of flood risk assessment (Bründl *et al*., 2009; Kappes *et al*., 2012; Puissant *et al.*, 2013).

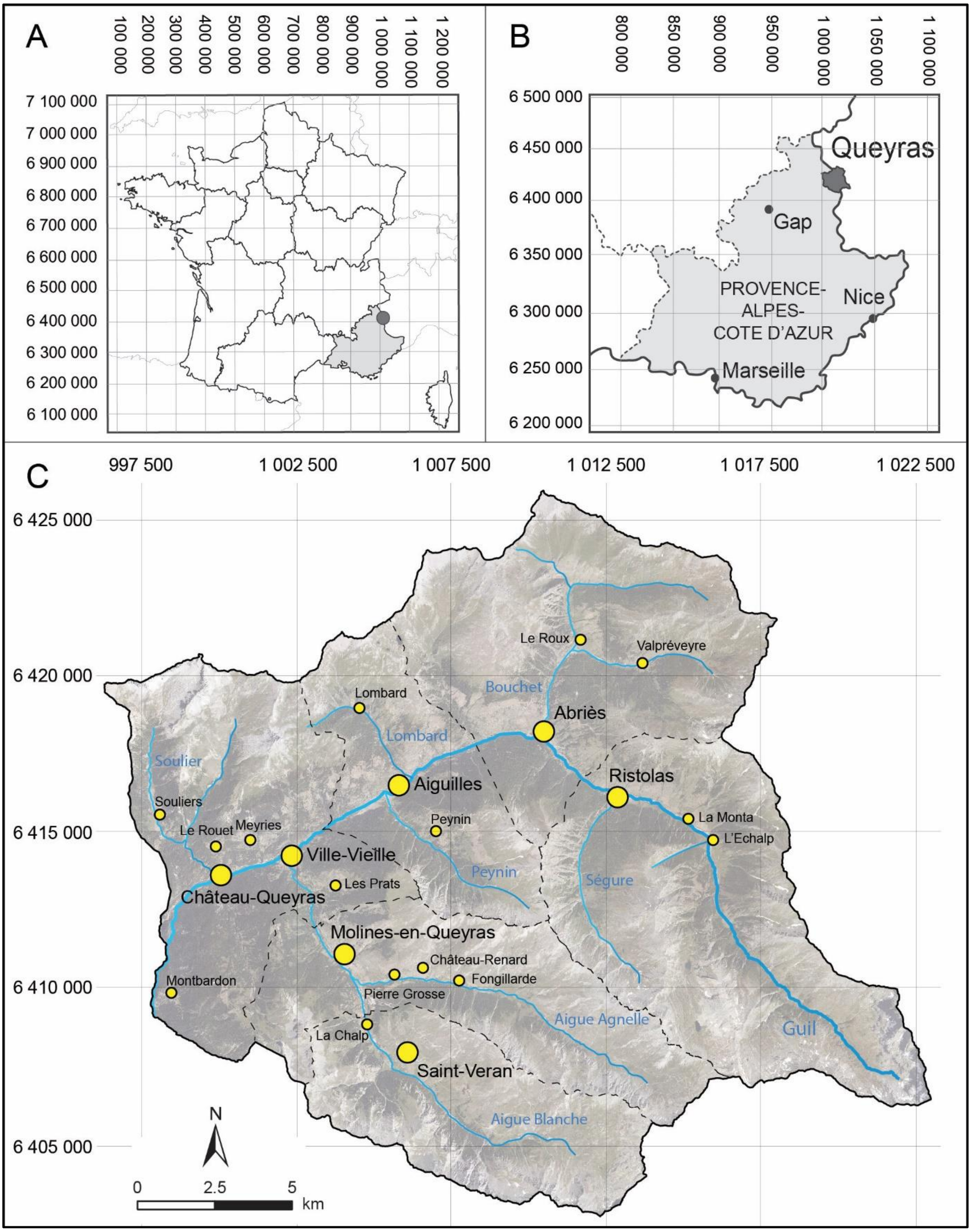

Figure 1: Location map of the Upper Guil catchment and its six communities.

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1. Study area

The area of interest is the Upper Guil catchment, a 366 km² area covering 6 small municipalities (< 400 inhabitants): Ristolas, Abriès, Aiguilles, Château-Ville-Vieille, Molines-en-Queyras and St-Véran. It broadly corresponds to the historic territory of Queyras, a landlocked area located in the "Hautes-Alpes" French department, near the Italian border (Fig. 1). The altitude ranges from 1200 m.a.s.l. at the outflow of the River Guil to over 3300 m.a.s.l. along the highest summits surrounding the catchment.

1.1 Physical context

Due to some predisposing (schist bedrock supplying abundant debris, structural opposite slopes, strong hillslope channel connectivity) and triggering (summer and winter Mediterranean rainstorms) factors, the Upper Guil catchment is particularly prone to hydrogeomorphic hazards such as torrential floods, debris flows, landslides, rockfalls or avalanches (Fort *et al*., 2002, 2014; Arnaud-Fassetta *et al*., 2004, 2005, 2014). These hazards frequently impact the local population (fatalities, destruction of buildings and infrastructures, loss of agricultural land, road closures) causing difficulties for local managers, who also have to cope with the legislation and management procedures of the *Parc Naturel Régional du Queyras* (PNRQ) (Arnaud-Fassetta *et al*., 2004, 2005). Most catastrophic episodes are related to torrential floods as in 1957, 2000, 2002, 2008 and 2011 (PNRQ, 2016). The two main events described in the literature took place in June 1957 (> 100 year R.I., 15 million euros damage) and June 2000 (30 year R.I., ≈ 5 million euros damage) (Arnaud-Fassetta *et al*., 2004; Tricart, 1958). These catastrophic episodes have severely impacted the mentalities and entailed considerable expenses in terms of risk management and protective structures (dykes, embankments, thresholds etc.) (Fig.2). Due to the obsolescence of protective measures and local planner needs in new studies, it was necessary to assess vulnerability in this area.

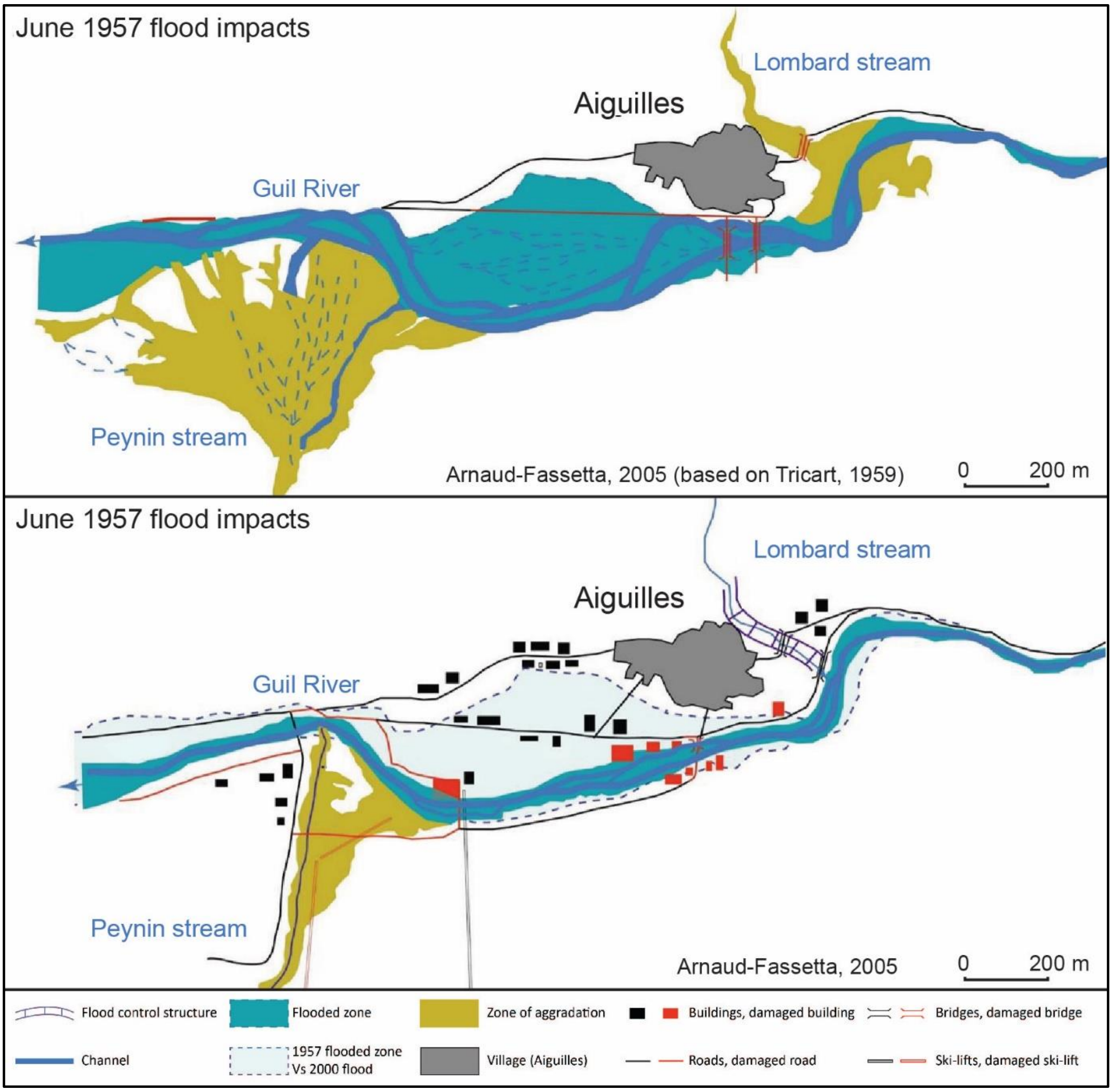


Figure 2: Impacts of the June 1957 and June 2000 flood on Aiguilles village.

1.2 Socio-economic context

Today, the area counts 1770 inhabitants (Insee, 2012), making it one of France's less densely populated districts (< 5 inhabitants by km^2). However, during the peak of touristic season (summer and winter holidays), the resident population can be multiplied by a factor of 10 (Insee, 2006). Since the second half of the 20th century, the territory has experienced significant changes on its land cover/uses and economic activities. The progressive decline of agro-pastoralism and the development of skiing tourism activities led to a concentration of human stakes in areas that are particularly exposed to several natural hazards (torrential fans and valley bottom). The current land cover/use is the result of a combination of these important changes in human activities together with the impacts of past catastrophic events. Actually, land cover classes count 29 % of forest, around 30 % of bare rocks and alluvial deposits, 38 % of grassland, 3 % of agricultural lands and less than 1 % of building areas. Apart from houses, major stakes are public services/administration (city-hall, schools, hospital, fire station etc.), industrial/artisanal warehouses and, of course, touristic infrastructures (shops, hotels, museum, ski resorts etc.). The departmental road (D947) is the most important lifeline ensuring the link with the nearest urban centres (Guillestre, Embrun, Gap). These relatively recent stakes are mostly located on areas exposed to natural hazards (Arnaud-Fassetta *et al*., 2004).

2. Methods and data

Potential Consequences Index (PCI) is used to assess the physical and social consequences of a hazard on elements at risk (people, buildings, networks and land cover/uses). It consists in an upgrade of the *Potential Damage Index* (PDI) developed by Puissant *et al.* (2006; 2013). To a better understand the method, we will first describe the PDI methodology and then take a look at the upgrade made to obtain the PCI.

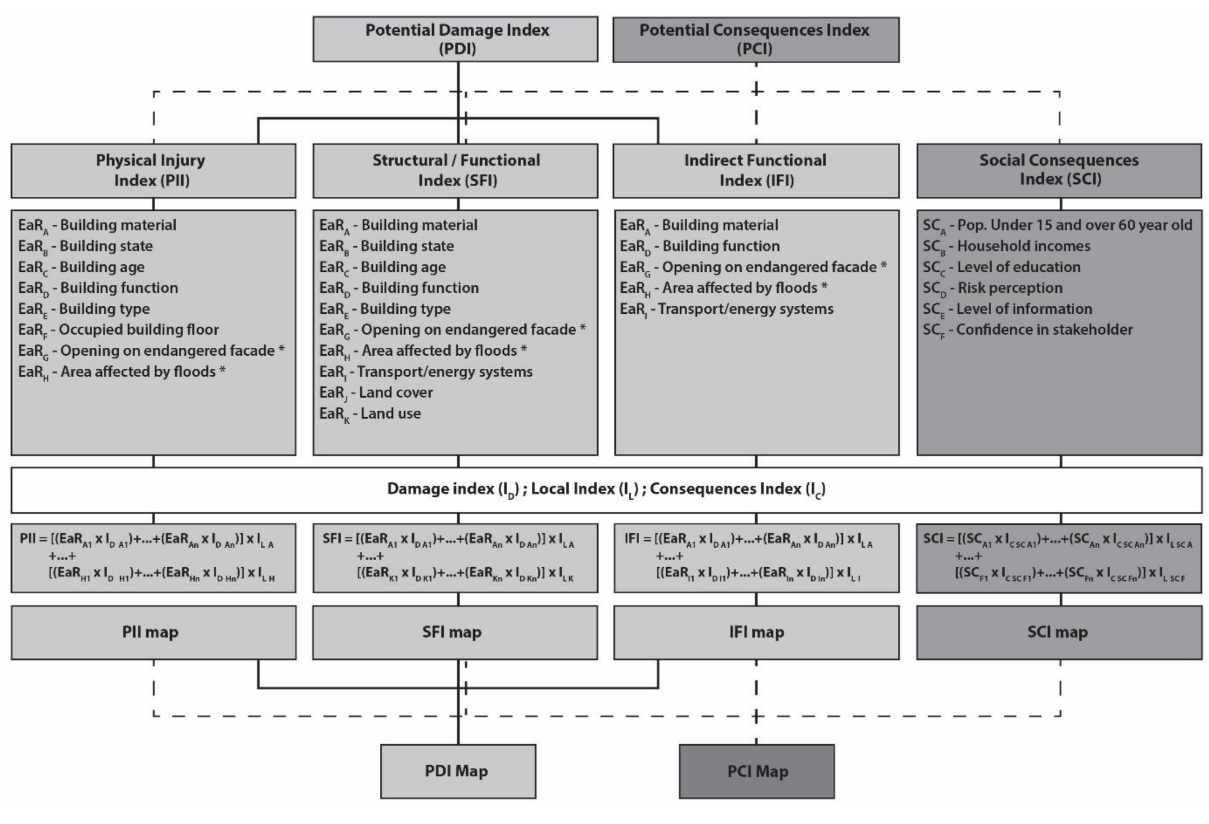


Figure 3: Framework of the Potential Damage Index (PDI) compared to the Potential Consequences Index (PCI).

2.1 General Framework of the Potential Damage Index (PDI)

The PDI methodology is indicator-oriented. To be used in practice, it is based on the use of commercial databases, aerial imagery and GIS technologies. In the PDI, consequences are expressed in a semi-quantitative way through an index called *Total Consequences Index* (CTI). CTI is obtained by combining 3 sub-indices representing the direct and indirect consequences of a hazard on elements at risk (Fig. 3): (1) the *Physical Injury Index* (PII) represents the consequences on people in their physical integrity, (2) the direct *Structural and Functional Index* (SFI) expresses the direct and short term effects on buildings, infrastructures and human activities, and (3) the *Indirect Functional Index* (IFI) illustrates the long term effects on socio-economic activities (Puissant *et al.* 2013).

EaR-A	Building material	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
A1	Wood	1	2	2	2
A2	Concrete	0.80			
A3	Mixture (wood & concrete)	0.80			
A4	Stone & wood (traditional)	0.60			
A5	Metal	0.40			
EaR-B	**Building State**	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
B1	Good	1	2	2	n/a
B2	Moderate	0.70			
B3	Bad	0.30			
B4	Very bad (ruin)	0.10			
EaR-C	**Building Age**	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
C1	> 2010	0.80	2	2	n/a
C2	2000 - 2010	1			
C3	1990 - 2000	1			
C4	1970 - 1990	0.90			
C5	1950 - 1970	0.70			
C6	1900 - 1950	0.50			
C7	< 1900	0.30			
EaR-D	**Building Function**	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
D1	Education	1	2	3	3
D2	Emergency	1			
D3	Public administration	0.90			
D4	Tourism	0.80			
D5	Trade	0.80			
D6	Accommodation	0.80			
D7	Industry / Craft	0.70			
D8	Agricultural	0.40			
D9	Religious	0.20			
EaR-E	**Building type**	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
E1	"Sensitive" (city hall, hospital, fire station)	1	1	1	n/a
E2	Housing	0.90			
E3	Tourism activity	0.70			
E4	Shed and warhouse	0.50			
E5	Cultural heritage	0.30			
E6	Hut	0.10			

EaR-F	Occupied floors	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
F1	> 6	1	3	n/a	n/a
F2	4 - 6	0.80			
F3	2 - 3	0.60			
F4	1	0.40			
F5	0	0.10			
EaR-G	**Opening on endangered facade ***	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
G1	> 6 (or glass wall)	1	2	1	n/a
G2	4 - 6	0.80			
G3	1 - 3	0.60			
G4	Absence	0.10			
EaR-H	**Building in an area affected by flood**	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
H1	RI 10 & RI 30 - 50 & RI 100 & RI > 100 flood	1	3	3	3
H2	RI 30 - 50 & RI 100 & RI > 100 flood	0.80			
H3	RI 100 & RI > 100 flood	0.60			
H4	RI > 100 flood	0.40			
H5	Absence	0.10			
EaR-I	**Transport & energy systems**	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
I1	High-voltage line	1	n/a	2	4
I2	Main road	1			
I3	Secondary road	0.80			
I4	Ski lift	0.70			
I5	Gravel road	0.50			
I6	Track	0.10			
EaR-J	**Lancover**	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
J1	Urban	0.60	n/a	2	n/a
J2	Farming / Pasture	0.35			
J3	Forest	0.20			
J4	Grass	0.15			
J5	Water surface	0.10			
J6	Bare rock, colluvium & alluvium	0.05			
EaR-K	**Land use**	I_D	I_{L-PIC}	I_{L-SFC}	I_{L-IFC}
K1	Urban	1	n/a	4	n/a
K2	Winter tourist activities	0.80			
K3	Summer tourist activities	0.60			
K4	Arable land	0.40			
K5	Protected area	0.20			

Figure 4: Detail of weights assigned to the criteria used in PDI calculation.

To obtain these indices and compute the *Total Consequences Index*, 3 steps are required (Puissant *et al.*, 2006). First, the element at risk and its relevant attribute are identified and compiled into a complete database. Then, each modality of the attribute compiled is ranked through an expert weighting (Fig. 3 and 4). The value applied is called Damage Index (di). It is standardized on a scale from zero to one, with higher index values indicating higher potential consequences (Fig. 4). In the third step, direct (PII and SFI) and indirect (IFI) consequences are modelled using linear combination. In this step, a coefficient is assigned to each variable with respect to the socioeconomic context of the region and the type of consequence assessed (direct or indirect) (Fig. 3 and 4). The coefficient, called *local index* (*li*) varies from 1 to 4. To finish, the 3 sub-indices are combined to obtain the *Potential Damage Index* (PDI). In order to be used in a risk analysis, PDI is reclassified in 5 classes and mapped. With a matrix, PDI map is then

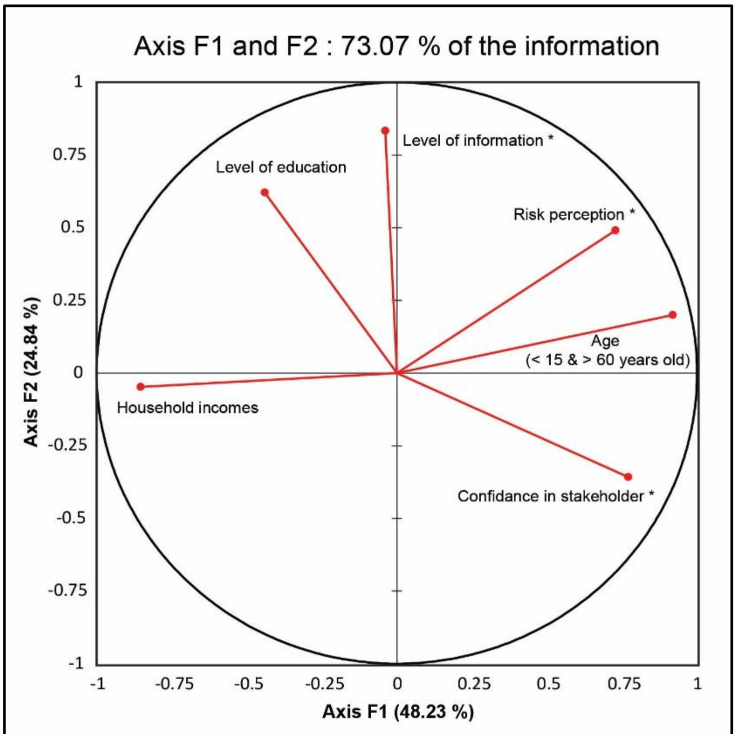
		Hazard exposure				
		1	2	3	4	5
Consequences	10	11	12	13	14	15
	20	21	22	23	24	25
	30	31	32	33	34	35
	40	41	42	43	44	45
	50	51	52	53	54	55

Figure 5: Matrix used to combine hazard exposures with PDI and PCI.

combined with a hazard map (reclassified in 5 classes as well) to obtain a type 1957 flood risk map (Fig. 5). As support for this work, data sets from *Institut National de l'Information Géographique et forestière* (IGN, BD ORTHO, 2009; BD TOPO, 2009) were used. To complete our database, an intensive field investigation in association with the use of *Google Street View*® and *OpenStreetMap*® software was realized. Land cover and land uses maps were produced on GIS by combining photo interpretative work with data on natural protected areas (DREAL PACA, 2016), agricultural land (RPG, 2012) and touristic infrastructures (prospectuses, touristic maps etc.).

2.2 General Framework of the Potential Consequence Index (PCI)

In the proposed *Potential Consequences Index* (PCI), PDI methodology has been modified to assess both physical and social consequences. The upgrade consists in the addition of a fourth sub-index in the calculation of the *Total Consequence Index* (Fig. 3). This sub-index, called *Social Consequences Index* (SCI) is built to represent the social consequences of a hazard on community resilience. The use of an indicator to assess social consequences requires the selection of specifics criteria that unequivocally represents the different aspects of social vulnerability (Cutter *et al*. 2000; Rygel *et al*., 2006). Literature on vulnerability identifies many elements contributing to differential ability to cope with hazards (Tab. 1). Today, the majority of the analyses produced use data from national census to build social vulnerability indices (Cutter *et al*. 2000; 2008; Wu *et al*. 2002; Chakraborty *et al*., 2005; Fekete, 2009; Guillard-Gonçalves *et al*., 2014, Zhang and You, 2014; Huang *et al.*, 2015; Koks *et al.*, 2015; Nelson *et al.*, 2015; Frigerio *et al*., 2016; Karagiorgos *et al.,* 2016; Rogelis *et al.*, 2016; Aroca-Jimenez *et al*., 2017; Davis and Heß, 2017). Some indicators repeatedly appear in these analyses such as poverty, age, education or disabilities (Tab. 1).



Social Consequencies (SC) variables	Contribution of SC variables on axis F1 (in %):	Contribution of SC variables on axis F2 (in %):
SC - A: Age (under 15 and over 60 years old)	29.190	2.671
SC - B: Household incomes	25.197	0.153
SC - C: Level of education	6.691	25.876
SC - D: Risk perception *	18.326	16.163
SC - E: Level of Information *	0.052	46.537
SC - F: Confidance in stakeholders *	20.544	8.600

Figure 6: Principal Component Analysis (PCA) realised and criteria selected for SCI calculation.

In agreement with these existing published references, socio-economic data were collected for the six municipalities of the Upper-Guil Catchment. A set 21 criteria was first selected (Tab. 2). 16 of them are coming from the open access French national statistical database of the *Institut National de la Statistique et des Etudes Economiques* (INSEE) (Insee, 2012; 2015). 5 other were selected in a risk perception survey realized during the SAMCO project. This survey consisted in a questionnaire (38 questions) carried out during the autumn 2014 and the summer 2015 and 2016 on the six municipalities of the Upper-Guil catchment (Fig. 1). It is focused on 3 main issues: (1) inhabitant perception of the different risks (torrential floods, avalanches, landslides and rockfalls) (2) inhabitant knowledge of preventive and protective measures and (3) inhabitant confidence in stakeholders. 100 questionnaires were collected (about 5% of the total population): 8 in Ristolas (10.53 %), 22 in Abriès (6.85 %), 22 in Aiguilles (4.95 %), 16 in Château-Ville-Vieille (4.58 %), 17 in Molines-en-Queyras (5.45 %) and 15 in St-Véran (5.86 %). People were surveyed by an interviewer in-person or by paper questionnaires delivered and recovered in person. Special attention was made to have a representative view of the socio-economic characteristics of the local population. Indeed, in the second and third campaign, the surveyed people were selected for their demographic and socio-economic characteristics according to INSEE census data (Insee, 2012; 2015). To reduce the number of variables and avoid useless repetition we realized a principal component analysis (PCA) on our dataset. We conserved only the criteria containing the highest percentage of information on axis F1 and F2 (Fig. 6). They were 6: (1) Age, (2) household incomes, (3) level of education, (4) flood risk perception, (5) level of information on flood risk and (6) confidence in stakeholders (Fig. 6). With respect to PDI methodology, the modalities of the 6 selected criteria were ranked and a value of 0 to 1 was assigned to them (Fig. 7). In PCI methodology the term of *consequence index* (ci) is preferred to *damage index* (id) from PDI. A *local index* (il) is then assigned to the 6 criteria with respect to their relative importance in the PCA produced. SCI is calculated using linear combinations on GIS (raster calculator tool on ArcGIS) and applied to each building of the six studied municipalities. Due to the lack of data at building scale, SCI is equally applied for all the buildings of a same community. *Potential Consequences Index* is then calculated by adding the index scores of the 4 sub-indices (SCI, PII, SFI and IFI) (Fig. 3). PCI is finally reclassified in 5 classes and mapped. Using a matrix, PCI map is combined with a flood hazard map (in 5 classes) to obtain a type 1957 flood risk map (Fig. 5).

SC - A	Pop. Under 15 and over 60 year old Population under 15 or over 60 years old (in %)	I_{C-Sc}	I_{L-SC}
SC - A1	More than 50 %	1	
SC - A2	45 to 50 %	0.80	
SC - A3	40 to 45 %	0.60	2
SC - A4	35 to 40 %	0.40	
SC - A5	Less than 35 %	0.10	
SC-B	Household incomes Household incomes / average national household incomes (in %)	I_{C-SC}	I_{L-SC}
SC - B1	Less than 60 %	1	
SC - B2	60 to 70 %	0.80	
SC - B3	70 to 80 %	0.60	2
SC - B4	80 to 90 %	0.40	
SC - B5	90 to 100 %	0.10	
SC-C	Level of education Population with no high diploma (> BAC) (in %)	I_{C-SC}	I_{L-SC}
SC - C1	75 to 100 %	1	
SC - C2	50 to 75 %	0.70	2
SC - C3	25 to 50 %	0.40	
SC - C4	Less than 25 %	0.10	
SC-D	Risk perception Investigated population considering flood-risk as low* (in %)	I_{C-SC}	I_{L-SC}
SC - D1	75 to 100 %	1	
SC - D2	50 to 75 %	0.80	
SC - D3	25 to 50 %	0.60	2
SC - D4	10 to 25 %	0.40	
SC - D5	Less than 10 %	0.10	
SC-E	Level of information Investigated population considering themselves as unsufficiently informed on risk* (in %)	I_{C-SC}	I_{L-SC}
SC - E1	75 to 100 %	1	
SC - E2	50 to 75 %	0.80	
SC - E3	25 to 50 %	0.60	3
SC - E4	10 to 25 %	0.40	
SC - E5	Less than 10 %	0.10	
SC-F	Confidence in stakeholder Investigated population who have not confidence in local planners* (in %)	I_{C-SC}	I_{L-SC}
SC - F1	75 to 100 %	1	
SC - F2	50 to 75 %	0.80	
SC - F3	25 to 50 %	0.60	2
SC - F4	10 to 25 %	0.40	
SC - F5	Less than 10 %	0.10	

** Data from SAMCO risk perception survey*

Figure 7: Detail of weights assigned to the criteria used in SCI calculation. Criteria with an * are those derived from the risk perception survey.

Criteria \ Authors	Clark *et al.*, 1998	Cutter *et al.*, 2003	Fekete, 2009	Flanagan *et al.*, 2012	Guillard-Goncalves *et al.*, 2014	Zhang and You, 2014	Chang *et al.*, 2015	Huang *et al.*, 2015	Koks *et al.*, 2015	Nelson *et al.*, 2015	Frigerio *et al.*, 2016	Karagiorgos *et al.* (2016)	Rogelis *et al.*, 2016	Armas *et al.*, 2017	Aroca-Jimenez *et al.*, 2017	Heß, 2017	Total
Age	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	16
Education level	■	■	■	■	■	■		■			■	■	■	■	■	■	14
Employment	■	■	■	■	■		■	■		■	■	■	■	■	■	■	14
Special need population	■	■	■	■	■		■	■		■	■	■	■	■	■		13
Income	■	■	■	■	■	■		■	■	■		■	■			■	12
Gender	■	■	■		■	■		■		■	■		■	■		■	11
Race and ethnicity	■	■	■	■	■		■	■	■	■	■						10
Family structure	■	■			■			■	■	■	■	■		■			9
Medical service		■	■		■	■		■		■	■		■		■		9
Population (number or density)			■		■		■		■		■			■	■	■	8
Mobility	■			■		■	■	■		■	■						7
Equipement	■	■		■	■	■		■							■		7
Recent arrival	■		■					■		■					■	■	6
Employment in primary sector	■				■	■	■	■									5
Owner/Tenant		■			■							■		■			4
Municipality budget			■			■									■		3

Table 1: Synthesis of the criteria usually used for the social vulnerability assessment.

Table 2: First set of criteria selected for the calculation of SCI and their impacts on social vulnerability.

Variable	*Increase (+) or decrease (-) social vulnerability if high*
Percent of children15 and under	+
Percent of population 60 years or older	+
Population density (in habs / km^2)	+
Percent of unemployed people	+
Percent of population with high socioeconomic status*	-
Percent of population employed in primary sector	+
Percent of household with no vehicle available	+
Household incomes / average national household incomes	-
Percent of population which is mentally disabled	+
Percent of foreign population	+
Percent of population with no high diploma (> BAC)	+
Percent of single-parent family	+
Percent of principal residence	-
Percent of the population which moved in less than 2 years ago	+
Distance to nearest medical centre (in decimal h)	-
Communities financial solvency (cash flow = operating charges - debt annuity /incomes)	+
Percent of IP who never experienced a catastrophic event**	+
Percent of IP considering risk as low**	+
Percent of IP considering themselves as sufficiently informed on risk**	-
Percent of IP who responded not knowing what to do if a catastrophic event occurs**	+
Percent of IP who have not confidence in local planners**	+

IP: investigated population

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*** Data from SAMCO risk perception survey*

2.3 Flood hazard mapping

Several hazard maps were produced in the SAMCO project. To focus ourselves on the new method found to assess physical and social consequences, a single scenario of flooding is considered in this paper. The selected scenario represents a flood type 1957 (R.I. >100 years). We voluntarily selected a scenario with the more important spatial extend to highlight the differences between the PDI and the PCI. The "type 1957" flood map was realized using the hydraulic modelling software HecRAS®. Fifteen cross sections representing a linear stream of 58.2 km were characterized (Tab. 3). Due to the lack of accurate data for all the streams of the sub-catchment, only eight of them were taken into account in our model (Tab. 3). Geometry (stream, river banks and flood plains) was extracted from a DEM (Digital Elevation Model) at 1 m resolution. This DEM was produced with LIDAR data (*LIght Detection And Ranging*) provided by the Regional Natural Park of Queyras (PNRQ). Flooded surfaces (extend, deep, speed) were extrapolated using 371 sections, extracted from our DEM. To take into account the protection along the reaches, dikes and artificialized channels were incorporated into the model. The flooded surface generated has an extension of 2.88 km². This envelope provides a good overview of the water flows and allows a quick and clear visualization of the potentially flooded areas. The flood map used in this paper was reclassified in 5 classes considering water elevation (Fig. 8).

Reach	Reach description	Lenght (in m)	Cross-sections (nb)	Flow, type 1957 (in m³/s)
T1	Guil River, upstream to the confluence with the Ségure torrent	11.3	50	180
T2	Ségure torrent	1.29	17	89
T3	Guil River, upstream to the confluence with the Bouchet torrent	3.05	17	269
T4	Bouchet, upstream to the confluence with the Montette torrent	3.15	42	30
T5	Montette torrent	0.48	8	30
T6	Bouchet, downtream to the confluence with the Montette torrent	3.31	20	160
T7	Guil River, upstream to the confluence with the Lombard torrent	4.54	23	429
T8	Lombard torrent	0.52	16	50
T9	Guil River, usptream to the confluence with the Peynin torrent	1.09	11	479
T10	Peynin torrent	0.9	24	55
T11	Guil River, upstream to the confluence with the Aigues Torrent	4.1	23	534
T12	Aigue Agnelle torrent	5.1	26	136
T13	Aigue Blanche torrent	5.18	26	103
T14	Aigues torrent, downstream to the confluence between the 2 Aigues torrents	5.43	37	239
T15	Guil River, dowstream to the confluence with the Aigues torrent	8.84	21	773

Table 3: Additional information on the hydrological model produced with HecRAS® software.

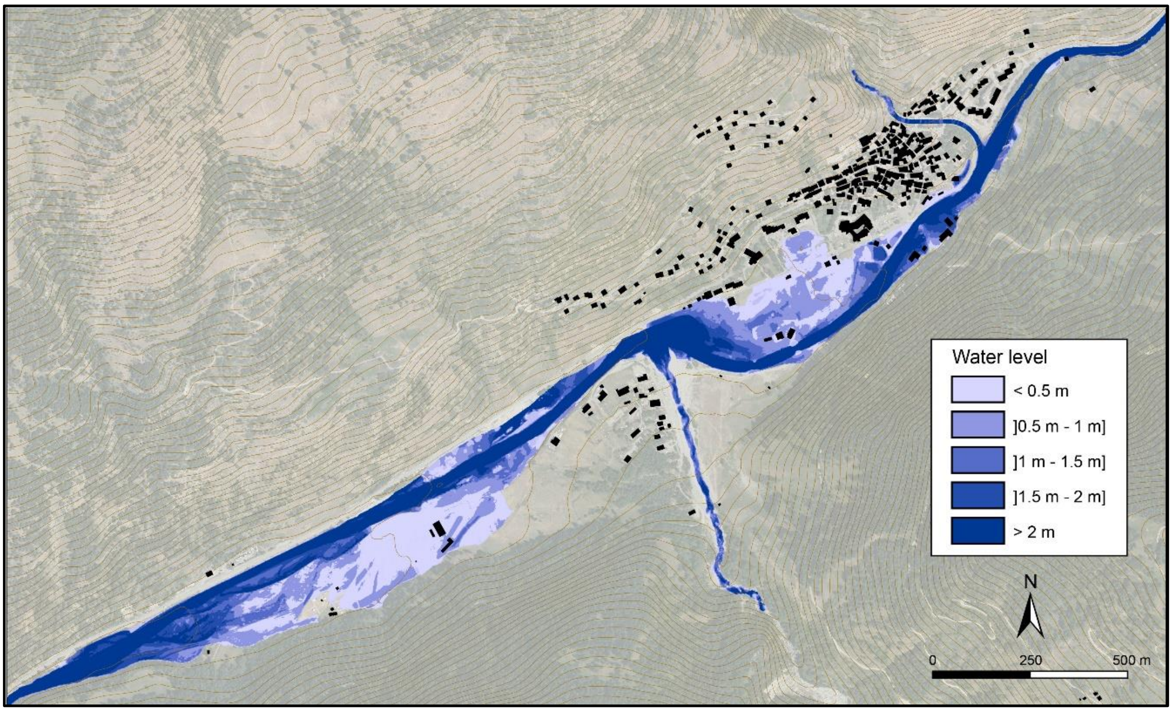

Figure 8: Zoom on type 1957 flood map produced for Aiguilles village.

3. Results

Using the methods previously described, PDI and PCI were calculated and mapped for the six municipalities of the Upper-Guil catchment. The distribution of the values calculated for both PDI and PCI are symmetric. As a consequence we chose to classify all the maps in five classes using average and standard deviation. To get a better understanding, PDI results are described before PCI's one. Then, a complete comparison between PDI and PCI results is proposed. To highlight differences between the two models, networks and land cover/uses are ignored in this part of the analysis.

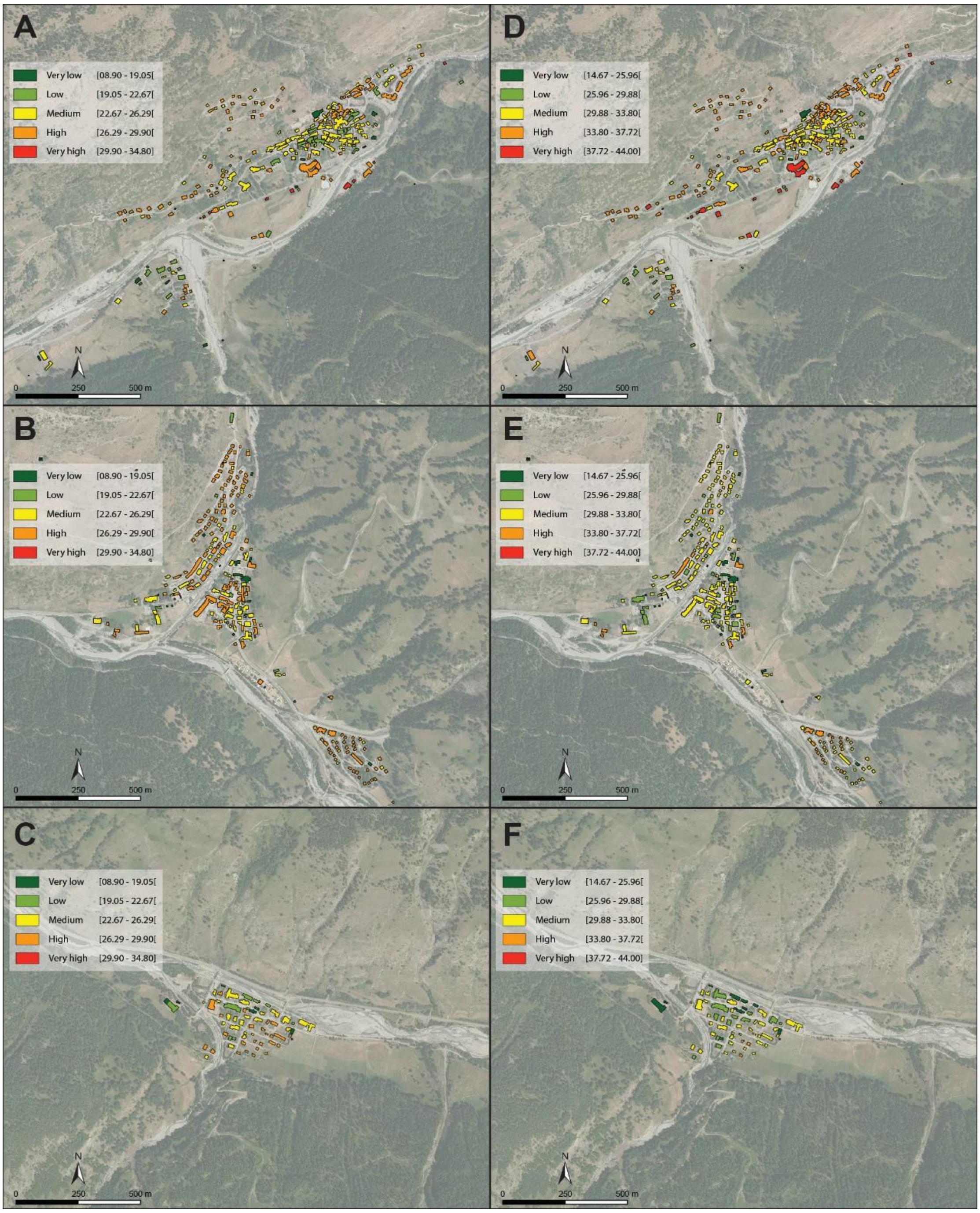

Figure 9: Comparison between PDI and PCI maps. A – Zoom on PDI map produced for Aiguilles village; B – Zoom on PDI map produced for Abriès village; C – Zoom on PDI map produced for Ristolas village; D – Zoom on PCI map produced for Aiguilles village; E – Zoom on PCI map produced for Abriès village; F – Zoom on PCI map produced for Ristolas village.

3.1 Description of the PDI results

The PDI map for flooding is obtained for the Upper Guil catchment by summing the direct *Physical Injury Index* (PII), *Structural and Functional Index* (SFI) and *Indirect Functional Index* (IFI) (Fig. 3). CTI scores for buildings range between 8.9 and 34.8 (mean: 24.5) (Fig. 9, A, B and C). Looking for the sub-indices, the highest scores are generally observed for the *Physical Injury Index* (mean: 10.9) and the lowest for the *Socio-Economic Index* (mean: 4.1). *Structural and Functional Index* scores are comprised between the both (mean: 9.5). Zooms on Aiguilles, Abriès and Ristolas villages are shown in Fig. 9, A, B and C. The produced map displays a majority of buildings with moderate to high scores of total potential consequences for the all studied communities. Buildings with the highest scores are mainly located in the vicinity of the Guil River or one of its main tributaries (Fig. 9, A, B and C). Major stakes such rescue centres (hospital, fire-station etc.), town-halls and schools are also classified with a high degree of potential consequences. This is due to their important function in local life. Conversely, churches, sheds and warehouses have a low degree of potential consequences. In town centres, buildings with trading or touristic function are generally in the "high" consequence class whereas those which only have a housing function are classified as "moderate". Sparse housing areas (mostly located on the heights), have a high degree of total potential consequences because they were not constructed to resist floods (large opening on ground floor, less resistant building material etc.). In most cases, these houses have virtually no chance to be impacted by a flood because they are located away from the torrential streams.

3.2 Description of the PCI results

The PCI is obtained by summing the direct *Physical Injury Index* (PII), the direct *Structural and Functional Index* (SFI), the *Indirect Functional Index* (IFI) and the new *Social Consequences Index* (SCI) (Fig. 3). PCI scores calculated for building range from 14.7 to 44 (mean: 31.8) (Fig. 9, D, E and F). SCI scores calculated for the six municipalities ranged between 5.2 and 9.2 (mean: 7.2) (Fig. 10). They are in the same order of magnitude than those of the 3 other indices used in PCI calculation (PII, SFI and IFI). The PCI map produced for the Upper-Guil catchment displays a majority of buildings classified with moderate degree of total potential consequences. (Fig. 9, D, E and F). At the community level, buildings classified with high or very high degree of potential consequences are mainly located near the Guil River or one of its main tributaries. Collective housing and major stakes (hospital, town-halls, schools etc.) are generally classified with higher potential consequences (Fig. 9, D, E and F) than individual housing. In most case, churches, sheds and warehouses are classified with a low or very low degree of potential consequences. Despite these general tendencies, we observe differences from a community to another. At the Upper-Guil catchment level, the studied communities can be divided in 3 groups (Fig. 9 and 10). A first group is made of communities with a large number of building classified with a high and very high degree of total potential consequences: Aiguilles and Saint Véran. A second one is formed by communities with most of their buildings being classified with moderate potential consequences: Château-Ville-Vieille and Molines-en-Queyras. The third group is composed by communities with buildings classified with low to moderate total potential consequences: Abriès and Ristolas. These differences between communities are directly related to *Social Consequences Index* (SCI) scores. The comparison between Ristolas and Aiguilles communities speaks for itself (Fig. 9, D and F). Ristolas community has the lowest SCI score (Fig. 10). People living here have a good perception of flood related risks indicating a high level of preparedness. They have confidence in local managers and there is only a few dependent people (children or elderly people) to care of when an unexpected situation arises. This suggests a good capacity to react when confronted to a catastrophic episode. In addition, they are globally wealthier than the other studied communities. They have theoretically a better ability to quickly recover after a material loss By contrast, Aiguilles community has high CTI and SCI scores indicating a lower ability to cope with hazards (Fig. 10). Compared to other communities, Aiguilles have more dependant people to care of. In addition, people have a lack information on flood risks and tends to underestimate the danger represented by floods. Aiguilles citizens earn less and have less confidence in their local managers. In the case of Ristolas, CSI tend to reduce the total potential consequences contrary to Aiguilles. In other words, a community with resilient population can qualify results obtained for physical consequences.

SC - Variable / Community	SC - A	SC - B	SC - C	SC - D	SC - E	SC - F	Score obtained for Social Consequences
Ristolas	0.10	0.10	1	0.10	0.60	0.40	5.20
Abriès	0.60	0.40	0.70	0.40	0.10	0.60	5.70
Aiguilles	0.80	0.80	0.70	0.80	0.60	0.60	9.20
Château-Ville-Vieille	0.40	0.40	0.70	0.60	0.40	0.60	6.60
Molines-en-Queyras	0.80	0.40	0.70	0.60	0.60	0.40	7.60
Saint-Véran	0.80	0.40	1	1	0.60	0.40	9.00

Figure 10: SCI scores calculated for the 6 municipalities of the Upper-Guil catchment.

3.3 Comparison between PDI and PCI maps

The PCI is developed as an upgrade of the PDI method. As a consequence, we can observe some similarities between PDI and PCI maps produced (Fig 9). In most of case, buildings classified with the highest level of potential consequences are buildings considered as essential in the local life (city hall, hospital, police and fire station etc.). In both maps, buildings located in an area previously inundated are also classified with high degree of total potential consequences (Fig. 9, A, B, D and E). Likewise, building classified with low or very low potential consequences are generally buildings with no essential function in local life like churches, sheds, warehouses or empty buildings. Moreover, buildings constructed in the last 20 years (mostly individual housing) have generally a higher degree of potential consequences than older buildings. With the PCI method, the influence of the physical consequences indices (PII, SFI and IFI) is thus globally preserved at the community level. The introduction of SCI allows us to qualify the total potential consequences of the elements at risk with regard to the ability of each community to cope with hazards. Ristolas and Abriès have low SCI scores. Floods will have less impact for these communities. As a result element at risks are classified with lower total potential consequences in comparison with PDI. By contrast Aiguilles and Saint Véran communities have high SCI scores indicating a low ability to cope with hazard. The buildings of these two communities are thus classified with higher total potential consequences in the PCI map and higher potential risk in the risk map produced (Fig. 11). As SCI is equally applied for all the buildings of a same community, it tends to homogenise PCI scores at the community level. In comparison with PDI map, the minimum scores values are uplifted resulting in a partial loss of information. This is particularly true in the communities with the highest SCI scores (Aiguilles and Saint-Véran). This partial loss has however, a positive impact on the readability of the maps. The global level of potential consequences of each community is evident and allows us to compare each community with one another. This is not so clear with the PDI method. In addition, the smoothing of the results tends to highlight the most vulnerable stakes. As a result, the PCI map is easier to understand for local managers than the PDI map.

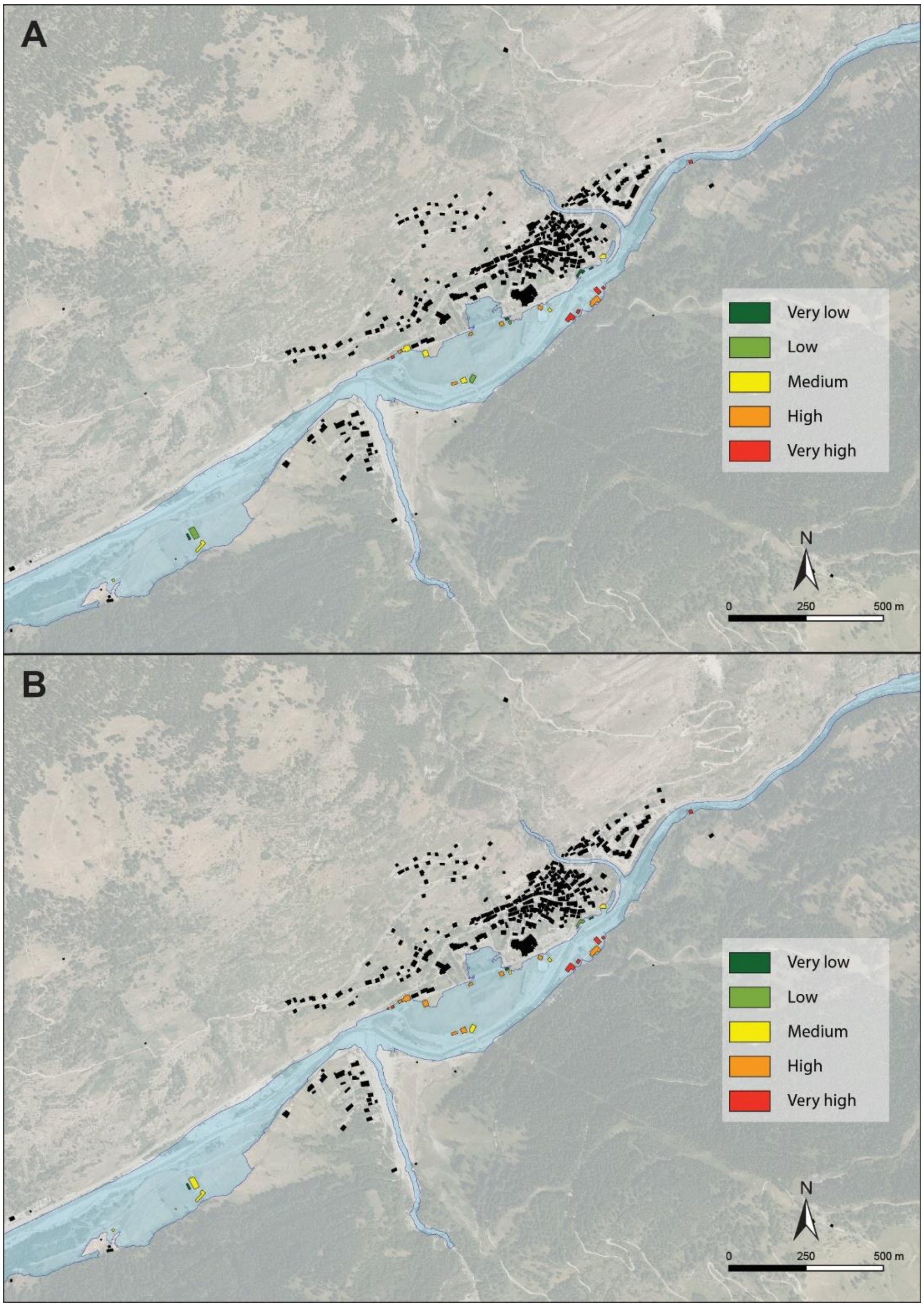

Figure 11: Comparison between type 1957 flood risk maps produced using PDI and PCI. A – Flood risk map produced using PDI; B – Flood risk map produced using PCI.

Conclusions and perspectives

In the present paper we explored the possibility to assess the physical and the social vulnerability together through an indicator based method. To perform this study, we opted for an upgrade of the *Potential Damage Index* method, which was originally developed to assess the physical consequences of defined hazards on element at risks. After an intensive review of the existing published reference on social vulnerability we selected 6 criteria derived from national French census data and a risk perception survey carried out on the field. These criteria were combined to produce a new sub-index representing the ability of communities to cope with hazard. The new *Social Consequence Index* was integrated in the PDI methodology to obtain the *Potential Consequences Index*. The PCI is then tested on the six municipalities of the Upper-Guil catchment to assess the potential consequences of a high magnitude flood event on element at risks (R.I. >100 years).

The upgrade made on the PDI method provides many benefits. First, the new SCI introduces criteria providing information on the three phases of risk management: preparedness, crisis management and recovery. By using data derived from a survey, the PCI method also displays information on the perception of the inhabitants regarding risk management. The introduction of elements coming from social vulnerability adds thus an extra-dimension to the total consequence map. It allows us to qualify the potential physical consequences (physical injury, structural and functional consequences) on element at risk considering the global resilience of local communities. Then, with the PCI method the level of potential consequences of each community is clearly displayed and the most vulnerable elements at risks are easy to identify. Therefore, PCI method allow us to quickly compare communities in their ability to cope with hazard. The PCI map is consequently easily understandable by risk managers or local decision makers and will help them set up adapted mitigation measures on the most vulnerable areas. Another benefit of the method result in the data used. Because it is mostly based on national data, it is easy to transpose in other places.

The main limitation of the PCI method is that a unique value of the SCI is applied to the overall building of a same community. By proceeding so, SCI tends to homogenize PCI by uplifting minimum values. For the communities with high SCI scores, this may simplify the information displayed. This scaling issues can imply a loss of information which may affect the distribution of PCI scores and thus, the choices of mapping classes. The amount of data required to perform this kind of analysis represents another limit. The method is based on the utilisation of many different criteria. Collecting them requires consequent fieldwork and must be time-consuming. This is especially true for criteria derived from a risk perception survey. Consequently, the use of the PCI model at large scale will be quite difficult.

Some elements which may improve the PCI model will be investigated in future works. First of all, we will expand the scale of our study by including other communities of Southern French Alps studied in the SAMCO project. Located in the Ubaye valley, near our study area, these communities display similar physical and socio-economic characteristics. Their inclusion will provide a more representative selection for statistics investigations. Another lead will be an adaptation of the survey protocol in order to get data at smaller scale such as district scale. Another solution to gain in precision will be the use of a desegregation model to distribute PCI at building scale.

The method presented in this paper will be a source of significant progress for vulnerability assessment. By considering the two main components of vulnerability, the physical one and the socio-economic one, this work may provide an important tool for local authorities. The PCI will help them to better understand their strength and weakness and will be useful to develop appropriate mitigation measures at the local and regional level.

Author contribution

Benoît Carlier and Anne Puissant designed the experiments and carried them out. Benoît Carlier developed the model and performed the simulations. Benoît Carlier and Constance Dujarric realised the questionnaire survey. Gilles Arnaud-Fassetta supervised Benoît Cralier and Constance Dujarric works. Benoît Carlier prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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