Response to reviewers' comments

Anonymous Referee #1

Comment n° 1:

"The title represents the content of the paper, however, it could sound a lot more attractive (and more suitable) if the word "improvement" would be replaced with "Upgrading" or Extend/Expand". Moreover, the term "consequence analysis" shows the inconsistency in using the terms within the entire paper. "Consequence analysis" in the title is considered the same as "vulnerability assessment" and "potential damage" in the text".

Response to comment n°1:

We have taken the comment into account and changed the title of the paper.

As recommended we also harmonised the terms used throughout the paper.

Comment n° 2:

Clarifications of hazard type, intensity and scenarios: some basic information is missing from the text. Which type of hazard is addressed in the study? The PDI was originally developed for landslides. Nevertheless, the area under study is susceptible to torrential flooding, rock fall, debris flow and avalanches (page 3, line 80 and page 4, line 85-86) and, apparently, the questionnaire was about all hazards. There is a discussion in the literature about vulnerability being hazard or non-hazard related. Physical vulnerability is considered usually hazard related and the social not. This discussion in very relevant to the paper and I strongly believe that it has to be included in the introduction (page 2, paragraph 2). Moreover, the question that often has to be answered when doing vulnerability assessment is "vulnerability to what?". The issue of intensity in vulnerability studies is a challenging one. How can we include the intensity of a processes within the vulnerability assessment? For example, why do you use indicators such as wall>1,5m? (Figure 5) What if the height of the flood or debris (we still do not know which type of hazard is considered here) is less than 1m? Are you considering a specific scenario before conducting the analysis? And if yes, which one? Please include the issues of including intensity in the assessment of vulnerability and explain clearly how you include it in this study.

Response to comment n°2:

We have taken the comment into account and addressed the lack of information on hazard type and scenario. The scenario considered is now cited in the abstract (line 18) and in the introduction (line 116-117). Detailed information is provided in section 2.3: "Flood hazard mapping" (line 254 to 268).

Moreover, a discussion on vulnerability assessment was added to the introduction (line 52 to 106).

Comment n° 3:

Incomplete literature review: There is some reference to similar studies in the paper, however, there are more studies that focus on the combination of social and physical vulnerability for a number of hazard types and are not referred to in the paper. For example, Armas and Gavris (2013) combine social and economic vulnerability with housing quality and Chang et al (2015) use vulnerability indicators considering the economic, social, built and natural capital. Moreover, institutional vulnerability indicators have been used by Rogelis et al (2016). Additionally, the studies regarding social vulnerability assessment listed in Table 1 are rather old. Studies like the one of Cutter (2003) should definitely be included but only 4 out of 12 studies listed in Table 1 were carried out in the last 5 years. A discussion on the use of indicators in general and other alternatives is crucial for the paper. The authors begin to do so in page 2 (paragraph 2) but more benefits and limitations of using indicators should be added from the following publication: Papathoma-Köhle, M., Gems, B., Sturm, M., Fuchs, S. 2017. Matrices, curves and indicators: a review of approaches to assess physical vulnerability to debris flow. Earth-Science reviews, 171, 272-288. Finally, references to other methods of assessing physical vulnerability (e.g. vulnerability curves), is in my opinion, also absolutely necessary.

Response to comment n°3:

In accordance with the referee comment, the literature review was completed with recent studies. All the papers mentioned were included and discussed.

In addition the discussion on the use of different methods to assess vulnerability was completed according to the referee comment (line 82 to 106)

Comment n° 4:

The theoretical background of the paper is rather weak. Different terms are used to describe the same concept throughout the text (see comment 1). This is also evident by statements such as "it was necessary to reassess vulnerability and risk in the area" (page 4, line 90) and "social and institutional vulnerability index" (page 4, line 116). The authors do not conduct risk assessment and they do not assess institutional vulnerability. What is institutional vulnerability anyway and which would be the relevant indicators?

Response to comment n°4:

We have taken the comment into account and homogenised the terms used in the text.

We modified the text in order to conduct a risk analysis (see fig. 11 A and B).

Following the referee comments, we chose to ignore institutional vulnerability in this paper.

Comment n° 5:

Serious scale issues: the scale used in the study is not clear from the beginning. The social vulnerability index seems to be calculated at community level. However, the PDI is calculated at building level. These two, however, are added in a last step. In my opinion, this needs to be thoroughly discussed in the discussion section and the loss of information and associated uncertainties have to be outlined.

Response to comment n°5:

In accordance with the referee comment, we developed the discussion on scaling issues in the third paragraph of the "Conclusions and perspectives" part (line 378, to 393).

Comment n° 6:

The aim of the study and the end users of the method are not clearly demonstrated within the paper. Tangible examples of the usefulness of the maps should be more evident and should highlight the importance of the method.

Response to comment n°6:

In accordance with the referee comment we clarified the objectives of the study. A first indication on the use of the produced map is given line 116. Other information are given in the "Conclusions and perspectives" part (line 366 to 378 and 395 to 399).

Comment n° 7:

Mapping: the maps in figures 7 and 8 are difficult to read and interpret. Who can use them and how? Is it necessary to map the results in this case or would a table showing the scores for each municipality be enough?

Response to comment n°7:

We have taken the comment into account and replaced the maps by a table (Fig. 10).

Comment n° 8:

The study on the risk perception sounds very interesting. More information on the questionnaire (questionnaire as appendix?) is desirable since this study apparently has not be published individually somewhere else. Some important information should be also included here, for example, what is your confidence level with such a small sample (around 70%?). Is the sample 5% for each municipality? (probably not). How did you manage to have a representative view of the socio-economic characteristics?

Response to comment n°8:

In accordance with the referee comment more information on the questionnaire is given in section 2.2 (line 229 to 240). The questionnaire is in appendix.

Comment n° 9:

Some aspects of the methodology are not clear: -Are all the indicators equally important or did you weight them as well? -Why three indices to make a SIVI when all three are dependent from more or less the same variables? -EaR-C: are (ok, the old farmer houses in some mountain areas have very thick walls and might be stronger). Is this what you mean? (Fig.5) -which score do you give a building which has more than one of the characteristics listed under Ear-D? -Score 0 needs to be discussed. Are you 100% sure that these buildings will not be damaged at all? This brings us back to the discussion about the intensity. A building that is more than 50m away from the torrent will NOT be damaged. For which event are we talking about? -the Cemetery and the Car park in EaR-J are not buildings. -why very important indicators regarding participation, existence of information campaigns and insurance are not considered in the Preparedness, Crisis management and Recovery indices? -why are winter activities (0,8) more “vulnerable” than summer activities?

Response to comment n°9:

We have taken the comment into account and modified the text (section 2.2, line 186 to 210) and the figures (Fig. 3, 6, 7 and 10) accordingly. Now there is only 1 social indicator instead of 3. To select relevant criteria and avoid redundancy we use a Principal Component Analysis (PCA). Weights were assigned through an expert weighting with regard to the PCA realised.

We consider that older houses are more robust than new ones. To get more details on the weights assigned, we kindly invite you to read the following papers: Puissant, A., Malet, J.P., Maquaire, O.: Mapping landslide consequences in mountain areas: a tentative approach with a semi-quantitative procedure, SAGEO, 1-16, 2006.; Puissant, A., Van Den Eeckhaut, M., Malet, J.P., Maquaire, O.: Landslide consequence analysis: a region-scale indicator-based methodology, Landslides, 1-16, DOI: 10.1007/s10346-013-0429-x, 2013.

There were problems with EAR-D and we decided to delete this criteria for the present paper.

In accordance with the referee comment we changed our weights from 0 to 0.1 to avoid null values (Fig. 4 and 7). In addition, we replaced the EAR-F by a new criteria based on the areas previously impacted by flood (EAR-H area affected by floods; Fig. 3 and 4).

Cemetery and car parks were deleted from our building database. These elements are now in our "land-uses" database (Fig. 3 and 4).

Following the referee comments, we chose to ignore institutional vulnerability in this paper. As a consequence, the mentioned indicators are not especially relevant for our analysis.

In the studied area, winter tourism activities bring more money to the communities than summer tourism activities. Moreover, winter tourism infrastructures are globally more expansive than summer tourism infrastructures (ex: ski resort).

Comment n° 10:

Not clear what is the difference between CV and AV and why comparing them. Is it necessary and why you do not refer to it before page 9? Please consider it as part of the methodology and explain clearly what is the difference between the two approaches is. Why "Classic" and not "Universal" or "General"?

Response to comment n°10:

With regards to the referee comment n° 9, we introduced significant changes in our method. We simplified our social indicator and deleted the text on the difference between AV and CV.

Comment n° 11:

Since you present a new methodological approach you should be critical with it at the end. Were there any limitations and assumptions? Which indicators are missing? What are the sources of uncertainty? What are the benefits of the methodology and what are the drawbacks? How can it be improved in the future?

Response to comment n°11:

We have taken the comment into account and developed the advantages and limitations of our method in the "Conclusions and perspectives" part (line 366 to 399).

Comment n° 12:

The main aim of the paper is the combination of a physical damage index with the social vulnerability. Yet, there is no discussion about the added value of this action. Why is it important to combine them? What are the interactions or relationship between the two faces of vulnerability?

Response to comment n°12:

We have taken the comment into account and modified the text accordingly. A discussion on the interest of combining social and physical vulnerability together is made in the introduction (line 52 to 81) and the conclusion and perspectives (line 366 to 378).

Comment n° 13:

Last but not least, there is a fair amount of grammatical mistakes and typos. The text should be revised if possible by a native speaker.

Response to comment n°13:

Following the referee comment, the text was reviewed by a professional translator.

Anonymous Referee #2

Comment n° 1:

Strictly speaking a real consequence analysis is not performed. It is advisable to stick to the main objective related to the fusion of "physical" and social vulnerability". Otherwise, using consequence analysis as a key term, it is mandatory to analyse in detail the impacts generated by the hazard process and constantly refer to a specific set of hazard scenarios which should reflect the perturbation of the exposed system.

Response to comment n°1:

We have taken the comment into account and addressed the lack of information on hazard type and scenario. The scenario considered is now cited in the abstract (line 18) and in the introduction (line 116-117). Detailed information is provided in section 2.3: "Flood hazard mapping" (line 254 to 268).

Comment n° 2:

You claim that "the social approach in which vulnerability is viewed as a combination of socio-economic variables determining people's ability to anticipate before a catastrophic event, to react during it, and to recover after it". This statement if confusing, at least to me. First, describing the social approach simply as a combination of socioeconomic variables is rather reductive either in scope and also in epistemic terms. Second, it is not clear what people should be able to anticipate. If people should be able to anticipate the consequences, then it is also essential to analyse the process impacts. Rigorously, this is possible only by mirroring a certain set variables quantifying the intensity of the underlying process. If this deduction holds, then hazard analysis, conceived as an ancillary element of vulnerability assessment from a natural science perspective, comes again decisively into play, perhaps not as the only starting point of vulnerability assessment endeavours but, in any case, as one essential component. In my view the hazard analysis is only rudimentarily addressed throughout the manuscript and I really suggest to reinforce this part.

Response to comment n°2:

We have taken the comment into account and developed the description of the social approach (line 66 to 71).

However, we don't understand the second part of the comment. The ability to "anticipate" a catastrophic event refers to risk knowledge, risk memory and more widely, to preparedness. Preparedness is commonly admitted as an essential component of risk management. For us, a resilient population should be able to anticipate a hazard.

In accordance with the referee comment, we developed our hazard analysis (line 254 to 268).

Comment n° 3:

The last sentence of the abstract reads "GPDI scores are globally lower than PDI scores indicating that resilient population may qualify results obtained for physical consequences" and is meant to summarize the specific insights gained through the application of the employed methodology. This conclusion is really general and, at least in my opinion, is only marginally useful for any risk management endeavour. It would be beneficial to provide a more tangible concluding sentence.

Response to comment n°3:

We have taken the comment into account and modified the text accordingly. A discussion on the interest of combining social and physical vulnerability together is made in the introduction (line 52 to 81) and *the conclusions and perspectives (line 366 to 378). We also developed the advantages and limitations of our method in the "Conclusions and perspectives" part (line 366 to 399).*

Comment n° 4:

In the introduction you state that in mountain areas local communities are particularly exposed to natural hazards due to some characteristics inherent to the physical and socio-institutional environment. Since you build your case upon these characteristics it is necessary to unveil them. The second sentence starts with "This leads to important costs for communities..." Also this sting of argumentation remains unspecified until you do not clearly state the characteristics that determine exposure to natural hazards. To conclude this line of thought I suggest to better convey the reasons that moved you in trying to improve the index based methodology for vulnerability assessment.

Response to comment n°4:

We have taken the referee comment into account and modified the text accordingly. We developed our argumentation line 36 to 52.

Comment n° 5:

You contend that reducing susceptibility to hazard and create disaster-resilient communities, necessitate to combine the "engineering approach" and "socio-economic approach". I completely agree with this statement. The problem resides in how these approaches are combined. Personally I think that the engineering approach is rigorous but is only partially capable to assess the broad spectrum of consequences of a natural hazard event. On the other side, the social views on vulnerability tend to dismiss the importance of the frequency, intensity (and magnitude) of the perturbation as well as its spatio-temporal dynamics. Hence, a certain margin of vagueness still risks to persist. This may be somewhat detrimental for an efficient risk management process. Why compress hazard impact analysis into a set of qualitative indicators if modelling approaches allow for a reliable spatial representation of the hazard scenarios? Hence, to be concise, I'd rather retain the strengths of the engineering view and would prefer to look for ways on how to embed these methods in a broader methodological architecture aimed at contextualizing all relevant and concurrent determinants of social and economic vulnerability. Given these premises I'd like to invite the authors to expand the rationale of their work and explain at their best the suitability of they approach.

Response to comment n°5:

The referee comment was taken into account and the text was modified accordingly.

Comment n° 6:

The first subsection of the section study area is called "Physical context". I miss, however, relevant physical information about the mentioned hazard events. It could be insightful to provide a description of the main events and to display the inundated areas. Moreover, I suggest to highlight, through an appropriate set of symbols, the damages caused by, at least, the most severe among the mentioned events.

Response to comment n°6:

We have taken the comment into account and addressed the lack of information on hazard type and scenario. The scenario considered is now cited in the abstract (line 18) and in the introduction (line 116-117). Detailed information on the scenario used is provided in section 2.3: "Flood hazard mapping" (line 254 to 268). In accordance with the referee comment, we produced a figure showing the damage caused by the 1957 and 2000 flood events (Fig. 2).

Comment n° 7:

Section: Methods and data: I have several concerns in relation to this section: You explicitly state that "in the context of the French funded ANR project SAMCO (Society Adaptation for coping with Mountain risks in a global change Context), you applied these principles to set up a systemic analysis of mountain risk including elements of all the components of vulnerability (i.e. structural, functional, social, economic and institutional). It is not clear to me which are the principles applied. Please describe them clearly. Moreover, you say that you include elements of all the components of vulnerability. In relation to the hazard process, for example, you propose the distance to the torrent as main "indicator". In my opinion this indicator is rather unsuitable. This choice signals a weakness in incorporating the hazard process dynamics and indicates, as a reflection, a potential failure in successfully combining the different views on vulnerability. It is not intelligible how hazard processes of different intensity affect the built environment. As a consequence, it is not clear to me, how the damage generation occurs and how the direct and indirect consequences could materialize. With respect to the employed methodological apparatus I miss a coherent weighting of the single factors (indices) contributing to the overall vulnerability of the system. Several mentioned criteria concur to determine a plurality of different indices at different hierarchical levels. In aggregating the weight of these indices serious troubles of consistency may arise. More theoretical background on the employed methodology is necessary backbone your methodological structure. In relation to the selected criteria and in particular looking to figure 4, it is not understandable what torrentiality means associated to several criteria (e.g. land-use, land cover, transport and energy systems etc.). To sum up, in its present form, the methodological workflow is rather unintelligible. Please put efforts in significantly enhancing the clarity of the description of the single methodological steps.

Response to comment n°7:

The referee comment was taken into account and the text was modified accordingly. In the context of the Samco project we adopted a systemic point of view by studying different elements of the risk system (processes, hazard, risk perception, physical vulnerability, climatic and socio-economic changes etc.). The present paper is only focused on the development of a method to combine social and physical vulnerability.

The indicator "distance to the torrent" was deleted and replaced by a new criteria based on the areas potentially impacted by different scenarios of flood (EAR-H area affected by floods; Fig. 3 and 4).

This paper is an upgrading of an existing method. The description of how hazard process affects buildings is discussed in the following paper: Puissant, A., Malet, J.P., Maquaire, O.: Mapping landslide consequences in mountain areas: a tentative approach with a semi-quantitative procedure, SAGEO, 1-16, 2006.; Puissant, A., Van Den Eeckhaut, M., Malet, J.P., Maquaire, O.: Landslide consequence analysis: a region-scale indicator-based methodology, Landslides, 1-16, DOI: 10.1007/s10346-013-0429-x, 2013.

We made significant modifications in our method. Re-writing the paper, we made an effort to be more intelligible in the description of our method.

Comment n° 8:

In relation to the construction and organization of the SIVI you present a synthesis table of the criteria usually employed, citing several papers where these criteria were proposed and used. I invite you to rigorously check the reference list for completeness.

Response to comment n°8:

Following the referee comment, the literature review was completed with recent papers.

Comment n° 9:

Results, conclusions and perspective: You claim that the organization of the obtained results, and, hence, also their representation form (i.e. maps) is easily interpretable by risk managers or local decision makers. Can you corroborate this statement? What exactly can be deduced better in terms of an enhanced elaboration of risk management strategies? Ideally, an assessment procedure should also provide opportunities to understand how to increase cost-effectively the resilience of a system by design. Your systemic analysis seems to be a bit week in this respect. What should be done? What should be prioritized? What should engineers know in order to improve their design?

Response to comment n°9:

In accordance with the referee comment we clarified the objectives of the study. A first indication on the use of the produced map is given line 116. Other information is given in the "Conclusions and perspectives" part (line 366 to 378 and 395 to 399).

Comment n° 10:

In this review, I preferred to prioritize content related aspects to be improved. The text contains also several grammatical and orthographical mistakes and it would benefit from a thorough revision by a native speaker.

Response to comment n°10:

Following the referee comment, the text was reviewed by a professional translator.

~~improvement~~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 ~~the exposed~~ 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~~ before~~, cope with and recover from a catastrophic event~~, to react during it, and to recover after it.~~. Finding a way to combine these two approaches is a key issue for a global vulnerability assessment. ~~The objective of~~In this paper ~~is to improve~~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~~) originally developed to assess the physical, structural and functional consequences of landslide hazard,~~), by including social ~~and institutional~~ criteria. ~~These 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 ~~were selected~~conducted on the field. By combining the 4 indexes (PIC, SFC, IC and SC), we managed to ~~represent the three main phases of risk management: preparedness, crisis management and recovery. The new *Global*~~create a new index called *Potential ~~Damage~~Consequences Index* ~~is then applied~~(PCI). The new PCI was tested on the Upper Guil Catchment to assess ~~torrential floods.~~the consequences of a high magnitude flood event (R.I. > 100 years). Results of the PDI ~~are~~were compared with the ~~GPDI~~PCI and show significant differences. ~~GPDI scores are globally lower than PDI scores indicating that resilient population may~~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 ~~results obtained for~~the potential physical consequences~~. ~~ (physical injury, structural and functional consequences) on element at risk by considering the global resilience of local communities.

Introduction

In ~~mountainous area, local~~Europe, small alpines communities are particularly exposed to natural hazards due to ~~some~~ characteristics inherent to the physical and the socio-~~institutional~~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~~). This~~), 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 ~~for communities with often limited resources and have~~ and has a significant impacts on the public opinion (Barroca *et al.*, 2005). ~~In a context a~~As the global ~~changes (i.e.~~ climatic~~, socio-economics and institutional)~~ and socio-economic environment changes drastically, this concern is growing up (Pachauri *et al.*, ~~2007~~2007; Papathoma-Köhle *et al.*, 2011; 2016; Aitsi-Selmi *et al.*, 2015; Alcántara-Ayala *et al.*, ~~2015) and thus, communities request for studies~~2015). The Alpines environment is in fact, very sensitive to global changes (IPCC, 2012). The impacts of such changes on ~~risk assessment are increasing too.~~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 ~~and consequently~~. As a consequence, the vulnerability component is often limited (Reghezza, 2006; Reghezza ~~&~~and Rufat, 2015; Zahran *et al.*, 2008; Jeffers, 2013). ~~Even when vulnerability is taken into account, few multidisciplinary studies apprehending the overall components~~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 (~~social, institutional, physical, structural and functional aspects) exists (Fuchs, 2009; Barroca *et al.*, 2005). Vulnerability is~~ 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).~~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 ~~viewed as~~ 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 ~~on~~ human ~~stakes~~interests (Glade, 2003; Fuchs *et al.*, 2007; ~~Kappes *et al.*, 2012). In this approach, the emphasis is focused on structural and functional consequences on building, network and landcover/use (~~Puissant *et al.*, ~~2006;~~ 2013). ~~For social~~Social scientists~~,~~ define vulnerability ~~is mainly considered as a combination of socio-economic variables determining people’s ability~~as “the characteristics of a person or group in terms of their capacity to anticipate~~ a catastrophic event, to react during it, and to~~, cope with, resist and recover ~~after it~~from impacts of a hazard” (Blaikie *et al.*, 1994; Cutter *et al.*, 2003; ~~Clark *et al.*,~~ Steinführer *et al.*, 2009). It~~1998; Cutter *et al.*, 1996; 2003; Wu *et al.*, 2002; Chakraborty *et al.*, 2005). In that case, social vulnerability~~ 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).~~

~~Reducing~~2011). These two theories must be combined in order to reduce susceptibility to hazard and to create disaster-resilient communities~~, necessitate to combine these two theories (Fuchs, 2009; 2012). For Rygel *et al*., 2006, and Birkmann, 2006,~~ (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 ~~is flexible enough to be adjusted to different hazards and places (Kappes *et al*., 2012) and it permits~~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 ~~its~~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*), ~~we applied these principles to set up a systemic~~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 ~~including elements of all the~~

components of 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 (i.e. structural, functional, social, economic and institutional).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 achieve this, we perform this work, we opted for an indicator-based vulnerability approach. The proposed a modified version of the 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).

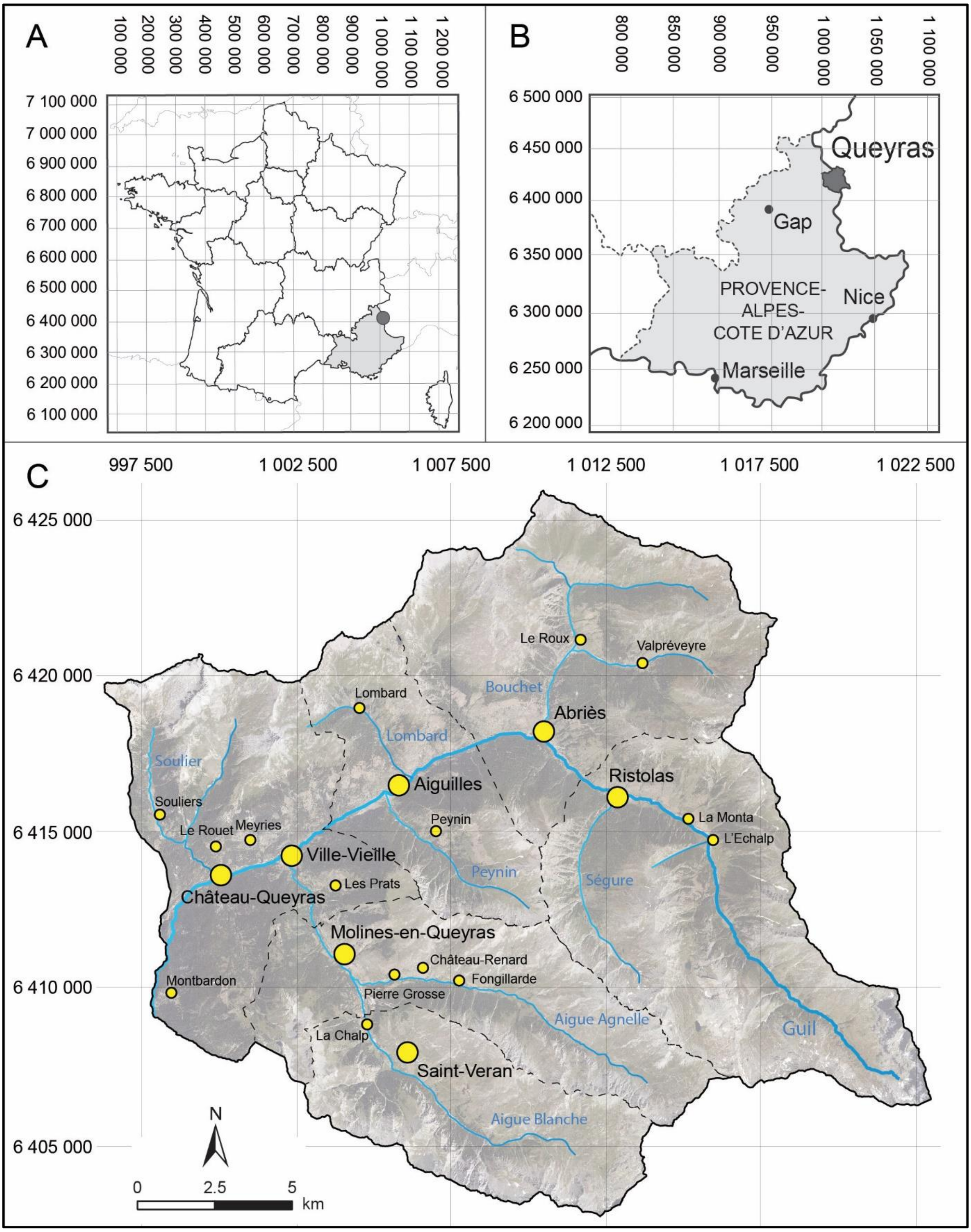


Figure 1: Location map of the Upper Guil catchment and its six communities.

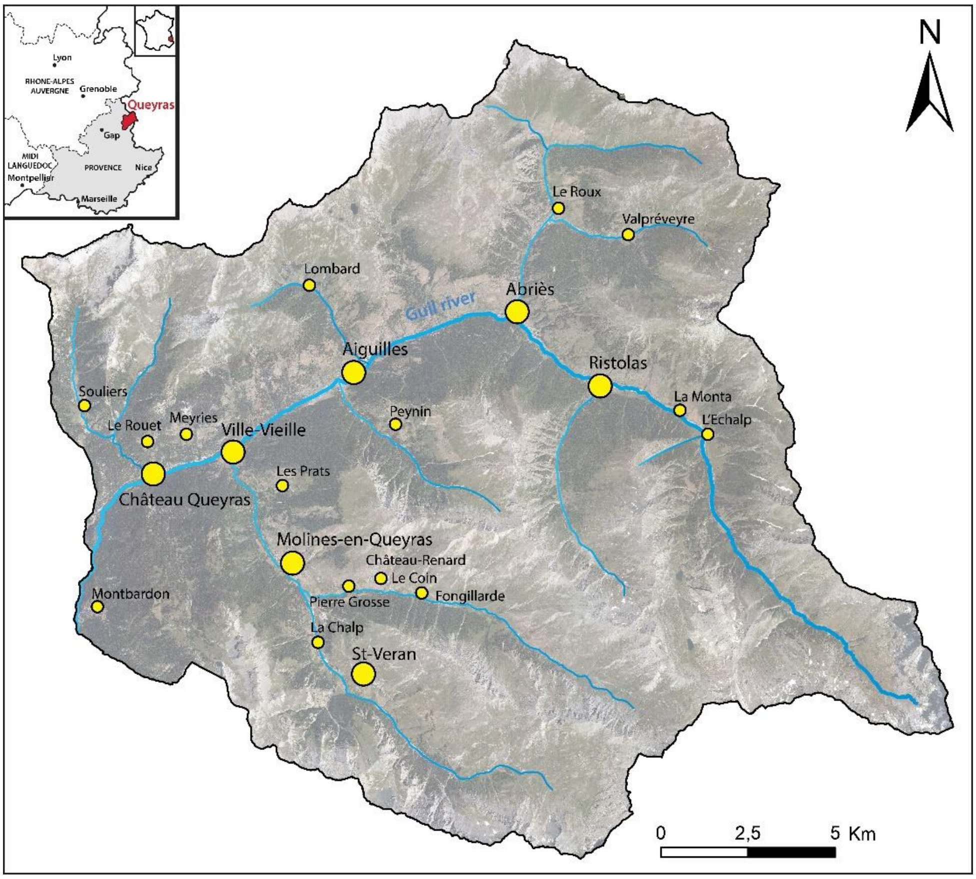
The PCI consists in upgrading an existing index called *Potential Damage Index* (PDI) originally). The PDI was developed and improved by Puissant *et al.* (2006; 2013) to estimate the total potential consequences of a natural multi-hazardshazard on elements at risk (building, network and land occupation). In its first version, the PDI was It is obtained by combining three indices representing direct (- physical injury and structural and functional impacts)consequences - and indirect consequences (-

indirect functional consequences - of hazards on the element at risk. These 3 indices are built with data representing the characteristics of each element at risk (material, age, number of occupied floors etc.). In the PCI we added a fourth index called *Social Consequences Index* (SCI) representing the socio-economic impacts). In order to include elements of social and institutional vulnerability from consequences of a hazard on the community resilience. SCI variables are derived from French national census data and at community level (INSEE) and data from a risk-perception surveys we proposed to replace the physical injury component by adding several elements of the three phases of risk management: preparedness, crisis management and recovery. The new index called *Global*survey conducted in the six municipalities of the Upper-Guil catchment (Ristolas, Abriès, Aiguilles, Château-Ville-Vieille, Molines-en-Queyras and Saint-Véran). The *Potential Consequences Index* is obtained by combining the new *Social Consequences Index* with the *Physical Injury Index*, the *Structural and Functional Index* and the *Indirect Functional Index* coming from the PDI. Results obtained for the *Potential Consequences Index* are then applied to the Upper-Guil catchment and compared to those obtained with the *Potential Damage Index* (GPDI) is tested to map consequences of multi-hazards in the Upper Guil catchment (torrential flood, landslide and avalanche). .

In the first section of this paper, the physical and socio economic context of the study area is exposed. Then, the second section present the data and methods used to obtain PDI and GPDI and explain the different tests made to evaluate the influence of the new variables introduced. After an exposition of SIVI results, the third section show a comparison between PDI and GPDI.

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.



~~**Figure 1:** The Upper Guil catchment and its six communities.~~

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 ~~flood~~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 ~~reassess~~assess vulnerability~~ and risk~~ in this area.

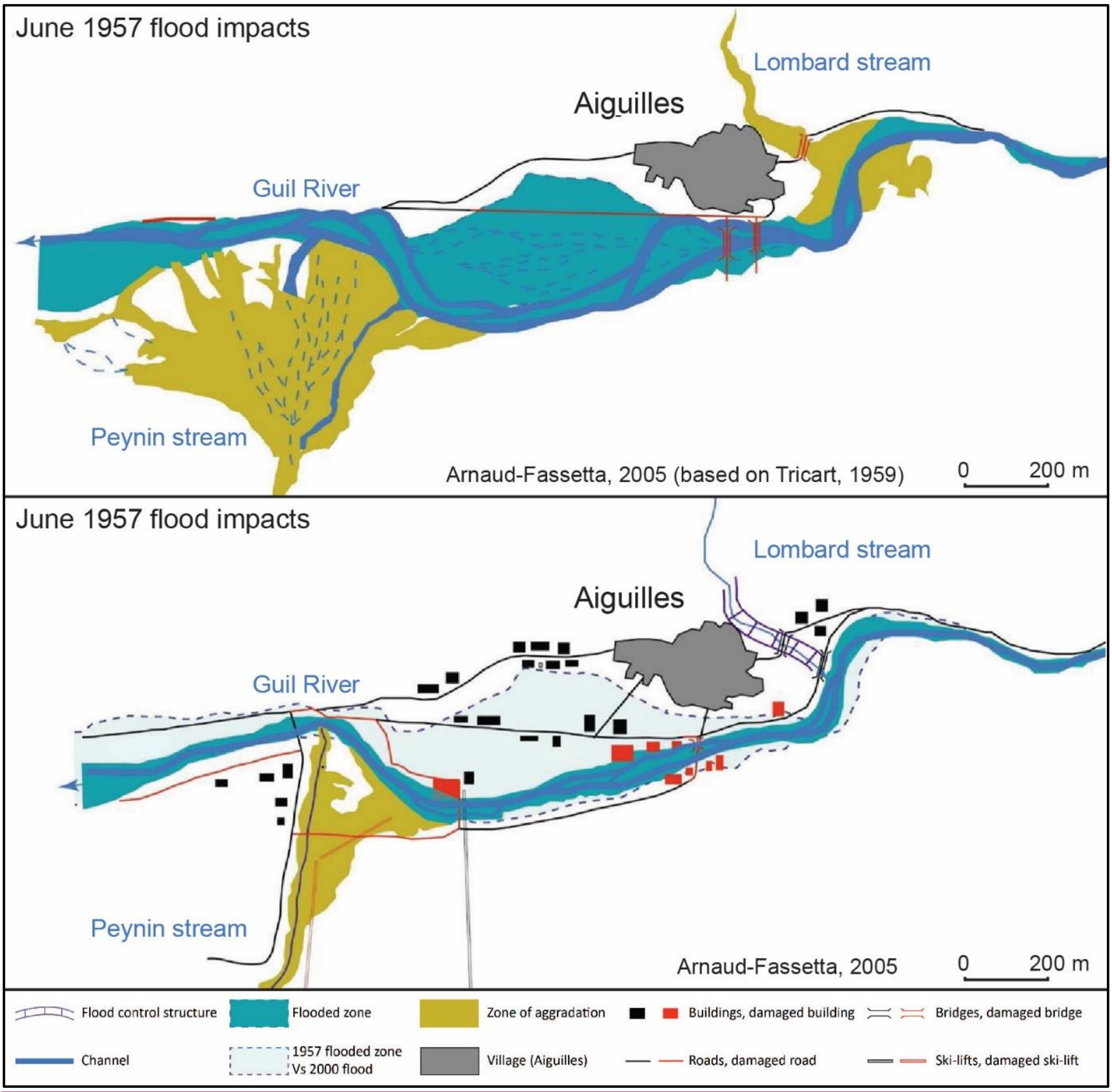


Figure 2: Impacts of the June 1957 and June 2000 flood on Aiguilles village.

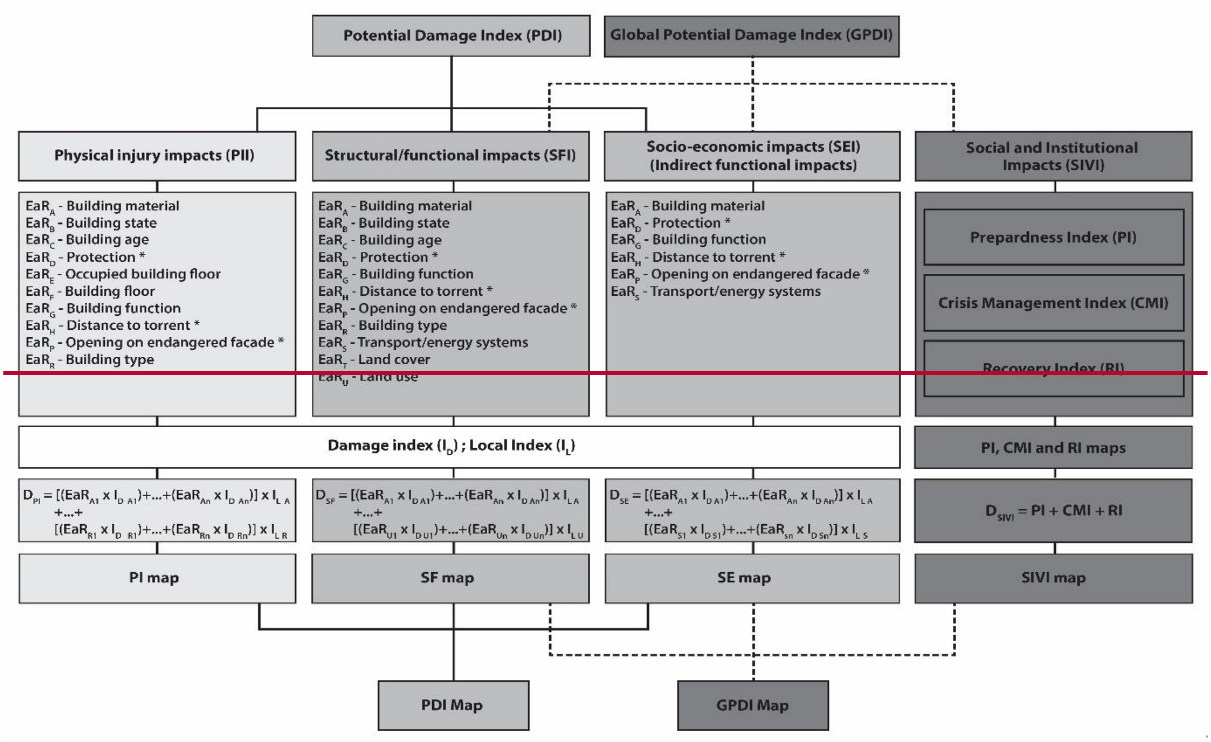
1.2 Socio-economic context

~~Currently~~Today, the ~~permanent population of the~~ area ~~reach~~counts 1770 inhabitants (Insee, 2012~~) and thus, it's~~), making it one of ~~the~~France's less densely populated districts ~~in France (<~~(< 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~~Alpine territories have experienced significant changes ~~concerning its~~on their land cover/uses and economic activities~~. The~~ (Fuchs et *al*., 2013). In the Queyras, 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 (~~described above).~~torrential fans and valley bottom). The current land cover/use is~~ hence~~ 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 ~~parks~~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 ~~endangered areas and cause an increase of vulnerability for the communities~~areas exposed to natural hazards (Arnaud-Fassetta *et al*., 2004).

2. Methods and data

~~*2.1 General Framework of the GPDI*~~

~~*Our Global*~~ *Potential* ~~*Damage*~~*Consequences Index* (PCI) is ~~proposed in order~~used to assess the physical and social ~~and institutional~~ consequences ~~together with physical, structural and functional consequences. As the PDI, it consists in an empiric semi-qualitative and semi-quantitative analysis of the total potential consequences (i.e. structural, functional, social and institutional) for~~ of a ~~considered~~ hazard~~. It is also index based method which combines spatial analysis (GIS) and statistical modelling (linear combination). In order to focus our attention~~ on ~~the method improvement, we choose to only consider torrential floods in this paper.~~



~~**Figure 2:** General framework~~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.

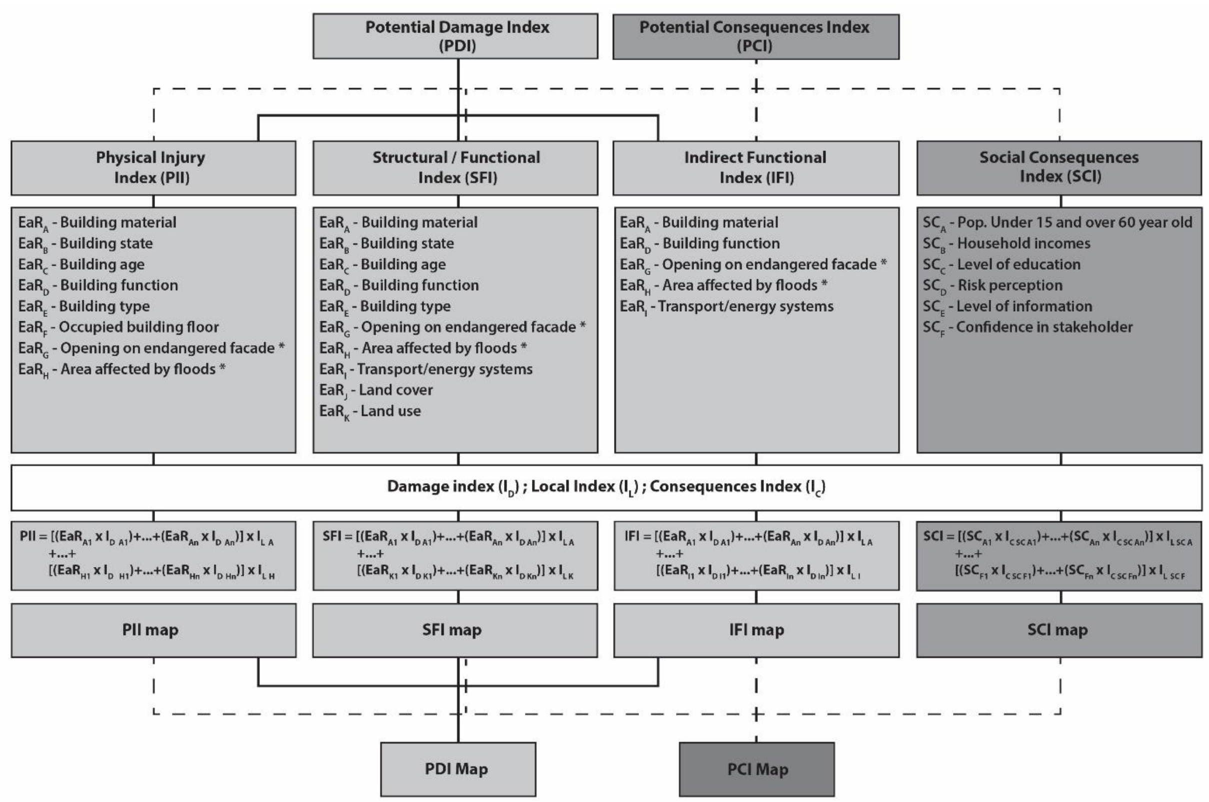


Figure 3: Framework of the Potential Damage Index (PDI) compared to the ~~Global~~ Potential Consequences Index (PCI).

2.1 General Framework of the Potential Damage Index (~~GPDI).~~ PDI)

~~*Potential Damage Index* (PDI) was obtained by combining three indices: the *Physical Injury Index*, the *Structural and Functional Index* and the *Socio-Economic Index*. In the proposed GDPI, the Physical Injury (PI) Index is replaced by a *Social and Institutional Vulnerability Index* (SIVI) (Fig. 2). The SIVI was itself obtained by a sum of three score based on the three main phases of risk management: *Preparedness Index* (PI), *Crisis Management Index* (CMI) and *Recovery Index* (RI) (Fig.3). These~~

indices are built by using national and municipal French census data (INSEE) at community scale and data derived from a risk perception surveys made in the frame of the SAMCO project (Table 2).

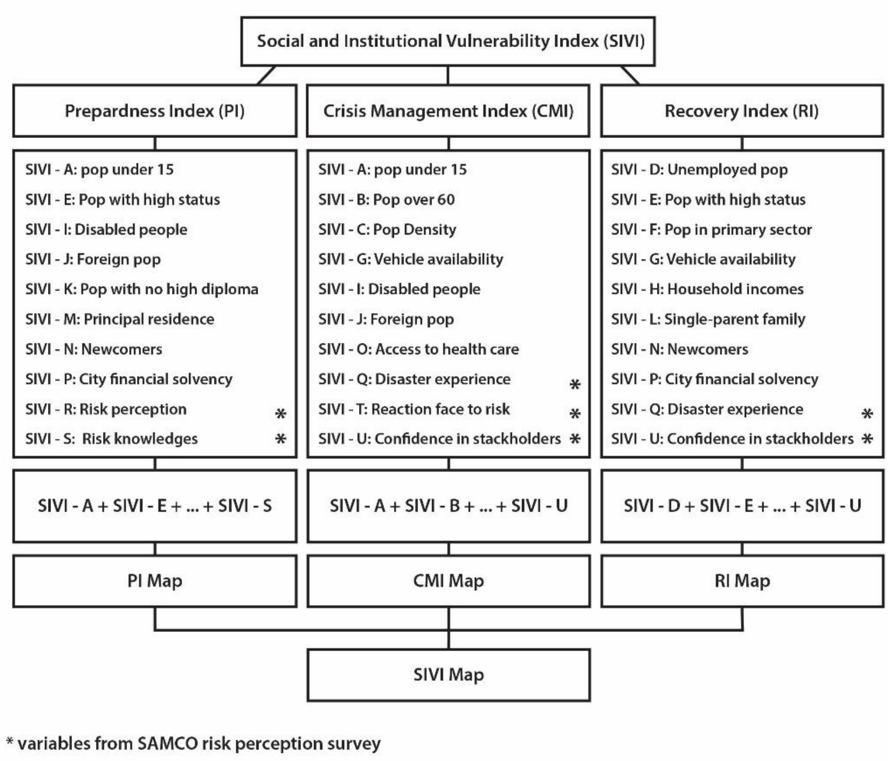


Figure 3: Framework for the calculation of the Social and Institutional Vulnerability Index (SIVI). Criteria with an * are those derived from the risk perception survey.

After the identification of the major stakes, the second step consisted in assigning a weigh to each modality of the considered variables. The value of each modalitiesThe 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~~. A complete description of the considered variables and associated weights are shown in~~ (Fig. 4~~ and 5.~~

~~Then,~~). In the third step, direct (~~i.e. physical injury, structural and functional impact~~PII and SFI) and indirect (IFI) consequences ~~(socio-economics) were~~ are modelled using linear combination. In this step, ~~minor modifications~~a coefficient is assigned to each variable with respect to the socioeconomic context of the region and the type of ~~the originally presented model were integrated to its adaptation for flooding (see * in~~ consequence assessed (direct or indirect) (Fig.~~2~~ 3 and 4). ~~*Preparedness Index, Crisis Management Index* and *Recovery Index* were calculated and~~The coefficient, called *local index* (*li*) varies from 1 to 4. To finish, the 3 sub-indices are combined to obtain the ~~*Social and Institutional Vulnerability Index* for the six studied municipalities. PDI and GPDI were finally calculated for each stakes combining the index scores of previously calculated indices (Fig. 2).~~

		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.

~~***2.2 Database on elements at***~~*Potential Damage Index* (PDI). In order to be used in a risk~~, *census data and*~~ analysis, PDI is reclassified in 5 classes and mapped. With a matrix, PDI map is then combined with a hazard map (reclassified in 5 classes as well) to obtain a type 1957 flood risk ~~***perception survey***~~

~~As described in Puissant *et al*. (2006, 2013), the first step consisted in elaborating a complete database for elements at risk (i.e. buildings, networks and land cover/uses) on GIS.~~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 ~~fill this~~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.).

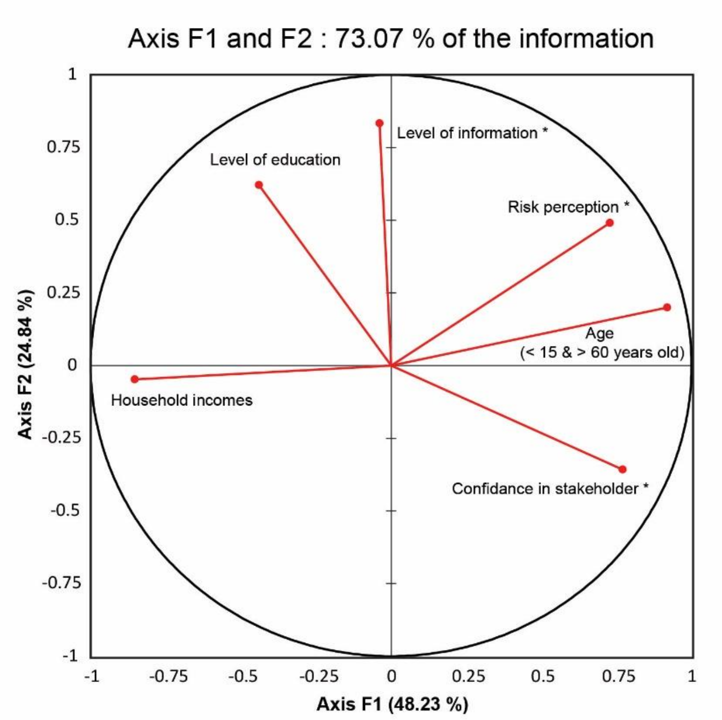
EaR-A	Building material	
	Concrete	0,8
	Wood	1
	Mixture (wood & concrete)	0,8
	Metal	0,4
	Stone & wood (traditional)	0,8
	Natural	0,4
	Coated, asphalted surfaces	0,2
EaR-B	Building State	
	Good	1
	Moderate	0,7
	Bad	0,2
	Very bad (ruin)	0
EaR-C	Building Age	
	<1900	0,3
	1900-1950	0,5
	1950-1970	0,7
	1970-1990	0,9
	1990-2000	1
	2000-2010	1
	>2010	1
EaR-D	Building protection *	
	Absence	1
	Sparsed hedge	0,9
	Dense hedge	0,8
	Wire fence	0,8
	Low wall (dry stone)	0,7
	Low wall (masonery)	0,7
	Wooden fence	0,6
	Mixed (low wall & hedge or fence)	0,5
	Wall >1,5m	0,3
	Shutter on opening exposed to hazard	0,4
	Building protecting other building	0,1
	Snow supporting structure	0
EaR-E	Occupied floors	
	>6	1
	3 - 6	0,7
	<3	1
	0	0
EaR-F	Number of floors	
	>3	0,5
	3	0,5
	2	0,7
	1	1
EaR-G	Building Function	
	Education	1
	Emergency	0,95
	Trade	0,9
	Industry/Craft	0,9
	Public administration	0,7
	Accommodation	0,8
	Agricultural	0,4
	Tourism	0,8
	Religious	0,2

EaR-H	Distance to torrent *	Torrentiality
	<10m	1
	10m to 20m	0,8
	20m to 30m	0,6
	30m to 40m	0,4
	40m to 50m	0,2
	>50m	0
EaR-I	Opening on endangered facade *	Torrentiality
	Absence	0
	1 - 3	0,6
	4 - 6	0,8
	>6 (or glass wall)	1
EaR-J	Building type	Torrentiality
	"Sensitive" building (city hall, hospital, fire station)	1
	Housing	1
	Tourism activity	0,8
	Cultural heritage	0,3
	Shed and warhouse	0,5
	Car park	0,2
	Hut	0,1
	Cemetery	0
EaR-K	Transport & energy systems	Torrentiality
	Main road	1
	Secondary road	0,8
	Gravel road	0,6
	~~Track~~	~~0,1~~
	Ski lift	0,7
	High-voltage line	1
EaR-L	Lancover	Torrentiality
	Urban	0,6
	Farming/pasture	0,35
	Forest	0,2
	Grass	0,15
	Water surface	0,1
	Alluvium	0,05
	Bare rock & colluvium	0,05
EaR-M	Land use	Torrentiality
	Urban	1
	Arable land	0,25
	Winter tourist activities	0,8
	Summer tourist activities	0,5
	Protected area	0,15

~~**Figure 4:** Detail of weights assigned to the attributes of the physical stakes in PDI. Criteria with an * have been added in order to adapt the model for flooding.~~

~~Census data used for the social and institutional vulnerability assessment were provided by the *Institut National de la Statistique et des Etudes Economiques* (INSEE) or were calculated from data collected by the INSEE. When this work started, the 2014 census data were not fully accessible. Therefore, we used data from the 2012 and 2006 Census to complete our data. All the data used are available in the statistical database on the INSSE website, and in a publication of the 2014 Legal Population Census of France. Information related to the communities' financial solvency came from the different websites of the studied communities.~~

~~A risk perception survey consisted in a questionnaire (38 questions) carried out on the six studied municipalities have been done during the autumn 2014 and the summer 2015/2016. It was focused on 3 main issues: (1) inhabitant perception of the different risks, (2) inhabitant knowledges about preventive and protective measures and (3) inhabitant confidence in stakeholders. One hundred questionnaires were collected (about 5% of the total population): 8 in Ristolas, 22 in Abriès, 22 in Aiguilles, 16 in Château-Ville-Vieille, 17 in Molines-en-Queyras and 15 in St-Véran. People were surveyed by an interviewer in person or by paper questionnaires delivered in person. Special attention was made in order to have a representative view of the socio-economic characteristics of local population. In the second and third campaign, surveyed people were selected for their demographic and socio-economic characteristics according to INSEE census data.~~



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

~~*2.3 Construction and organisation of the SIVI*~~

~~As previously mentioned, the SIVI is structured on three indices representing the main phases of risk management: preparedness, crisis management and recovery. Using this type of approach requires the selection of specific criteria that unequivocally represent the different forms of social and institutional vulnerability (Rygel *et al*., 2006). The literature~~

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~~. An intensive review of published data on social vulnerability indices was performed in view to select a set of pertinent indicators (Table 1).~~

~~Actually, most of~~ (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, ~~ethnicity and~~ education or disabilities (~~Table~~Tab. 1).

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

In agreement with these existing published references, ~~socioeconomic~~ socio-economic data were collected for the six ~~studied~~ municipalities~~. 15~~ of the Upper-Guil Catchment. A set 21 criteria ~~were~~was first selected ~~in the INSEE census~~(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~~) (Table 2) and~~). 5 ~~from the~~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 the frame of the SAMCO project (2014-2015) (see * in Table 2). 2 other criteria were calculated with derived data (Insee, 2015) bringing the total number of criteria to 22 (Table 2).~~

	Chakrabortyet al., 2005	Clarket al., 1998	Cutteret al., 2003	Fekete, 2009	Flanaganet al., 2012	Frigerioet al., 2016	Johnsonet al., 2012	Nelsonet al., 2015	Schmidtleinet al., 2008	Wu et al., 2002	Zahranet al., 2008	Zhang & You, 2014	Total
Age	■	■	■	■	■	■	■	■	■	■		■	11
Income	■	■	■	■	■		■	■	■	■	■	■	11
Race and ethnicity		■	■	■	■	■	■	■	■	■	■		10
Gender		■	■	■		■	■	■	■	■		■	9
Education level	■	■	■	■	■	■	■		■			■	9
Employment		■	■	■	■	■		■	■				7
Special need population	■	■	■	■	■	■		■					7
~~Family structure~~		■	■			■	■	■		■			~~6~~
Mobility	■	■			■	■		■				■	6
Equipement	■	■	■		■							■	5
Medical service			■	■		■		■				■	5
Population (number/density)	■			■		■				■			4
Employed in primary sector		■							■			■	3
Recent arrival		■		■				■					3
Municipality budget				■								■	2
Owner/tenant			■							■			2

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).

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

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*

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	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16
Education level	X	X	X	X	X	X		X			X	X	X	X	X	X	14
Employment	X	X	X	X	X		X	X		X	X	X	X	X	X	X	14
Special need population	X	X	X	X	X		X	X		X	X	X	X	X	X		13
Income	X	X	X	X	X	X		X	X	X		X	X			X	12
Gender	X	X	X		X	X		X		X	X		X	X		X	11
Race and ethnicity	X	X	X	X	X		X	X	X	X	X						10
Family structure	X	X			X			X	X	X	X	X		X			9
Medical service		X	X		X	X		X		X	X		X		X		9
Population (number or density)			X		X		X		X		X			X	X	X	8
Mobility	X			X		X	X	X		X	X						7
Equipement	X	X		X	X	X		X							X		7
Recent arrival	X		X					X		X					X	X	6
Employment in primary sector	X				X	X	X	X									5
Owner/Tenant		X			X							X		X			4
Municipality budget			X			X									X		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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The three indices representing the phases of risk management were then constructed using the selected criteria (Fig. 3). The first one, the *Preparedness Index* (PI), is focused on inhabitant experiences about risks and deployed preventive measures. The second one, the *Crisis Management Index* (CMI), insists on people abilities to react aptly facing a catastrophic event. The third, the *Recovery Index* (RI), concerns the people capacities to recover after a disaster, thus it is mostly constructed with economic criteria.

According to PDI methodology, weights among 0 to 1 were affected at each proxy of the 22 criteria used in the SIVI model (Fig. 5). PI, CMI, and RI were then calculated using linear combinations on GIS (raster calculator tool on ArcGIS). SIVI was finally

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.

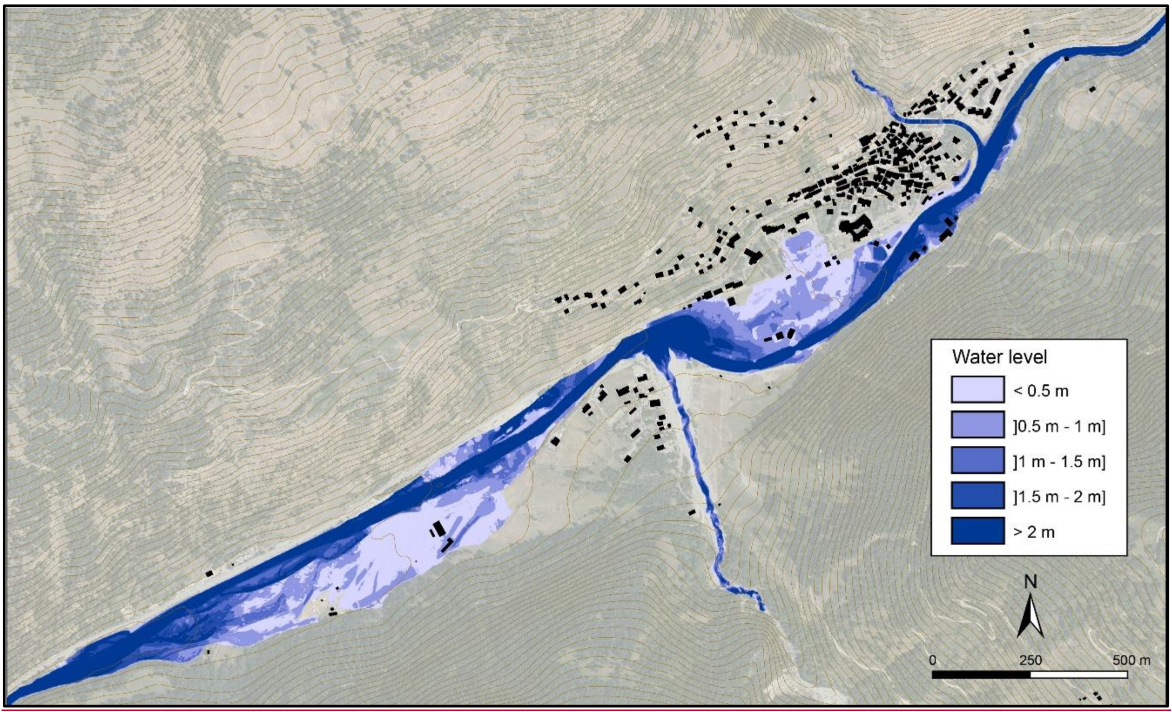

Figure 8: Zoom on type 1957 flood map produced for Aiguilles village.

3. Results

Using the methods previously described, PDI and PCI were calculated by summing the index scores of the three indices and included in the PDI to obtain GPDI (Fig. 2).

Variable code	*Variable*	*Increase (+) or decrease (-) social vulnerability if high*
SIVI - A	Percent of children15 and under	+
SIVI - B	Percent of population 60 years or older	+
SIVI - C	Population density (in habs / km²)	+
SIVI - D	Percent of unemployed people	+
SIVI - E	Percent of population with high socioeconomic status*	-
SIVI - F	Percent of population employed in primary sector	+
SIVI - G	Percent of household with no vehicle available	+
SIVI - H	Household incomes / average national household incomes	-
SIVI - I	Percent of population which is mentally disabled	+
SIVI - J	Percent of foreign population	+
SIVI - K	Percent of population with no high diploma (> BAC)	+
SIVI - L	Percent of single-parent family	+
SIVI - M	Percent of principal residence	-
SIVI - N	Percent of the population which moved in less than 2 years ago	+
SIVI - O	Distance to nearest medical centre (in decimal h)	-
SIVI - P	Communities financial solvency (cash flow = operating charges - debt annuity /incomes)	+
SIVI - Q	Percent of IP who never experienced a catastrophic event**	+
SIVI - R	Percent of IP considering risk as low**	+
SIVI - S	Percent of IP considering themselves as sufficiently informed on risk**	-
SIVI - T	Percent of IP who responded not knowing what to do if a catastrophic event occurs**	+
SIVI - U	Percent of IP who have not confidence in local planners**	+

IP: investigated population
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Table 2: Criteria selectedmapped for the calculation of SIVI and their impacts on social and institutional vulnerability.

2.4 Test runs and comparisons between PDI and GPDI applied to torrential floods

~~To evaluate the pertinence of our model, we proceeded to different test runs. First, we declined the SIVI in two versions: standardized and adapted to our field~~six municipalities of the Upper-Guil catchment. The ~~classical version (CV) correspond to the "theoretical SIVI" with standardized modalities and weighting. It is mostly constructed on~~ 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 ~~national data, and so give us an estimation of social and institutional vulnerability comparable to other French communities. The adapted version (AV) correspond to a SIVI adapted for our study area and dataset. It permit to qualify the social and institutional vulnerability comparing to proximal communities. The aim of this test was to establish the flexibility of our model and its possible transposition to a specific study area. Modalities and weighting are thus, quite different (Fig.5).~~

~~A second run was computed to test the influence of the variable coming from risk perception surveys. To achieve this, PI, CMI, RI and SIVI score were calculated without the data from questionnaires and compared with original model scores. Complete comparison of the two versions of SIVI is showed in Fig. 8.~~

~~Last, a~~ and standard deviation. To get a better understanding, PDI results are described before PCI's one. Then, a complete comparison between ~~the *Potential Damage Index* and the two version (classical and field adapted) of the *Global Potential Damage Index* was made for flooding (Fig. 9 and 10).~~

Variable code	Variable	Modality for a normal distribution	Modality for an asymmetric distribution	Weighting for a normal distribution	Weighting for an asymmetric distribution
SIVI-A	Percent of children15 and under	Less than 20% 20-30% 30 -40% 40-50% More than 50 %	Less than 15% 15-20% 20-25%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,8
SIVI-B	Percent of population 60 years or older	Less than 20% 20-30% 30 -40% 40-50% More than 50 %	Less than 20% 20-25% 25-30% More than 30%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1
SIVI-C	Population density (in habs / km²)	Less than 25 habs/km² 25-50 habs/km² 50-100 habs/Km² 10-200 habs/km² More than 200 habs/km²	Less than 1 habs/km² 1-5 5-10 More than 10 habs/km²	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1
SIVI-E	Percent of unemployed people	Less than 8% 8-10% 10-12% More than 12%	0% 0-5% More than 5%	0,1 0,4 0,7 1	0,1 0,4 0,8
SIVI-F	Percent of population with high socio-economic status*	Less than 10% 10-25% 25-50% 50-75% 75-100%	Less than 10% 10-15% 15-20% More than 20%	1 0,8 0,6 0,4 0,1	1 0,7 0,4 0,1
SIVI-G	Percent of population employed in primary sector	Less than 5% 5-10% 10-15% 15-20% More than 20%	0% 0-5% 5-10% More than 10%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1
SIVI-H	Percent of household with no vehicle available	Less than 10% 10-25% 25-50% 50-75% 75-100%	Less than 5% 5-10% More than 10%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,8
SIVI-I	Household incomes / average national household incomes	Less than 60% 60-70% 70-80% 80-90% 90-100%	Less than 80% 80-90% 90-100%	1 0,8 0,6 0,4 0,1	0,8 0,4 0,1
SIVI-J	Percent of population which is mentally disabled	Less than 5% 5-10% More than 10%	Less than 10% 10-15% More than 15%	0,1 0,5 1	0,1 0,5 1
SIVI-K	Percent of foreign population	Less than 5% 5-10% 10-15% 15-20% More than 20%	Less than 1% 1-2% More than 2%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,8
SIVI-L	Percent of population with no high diploma (> BAC)	Less than 25% 25-50% 50-75% 75-100%	Less than 70% 70-75% More than 75%	0,1 0,4 0,7 1	0,1 0,4 0,8
SIVI-M	Percent of single-parent family	Less than 10% 10-15% 15-20% 20-25% More than 25%	Less than 10% 10-15% 15-20%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,8
SIVI-N	Percent of principal residence	Less than 25% 25-50% 50-75% 75-100%	Less than 20% 20-30% More than 30%	0,1 0,4 0,7 1	0,1 0,4 0,8
SIVI-O	Percent of the population which moved in less than 2 years ago	Less than 10% 10-25% 25-50% 50-75% 75-100%	Less than 10% 10-15% More than 15%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,8
SIVI-P	Distance to nearest medical centre (in decimal h)	Less than 0,25 h 0,25-0,50 h 0,50-0,75 h 0,75-1,00 h More than 1,00 h	0-0,10 0,10-0,20 h 0,20-0,30 h More than 0,30 h	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1
SIVI-Q	Communities financial solvency (cash flow = operating charges - debt annuity /incomes)	Less than 0,50 0,50-0,75 0,75-1 1-1,25 More than 1,25	Less than 0,90 0,90-1,00 1,00-1,10 More than 1,10	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1
SIVI-R	Percent of interogated population who never experienced a catastrophic event**	Less than 10% 10-25% 25-50% 50-75% 75-100%	Less than 15% 15-20% 20-25% More than 25%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1
SIVI-S	Percent of interogated population considering risk as low**	Less than 10% 10-25% 25-50% 50-75% 75-100%	Less than 25% 25-50% 50-75% More than 75%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1
SIVI-T	Percent of interogated population considering themselves as sufficiently informed on risk**	Less than 10% 10-25% 25-50% 50-75% 75-100%	Less than 20% 20-30% 30-40% More than 40%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1
SIVI-U	Percent of interogated population who responded not knowing what to do if a catastrophic event occurs**	Less than 10% 10-25% 25-50% 50-75% 75-100%	Less than 25% 25-50% More than 50%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,8
SIVI-V	Percent of interogated population who have not confidence in local planners**	Less than 10% 10-25% 25-50% 50-75% 75-100%	Less than 20% 20-25% 25-30% More than 30%	0,1 0,4 0,6 0,8 1	0,1 0,4 0,7 1

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~~**Figure 5:** Detail of weights assigned to the attributes used in SIVI calculation. Criteria with an * are those derived from the risk perception survey.~~

3. Results and discussion

3.1 Classical and adapted version of SIVI

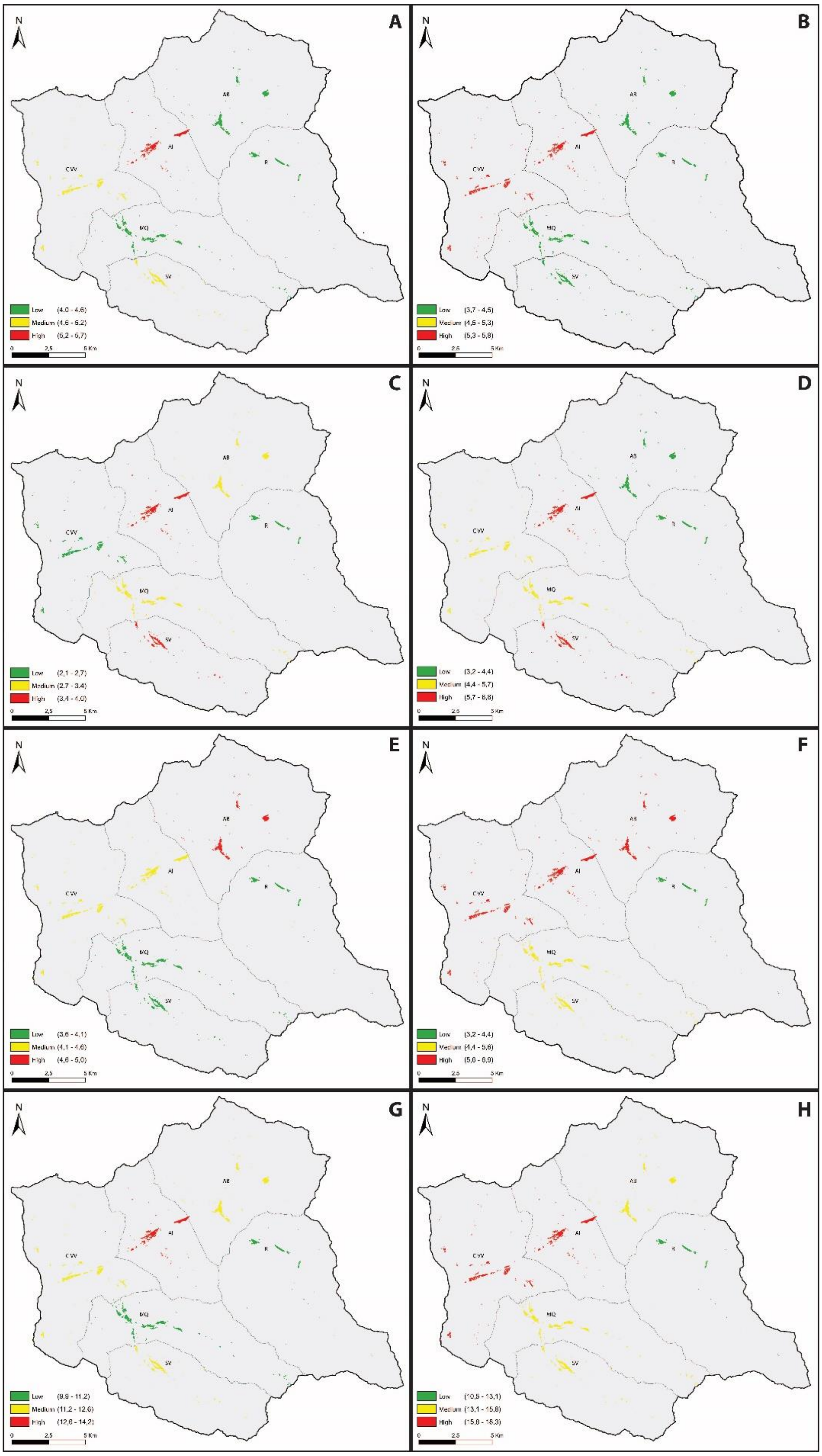


Figure 6: Indices maps for classical version (CV) and adapted version (AV) of the Social and Institutional Vulnerability Index (SIVI):
(A) Preparedness Index map for CV,
(B) PI map for AV,
(C) Crisis Management Index map for CV,
(D) CMI map for AV,
(E) Recovery Index map for CV,
(F) RI map for AV,
(G) Social an Institutional Vulnerability map for CV,
(H) SIVI map for AV.
R= Ristolas,
AB = Abriès,
AI = Aiguilles,
CVV = Château-Ville-Vieille,
MQ = Molines-en-Queyras
SV = St-Véran.

Using the different methods previously described (Fig. 3), SIVI was calculated for the six municipalities of the Upper Guil catchment. PI, CMI, RI and SIVI scores were obtained and classified for classical (CV) and adapted versions (AV) of the model (Fig. 6). Due to the limited number of studied communities, all the indices were represented in three classes. Because statistical series are symmetric, classification was made using, median and standard deviations.

Looking for produced maps (Fig. 6), some first elements can be pointed out: (1) Index scores are globally higher for the adapted version than for the classical version, (2) intervalsPDI and PCI results is proposed. To highlight differences between extremes are more important for AV and, (3) there are more communities in the higher vulnerability class in AV maps than in CV maps. These first results are in conformity with those expected. Because CV is mostly constructed on national averaged data's, some modalities of its variable components are not represented here. In fact, there is only few studied communities and their proximity make them broadly similar in terms of vulnerability. Inversely, AV was constructed in order to have its all modalities expressed. As a result, indices scores are generally lower in CV than in AV. Furthermore, we note that, between the two versions, *Preparedness Index*, *Crisis Management Index* and *Recovery Index* don't have the same importance. In CV, *Preparedness Index* is the more influent component of SIVI while in AV it is the *Recovery Index* followed by *Crisis Management Index*. These elements apart, similar tendencies are observed for normal and adapted versions of PI, CMI, RI and SIVI maps (Fig.6).

Preparedness Index maps are closed and extremes are preserved from CV (Fig.6, A) to AV (Fig.6, B). AV give us complementary information's on Château-Ville-Vieille and St-Véran villages indicating in which direction tends their vulnerability. Here, communities with better index scores are those which are the well prepared, with a great proportion of their population living here for long time and having experienced various catastrophic events. They are also those managed by local councillors particularly involved in developing preventive measures (communication on risk, security planning, crisis simulation exercises etc.).

Crisis Management Index maps (Fig.6, C and D) are similar too. Differences between CV and AV are related to Château-Ville-Vieille and Abriès villages. These two communities have similar scores. Because these scores are close to a class limit (between "low" and "medium" vulnerability class) we observe a reversal between the ranking of Abriès and Château-Ville-Vieille village. Communities with highest scores actually have the highest proportion of people unable to aptly react to a catastrophic event. Concerned people include those recently settled, or isolated or/and dependant (children, elderly, disabled persons etc.) populations. People who develop the less confidence in local authorities to protect them against risks are also included here

In *Recovery Index* maps the same organisation is observed for CV (Fig.6, E) and AV (Fig.6, F). In both case, there is a partition between a group with a high index scores (Château-Ville-Vieille, Aiguilles and Abriès villages) and a lowest index score group (Ristolas, Molines-en-Queyras and St-Véran villages). In these maps, communities with lower scores are those more able to recover quickly their functionalities after a catastrophic event. Their population have, globally, a better social status and are richest than those of the other communities. These municipalities have also a better fiscal health and thus have more chances to quickly repair damage caused by hazards.

Social and Institutional Vulnerability Index represents a synthetic view of the vulnerability issued from the 3 identified phases of risk management. Here, communities with low score are theoretically the more resilient. Their populations are well prepared, know how to react to a catastrophic event, have confidence in local authorities for risk management and are more able to recover quickly if they are directly impacted. Associated maps for classical version (Fig.6, G) and field adapted version (Fig.6, H) display similar results. Aiguilles village that has high scores for all the indices of two versions appears as the less resilient community. Conversely, Ristolas, which has the lower scores, can be considered as the more resilient. Abriès village has high scores for *Recovery Index* but low scores for the other indices, consequently it is in the medium vulnerability class. St Véran village has high scores for *Crisis Management Index* but this is partially counterbalanced by its relatively low scores for *Preparedness Index* and *Recovery Index*. Its social and institutional vulnerability is so, medium in both versions. Molines-en-Queyras and Château-Ville-Vieille communities appear as those having experienced the more important weight changes between the two versions. Respectively classified as low and moderately vulnerable in classical version they are, in fact, classified as moderate and high in field adapted version.

3.2 SIVI with and without questionnaires data

The second test was made to evaluate the influence of criteria coming from the risk perception survey. *Social and Institutional Vulnerability Index* was calculated without the data from risk perception survey and compared with complete SIVI (Fig. the two models7). For the sake of readability, we only presented here the test for the adapted version of the model.

Removing the variables from risk perception survey necessarily imply changes in SIVI results. At first reading, vulnerability appears as higher in the truncated version for *Preparedness Index* (Fig. 7, B) and *Crisis Management Index* (Fig. 7, D) and lesser for *Recovery Index* (Fig. 7, F). Considering indices scores, changes are more consequent for the *Crisis Management Index* since it's the index containing the most of perception survey variables. At the opposite, smaller changes are observed for *Recovery Index*. In both version, *Recovery Index* have the highest score and remain the one, which mostly influence SIVI results. Paradoxically, *Recovery Index* experienced the most important change in terms of vulnerability class between the version with and without questionnaire data's.

The low importance of *Crisis Management Index* comparing to *Preparedness Index* and *Recovery Index* is illustrated by truncated SIVI map (Fig. 7, H). For instance, despite high *Crisis Management Index* scores for St-Véran and Molines-en-Queyras, the two communities are classified as low vulnerable in SIVI. Therefore, the loss of information resulting of the removing of survey variables is reflected by clear-cut results. There is, in fact, a strong opposition between the more active and populated communities (Abriès, Aiguilles and Château-Ville-Vieille) and the modest ones (Ristolas, Molines-en-Queyras and St-Véran). Based only on classical socio-economics data, main villages appear as highly vulnerable while the other villages appear as low vulnerable.

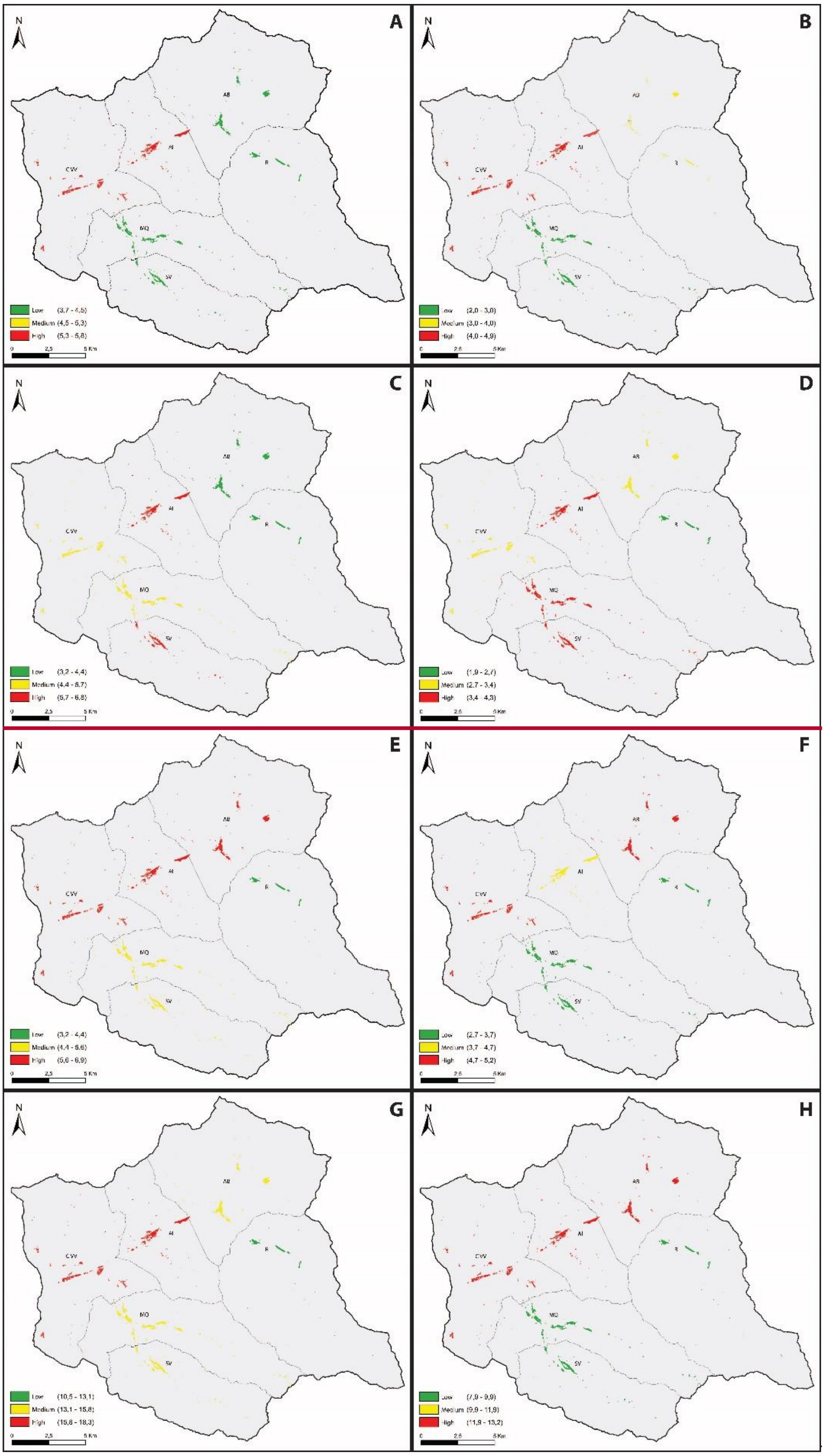
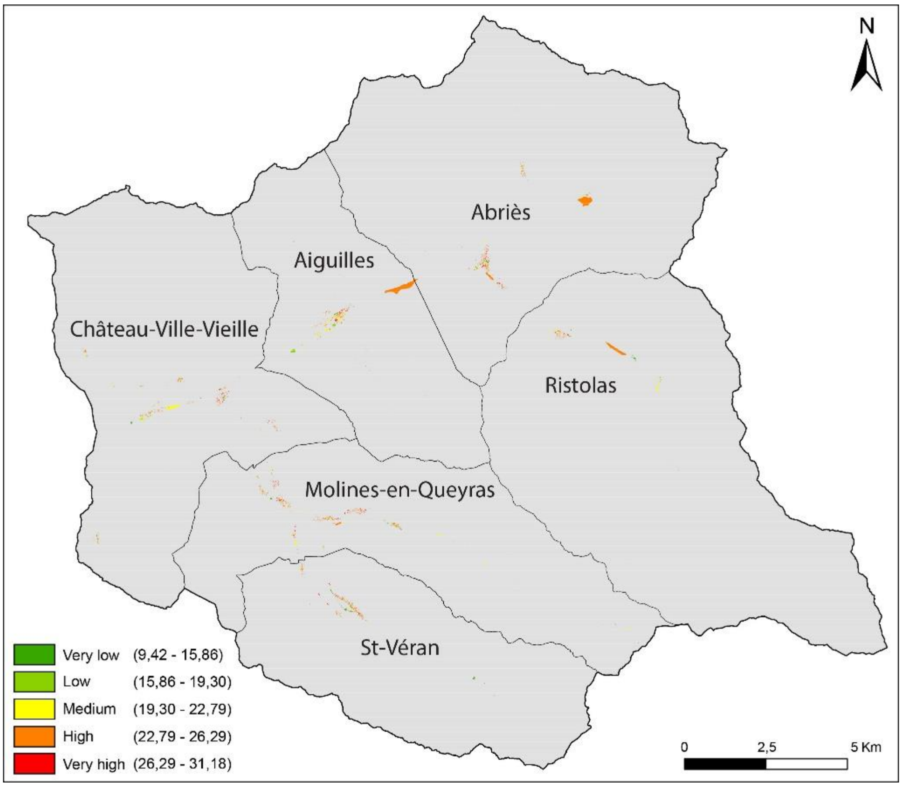


Figure 7: Indices maps for adapted version with and without criteria derived from risk perception survey: (A) PI map with survey criteria, (B) PI map without survey criteria, (C) CMI map with survey criteria, (D) CMI without survey criteria, (E) RI map with survey criteria, (F) RI map without survey criteria, (G) SIVI map with survey criteria, (H) SIVI map without survey criteria. R= Ristolas, AB = Abriès, AI = Aiguilles, CVV = Château-Ville-Vieille, MQ = Molines-en-Queyras and SV = St-Véran.

3.3 Comparison between PDI and GDPI



PDI model is an efficient tool to estimate potential physical consequences on human stakes. In this part, we investigate the possibility to adapt it in order to estimate social and institutional consequences too. Original PDI map for flooding was obtained for the Upper Guil catchment (Fig. 8) by summing the classified *Physical Injury Index (PII)*, *Structural and Functional Index (SFI)* and *Socio-Economic Index (SEI)*. Here, the three indices have

Figure 8: Original PDI map for the Upper Guil catchment

symmetric distributions, thus, they are ranked in five classes using median and standard deviations. For buildings, highest scores are generally observed for *Physical Injury Index* (median: 12.5) and lowest for *Socio-Economic Index* (median: 4). *Structural and Functional Index* scores are comprised between the both (median: 8.7). Zooms on Aiguilles and Abriès villages are shown in Fig. 10, A and B.

Two versions of GPDI were then calculated using classical (Fig. 9, A) and adapted versions (Fig. 9, B) of SIVI. Zooms on Aiguilles and Abriès village are shown in Fig. 10. To highlight differences between PDI and the two GPDI versions, networks and land cover/uses are ignored in this part of the analysis.

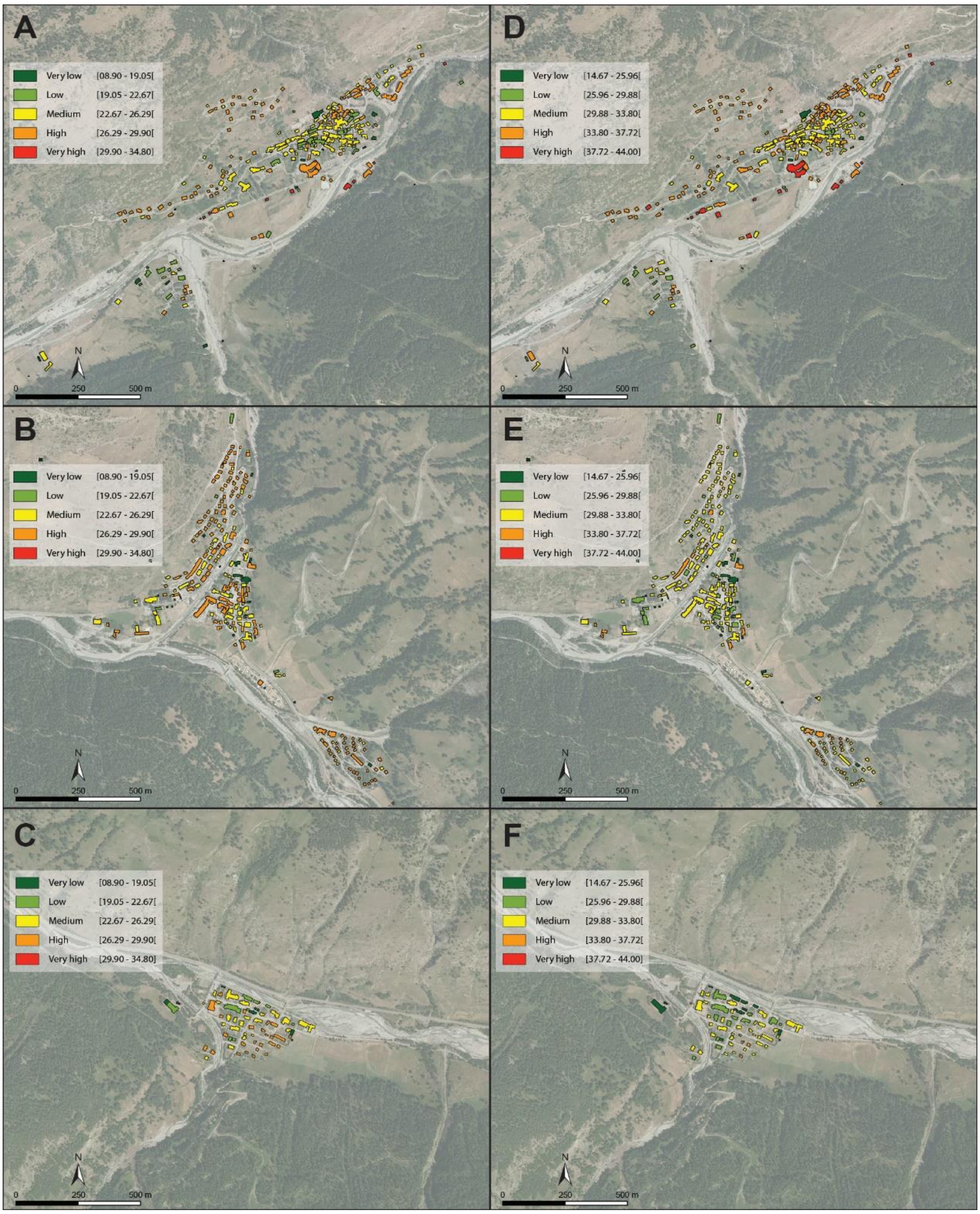
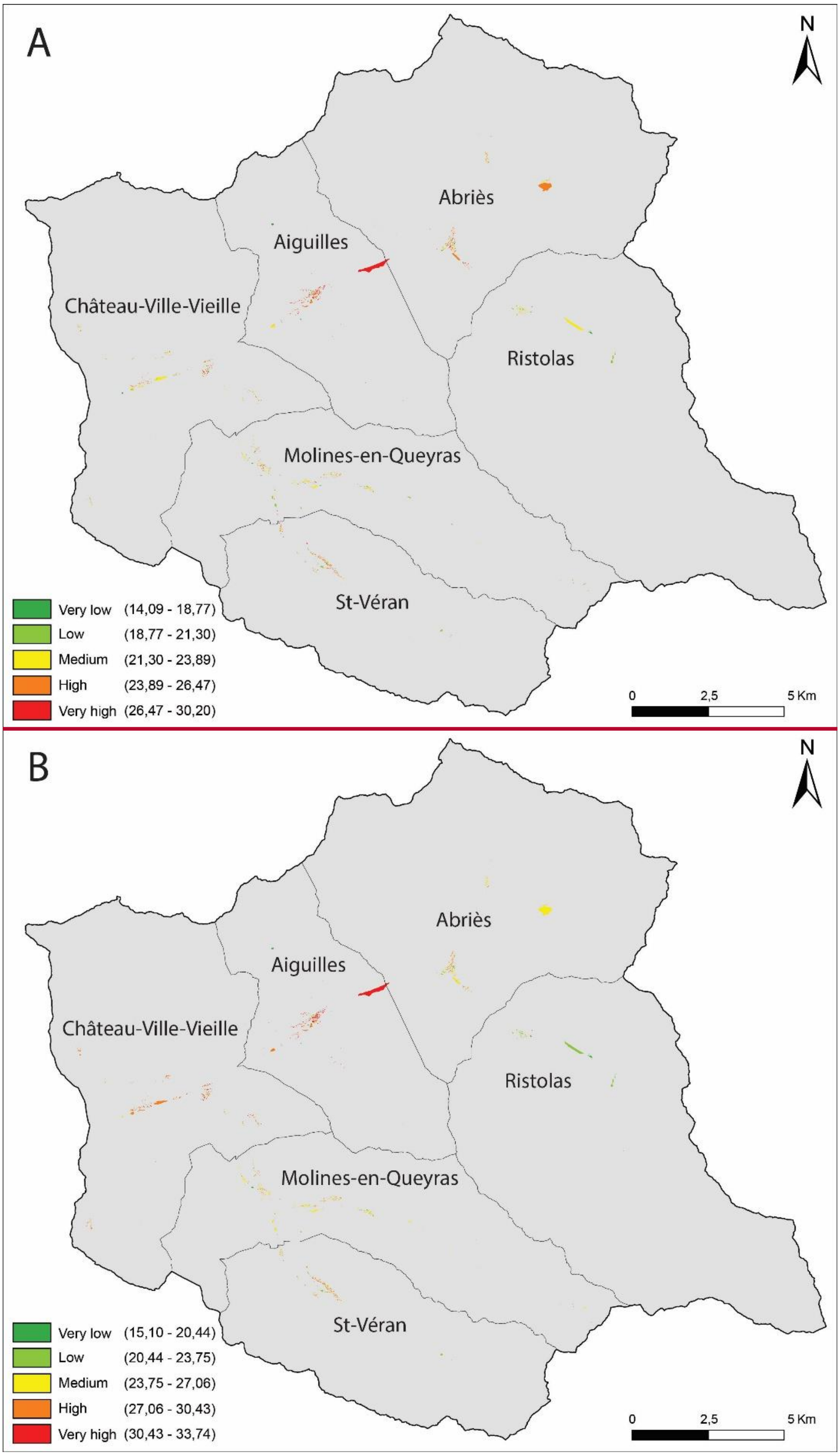


Figure 9: Comparison between PDI and PCI maps. A – Zoom on PDI map ~~for flooding (Fig. 8)~~produced for Aiguilles village; B – Zoom on PDI map produced for Abriès village; C – Zoom on PDI map produced for Ristolas village; D – Zoom on PCI map produced for Aiguilles village; E – Zoom on PCI map produced 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 ~~PDI~~ scores are mainly located in ~~close proximity to~~the vicinity of the Guil River or one of its main tributaries (Fig. ~~10~~9, A, B and ~~B~~C). Major stakes such rescue centres (hospital, fire-station etc.), town-halls~~,~~ and schools ~~and purification plant have~~are also classified with a high degree of potential consequences~~ because of~~. This is due to their important function in local life. Conversely, churches, ~~car parks,~~ sheds and warehouses have a low degree of potential consequences. In town centres, buildings with trading or touristic function are generally ~~classified as~~ in the "high~~ beside~~" consequence class whereas those ~~with~~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~~. They~~ because they were~~, in fact,~~ not constructed to resist ~~to~~ 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 ~~of their remoteness to~~they are located away from the torrential streams.



~~**Figure 9:** GPDI maps with classical and adapted version of SIVI: A) GPDI map with classical SIVI, (B) GPDI map with adapted version of SIVI.~~

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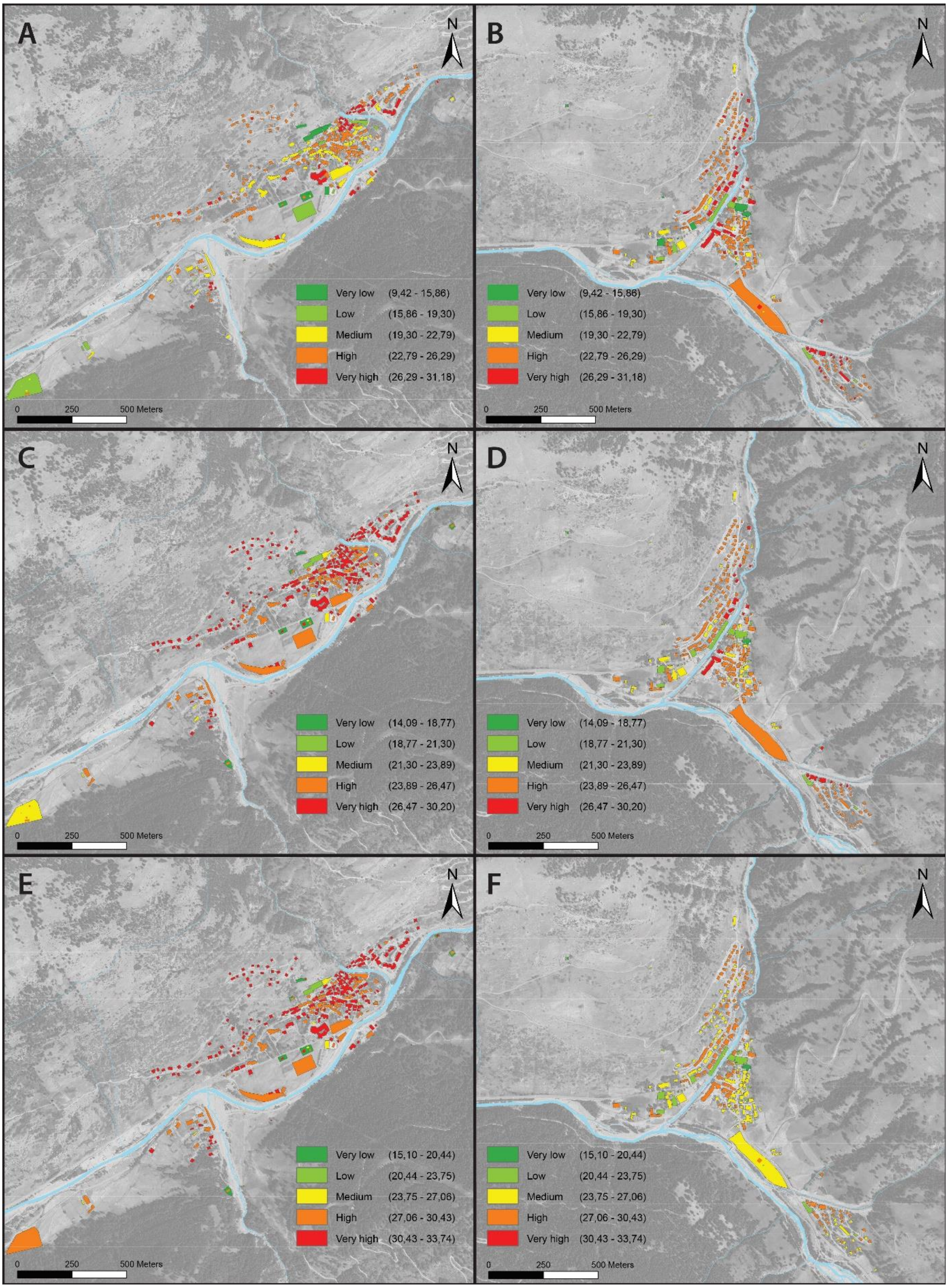
~~**Figure 9:** Zoom on Aiguilles and Abriès villages for PDI and GPDI map: (A) PDI map for Aiguilles village, (B) PDI map for Abriès village (C) GPDI map with classical SIVI for Aiguilles village, (D) GPDI map with classical SIVI for Abriès village, (E) GPDI map with adapted version of SIVI for Aiguilles village, (F) GPDI map with adapted version of SIVI for Abriès village.~~



GPDI maps for flooding displays result different from a community to another. This is due to the influence of SIVI, which is equally applied for the all buildings of a same community. This tend to homogenise GPDI score by uplifting minimum values. Despite these scores variations, we observe some similarities between PDI and GPDI at community scale. Maximum scores for PDI and GPDI are in the same order of magnitude and buildings with high scores are in the vicinity of the Guil Rivers and its main tributaries or are major stakes (hospital, fire station, town hall etc.). Conversely to PDI, GPDI scores mapping at regional scale tend to highlight the differences between the studied communities. GPDI scores mapping are globally lower than those of PDI for both classical (Fig. 9, A) and adapted version (Fig. 9, B). The main exception is Aiguilles village (Fig. 10, C and E) because of it high SIVI score. This indicate that resilient population may qualify results obtained for physical consequences.

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.

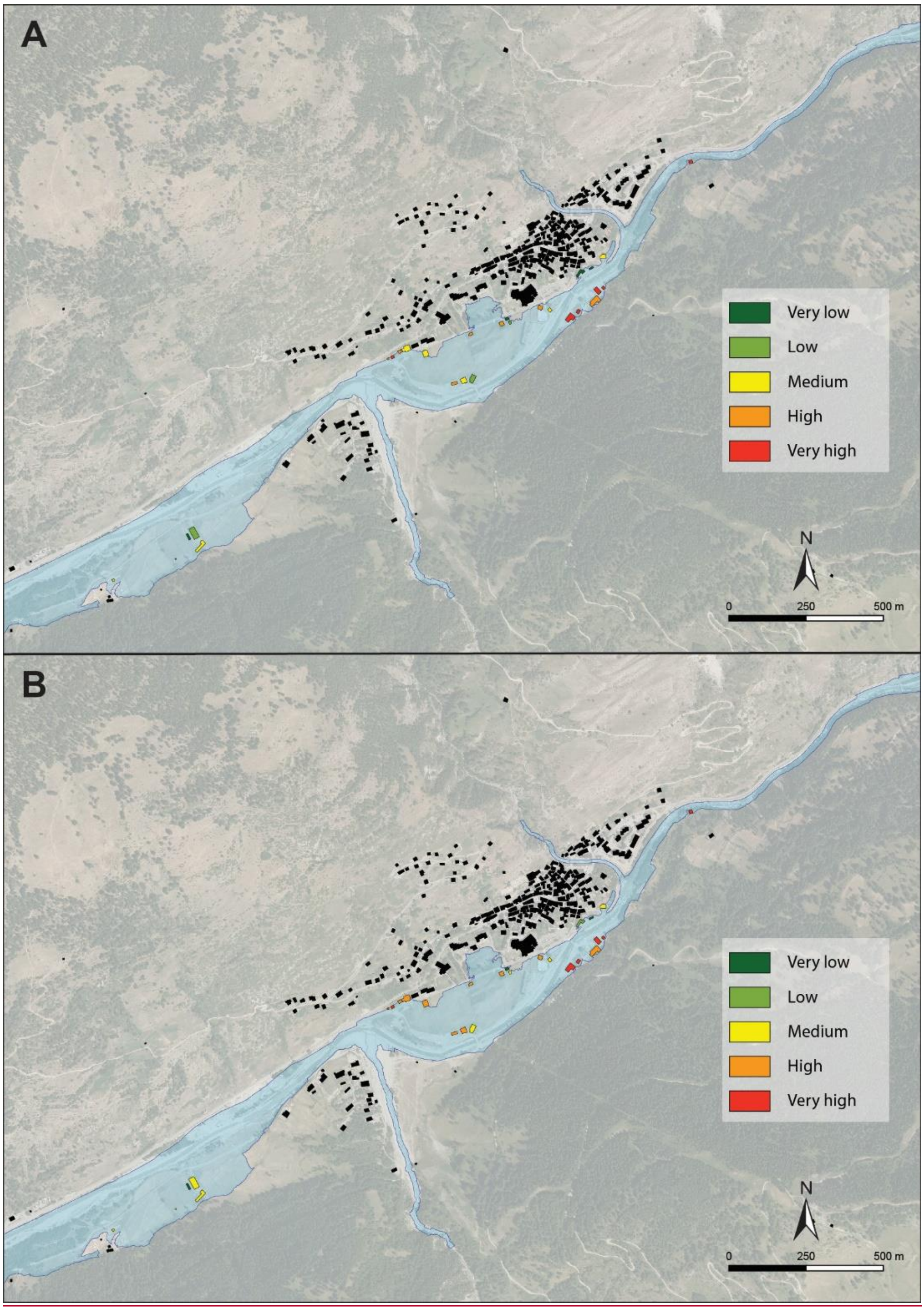


Figure 11: Comparison between type 1957 flood risk maps produced using PDI and PCI. A – Flood risk map produced using PDI; B – Flood risk map produced using PCI.

Conclusions and ~~perspective~~perspectives

~~Looking for results some remarks can be made concerning the uses of the GPDI model. Classical version appears as more efficient to estimate and compare social and institutional vulnerability at a large scale. Because it is mostly based on national averaged data, it gives us a level of vulnerability, which must be compared to results obtained in different places of a same country. Adapted version allows to detail the results of classical version highlighting the similarities and differences of nearby communities. AV is fine at county or regional level but, conversely to CV, it is not directly transposable to all areas. However, all these elements require a confirmation due to the short number of studied communities in this analysis.~~

~~One of the originality of SIVI is its sub-division in three indices representing the main phases of risk management: *preparedness*, *crisis management* and *recovery*. This organization get the advantage to display information easily interpretable by risk managers or local decision makers. Furthermore, it allow developing mitigation measures adapted to local population indicating the most relevant vulnerability aspect to analyse. Until now, *Social and Institutional Vulnerability Index* is calculated by summing *Preparedness Index*, *Crisis Management Index* and *Recovery Index*. This may introduce an imbalance in the representability of each index into SIVI. Using a qualitative matrix to obtain SIVI will possibly solve this problem.~~

~~Another original aspect of SIVI is the integration of data derived from risk perception survey. This makes possible to qualify results which are usually obtained with only census data. However, because questionnaire surveys take time and require consequent fieldwork, it is clear that use of SIVI model at large scale will be quite difficult. If removing the data from survey implies necessarily a loss of information, the model appears as sufficiently robust to be used without these data.~~

~~Originally, SIVI was developed as an add-on for the *Potential Damage Index*. Until now, results are still mitigated yet encouraging. The main problem remains~~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 ~~SIVI~~the SCI is applied ~~for~~to the overall building of a same community. By proceeding so, ~~SIVI has a great influence on PDI and~~SCI tends to homogenize ~~it. While, the simplification of the information which results from it highlight the more vulnerable areas and thus, make results easily understandable for local manager.~~ 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 ~~GPDI~~the PCI model will be investigated ~~later.~~in future works. First of all, we will ~~enlarge~~expand the scale of our study by including other communities of Southern French Alps studied in the ~~frame of the~~ SAMCO project. Located in the Ubaye valley, near our study area, these communities display similar ~~structural~~physical and socio-~~economics~~economic characteristics. ~~So, their~~Their inclusion will provide a more representative selection for statistic~~s~~ investigations. ~~In addition, we will simplify the SIVI and reduce its importance into GPDI by reducing the number of its variables. Doing that, the information on structural and functional consequences will be brought out more clearly.~~ Another lead will be an adaptation of the survey protocol in order to get data at ~~finer~~smaller scale such as district scale. Another solution to gain in precision will be the use of a desegregation model to distribute ~~SIVI~~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 ~~component~~components of vulnerability, the physical one and the socio-economic one, this work may provide an important tool for local authorities. ~~GPDI~~The PCI will help them to better understand their strength and weakness and ~~thus~~ will be useful to develop ~~appropriated~~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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This research is a part of the PhD research work of B. Carlier (*Evaluation, cost and management of torrential and gravitational risk in mountainous environment*; defence thesis in 2018).

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