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Natural Hazards and Earth System Sciences
Discussions

# *Interactive comment on* "Regional prioritisation of flood risk in mountainous areas" *by* M. C. Rogelis et al.

**M. C. Rogelis et al.**

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We would like to thank the anonymous referee for an extensive review of our manuscript and for providing us with helpful and constructive comments. For ease of reading we have copied the reviewer comments, as well as our response.

**GENERAL COMMENTS**

C2543

**The authors present an approach to rank different watersheds according to the height of flood risk for a more effective mitigation planning. As such, this is a topic of considerable relevance to the readers of Natural Hazards and Earth System Sciences. Therefore, the work should be considered for publication. However, some of the content needs additional efforts before this manuscript may become acceptable for publication, and the structure of the paper has to be improved in order to better allow the readers to follow the string of argumentation.**

**In general there seems to be a particular lack in the method description as well as in the target of this manuscript. It is not entirely clear which hazard the authors are assessing, if it is flash floods, debris flows or static/dynamic inundation. Moreover, the PCA is not sufficiently explained and how the results were achieved. The results section needs a better structure, and the discussion section is missing reference to limits and uncertainties as well as the results of comparable studies in order to show how the method can be used to improve still existing gaps in risk assessment. Furthermore, I am missing a sound definition of vulnerability, susceptibility, risk and so that the specific niche of this work seems a bit unfocused. More specific concerns are listed below.**

RESPONSE:

The literature review was complemented as suggested by the reviewer. The structure of the document was improved according to the specific comments of the reviewer. The methodology section was improved according to the specific comments. The explanation on the aim of the document was improved in the introduction section. The clarification on the type of hazard was included in the introduction and the methodology. The discussion section was improved including the discussion of the limitations of the method and its advantages. The definitions used in the paper were improved in the introduction and Section 2.

**SPECIFIC COMMENTS**

1 Introduction

1. ***P. 4266/4277: Effective disaster risk reduction requires a comprehensive assessment of hazard and vulnerability. Flood risk represents the probability of negative consequences due to floods and emerges from the convolution of flood hazard and flood vulnerability (Schanze et al., 2006). Assessing flood risk can be carried out at national, regional or local level (IWR, 2011), with the regional scale aiming at contributing to regional flood risk management policy and planning. Regional approaches vary widely, including hydrodynamic model-based hazard analyses with damage estimations (Liu et al., 2014; Su and Kang, 2005) as well as indicator-based analyses (Chen et al., 2014; Safaripour et al., 2012; Greiving, 2006), with the latter being less data-demanding. A common approach is to obtain grades (e.g. high, medium and low) for the risk categories that allow prioritisation or ranking of areas for implementation of flood risk management measures such as flood warning systems and guiding preparations for disaster prevention and response (Chen et al., 2014).***
   **From my point of view this introduction is not leading to the hypotheses of this manuscript. Moreover, I have the feeling that the authors just mixed some of the terms without connecting them one by one. To give an example, while the first sentence addresses DRR and calls for the assessment of hazard and vulnerability in general, the second sentence suddenly introduces flood risk. How are they connected? -> Needs revision.**
   RESPONSE: The first sentence was deleted to underline that we are focusing exclusively on flood risk, and we have tried to improve the linkages between terms introduced. The paragraph was modified as follows:



*Flood risk represents the probability of negative consequences due to floods and emerges from the convolution of flood hazard and flood vulnerability (Schanze et al., 2006). Assessing flood risk can be carried out at national, regional or local level (IWR, 2011), with the regional scale aiming at contributing to regional flood risk management policy and planning. Approaches used to assess flood risk vary widely. These include the assessment of hazard using model-based hazard analyses and combining these with damage estimations to derive a representation of risk (Liu et al., 2014; Su and Kang, 2005), as well as indicator-based analyses that focus on the assessment of vulnerability through composite indices (Chen et al., 2014; Safaripour et al., 2012; Greiving, 2006). The resulting levels of risk obtained may subsequently be used to obtain grades of the risk categories (e.g. high, medium and low) that allow prioritisation, or ranking of areas for implementation of flood risk reduction measures, such as flood warning systems and guiding preparations for disaster prevention and response (Chen et al., 2014).*

2. ***Page 4267: This kind of damage or loss modelling, typically provides an estimate of the expected monetary losses (Seifert et al., 2009). However, more holistic approaches go further than including just physical vulnerability and incorporate social, economic, cultural and educational aspects, which are in most cases the cause of the potential physical damage (Cardona, 2003).***
   **Depending on the school and scientific background, there are many conceptualisations of vulnerability. As such the authors should not judge that "just" physical vulnerability is not enough, and it remains debatable whether or not social vulnerability leads to physical vulnerability. If the authors think so they should precisely argue why, and provide citations. Moreover, I kindly would like to suggest that the authors have a closer look to the more recent literature, being either in the IPCC or in the UN/ISDR (Sendai) context; and with the focus on the hazards introduced later on**

**maybe also some reference to the scholars from mountain hazard risk assessment, not just from those working on the larger rivers of the lowlands. For physical vulnerability maybe not only an article solely addressing industrial assets.**
RESPONSE: We agree that the debate whether or not social vulnerability leads to physical vulnerability is active; therefore the word "just" was deleted. References to literature on mountain hazards were included. The importance of a holistic analysis was included with references, incorporating those of the IPCC and The Sendai General Assembly. The paragraph was modified as follows:

*A risk analysis consists of an assessment of the hazard as well as an analysis of the elements at risk. These two aspects are linked via damage functions or loss models, which quantitatively describe how hazard characteristics affect specific elements at risk. This kind of damage or loss modelling, typically provides an estimate of the expected monetary losses (Seifert et al., 2009; Luna et al., 2014; van Westen et al., 2014; Mazzorana et al., 2012). However, more holistic approaches go further, incorporating social, economic, cultural, institutional and educational aspects, and their interdependence (Fuchs, 2009). In most cases these are the underlying causes of the potential physical damage (Cardona, 2003; Cardona et al., 2012; Birkmann et al., 2014). A holistic approach provides crucial information that supplements flood risk assessments, informing decision makers on the particular causes of significant losses from a given vulnerable group and providing tools to improve the social capacities of flood victims (Nkwunonwo et al., 2015). The need to include social, economic and environmental factors, as well as physical in vulnerability assessments, is incorporated in the Hyogo Framework for Action and emphasized in the Sendai Framework for Disaster Risk Reduction 2015-2030, which establishes as a priority the need to understand disaster risks in all its dimensions (United Nations General Assembly, 2015). However, the multi-dimensional nature of vulnerability has been addressed by few studies (Papathoma-Kohle et al., 2011).*



3. ***Page 4267: As important as the understanding of the hazard, the knowledge of the social system and its vulnerabilities is a key element of risk, and determines the social response to floods (Barroca et al., 2006). Birkmann (2006) suggests that indicators and indices can be used to measure vulnerability from a comprehensive and multidisciplinary perspective, capturing both direct physical impacts (exposure and susceptibility), and indirect impacts (socio-economic fragility and lack of resilience).***
**Here the authors could indicate why they are jumping back to social vulnerability (and the social response to floods). The authors could also consult other comprehensive works from scholars such as Papathoma-Köhle et al. (2011), Fuchs (2009) or even the editorials to the recently published special issues on vulnerability in the journal Natural Hazards. Moreover, the distinction between indicator-based approaches and other approaches seems not be sufficient in the current version of the manuscript.**
RESPONSE: We agree that the sentence on social vulnerability is out of place in this paragraph therefore it was deleted. The recommended references were reviewed and the citations included in the paper (see the response to the previous comment). A reference to the empirical and analytical methods for physical vulnerability was included as a contrast to the indicator-based methodologies for multi-dimensional assessment of vulnerability. The paragraph was modified as follows:

*The quantification of the physical dimension of vulnerability can be carried out through empirical and analytical methods (Sterlacchini et al., 2014). However, when the multiple dimensions of vulnerability are taken into account, challenges arise in the measurement of aspects of vulnerability that can not be easily quantified. Birkmann (2006) suggests that indicators and indices can be used to measure vulnerability from a comprehensive and multidisciplinary perspective, capturing both direct physical impacts (exposure and susceptibility), and indirect impacts (socio- economic fragility and lack of resilience). The importance*

*of indicators is rooted in their potential use for risk management since they are useful tools for: (i) identifying and monitoring vulnerability over time and space; (ii) developing an improved understanding of the processes underlying vulnerability, (iii) developing and prioritising strategies to reduce vulnerability; and for (iv) determining the effectiveness of those strategies (Rygel et al., 2006). However, developing, testing and implementing indicators to capture the complexity of vulnerability remains a challenge.*

4. ***Page 4268: Furthermore, the complex interrelations between hazard and vulnerability, which are mutually conditioning (Cardona, 2003), constitute a key aspect in the comprehension of risk.***
   **this statement is absolutely not clear, the authors should specify how hazard and vulnerability are "mutually conditioning".**
   RESPONSE: the sentence was clarified as follows:

   *Furthermore, the complex interrelations between hazard and vulnerability, which are mutually conditioning (none can exist on its own) (Cardona, 2003), constitute a key aspect in the comprehension of risk.*

5. ***Page 4268: Vulnerability is closely tied to natural and man made environmental degradation at urban and rural levels (Cardona, 2003), while at the same time the intensity or recurrence of flood hazard events can be partly determined by environmental degradation and human intervention in natural ecosystems (Cardona et al., 2012). This implies that human actions on the environment determine the construction of risk, influencing the exposure and vulnerability as well as enhancing or reducing hazard, or even creating new hazards.***
   **this statement is also not entirely clear, the authors should specify and maybe in general also use other sources than Cardona (which is not bad, but maybe there are also other viewpoints worth being discussed).**
   RESPONSE: The paragraph has been simplified and a sentence has been added



at the end of the paragraph to provide an example. The recommendation to include other sources has been taken into account not only in this paragraph but throughout the whole paper. The paragraph was changed as follows:

*Vulnerability is closely tied to natural and man made environmental degradation at urban and rural levels (Cardona, 2003; UNEP, 2003). At the same time the intensity or recurrence of flood hazard events can be partly determined by environmental degradation and human intervention in natural ecosystems (Cardona et al., 2012). This implies that human actions on the environment determine the construction of risk, influencing the exposure and vulnerability as well as enhancing or reducing hazard. For example, the construction of a bridge can increase flood hazard upstream by narrowing the width of the channel, increasing the resistance to flow and therefore resulting in higher water levels that may inundate a larger area upstream.*

6. ***Page 4268/69: The complex interaction between hazard and vulnerability is explored in this paper in the context of small watersheds where human-environment interactions that determine risk levels take place in a limited area. The mountainous environment and the particular sensitivity to anthropic intervention of flash flood prone watersheds provide an ideal scenario to study the dynamics of risk conditions in the urban environment. Unplanned urbanisation characterised by a lack of adequate infrastructure and socioeconomic issues (both contributors to vulnerability), may result in severe environmental degradation, which increases the intensity of natural hazards (UNISDR, 2004). The consequence of the interaction between hazard and vulnerability in the context of small watersheds is that those at risk of flooding themselves play a crucial role in the processes that enhance hazard.***
   **I have several concerns here. Firstly, again the authors used the wording "complex" without explaining why the relation between hazard and vulner-**

**ability may be complex (see my remarks above). Secondly, I do not understand why small watersheds are particularly prone to anthropogenic intervention – and if this manuscript is centered on small mountain watersheds (and not flooding, which is not clear until here), the authors definitely should include the results of recent works from scholars working on mountain hazards, and discuss their approaches in comparison to the specific needs identified within this manuscript. Just relying on Cardona or UN/ISDR and Schanze/Merz etc. is definitely not enough simply because they were not working in small mountain watersheds. Moreover, the link between the UN/ISDR approaches and the current challenges remains unclear, as does the last sentence ("The consequence of the interaction between hazard and vulnerability in the context of small watersheds is that those at risk of flooding themselves play a crucial role in the processes that enhance hazard.") -> needs clarification.**
RESPONSE:
We have simpliefied the paragraph. The clarification that flood hazard is going to be addressed was included. Regarding the literature review, this was extended to authors in the specific subject of mountain hazards. The last sentence and the UNISDR reference were rephrased. The two paragraphs were modified as follows:

*The interaction between flood hazard and vulnerability is explored in small watersheds in a mountainous environment, where human-environment interactions that influence risk levels take place in a limited area. The hydrological response of these watersheds is sensitive to anthropogenic interventions, such as land use change (Seethapathi et al., 2008).*

*The consequence of the interaction between hazard and vulnerability in such small watersheds is that those at risk of flooding themselves play a crucial role in the processes that enhance hazard, through modification of the natural*



*environment. Unplanned urbanization, characterized by a lack of adequate infrastructure and socioeconomic issues (both contributors to vulnerability) may also result in environmental degradation, which increases the intensity of natural hazards (UNISDR, 2004). In the case of floods, such environmental degradation may lead to an increase in peak discharges, flood frequency and sediment load.*

7. ***This paper aims at the prioritisation of watersheds, which can be interpreted as a proxy for flood risk assessment, thus providing guidelines for the managing of those risks. A key factor is the determining of flood exposure at the regional level, which provides the areas where vulnerability is studied. Flood-prone areas are generally obtained through hydrologic and hydraulic modelling. These can be expensive and time consuming, particularly when large areas have to be modelled. Moreover, these require information that may not readily be available for all areas (Degiorgis et al., 2012). Flood hazard maps are therefore usually only available for limited areas. This creates difficulties when a regional assessment is needed. To overcome this challenge a combination of simplified existing methods is proposed in order to obtain the outline of the areas potentially exposed to floods. Vulnerability is then assessed through application of an indicator system that considers social, economic and physical aspects that are derived from the available data in the study area. This is subsequently combined with a flash flood susceptibility indicator based on morphometry and land cover (Rogelis and Werner, 2013). The resulting priority index reflects the watersheds with the highest damage potential that require detailed risk studies to establish appropriate flood risk management strategies.***

**The first sentence in this paragraph is unclear, needs specification. Priorisation for what? Why this is then a proxy for flood risk, and not**

**the height of flood risk. Moreover, vulnerability and exposure are totally different concepts -> needs thorough clarification here. Then, the authors focus on flood hazard, but this is not the only challenge when working on the regional level (also exposure and vulnerability are scale-dependent in their assessment). It is not clear to me why (if the authors already assessed the flood risk on the regional level) they need additional assessment of flash flood risk. Is the manuscript on flash floods or floods, and how are these defined? How is the last sentence connected to the previous ones? Which is the "resulting priority index" and how this index is computed/estimated/quantified?**

RESPONSE:

The objective of the prioritization was added and the sentence related to proxy for flood risk was explained. The aspects related to exposure were deleted and are explained in the section "Conceptualization of Vulnerability". The comment of the reviewer regarding the previous existence of a flood risk at regional level is not clear to us, as that previous study focused on hazard. We have added a sentence to help clarify. The clarification of the type of floods was included and the definition was added in the methodology. The paragraph was modified as follows:

*In this paper a method to identify montane watersheds with the highest flood damage potential at the regional level is proposed. Through this, the watersheds to be subjected to more detailed risk studies can be prioritized in order to establish appropriate flood risk management strategies. The method is demostrated in the montane watersheds that surround the city of Bogota (Colombia), where floods typically occur as flash floods and debris flows.*

*The prioritisation is carried out through an index composed of a qualitative indicator of vulnerability and a qualitative indicator of the susceptibility of the watersheds to the occurrence of flash floods/debris flows. Vulnerability is assessed through application of an indicator system that considers social, economic and*



*physical aspects that are derived from the available data in the study area. This is subsequently combined with an indicator of flash flood/debris flow susceptibility that is based on morphometry and land cover, and was applied to the same area in a previous study (Rogelis and Werner, 2013). In the context of the flash flood/debris flow susceptibility indicator, susceptibility is considered as the spatial component of the hazard assessment, showing the different likelihoods that flash floods and debris flow occur in the watersheds. In contrast, risk is defined as the combination of the probability of an event and its negative consequences (UNISDR, 2009). The priority index can be considered a proxy for risk, identifying potential for negative consequences but not including probability estimations.*

8. ***Page 4269/70: The paper is structured as follows. Section 2 reviews the conceptual definition of vulnerability as the foundation of the paper. Subsequently, Sect. 3 describes the study area, and the data and methodology used; to delineate areas susceptible to flooding; to chose indicators and carry out the principal component analysis; to carry out the sensitivity analysis of the vulnerability indicator; to create categories of recorded damage in the study area; and to prioritise the watersheds. Section 4 presents the exposure areas obtained through the simplified methods; the results of the principal component analysis in terms of a socio-economic fragility indicator, a lack of resilience indicator and a physical exposure indicator; the overall vulnerability indicator obtained from the combination of the socio-economic fragility, lack of resilience and physical exposure indicators; the sensitivity analysis of the vulnerability indicator; and the prioritization of watersheds according to the qualitative risk indicator and comparison with damage records. Section 5 section interprets the results of the exposure area delineation, the representativeness and relative importance of the indicators obtained from the principal component analysis; the sensitivity of the vulnerability indicator; and the interrelations***

***between susceptibility and vulnerability in the prioritisation indicator. The conclusions are summarised in Sect. 6.***

**I have different problems with this paragraph being quite central for the conclusion of an introduction. Firstly, the structure is not entirely clear; "to chose (sic!) indicators and carry out the principal component analysis [indicators for what?, principal component analysis?]; to carry out the sensitivity analysis of the vulnerability indicator [which vulnerability indicator?, sensitivity is mentioned here for the first time, but is quite central once such methods are used to represent a proxy for vulnerability on a regional scale]". Secondly, terms are used that have not been introduced before, such as fragility indicators or resilience – the concept of resilience and vulnerability is maybe coupled, but there are scholars who argue differently. Thirdly, why the focus is now on exposure (Section 5) when the authors were only addressing vulnerability as the central component? needs a thorough definition and separation. . .**

RESPONSE:

An introduction to the sensitivity analysis was added in line 121 (new version of the paper, see attached pdf). The added sentence is:

*Since, no variable has yet been identified against which to fully validate vulnerability indicators, an alternative approach to assess the robustness of indices is to identify the sensitivity of how changes in the construction of the index may lead to changes in the outcome (Schmidtlein et al., 2008).*

The paragraph was modified as follows:

*The paper is structured as follows: (i) Section 2 reviews the conceptual definition of vulnerability as the foundation of the paper; (ii) Section 3 describes the study area, and the data and methodology used; (iii) Section 4 presents the results of the analysis. This includes the construction of the indicators and the correspond-*



*ing sensitivity analysis, as well as the prioritisation of watersheds; (iv) Section 5 interprets the results that lead to the final prioritisation; (v) The conclusions are summarised in Section 6.*

## 2 Conceptualization of Vulnerability

9. **From my point of view the authors mix up some concepts here, above all different approaches to vulnerability.**
   RESPONSE:
   The section "Conceptualization of vulnerability" was restructured in order to reduce the mix concepts identified by the reviewer. The concepts of vulnerability are presented based on two perspectives (natural sciences and social sciences). Please see the new section in the new version of the paper.

10. **Vulnerability to flash flooding and to flooding follows completely different patterns because of the different underlying process dynamics. This should be more carefully addressed here.**
    RESPONSE:
    The section was focused on torrential processes with high dynamics as is common in small mountainous watershed (see previous references that have been included to clarify), therefore the presentation of concepts related the natural science perspective of vulnerability refers exclusively to them to avoid confusion with flooding concepts.

11. **It is common sense that "vulnerability to environmental hazards means the potential for loss" but what does this mean for the present study?**
    RESPONSE:
    The meaning of potential for loss was added as follows:

    *An analysis of physical vulnerability through vulnerability curves is not incorporated, instead the expected degree of loss is assessed qualitatively through the*

*consideration of physical exposure and factors that amplify the loss (socioeconomic fragility and lack of resilience). This means the expected degree of loss depends on the extent of the flash floods/debris flows, and not on the intensity of those events.*

12. **Also the statement that "the definition of vulnerability depends on the type of study, on the results required, on the kind of hazard (flashflood or slow evolving-flood) on the spatial and temporal scale of study,on the characteristics of the study area, and on the temporality (prevention, crisis, postcrisis)" is not very targeted in this context.**
    RESPONSE:
    The sentence was deleted.

13. **If vulnerability is so important for this study the authors need a broader review on the published material (at least from social sciences and natural sciences), also with respect to hydrological hazards in mountain watersheds.**
    RESPONSE:
    The restructured section presents a broader review of vulnerability focusing on hazards in mountain watersheds.

14. **The publications of The Worldbank are maybe not suitable for application at regional scale in mountain environments: "Jha et al. (2012) see vulnerability as the degree to which a system (in this case, people or assets) is susceptible to, or unable to cope with the adverse effects of natural disasters. It is a function of the character, magnitude and rate of hazard to which a system is exposed, the sensitivity or degree to which a system is affected adversely or beneficially, and its adaptive capacity (the ability of a system to adjust to changes, moderate potential damages, take advantage of opportunities or cope with the consequences)" -> vulnerability is depending**



**on the magnitude and frequency of a hazard (in its broadest sense), the exposure and the coping capacity. The idea of adaptive capacity is tricky, and should be more precisely explained.**
RESPONSE:
We agree that the reference is not suitable, therefore it was deleted.

15. **The following paragraphs need more research efforts. While e.g. the approaches from UN/ISDR and UNDP address certain aspects of vulnerability, remote sensing scholars (Taubenböck et al.) may address other issues. What are the differences of these approaches presented, and how can these be used within the presented study. At the moment it seems more like a quick and non-targeted literature review where the authors did not manage to use the right key words in the search engine (very sorry for my harsh words). . . Why did the authors not focus on available reviews on the vulnerability concept? Moreover, the internal and external side of vulnerability, here ascribed to Birkmann, were originally from Bohle (2001) which again highlights the weakness of Section 2 – nevertheless, Bohle is cited in Section 5.4 with respect to susceptibility versus vulnerability.**
    RESPONSE:
    The section was restructured and a more detailed literature review was incorporated focused on available reviews of the vulnerability concept and in the context of mountain hazards.

16. **Since the authors use "the approach to vulnerability assessment (. . .) corresponding to the holistic approach proposed by Cardona (2001)", they simultaneously state that there was not progress in vulnerability science since then, which is simply not true. Moreover, one could even ask the question more nuanced: When the authors just use an approach originally published by 2001, the scientific novelty of the manuscript content can be questioned.**

RESPONSE:
We agree with the reviewer that the objective is not to suggest that there has been no progress since 2001. We have updated the references that support the criteria used to classify the variables used in the vulnerability analysis.

The paragraph was modified as follows:

*Birkmann et al. (2014) and Birkmann et al. (2013) identify exposure, fragility and lack of resilience as key causal factors of vulnerability, as well as physical, social, ecological, economic, cultural and institutional dimensions. In this study, physical exposure (hard risk and considered to be hazard dependent), socioeconomic fragility (soft risk and considered to be non hazard dependent) and lack of resilience and coping capacity (soft risk and is mainly non hazard dependent) (Cardona, 2001) are used to group the variables that determine vulnerability in the study area. In this paper, the risk perception and the existence of a flood early warning, which are hazard dependent, are considered as aspects influencing resilience since they influence the hazard knowledge of the communities at risk and the level of organization to cope with floods.*

3 Methods and Data

3.1 Study area

17. **Please provide more information on the hazard source, could be a table with the number of torrents (?) and the damages occurring in recent years to provide more information on the selection of the study site.**
RESPONSE:
A table presenting information on the number of watersheds and recent flooding events was added.

3.2.1 Delineation of exposure areas



18. **Here for the first time the authors address debris flows, so is the study on flash floods, debris flows, floods,. . .???**
RESPONSE:
This issue has already been raised and addressed to some degree in the introduction. The following paragraph was added at the beginning of Section 3.2.1 to clarify further:

*Flood events in the watersheds considered in this study typically occur as flash floods given their size and mountainous nature. Flash floods in such small, steep watersheds can further be conceptualized to occur as debris flows, hyperconcentrated flows or clear water flows (Hyndman and Hyndman, 2008; Jakob et al., 2004; Costa, 1988). Costa (1988) differentiates: (i) clear water floods as newtonian, turbulent fluids with non-uniform concentration profiles and sediment concentrations of less than about 20% by volume and shear strengths less than 10 N/m2; (ii) hyperconcentrated flows as having sediment concentrations ranging from 20 to 47% by volume and shear strengths lower than about 40 N/m2; and (iii) debris flows as being non-Newtonian visco-plastic or dilatant fluids with laminar flow and uniform concentration profiles, with sediment concentrations ranging from 47 to 77% by volume and shear strengths greater than about 40 N/m2. Debris flow dominated areas can be subject to hyperconcentrated flows as well as clear water floods (Larsen et al., 2001; Santo et al., 2015; Lavigne and Suwa, 2004), depending on the hydroclimatic conditions and the availability of sediments (Jakob, 2005), and occurrence of all types in the same watersheds has been reported (Larsen et al., 2001;Santo et al., 2015). Therefore, the areas exposed to clear wa- ter floods and debris flows were combined. This provides a conservative delineation of the areas considered to be exposed to flooding.*

19. **Moreover, I would like to see a proper explanation why "debris flow dominated areas can also be subjected to clear water floods" because these process groups are usually quite well separated from each other.**

RESPONSE:
The possibility of occurrence of a flow that exhibits different flow types at different points along the flow path and at different times during the same event has been reported in literature (USGS 2005). Giraud (2005) indicates that all three flow types (water, hyperconcentrated and debris flow) can occur during a single event. Furthermore, Jakob (2005) indicates that debris flow occurrence probability is a function of the availability of erodible sediments, the occurrence probability of debris slides and the frequency at which climatic thresholds are exceeded. This means that if hydrologic conditions are met for a clear water flood or hyperconcentrated flood, but not all conditions are met for a debris flow, a clear water or hyperconcentrated flood will occur. Jakob (2005) differentiates two types of basins: supply-limited and supply-unlimited. The supply-unlimited can produce debris flows at a wide range of return periods and are able to produce debris flows each time a hydroclimatic threshold is exceeded. In supply-limited watersheds, debris flows are only triggered during exceptional climatic events, often combined with unusually high antecedent moisture conditions. In these watersheds the channel is often completely scoured and future occurrence depends on the time needed to recharge the channel with sediment and the occurrence of another low-frequency event.

With reference to the separation of processes, in the studies aimed to identification of debris-flow catchments and clear water flood catchments, an intermediate area in which the catchments can not be clearly ascribed to either process has been identified suggesting that they are likely subject to both processes (Borga et al. 2014).

Examples of the occurrence of several processes in the same watersheds have been reported in literature. E.g Larsen et al. (2001), Santo et al. (2015).

In order to provide more clarity on this subject, the references in the paper were extended as shown in the response to the previous comment.



20. **Does clear water flow mean without transport of coarse sediment?**
RESPONSE:
The definitions of the limits between a clear-water flood, a hyperconcentrated flow and a debris flow have been added in response to a previous comment in section 3.2.1..

21. **Moreover, the different methods to delineate floodplains need explanation; if for flood plain delineation a sensitivity analysis is carried out why this was not done for the assessment of areas prone to debris flows?**
RESPONSE:
The validation of the debris flow prone areas was carried out by Rogelis and Werner (2013). The paragraph was modified as follows:

*In order to evaluate the results of the MRVBF index and the threshold buffers, flood maps for the study area were used. These are available for only 9 of the 106 watersheds, and were developed in previous studies through hydraulic modelling for return periods up to 100 years. The delineation of the flooded area for a return period of 100 years was used in the nine watersheds to identify the suitability of the floodplain delineation methods to be used in the whole study area. With respect to areas prone to debris flows, these were validated with existing records in the study area by Rogelis and Werner (2013).*

3.2.2. Choice of indicators and principal component analysis for vulnerability assessme

22. **"The complexity of vulnerability requires a reduction of available data to a set of important indicators that facilitate an estimation of vulnerability (Birkmann, 2006)" -> this is a general statement (apart from my concern why vulnerability is complex). Moreover, in the introduction the authors were also writing that they reduced the indicators used as a proxy for vulnerability due to the availability of data, which is a contrast to the above**

**sentence.**
RESPONSE:
We agree that the sentence can be confusing. The word reduction is probably not the best here; therefore the sentence was modified as follows: *The complexity of vulnerability requires a transformation of available data to a set of important indicators that facilitate an estimation of vulnerability (Birkmann, 2006).*

23. **I doubt that only using PCA for variables were the results look nice is a scientific procedure. So the setting of the methods is highly debatable and needs more clarification. From my point of view the indicators selected should be either treated all with the same method (so all with PCA, and then the results discussed accordingly), or somehow combined in a different manner. Personally I believe that sentences such as "(. . .) PCA was applied only to the variables education, illiteracy, access to information, infrastructure/accessibility, hospital beds and human resources in health. The other variables were treated independently due to their particular meaning (. . .) and lack of interpretation in the PCA" show a clear lack of scientific method development.**
RESPONSE:
The main objective of PCA is to transform a set of correlated variables into a new set of uncorrelated variables. In the construction of indicators, this has the advantage of revealing how different variables change in relation to each other and how they are associated (OECD 2008). Although principal component analysis is designed primarily for continuous variables, methods exist to consider categorical data in the analysis (e.g. Hoffmann (2010)). PCA has the disadvantage that correlations do not necessarily represent the real influence of the individual indicators on the phenomenon being measured (OECD 2008). This means that even if a model can be statistically constructed, the real influence of the variables may not be taken into account. This is common to any statistical method. This



issue has been identified in other studies (Esty et al. 2006) and the approach that has been proposed is to combine PCA with equal weighing. The rationale is that each principal component is by itsef an indicator, therefore what is defined is the aggregation method of the indicators to obtain a composite indicator, given that PCA can not describe the whole dataset and provide all the weights.

The text of the paper was modified as follows:

*PCA has the disadvantage that correlations do not necessarily represent the real influence of the individual indicators and variables on the phenomenon being measured (Commission, 2008). This can be addressed by combining PCA weights with an equal weighing scheme for those variables where PCA does not lead to interpretable results (Esty et al., 2006). In the construction of the lack of resilience and coping capacity indicator, this issue led to a separation of variables in four groups:*
*–Robberies and participation: These were treated separately from the rest of the variables to maintain interpretability as a measure of cohesiveness of the community. Cohesiveness of the community was identified as a factor that influences the resilience since the degradation of social networks limits the social organisation for emergency response (Ruiz-Perez and Gelabert Grimalt, 2012). Since there are only two variables to measure this aspect of resilience, PCA was not applied, and the average of the variables was used instead.*
*–Risk perception and early warning: Risk perception depends on the occurrence of previous floods, thus it depends on hazard exclusively. The existence of early warning is manly an institutional and organizational issue. Therefore, an interpretation of correlation of these variables with other variables in the group of lack of resilience and coping capacity is not possible. These variables were considered separated intermediate indicators. Risk perception and early warning decrease the lack of coping capacity (Molinari et al., 2013), and therefore an equal negative weight was assigned to these indicators summing up to -0.2. This value was*

*chosen so that their combined influence is less than the individual weight of the other four indicators. The sensitivity of this subjective choice was tested. The effectiveness of flood early warning is closely related to the level of preparedness as well as the available time for implementation of appropriate actions (Molinari et al., 2013). Due to the flashy behaviour and configuration of the water- sheds in the study area, flood early warning actions are targeted at reducing exposure and vulnerability and not at hazard reduction.*
*–Rescue personnel: this variable was initially used in the PCA with all lack of resilience and coping capacity variables. However, it was found to increase with lack of resilience and coping capacity. This implied that the statistical behaviour of the variable did not represent its the real influence on vulnerability. It was therefore treated independently.*
*–Level of education, illiteracy, access to information, infrastructure/accessibility, hospital beds and health care HR: PCA was applied to these variables, since they exhibit high correlation and are interpretable in terms of their influence on vulnerability.*
*To combine all the lack of resilience and coping capacity intermediate indicators into a composite indicator, equal weights summing up to 1 were assigned (see Section 4.3 for an explanation of the resulting intermediate indicators).*

3.2.3 Sensitivity of the vulnerability indicator

24. **So did I get it right that the sensitivity of vulnerability indicators was just tested for those variables were PCA was performed? What about the other indicators? In combination with Section 3.2.2 I am decreasingly convinced that the method applied is sound and robust.**
RESPONSE:
This is not correct, and the sensitivity of all subjective choices was explored. To clarify this point, the subsection was restructured as follows:



*The influence of the subjective choices applied in the construction of the indicators was analysed. These include:*
*1. For the application of PCA, sensitivity to the following choices was explored:*
*(a) Four alternatives for the number of components to be retained were assessed as explained in Section 3.2.2.*
*(b) Five different methods in addition to the varimax rotation were considered: Unrotated solution; quatimax rotation (Carroll, 1953; Neuhaus, 1954); promax rotation (Hendrickson and White, 1964); oblimin (Carroll, 1957); simplimax (Kiers, 1994); and cluster (Harris and Kaiser, 1964).*
*2. For the weighting schemes*
*(a) The weights used in the four groups of variables that describe lack of resilience and coping capacity were varied by $\pm$ 10%.*
*(b) The weights used to combine the three indicators that result in the final vulnerability composite indicator were varied by $\pm$ 10%.*
*All possible combinations were assessed and the results in terms of the resulting vulnerability category (high, medium and low) were compared in order to identify substantial differences as a result of the choices of subjective options.*

3.2.4 Categories of recorded damage in the study area

25. **A database of historical flood events was used to classify the watersheds in categories, depending on the recorded damages. However, the temporal resolution of these data was only 12 years. Moreover it is not clear why the authors assessed these data (apart from my remarks for the Section 3.1) – for classification of watersheds? This should have been done already in the respective Section 3.2.1.**
RESPONSE:
The purpose of the classification of watersheds according to existing damage data was added to the general explanation of the methodology in section 3.2 as follows:

*The prioritisation of flood risk was carried out using watersheds in the study area as units of analysis. The watershed divides were delineated up to the confluence with the Tunjuelo River, or up to the confluence with the storm water system, whichever is applicable. First a delineation of areas exposed to flooding from these watersheds using simplified approaches was carried out. Subsequently a vulnerability indicator was constructed based on a principal component analysis of variables identified in literature as contributing to vulnerability. A sensitivity analysis was undertaken to test the robustness of the vulnerability indicator. From the vulnerability indicator a category (high, medium and low vulnerability) was obtained that was then combined with a categorisation of flash flood/debris flow susceptibility previously generated in the study area to obtain a prioritisation category. The tool that was used to combine vulnerability and susceptibility was a matrix that relates the susceptibility levels and vulnerability levels producing as output a priority level. The combination matrix was constructed through the assessment of all possible matrices using as assessment criterion the "proportion correct". In order to obtain the "proportion correct" an independent classification of the watersheds was carried out on the basis of the existing damage data.*

26. **Moreover, the selected scoring method itself seems to be highly subjective for an evaluation of loss height (or damage intensity).**
RESPONSE:
In the study area the impacts of flooding have been described only in terms of date, location, injured people, human losses, evacuated people, number of affected houses and indication whether the flood depth was higher than 0.5 m or not (information on the inundation depth at property level is not available). Data on the particular characteristics of the properties that have been flooded are not available (type of structure, areas, heights, depth/damage data, damage to structures, damage to household inventories, clean-up costs, evacuation costs etc). The limitations on data prevent the calculation of the value of damages. There-



fore we proposed a methodology based on the available data and on sorting the impacts according to pre-established criteria. In order to clarify the method, section 3.2.4 was modified as follows:

*A database of historical flood events compiled by the municipality was used to classify the watersheds in categories, depending on damages recorded in past flood events. For each of these events the database includes: date, location, injured people, human losses, evacuated people, number of affected houses and an indication of whether the flow depth was higher than 0.5 m or not. Unfortunately, no information on economic losses is available and as the database only covers the period from 2000 to 2012 it is not possible to carry out a frequency analysis. Complete records were only available for 14 watersheds. The event with the highest impact for each watershed was chosen from the records. Subsequently, the 14 watersheds were ordered according to their highest impact event. The criteria to sort the records and to sort the watersheds according to impact from highest to lowest were the following (in order of importance):*
*1. Human losses*
*2. Injured people*
*3. Evacuated people*
*4. Number of affected houses*
*Watersheds with similar or equal impact were grouped, resulting in 11 groups. The groups were again sorted according to damage. A score from 0 to 10 was assigned, where a score of 0 implies that no flood damage has been recorded in the watershed for a flood event, despite the occurrence of flooding, while a score of 10 corresponds to watersheds where human losses or serious injuries have occurred (see Table 3). The 11 groups were further classified into three categories according to the emergency management organization that was needed for the response: (i) low: the response was coordinated locally; (ii) medium: centralized coordination is needed for response with deployment of resources of mainly the emergency management agency; (iii) high: centralized coordination is*

*needed with an interistitutional response. This classification was made under the assumption that the more resources are needed for response the more severe the impacts are, allowing in this way a comparison with three levels of priority classification.*

3.2.5 Prioritization of watersheds

27. **I would like to know more details on how the ranking into high, medium, low was performed. According to the Figures it seems that the authors used equal intervals, but why did they not make use of natural breaks since the data distribution could be better mirrored?**
RESPONSE:
The use of natural breaks or equal intervals has low influence in the classification of the vulnerability levels in the study area. Furthermore, classification methods that do not depend on the distribution of the data have the advantage that the criteria of low, medium and high vulnerability do not change when data is updated, thus allowing a monitoring of evolution in time of vulnerability in the watersheds applying the same criteria. A clarification was added at the end of section 3.2.2, as follows:

*The indicators corresponding to socio-economic fragility, lack of resilience and coping capacity and physical exposure were combined, assigning equal weight to the three components, to obtain an overall vulnerability indicator. The watersheds were subsequently categorised as being low, medium or high vulnerability based on the value of the vulnerability indicator and using equal intervals. This method of categorisation was chosen to avoid dependence on the distribution of the data, so monitoring of evolution in time of vulnerability can be carried out applying the same criteria.*

4 Results



28. **Figs 4-6 would be much more accessible if reproduced in colour. In the present form they do not support the written results because of missing readability.**
RESPONSE:
We agree that the figures should be in full colour. These were improved and presented in colour.

5 Discussion

29. **General remarks: I kindly would like to suggest the authors to make use of the discussion in the discussion section. So what did other studies figure out by using comparable indicators? What are the limits of the approach used, and where are the benefits compared to e.g. more detailed/less detailed regional approaches, etc.**
RESPONSE:
Section 5 was restructured. Comparisons with other studies were included and limitations and benefits were discussed. Please see the new version of the discussion in the attached pdf.

5.3 Sensitivity of the vulnerability indicator

30. **I do not see any significance in Fig. 9 – simply because I do not know which indicators are presented there.**
RESPONSE:
A legend was added to Figure 9 (note that this is now figure 8), as well as the following explanation in section 4.7:

*Figure 8 shows the box plots of the values of the vulnerability indicator obtained from the sensitivity analysis in application of PCA as well as the weighting scheme as explained in Section 3.2.3. The values of the vulnerability indicator obtained from the proposed method were also plotted for reference.*

31. **I do not understand the content of this Section. If susceptibility is mainly defined by land cover (as a proxy for hazard susceptibility), and vulnerability is (also) determined by land cover indirectly, both factors are related. On the other hand, vulnerability is driven by the hazard type, which should be also discussed here. The hazard type is not so much a result of land use but more of topography (at least the distinction between flash floods (or debris flows) and more or less static inundation (named "clear-water flood" by the authors, or did they mean dynamic flooding?).**
RESPONSE:
Section 5.4 was restructured.

32. **My apologies but I will stop the detailed review here. To many new things come up in the results section that should have been presented in the method section, and the manuscript increasingly gets blurred in the presentation. Moreover, the authors were mixing up terms again in the conclusion section (Section 6, see concluding two sentences) so that I doubt that they put much effort in a proper definition of terms. This maybe an explanation also for the chaotic presentation used in Figure 2. I strongly suggest that the authors perform a major revision of the content, including the indicated extended literature review and the streamlining of the methods and results section; otherwise the manuscript should be rejected.**
RESPONSE:
A revision of the document was carried out. The literature review was extended and all the sections of the paper were restructured and improved according to the specific comments.