Journal: NHESS Title: **The hostel or the warehouse? Spatiotemporal exposure assessment for natural hazards**
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MS No.: nhess-2015-101 MS Type: Research Article

Dear Referee,
We kindly would like to acknowledge your detailed comments on our manuscript. In the following we will answer these comments as well as your concerns and suggestions step-by step. In red, you will find comments while in blue we included suggestions to improve the current version on the manuscript. Once the NHESSD interactive discussion is closed by the Editor, and we will have the permission to revise the manuscript, these parts will be used to improve the manuscript.

Iteration: First review
The objective of the paper is *"to show how detailed property level data can be used to improve the understanding of trends in hazard exposure on a national level, and how this knowledge provides valuable input for local-scale natural hazard risk management".*
To this aim authors make use of several local datasets to derive the spatio-temporal evolution of exposed buildings in Austria.
Despite the paper is well written, supplies all the information which is required to replicate the analysis in other areas, includes significant results, and is of interest for the academic audience, in my opinion the two main research questions are not fully addressed by the authors which mainly limit to describe findings in terms of spatio-temporal evolution of the building stock in Austria.
In the following the main shortcomings are supplied along with specific comments on minor issues that prevent the publication of the paper in the present version.

Major criticisms
The first research question (i.e. to show how detailed property level data can be used to improve the understanding of trends in hazard exposure on a national level) is actually not addressed by the paper. Despite authors state "The results presented confirmed that a spatially inclusive and comprehensive assessment of exposure provides more insights compared to previous studies" such a comparison is not supplied in the paper neither with local-scale studies or studies implementing aggregated data. Such a comparison would increase a lot the significance of the paper; the advantage of using object-based data to analyse national trends is actually the main innovative and promising aspect of the research. Of course major efforts must be balance by improved information.
Also the second research question is not addressed by the paper (i.e. to show how the knowledge of properly level data provides valuable input for local-scale natural hazard risk management).
Advantages reported in the conclusions section are general advantages of an object-based approach with respect to aggregated approaches, as corroborated by the fact that several scholars are quoted in the list of benefits. Benefits of object-based approached should be included in the introduction section to stress the importance of the research. In my opinion, the point risen by the authors cannot be considered actually a research question. It is quite evident that more detailed data are the bases for most robust, target decisions and strategies. However, it would be interesting in the paper showing some real evidences of such advantages, starting from results.

We agree and will provide a clearer and more accessible introduction in the revised version. The scope of this paper is to produce a nation-wide understanding of object-based exposure in Austria based on the recently available data set on buildings within the country. Moreover, temporal and spatial dynamics will be discussed.
As a result, we will change (and clarify) the research question based on identified gaps.

> Focusing on exposure, the effectiveness of natural hazard risk management depends on the availability of data and in particular an accurate assessment of elements at risk (Jongman et al.,

2014), which also requires a temporal and spatial assessment of their dynamics. It has been repeatedly claimed with respect to flood hazards in Europe that the main driver of increases in observed losses over the past decades is increased physical and economic exposure (Bouwer, 2013; Hallegatte et al., 2013; Jongman et al., 2014). Until now, however, in mountain regions of Europe such conclusions remain fragmentary since property data has only been available on the local scale as a result of individual case studies. These – often conceptual – studies related to the temporal dynamics of exposure to mountain hazards include both the long-term and the short-term evolution. Long-term changes were found to be a result from the significant increase in numbers and values of properties endangered by natural hazard processes, and can be observed in both rural and urban mountain areas of Europe (Keiler, 2004; Fuchs et al., 2005; Keiler et al., 2006a; Shnyparkov et al., 2012). Short-term fluctuations in elements at risk supplemented the underlying long-term trend, in particular with respect to temporary variations of people in endangered areas and of vehicles on the road network (Fuchs and Bründl, 2005; Keiler et al., 2005; Zischg et al., 2005). These results suggest that the spatial occurrence of losses is not so much dependent on the occurrence of specifically large events with high hazard magnitudes but more a result of an increased amount of elements at risk in endangered areas (Fuchs et al., 2012). Most of the recent works, however, rely on local object-based studies (Zischg et al., 2004; Fuchs et al., 2012) or aggregated land use data (Bouwer et al., 2010; de Moel et al., 2011; Cammerer et al., 2013), leading to substantial uncertainties if up-scaled to a larger spatial entity (de Moel and Aerts, 2011; Jongman et al., 2012a). Because of the limited data availability, comprehensive object-based and therefore spatially explicit analyses have thus not been extended beyond the local level (Kienberger et al., 2009; Huttenlau et al., 2010; Zischg et al., 2013), and studies focusing on the national level in mountain regions using such data remain fragmentary (Fuchs et al., 2013).
To contribute to this gap, we show how detailed property level data can be used to improve the understanding of trends in hazard exposure on a national level. We will explicitly focus on dynamics in elements at risk, neglecting (a) any changes in the natural process dynamics due to underlying changes in the natural system including the effects of climate change, (b) any shifts in exposure due to the implementation of technical mitigation measures, and (c) any changes in vulnerability. This allows for the assessment of dynamics in property exposure, and will provide insights in the impact elements at risk may have on changing risk in mountain environments leaving other risk-contributing factors constant.

The discussion section is actually a continuation of the results section, partly repeating some results and adding some information. I think that the two sections must be merged while the discussion section should focus more on the research question(s).

Thanks for your suggestions. We will re-write the results and discussion sections in order to be more concise and to better link the introduction section with the identified gaps to the results.

Specific comments
Title
I think the title should better recall the methodology (i.e. property level analysis) adopted in the paper

Our suggestions is to change the title to "A spatiotemporal multi-hazard exposure assessment based on property data"

Section 1

Pg 2421 line 4 *"A review of Fuchs et al. (2013) has shown that overall conclusions on the dynamics of natural hazards, including floods, landslides and snow avalanches, may be challenging due to the inherent complexity behind data"* → At this stage of the paper it could be sensible to explain/recall such complexity.

We will change the order of sentences in order to provide this information in a more accessible way.

> A review of Fuchs et al. (2013) has shown that overall conclusions on the dynamics of natural hazards, including floods, landslides and snow avalanches, may be challenging due to the inherent complexity behind data. Focusing on mountain regions, an increase in hazardous events and associated losses is repeatedly claimed (a) as a result of increasing exposure of elements at risk (Mazzorana et al., 2009; Preston, 2013), (b) due to natural fluctuations in flood frequencies (Schmocker-Fackel and Naef, 2010), and (c) due to the effects of climate change (e.g., Huggel et al., 2012; Korup et al., 2012).

Pg 2421 line 23 *"the effects of dynamics in exposure have so far not been studied sufficiently as a possible reason behind the process dynamics shown in Fig. 1"* → This is a very critical point. While correlation between exposure and damage is quite easy to explain, the analysis of the correlation between exposure and the number of events requires a deeper investigation, on how built-up environment influences the natural dynamics of hazard events (e.g. because of soil impermeabilization, less space for rivers, etc.). In the following, the exposure and the number of events are often compared, according to me in a wrong way (see comments to section 4). Is the intention of the authors to deal with this complicated topic? Otherwise exposure should be compared with observed damages along the paper.

In this paper we focus on exposure. Unfortunately, data on losses is not available for the entire country. We agree that the relationship between exposure and the number of damaging events is influenced by multiple dynamics (indicated in the previous comment). We will include a discussion on these challenges in a revised version of the manuscript.

Introduction:

> (…) Apart from hazard dynamics (the natural frequency and magnitude of events), decreasing dynamics in mountain hazard losses may result from (a) increased efforts into technical mitigation (Keiler et al., 2012), (b) an increased awareness of threats being consequently considered in land-use planning (Wöhrer-Alge, 2013; Thaler, 2014), both leading to less exposure, and (c) a decline in vulnerability (Jongman et al., 2015) which will not be further considered in the following sections. (…) Apart from the ongoing discussion of the effects of climate change influencing the hazard trigger (e.g., Auer et al., 2007; Keiler et al., 2010; Lung et al., 2013), the effects of dynamics in exposure have so far not been studied sufficiently as a possible reason behind the process dynamics shown in Fig. 1. Since spatially explicit data on the dynamics of exposure were missing so far, data on the temporal dynamics of natural hazards resulted in misleading conclusions, and studies on dynamics in hazardous processes may therefore have over-emphasized the effects of climate change. (…)To contribute to this gap, we show how detailed property level data can be used to improve the understanding of trends in hazard exposure on a national level. We will explicitly focus on dynamics in elements at risk, neglecting (a) any changes in the natural process dynamics due to underlying changes in the natural system including the effects of climate change, (b) any shifts in exposure due to the implementation of technical mitigation measures, and (c) any changes in vulnerability. This allows for the assessment of dynamics in property exposure, and will provide insights in the impact elements at risk may have on changing risk in mountain environments leaving other risk-contributing factors constant. [see also your comment on the research questions above]

Pg 2422 line 5 *"Such – often conceptual – studies related to the temporal dynamics of exposure to mountain hazards include both the long-term and the short-term evolution of risk indicators"*
→ Not clear please specify

Information is provided in the two subsequent sentences. We will delete the term "risk indicators" in order to be more precise.

> These – often conceptual – studies related to the temporal dynamics of exposure to mountain hazards include both the long-term and the short-term evolution. Long-term changes were found to be a result from the significant increase in numbers and values of properties endangered by natural hazard processes, and can be observed in both rural and urban mountain areas of Europe (Keiler, 2004; Fuchs et al., 2005; Keiler et al., 2006a; Shnyparkov et al., 2012). Short-term fluctuations in elements at risk supplemented the underlying long-term trend, in particular with respect to temporary variations of people in endangered areas and of vehicles on the road network (Fuchs and Bründl, 2005; Keiler et al., 2005; Zischg et al., 2005).

Section 2
Pg. 2424 line 7 *"... on more than 25 000 river km".* It should be interesting to know which is the percentage with respect to the total length of rivers in Austria

We will include this information in a revised version.

> (…) on more than 25,000 of a total of 39,300 river kilometres.

Section 3
Pg. 2429 line18 *"It can clearly be shown that snow avalanche hazard is not a major threat in the country, even if individual events occurred leading to considerable economic loss in recent decades"*
→ what it is shown is that exposure to avalanches is less than exposure to other hazards. No conclusions can be inferred on avalanche hazard.

We will change this statement in a revised version.

> Additionally, it can clearly be shown that exposure to snow avalanches is relatively low compared to other hazard categories, even if individual events occurred leading to considerable economic loss in recent decades (Fuchs et al. 2013).

Pg. 2431 line 4 *"a slight increase in the amount of elements at risk"* → of "new" element at risk?

We will change this statement in a revised version. Moreover, since Figure 4 (d) is a central Figure we will change it to a new Figure 5. This allows for a better comparison of results.

The results of a cumulative analysis including the entire building stock and focusing on inter-annual changes in the construction activity between exposed buildings and the total building stock are shown in Fig. 4d by the relation between annual dynamics in new constructions per year against the respective entire building stock. Because of the relatively low number of exposed buildings in the country (cf. Tab. 1), the resulting percentage is low. For river flooding, a slight increase in the share of elements at risk exposed from 9 % to 9.8 % is detectable until the 1960s and since then a slight decrease to 9.2 % can be proven. In contrast, with respect to torrential flooding, the percentage of annual new constructions is slightly decreasing from 5 % to 4.8 % for the period 1919-1944, subsequently increasing to 5.1 % until 1970, and decreasing again to 4.7 %. For snow avalanches, the values are slightly decreasing over the entire period under investigation from 0.6 to 0.4 %. The overall dynamics, however, are within percent range. The buildings exposed to river flooding and

torrential flooding are increasing in value compared to the non-exposed buildings, in particular during the period 1944-1990.

Section 4
Pg. 2433 line 10 "*a heavy increase in the entire building stock but also in exposed buildings is evident for the last decades (Fig. 4a). This growth of around a factor of six and a factor of four (snow avalanches) supports the suggestion that increased physical and economic exposure may be responsible for occurring losses even if loss data from the European Alps cannot directly support this conclusion: an analysis of destructive torrent events between 1950 and 2008… had shown a decreasing trend related to the overall number*" → Confusion is made here among correlation between exposure and damage, and correlation among exposure and number of events (see comments in section 1). As authors state in the following of the paper "the number of documented hazards as shown in Fig. 1 should not directly be used to draw conclusions on the development of losses and exposure".

Thanks for your suggestions. We will re-write the discussion section in order to be clearer and to better link the introduction section with the identified gaps to the results.

Pg. 2434 line 3 "*a time lack between actual planning decisions and their effects on risk becomes evident*" → For a better understanding, it could be useful to know when hazard mapping and hazard oriented land use planning was introduced in Austria. Please, correct "lack" with "lag".

Thanks for your suggestions. We will correct the typo, and we will include some statements on hazard mapping in Austria (due to the comments of the other referees this will be done in the methods section).

> In Austria, the method for hazard mapping is regulated by a national legal act {Republik Österreich, 1975 #1314} and an associated decree (Republik Österreich, 1976). The implementation of these regulations is assigned to the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and administrated by the governmental departments of the Austrian Service for Torrent and Avalanche Control (WLV). Since the mid-1970s, these governmental departments had been progressively compiling hazard maps for the communities affected by mountain hazards based on available data and information on hazards as well as modelling exercises (Holub and Fuchs, 2009). (…)

Pg. 2434 line 6 *"the ratio of annual constructions inside endangered areas is already decreasing starting with 1945 by reason of the relatively high amount of non-exposed buildings in Austria (almost 87% of the entire stock)"* → Why "by reason of the relatively high amount of non-exposed buildings in Austria". Not clear, please specify.

We believe that this statement is already explained in the current version of the manuscript.

> Comparing the ratio between new constructions and the existing building stock (Fig. 4d) and the annual ratio of new constructions inside hazard-prone areas and the total new constructions (Fig. 4e), a time lag between actual planning decisions and their effects on exposure becomes evident. While the ratio of buildings exposed to river flooding compared to the cumulative development of buildings stock is increasing until the 1960s, the ratio of annual constructions inside endangered areas is already decreasing starting with 1945 by reason of the relatively high number of non-exposed buildings in Austria (almost 87 % of the entire stock). With the exception of the decade 1981-1990, were a slight increase in this annual ratio is detectable, both the annual ratio of exposed to non-exposed buildings and the ratio between exposed buildings and the entire stock is decreasing. This may be interpreted as success of land-use planning activities (namely hazard mapping and the related ban of new constructions inside red hazard zones), even if a clear relation between new

constructions and the implementation of hazard maps cannot be deduced [see also your previous comments on hazard-adjusted land-use planning].

Pg. 2434 line 22 *"More precisely, the fewer buildings are exposed in comparison to the entire buildings stock, the longer land-use regulations enacted today will take to show success"* → Not clear, please specify

We believe that this statement is already explained in the current version of the manuscript. Nevertheless, we plan to revise the discussion and conclusion sections in order to be more concise. Therefore, we will include some additional thoughts on these issues.

Section 5

Thank you for these comments. Please be aware that we will revise the discussion and conclusion sections in order to be more concise.

Pg. 2435 line 21. "River flooding regularly causes economic loss of relatively low size per building, but affects larger regions than mountain hazards and may therefore produce a higher cumulative loss. In contrast, mountain hazards occur more locally but affect also human life". This is not evident from the paper, References are required.

We agree. We will include some references on these statements, e.g., Hilker et al. (2009) and the results published within the documentation of the 2005 flood events in Austria (BMLFUW 2006).

Pg. 2435 line 9 *"It has been shown that the repeatedly-stated assumption of increasing losses due to continued population growth and related increase in assets has to be opposed to the local development of building stock"* → is it right? I think that it's the opposite. Data show that both the amount and the economic value of exposed assets are increasing. Even if grow rates are decreasing they are always positive, which means that exposure is increasing. The meaning of the sentence is not totally clear to me, please better explain.

We will re-write this paragraph in the revised version, but the general message is already included in the current version.

> While some regions have shown a clearly above-average increase in assets, other regions were characterised by a below-average development. [this is in line with other studies on exposure such as Fuchs and Bründl (2005) who had shown on a community level that there are highly variable trends in the development of population and building numbers in the canton of Grisons, Switzerland. Some communities even had shown an absolute decreasing trend in both numbers since the 1950s] This mirrors the topography of the country, but also the different economic activities: as such, hotels and hostels were found to be extraordinary prone to mountain hazards, and commercial buildings as well as buildings used for recreation purpose to river flooding. Residential buildings have shown an average exposure, compared to the number of buildings of this type in the overall building stock.

Pg. 2436 line 11 *"It can be concluded that an object-based assessment has clear advantages compared to the traditional aggregated computation: exposure to natural hazards is heterogeneous, and follows small-scale patterns which cannot necessarily be satisfyingly modelled with the common approaches of aggregation".* The point is not "aggregating or not aggregating". Authors aggregate too. The crucial point is the level of detail of original data and the respective accuracy of aggregated data. I think this should be discussed.

We will re-write the conclusion section in order to better focus on the identified gaps (see introduction). As a result we will exclude the argument of aggregation since this is not the focus in this paper.

Bibliography
I did not check the bibliography at this stage of the review. I reserve to do this in a second time.

Tables
Tables 1 and 2. It is not clear whether presented results come from the present paper or a previous one. In the last case, the discussion and presentation of these results should be reduced in the paper, reminding to the quoted reference.

We will improve the captions accordingly. Even if the underlying preliminary but original study was done by Fuchs and Zischg (2013), the Tables in their present form contain new data and therefore we deleted this information.

> Tab. 1: Information on non-exposed buildings and buildings exposed to river flooding, torrential flooding and snow avalanches, aggregated on the level of Federal States in Austria. Additionally, information on multi-exposed buildings is given.
> Tab. 2. Information on non-exposed principal residents and principal residents exposed to river flooding, torrential flooding, and snow avalanches, aggregated on the level of Federal States in Austria. Additionally, information on multi-exposure is given.

Figures
Figure 3 is two small and difficult to read.

Together with the comments of another referee on exposed citizens we decided to exchange the set of maps right column and to include information on exposed citizens. The additional data will then also be included in the results section. The resolution will be enhanced in the revised version and we believe that the content is then visually accessible.

Figure 4. A caption is missing describing the meaning of the different plots (a,b,c,d,e). This reduces the comprehension of the figure. Figure 4 is too small.

Apart from the layout of Figure 4, which will be revised, we will also change the order of charts. Fig. (a) and (b) show the temporal development in terms of cumulative data, therefore the graphs are increasing (the number of buildings is increasing). Fig. 4 c will be converted in a new Figure 5 and separately discussed (also in the results section), we will also include the data on exposed citizens. Fig. (c) and (e) are based on averaged construction activities (the construction periods available in the dataset), and therefore the graphs are stepwise. We will also extend the Figure caption:

> Figure 4. Temporal development of building stock in Austria. In Fig. 4 (a), the cumulative absolute increase in the number of buildings is shown for non-exposed buildings and buildings exposed to snow avalanches, torrential as well as river flooding. In Fig. 4 (b), the relative increase of the building stock is shown for the total number of buildings and buildings exposed to snow avalanches, torrential as well as river flooding, 1919 = 1. In Fig. 4 (c) the average annual number of newly constructed buildings is shown for buildings exposed to snow avalanches, torrential as well as river flooding. In Fig. 4 (d) [in the current version = 4 (e)] the annual number of newly-constructed exposed buildings versus the total number of newly-constructed buildings is shown for buildings exposed to snow avalanches, torrential as well as river flooding.