Reply to Referee #2

First of all, we would like to thank the referee for the time and effort put into reviewing the manuscript. In the following, we provide our responses to the individual questions posed by the referee.

The objective of the paper is to contribute in filling the gap in current understanding of the roles of the different components of the risk chain on changes in flood risk. To this aim a simulation-based approach is implemented where, starting from the investigation of a baseline scenario, six components of the risk chain are changed (namely: climate change, implementation of reservoirs in the catchment, flood protection along the rivers, land use change, change in asset values and changes in the vulnerability of flood-affected objects) by both increasing and decreasing their reference value. Thanks to the implementation of the DFRA, this allows to simulate 729 damage series (of 4000 years) from which the EAD and the risk curve are derived and investigated: (i) at the catchment scale, (ii) at two typical upstream and downstream sub-basins, and (iii) for summer and winter seasons.
The topic of the paper is in the scope of NHESS and results can contribute to a better understanding of flood risk and risk mitigation strategies, also in the light of future climate change. The paper is overall clear, well-structured and well-written; conclusions are mostly supported by simulation results. Still, there are some points that need further clarification or that must be better explained in order to make the paper totally understandable; these are reported as "specific criticisms". On the other hand, in the following, some suggestions are reported that could increase the robustness and the completeness of the research.

We would like to thank the reviewer for his/her positive feedback. We will consider his/her suggestions to make the paper totally understandable.

Suggestions
- The choice of considering a double storage capacity as the change in the catchment hydrology is not totally clear to me. In the light of choosing "plausible deviations from the baseline", it makes more sense considering a change in the operational rules like, for example, in the value of the cut-off discharge. I suggest authors to explore also this scenario;

We thank the referee for this suggestion. However, the reconstruction of time varying operational rules for individual reservoirs is difficult due to lack of information which might lead to implausible results. Hence we built up the scenarios for this component considering the change in storage capacity only. Additionally, to maintain the symmetry and simplicity in the latter change (C2) we doubled the storage volume for each of the 25 implemented reservoirs at the respective sub-basin. As long as one has sufficient information about the operational rules for individual reservoirs considered in the model, one might explore more on the scenarios suggested by the referee.

Again, in the light of choosing "plausible deviations from the baseline", also the change in building quality should be investigated. This is a quite cheap strategy for risk mitigation that can be easily encouraged/achieved by public and private incentives. I suggest authors to explore also this scenario;

We agree with the referee that building quality is also an important damage-influencing parameter. However, there could be always some other damage-influencing parameters and different scenarios along the flood risk chain. Covering all is not easy task, e.g. there are many potential changes in the catchment that could affect flooding (soil compaction). We decided to focus on six significant components only. On the other hand, changing building quality may not always be a cheap and straightforward damage reduction strategy. To change building material is for instance not really possible.

The whole analysis is based on the estimation of damage to the only residential sector. Still, risk can be heavily affected by damage to other sectors like agriculture, commerce, tourism, population, etc. For some of these sectors flood damage is strongly related to the season of occurrence of the event (e.g. agriculture, tourism), and it may be the case that the effect of climate change on such sectors modifies present conclusions on EAD and on the role of the different components of the risk chain. I think that more than one sector should be included in the analysis or, at least, some considerations must be added on the possible role of damage to other exposed sectors.

The main objective of this paper was to propose an insight to possible impacts of different components on flood risk chain under selected assumptions. In the scope of this study, we have mainly focused on changes in risk where actual (true) EAD values for the study area are not primarily targeted. We agree that the impact on other sectors might be different, but this would not refute the presented conclusions. Including additional sectors or secondary losses would further complicate the analysis and increase the volume of the manuscript destructing from the main focus which is the risk sensitivity along the process chain. Furthermore, damage modelling bears high uncertainties compared to other models along the risk chain. Loss models for other sectors than residential are even more uncertain. We therefore would abstain from including damage models for other sectors into analysis.

Specific minor comments (which can increase the readability and clarity of the paper)
Section 1
Pg. 2 line 65 "A major problem is the superposition of several drivers of risk changes" = what authors mean here with "superposition"? Please, specify

Here, 'superposition' is standing for to explain that different drivers in the flood risk chain may mask each other's impact. Accordingly, we have given an explanation to this sentence by example in lines 66-68.

Section 3
Pg. 6 line 164 "the approach provides the complete flood hydrograph" = on a daily base, is it correct?

Yes, our approach provides the complete flood hydrograph on a daily base. This will be added to the revised version of the manuscript.

Pg. 6 line 166 "the spatial dependence between flood damages at different locations in the catchment is taken into account" = what authors mean with "spatial dependence between flood damages at different locations"? Please, specify

With this statement we mean that damage values at different locations (e.g. subbasins) are spatially consistent though they are heterogeneous, i.e. the losses correspond to a flood/inundation footprint resulting from the continuous simulation with the risk chain model. We would rephrase this sentence as follows: "Hence also spatial consistency of losses across the catchment is taken into account."

Pg. 7 line 183 "The weather generator is parameterized on a monthly basis." = this is already stated in the following page. The sentence can be deleted

This sentence will be deleted.

Pg. 8 lines 215 -221 = Some assumptions made for the modelling of reservoirs are not totally clear to me: (1) are reservoirs empty at the begging of the simulation? If yes, is it realistic? If no, which is the initial volume? Why? (2) What happens if the storage capacity is reached before the discharge falls below HQ100? (3) Why the return period of 100 years was chosen? Is it the design return period of dikes? (4)Which is the necessary information collected from Sächsisches Landesamt für Umwelt und Geologie?

(1) Reservoirs can be used for different purposes such as water storage, hydropower and flood protection. Although single-purpose flood control reservoirs are rather rare, in the scope of this paper, we considered the reservoirs that have only flood control function i.e. we implemented not the total reservoir volume in the model, but only the volume dedicated for flood control. Thus, one can think that the entire reservoir is always full to its non-operation capacity or the "flood protection" reservoir volume is empty at the beginning of the simulation. Because our focus is the flood protection purpose of reservoir in the presented sensitivity analysis, we believe this is a reasonable approach.
(2) If the storage capacity was filled before the discharge falls below HQ100, excess flow is routed downstream. If this is the case, we can still expect to observe impact of the reservoir at downstream because some part of the flood volume is held by the reservoirs.
(3) The information about the operation rules were not available for this study. There is certainly a threshold for deploying the reservoirs for the flood protection purposes. Otherwise, they would be inefficient if filled passively at the time of low discharges. For this sensitivity analysis a 100 year threshold was chosen, in order to capture large floods. Certainly, the exact risk estimates would depend on the selection of the threshold, but the general behaviour of changes in the risk curves should be invariant.

(4) We obtained information of reservoir locations and flood storage capacities from Sächsisches Landesamt für Umwelt und Geologie.

Pg. 9 line 226 "The calibration and validation results illustrate obvious improvement in this new model setup compared to the version used in Falter et al. (2015)" = I cannot appreciate this improvement in Figure 3. On the left, only results from the new model and observations are reported so I cannot see the difference between the two models. Graphs on the right suggest that the two models are mostly equivalent. Please, comment on this

We agree with the referee that overall the difference in model performance between the two model setups is modest looking at obtained NSE values and the plots in Figure 3. However with the statement, we would like to highlight the improvement of the new model setup with respect to the cut-off process of the extreme flood events, i.e the August 2002 flood. We will modify the text accordingly.

Pg. 9 line 231 "with the new setup, the SWIM model seems to be able to represent the cut-off process more accurately" = Of course, the old model did not consider cut-off

We thank and agree with the referee for this comment (which has been addressed by the reviewer #1 as well). We will remove the irrelevant text "more accurately" from the text.

Pg. 10 line 254 "the minimum height was assumed at 1.8 m" = on which bases?

Since we derived 761 cross sections of the modelled river network by extracting information from the 10 m DEM, the estimated dike height might be too low and additional dike information is not available at some locations. Therefore a threshold was introduced as a global correction value for the minimum dike height. We assumed the minimum dike height as 1.8 m following the study of Falter et al. (2015). We will explain this in the manuscript.

Pg. 10 line 255 "the 2D raster based model uses a 100 m resampled computational grid from DEM10, which was found an acceptable compromise for representation of inundation characteristics and computation time" = I think some considerations must be included on topography. 100 m can be enough in flat areas (i.e. downstream) but can introduce big errors in damage estimation in steep areas (i.e. upstream). Did authors consider different resampling of the DEM in different areas of the catchment?

We agree with the reviewer that 100 m resolution might be inappropriate in steep areas. Our approach is based on findings by Falter et al. (2013), which were carried out in more or less flat terrain. In this study, we focus on the sensitivity of the risk estimates rather than on estimating the actual (true) risk values in the study area. Hence, we consider the DEM resolution to be not of paramount importance for the derived conclusions, but rather a pragmatic choice to obtain plausible results from 729 simulation runs in reasonable time.

Pg. 10 line 265 "Although there is an underestimation of inundation, the model gives a reasonable estimate of inundation extent and depth for large-scale assessments" = which are the bases for this statement? 50% underestimation in flood extent is a significant error in my point of view

Yes, we agree with the reviewer that 50% underestimation is a significant error. We shall modify our statement that this is "a reasonable estimate of inundation extent" accordingly. This large error comes from the model inability to correctly represent dike breach locations and breaching processes. However, in this study we focus more on the change rather than the absolute risk value. Therefore, we decided to tolerate this mismatch and still believe this does not refute our conclusions.

Pg. 11 lines 275-282 = I think that assumptions made for the estimation of damage must be better explained: (1) which is the scale of analysis? The 100*100 m2 cell? The municipal scale? Other? (2) how building type and level of precaution are assessed? (3) do asset values depend on building quality and type?

We will add following answers to the manuscript to improve this section.
(1) All gridded input data (e.g. asset values and land use) were resampled to 100 m spatial resolution. The damage calculation is carried out for 100*100 m^2 cells and then aggregated to the level of municipalities.

(2) The composition of building types is defined using a cluster centre approach. In total five clusters are defined differentiating the share of single-family house, semi-detached/detached and multifamily houses. Average building quality is aggregated to two classes: high quality and medium/low quality (Thieken et al., 2008). Besides water level, return period, building type and building quality, private precaution are taken into account in the damage model. Private precaution is classified as none, good and very good precaution. Building quality, type and precautionary measures are taken as shares for each raster cell.
(3) Asset values are determined according to their reconstruction (replacement) costs. Therefore, implicitly asset values depend on building quality and type. In the damage model, the building quality and asset values are not directly related on a building-by-building basis since both characteristics are aggregated at the cell resolution.

Pg. 11 line 283 "The sum of damages for all communities was officially reported as €240 million" = does it refer to the total damage or damage to residential buildings?

It refers sum of damages to residential buildings for the August 2002 flood. The text will be modified accordingly.

Pg. 11 line 285 "This underestimation may be explained by uncertainty in asset values and their spatial distribution and uncertainty in the damage model" = and underestimation of flood extend I guess

The reviewer is right. This underestimation is also coming from the differences in simulated and observed inundation patterns. We certainly need to mention this in the manuscript.

Pg. 11 line 302 "For example, the baseline scenario of the catchment component is represented by a model version calibrated for a recent time period and including the current implementation of reservoirs in the catchment. The specific time periods and assumptions for the baseline scenarios are given in sections 3.1.1 to 3.1.4 where the implementation, calibration and validation of the different modules for the current situation are described" = the meaning of the baseline scenario is clear to the reader at this point of the paper. This sentence can be omitted.

We thank the reviewer. We will omit this sentence.

Pg. 13 line 356 – 360 = Are studies made in the Netherland transferable to the Mulde catchment? What authors mean with "potential" dike heightening? Potential with respect to what?

We could not find any study that shows dike heightening in Germany. Therefore, to make a reasonable assumption in terms of increment range, we used examples from the Netherlands. "Potential" stands for possible increases in dike heights due to alteration in design discharge value by time. For example, in one of the dike heightening strategy, each every 5 years using additional peak discharge data, new peak discharge probability distribution is calculated and dike height is updated (Hoekstra and Kok, 2008).

Pg. 13 line 364 "The change scenario EL2 is based on the increase in area of these two classes from 672 to 784 km2 between 1990 and 2012 where the change area was added to baseline scenario" = How the urban area was changed? I can understand this only at pg. 21

We will move "Land use change scenarios were created based on increase in residential areas between the years 1990 and 2012 by randomly changing the state of single pixels." to pg.13 line 364.

Pg. 13 line 367 "Pixels (100 x 100 m2) of the classes 111 and 112 were assigned to non-residential land cover classes (i.e. agricultural areas and semi-natural areas)" = how pixels were re-assigned? Why authors did not consider CORINE land use map of 1990? I think it is more realistic.

Thanks for the reviewer for this comment. That sentence should read as follows: "Pixels (100 x 100 m2) of the classes 111 and 112 were assigned to residential land cover classes and all other classes were assigned to non-residential land cover classes (i.e. agricultural areas and semi-natural areas)". We will modify this in the revised version. It means that there is no re-assignment. The reason for not considering CORINE land use map of 1990 is the difference in representation of residential land use classes for 1990 and 2012. Therefore, to be consistent and symmetric in scenarios we created two symmetric scenarios from baseline where subtraction scenario is still realistic.

Section 4

Pg. 14 line 405 "This non-symmetry in the effects of the catchment component is explained by the specific implementation of the reservoir capacity: Implementing a capacity of 106 million m3 reduces the EAD significantly, but doubling this reservoir capacity at the same locations does not further reduce the risk substantially, because the damage is primarily generated at other locations within the catchment" = not clear, the role of reservoirs is not reducing damage downstream? Please, clarify

We agree with the reviewer that the sentence is misleading. It should be rephrased as follows: "This non-symmetry in the effects of the catchment component is explained by the specific implementation of the reservoir capacity: Implementing a capacity of 106 million m^3 reduces the EAD significantly, but doubling this reservoir capacity at the same locations does not further reduce the risk substantially, because the reservoir capacity in the baseline scenario is already sufficient to capture floods above HQ100". We observed these by checking the cut-off volume in both scenarios and inundation extents. Differences with doubled reservoir volume were very small for most reservoirs.

Pg. 16 line 455 "Regarding the change in catchment hydrology (C), change in flood storage capacity has a more dominant impact upstream which is explained by the reservoir locations. Due to the assumped reservoir operation the reservoir impact is only visible for very low probability events at the downstream sub-basin" = I still do not understand the influence of reservoirs in the catchment. Readers should be supported by a better description/discussion of the location of reservoirs with respect to the sub-basins.

The size and location of the reservoirs are shown in the catchment map (Figure 1). For the analysis of the impact of reservoirs to upstream and downstream areas two specific reaches were selected (Figure 1). The (upstream) reach around Zwickau is directly downstream of a large reservoir. Doubling the capacity of this reservoir does not result in risk changes. At the downstream region influenced by several river branches, we observe aggregated impact from various reservoirs upstream. It seems that for very large events doubling of reservoir capacity still exerts a small impact on the risk downstream.

Pg.17 line 464 "From the risk curves of different land use scenarios, it should be noted that the increased urban area scenario (EL2) increases risk upstream for high probability events" = I cannot see the difference between EL2 and the baseline scenario in Figure 7. Is one curve missing?

There is no missing curve. In figure 7, EL2 and the baseline scenario behave almost identical upstream. The reason of this can be explained by that additional upstream residential areas in EL2 scenario are not inundated. Therefore, same residential areas are inundated upstream for both baseline and EL2 scenarios.

Pg. 17 line 468 "the baseline land use scenario (EL1) and the EL2 scenario behave almost identical upstream which can be explained by the steep topography" = I guess it depends on the rules adopted for increasing the urban area and on how the flood extent changes for different return periods

Thanks for the comment. This is also a reason of that why we get almost identical curves upstream. We shall reflect on this in the manuscript.

Pg. 17 line 472 "This can be explained by the specific setup of the residential buildings added in EL1 which are not exposed to floods." = not clear, please specify

This is similar to the situation between baseline and EL2 scenarios upstream. In this case, the sentence implies that additional downstream residential areas in the baseline scenario compared to EL0 scenario are not inundated.

Pg. 19 line 523 "Under the fixed A2 scenario, five scenario combinations are highlighted, each time altering a different component from its baseline value towards EAD decrease" = I can see four combinations leading to lower EAD. Could authors check?

We will modify this sentence by removing "towards EAD decrease".

Figures

Figure 1 – subcatchments are not visible in mountain areas

We thank the reviewer. We will modify Figure 1.

Figure 2 – (1) please specify what authors mean with XS profile (2) output of the flood loss model is missing (3) level of precaution and contamination are missing in the box related to FLEMOps

We thank the reviewer. We will modify Figure 2.

Figure 4 – I think that the figure is not explicative of the logic tree. Please, consider changes.

We will consider a change in the caption of this figure. We will change the capture of the figure. We will use "conceptual scheme" instead of "logic tree".

Figures 6, 7 and 8 are too small

We will make the fonts bigger in this figures.

Bibliography

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